ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΙΓΑΙΟΥ

ΣΧΟΛΗ ΕΠΙΣΤΗΜΩΝ ΤΗΣ ΔΙΟΙΚΗΣΗΣ

ΔΙΑΤΡΙΒΗ

για την απόκτηση διδακτορικού διπλώματος του
Τμήματος Ναυτιλίας και Επιχειρηματικών Υπηρεσιών

Γεώργιος Μαντζούρης

**« Πλαίσιο Εφαρμογής Πικοδορυφόρων
στην Πειρατεία και την Θαλάσσια Ασφάλεια »**

Συμβουλευτική Επιτροπή:

Νικήτας Νικητάκος,
Καθηγητής, Τμήμα Ναυτιλίας και
Επιχειρηματικών Υπηρεσιών,
Σχολή Επιστημών της Διοίκησης,
Πανεπιστήμιο Αιγαίου
(επιβλέπων)

Periklis Papadopoulos,
Professor, Department of Astronautical
Engineering, San Jose State University,
Silicon Valley, California

Alex Bordetsky,
Professor, Information Sciences
Department, US Naval Postgraduate
School, Monterey, California

Επταμελής Επιτροπή:

Νικήτας Νικητάκος,
Καθηγητής Τμήμα Ναυτιλίας και
Επιχειρηματικών Υπηρεσιών,
Σχολή Επιστημών της Διοίκησης,
Πανεπιστήμιο Αιγαίου
(επιβλέπων)

Periklis Papadopoulos,
Professor, Department of Astronautical
Engineering, San Jose State University,
Silicon Valley, California

Alex Bordetsky,
Professor, Information Sciences
Department, US Naval Postgraduate
School, Monterey, California

Ιωάννης Κούκος,
Καθηγητής, Σχολή Ναυτικών Δοκίμων,
Τομέας Συστημάτων Μάχης, Θαλασσίων
Επιστημών, Ναυτικών Επιχειρήσεων,
Τηλεπικοινωνιών & Ηλεκτρονικής

Θεόδωρος Λίλας,
Επίκουρος Καθηγητής, Τμήμα Ναυτιλίας
και Επιχειρηματικών Υπηρεσιών,
Σχολή Επιστημών της Διοίκησης,
Πανεπιστήμιο Αιγαίου

Άννα-Μαρία Κοτρίκλα,
Επίκουρη Καθηγήτρια, Τμήμα Ναυτιλίας
και Επιχειρηματικών Υπηρεσιών,
Σχολή Επιστημών της Διοίκησης,
Πανεπιστήμιο Αιγαίου

Γεώργιος Πρώϊος,
Επίκουρος Καθηγητής, Τμήμα Ναυτιλίας
και Επιχειρηματικών Υπηρεσιών,
Σχολή Επιστημών της Διοίκησης,
Πανεπιστήμιο Αιγαίου

ΧΙΟΣ, Οκτώβριος 2016

UNIVERSITY OF THE AEGEAN

SCHOOL OF BUSINESS ADMINISTRATION

DISSERTATION

in pursue of Doctor of Philosophy
Department of Shipping Trade and Transport

Georgios Mantzouris

« Application of Picosatellites framework in Maritime Piracy and Security »

Ph.D. Advisors:

Nikitas Nikitakos,

Professor, Department of Shipping Trade and Transport, School of Business Administration, University of the Aegean

(supervisor)

Periklis Papadopoulos,

Professor, Department of Astronautical Engineering, San Jose State University, Silicon Valley, California

Alex Bordetsky,

Professor, Information Sciences Department, US Naval Postgraduate School, Monterey, California

7-member Ph.D. committee:

Nikitas Nikitakos,

Professor, Department of Shipping Trade and Transport, School of Business Administration, University of the Aegean

(supervisor)

Periklis Papadopoulos,

Professor, Department of Astronautical Engineering, San Jose State University, Silicon Valley, California

Alex Bordetsky,

Professor, Information Sciences Department, US Naval Postgraduate School, Monterey, California

Ioannis Koukos,

Professor, Hellenic Naval Academy, Department of Combat Systems, Ocean Science, Naval Operations, Telecommunications & Electronics

Theodoros Lilas,

Assistant Professor, Department of Shipping Trade and Transport, School of Business Administration, University of the Aegean

Anna-Maria Kotrikla,

Assistant Professor, Department of Shipping Trade and Transport, School of Business Administration, University of the Aegean

Georgios Proios,

Assistant Professor, Department of Shipping Trade and Transport, School of Business Administration, University of the Aegean

Chios, Oct 2016

Jointly supervised by

University of the Aegean

Chios, Greece

Professor Nikitas Nikitakos

Department of

Shipping Trade and Transport

San Jose State University,

Silicon Valley, California

Professor Periklis Papadopoulos

Department of

Astronautical Engineering

US Naval Postgraduate School,

Monterey, California

Professor Alex Bordetsky

Department of

Information Sciences

Important note:

In pursue of this Ph.D. dissertation, three nanosatellites and two ground stations were designed and used:

- *Lambda satellite (www.lambdasat.com), designed, delivered for launch – NASA mission success (March 2015).*
- *Tubesat designed and used in US Naval Postgraduate School's (NPS) CENETIX Lab testbed (July 2016).*
- *UOA/MythPelSat (www.mythpelsat.com) designed and delivered to NASA for launch (August 2016).*
- *Ground stations in University of the Aegean and Hellenic Naval Academy sites.*

The author was Project Manager in the above initiatives acquiring for all mission success.

Αφιερώνεται,

*στη **Σύζυγό** μου που <u>πήρε το παρελθόν μου και το έκανε μέλλον</u>…*

*στον **Πατέρα** μου και στη **Μητέρα** μου που στήριξαν το παρελθόν μου και εξακολουθούν να στηρίζουν το παρόν και το μέλλον μου…*

*στα **Τέκνα** μου, τον Γιαννιό, τη Θεανούλα, τον Κυριακούλη και το Νικολή, που τους εύχομαι να κάνουν το παρόν μου αιωνιότητα…*

*στον **Πανάγαθο** που μας σκέπει.*

Dedicated to,

*my **Wife** who <u>derived from my past our future…</u>*

*my **Father** and **Mother** who supported my past and continue to support my present and future…*

*my **Kids**, John, Theano, Kiriakos and Nikolas, to whom I wish to take my present and make it eternity…*

***God** who safeguard us.*

Acknowledgements

The dissertation was a product of many years effort in order to finally reach a result. In this process I understood more than ever the values and principles of the word “teamwork”. Nothing could be done without the undivided support of the following people, who I would like to specifically thank as a minimum requital to the effort sacrificed for my Ph.D. research. I will mention here all of them in order not to ever forget that this result is not solely mine. It is because that all of them believed in my motivation and soul strength and the only thing I had to give them back is this research that I humbly believe will add something small but useful to the global scientific community.

With these words said I would like to deeply thank,

- First of all, **Professor Nikitas Nikitakos,** (my supervisor) who took all of my Ph.D. efforts, ideas, work and motivation on his shoulders and materialized them into vision. Without his unique support, enlighting guidance and infinite patience nothing would have happened,
- **Professor Periklis Papadopoulos,** (NASA Ames Research Center advisor and retired Director, Dean of Astronautical Engineering Dept. of San Jose State University, Silicon Valley, California), who believed in me directly and transformed my passion to be a project manager of real successful nanosatellite missions in NASA. Without his support there would be no real data collection on this dissertation,
- **Professor Alex Bordetsky,** (advisor, tenure Professor from US Naval Postgraduate School in Monterey, California) who always believes in my passion and supports my efforts, even though Atlantic Ocean and the Aegean Sea are dividing physically our locations of work. With his tremendous support, from 2009 up to now, I managed to complete difficult tasks and only under his supervision. The grants he gave me to visit NPS were decisive in completing my Ph.D. work. His visualization and leading by example methods, made me on a great extent what I am now.
- **Professor – Astronaut Jim Newmann**, (US Naval Postgraduate School Provost at time) who instilled in me the passion for successful satellite missions. By

saying to me, graduating from my MSc studies and having him advisor in class projects, some years ago “make your own birds Georgios” he plunged in me the passion to create nanosatellites in Greece and deliver them through NASA successfully to orbit. Through this Ph.D. trip he continued to support me on the background with his precious advises,

- **Professor Kolar Ramesh**, (US Naval Postgraduate School Astronautical engineering Professor – Master thesis advisor) who gave me the right path from my Master thesis and continued to support me throughout this long trip, by advising and granting me the first scholarship to move to NPS and start working primitively on my Ph.D.,

- **Professor Ioannis Koukos,** who supported me throughout this trip not only with his immense knowledge and experience being a former NASA JPL scientist, but also by giving me courage on a weekly basis in order to focus on my work and finish this difficult task. In parallel, he selected me multiple times to lecture his classes giving me by that way a huge opportunity to increase my lecturing confidence,

- **Admiral (ret.) Athanasios Makris,** (previous Commander of NATO Maritime Interdiction Operational Center in Souda Bay, Crete) who recognized my work and acquainted me with Professor Nikitas Nikitakos. Not so many people (Admirals) dedicate their precious spare time to a young Lieutenant (at that time back in 2010) and inspire into him their own motivation and experience,

Also, I would like to thank and recognize in this dissertation the tremendous and exemplary support I received from the following globally distinguished Professionals:

- **Dr Takis Papadopoulos,** who always supports our picosatellite efforts in Greece with his experienced way of thinking and directs safely our whole endeavor to success in future,

- **Mr Marco Manso**, CEO of RINICOM Ltd, who supported / funded directly (when needed for the execution of the Lambdasat picosatellite launch from NASA) our mission and provided us all the needed means for the creation of the University of the Aegean picosatellite ground station,

- **Mr Zacharias Sarris**, CEO of ALTUS CO for believing in my vision by supporting / funding the creation of the University of the Aegean picosatellite ground station,
- **Mr Eugene Bourakov**, (Chief Engineer of CENETIX NPS Lab, Information Sciences Dept.) who always supported me in my crazy ideas without complying when tens of hours sacrificed his mind and spare time to provide gold and valuable advices in order to promote our research efforts,
- **Mr Steve Mullins,** (Ph.dc in Information Sciences Dept. at NPS) who always gave solutions to any questions raised. He supported me psychologically to continue to move on taking into account that his position and mindset was and is similar to mine until now,
- **Dr Kyriakos Kourousis**, Assistant Professor in the University of Limerick, Scotland, where jointly worked and published with the author two journal papers. Kyriakos as a close friend gave me precious advice on drafting sound journal papers.
- **Mr Manolis Darkadakis**, previous President of the Radio Amateur Association of Greece, who gave me voluntarily all of his consolidated knowledge in order to build two ground stations in Greece and accumulate all the precious data for my research. He continues to support us whenever we ask that any time, any day.
- **Mr Ioannis Traikos**, President of the Radio Amateur Association of Greece, who literally built the ground stations voluntarily and continues to support all of our actions until now, any crazy time we ask for that.

Last but not least,

I would like to ascribe my success to the **Hellenic Navy,** for giving me the ability and opportunity to pursue my Master's Degree, in US Naval Postgraduate School, Monterey California and most importantly for all the time and resources sacrificed for my education from my cadet period up to now.

Index Table

Acknowledgements..5
List of Figures..12
List of Tables..14
List of Graphs..16
Σύνοψη..18
Η ιδέα του Picosatellite..19
Κίνητρα Έρευνας..20
Υπολογισμός Κινδύνου Πειρατείας - Θαλάσσιας Τρομοκρατίας..21
Σκοπιμότητα και Στόχοι της Διατριβής..21
Συμβολή της Διατριβής (Added Value)..22
Επίλογος..24
Ph.D. Dissertation Synopsis..28
Research Aim and Vision..28
Significance of Research - Added Value..28
Awards..32
Publications prior to official Ph.D. start..33
Publications in Ph.D..35
Thesis Advisory (Επίβλεψη Εργασιών)..37
Grants..38
PhD Methodology Graphical Representation..39
Chapter 1: Introduction..41
Aim..41
The Operational Maritime Dimension..43
Pico-satellite Approach – State of the Art Review..43
Geostrategic Effect..47
Maritime Security Data Survey..49
Maritime Piracy Resources..51
References..53
Chapter 2: Maritime Picosatellites - Literature Survey..56
Picosatellites Operational Characteristics..56
Doppler Shift in Picosatellites..66
References..69
Chapter 3: Orbital Propulsion for Picosatellites..71

Introduction 71
Background Theory 72
Propulsion Categorizations 78
Electric Propulsion Characteristics 81
Electric Propulsion Thrusters – Categories 84
Small satellites propulsion 88
Microwave Electrothermal Thrusters (MET) 94
Critical Analysis 106
Conclusion - Commercial on orbit propulsion for Picosatellites 114
References 116
Chapter 4: Picosatellites Radiation and Shielding - Literature Survey 120
Introduction 120
Vulnerability issues of satellites operating in LEO. 122
Environmental effects on satellites operating in LEO 127
Effects of the environment on the power supply and electronics 136
Shielding 139
Conclusions 144
References 146
Chapter 5: Maritime Security Scenarios 151
First Scenario: One ship - One Microsatellite (FO-29) 151
Second Scenario: One ship - One Picosatellite (Lambdasat) 162
Third Scenario: One ship with 4-6 picosatellites coverage 167
Fourth Scenario: One ship - One Picosatellite (Tubesat) 169
Fifth Scenario: One ship - Continuous (24/7) Coverage 169
References 170
Chapter 6: The Lambdasat Case 172
Lambdasat concept 172
NASA Mission Justification 173
Lambdasat Mission Milestones 176
Overall Mission Objectives 177
Pico-satellite Operational Characteristics 179
Lambdasat Design 180
Lambdasat Operational Characteristics 181
Lambdasat Link Budget - Communication 184
Ground Station Design 187

Experiments 190
Analysis of Acquired Orbital Data 200
Overall Facts - Findings - Results 202
Conclusion 215
Chapter 7: The Tubesat Case 218
Small Satellites in Maritime Situational Awareness 220
Picosatellites in MIO Networks 223
Picosatellite characteristics critical to MIO Support 227
Tubesat STK modeling - Support to MIO 231
Assembly of the Tubesat picosatellite 232
Picosatellite integration modeling results 235
Picosatellite Orbital Decay Effects 237
Orbital Analysis and Results 238
Orbital Mesh Competence Network Model 242
Market Available Mesh Tactical Equipment 253
Conclusions 254
References 257
Chapter 8: Risk Analysis in Maritime Security 259
Modeling Risk Assessment in Counter Piracy 259
Analysis 260
Risk Model - Space Index 261
Future Steps 268
Picosatellites Cost Benefit Analysis 268
Chapter 9: Conclusions - Recommendations - Proposals - Way Ahead 272
Appendices 281
Appendix 1: Orbitron Amateur Satellite Simulation Data 281
Appendix 2: Piracy text type message - LSAT decoding 284
Appendix 3: Ground Station Order - Cost Analysis 285
Appendix 4: Detailed Microsatellite Propulsion Analysis 287
Appendix 5: Tubesat Electrical - OBC Schematics 374
Appendix 6: L-sat signals decoder scheme (in Greek) 377
Appendix 7: Counter Piracy Competencies - Interlinked Networks 381
Appendix 8: Additional References Reviewed 419

List of Figures

Εικόνα	1.	Σκαριφηματική απεικόνιση του δορυφόρου Tubesat
Εικόνα	2.	Άποψη Υπολογισμού Κινδύνου Πειρατείας και Θαλάσσιας Τρομοκρατίας
Εικόνα	3.	Εναλλακτική απεικόνιση συμβάντων Πειρατείας και Θαλάσσιας Τρομοκρατίας σε περιβάλλον πραγματικού χρόνου
Εικόνα	4.	Απεικόνιση του δικτυακού ιστότοπου που δημιουργήθηκε με σκοπό την καταγραφή και ανάλυση των συμβάντων πειρατείας σε περιβάλλον πραγματικού χρόνου
Figure	5.	FO-29 Japanese microsatellite Doppler shift effect
Figure	6.	Analysis of the propulsion categories available for satellites and picosatellites
Figure	7.	Earth's Magnetosphere and its parts
Figure	8.	Earth's Radiation Belts (Van Allen Radiation Zones) with the depiction of South Atlantic Anomaly
Figure	9.	Graphical depiction of Earth's Radiation Belts and the usual orbits that satellites are using to perform their missions
Figure	10.	Vacuum Shielding on a CMOS electronic component
Figure	11.	Depiction of the process of discharge radiation shielding on a satellite
Figure	12.	Epoxy carbon is depicted (orange plate) for the protection of a critical hardware part of a satellite electronic circuit
Figure	13.	Image of the Japanese Amateur Microsatellite FO-29 (Fuji Oscar)
Figure	14.	Image of starting Point A (Malabo Island Gulf of Guinea) and ending Point B (Muscat -UAE - Strait of Hormuz) of MV's Georgios trip
Figure	15.	Total distance of merchant vessel trip from Point A to Point B
Figure	16.	Simulation of FO-29 microsatellite to cover the 3rd leg of the ship's trip
Figure	17.	Lambdasat picosatellite coverage to the area of operation
Figure	18.	Lambda satellite during construction and pre-launch phases
Figure	19.	Lambdasat picosatellite before launch
Figure	20.	Ground Station: University of the Aegean / Hellenic Naval Academy site
Figure	21.	UK Rinicom's representation of the tactical use of picosatellites
Figure	22.	Lambdasat Communications Flow
Figure	23.	Lambdasat and FO-29 microsatellites tracking using MixW
Figure	24.	First Lambdasat signal through Iridium proving mission success
Figure	25.	FO-29 Decoded message from UoA ground station
Figure	26.	Footprint and Orbit of FO-29 microsatellite during experiments
Figure	27.	Footprint and Orbit of Funcube picosatellite during experiments
Figure	28.	Lambdasat during launch from International Space Station to space on March 2015
Figure	29.	Illustration of the AIS messages recovered from Nanosat NTS
Figure	30.	Earth's shipping traffic density as it was acquired from NTSAT

Figure	31.	Coverage of M3MSat outside Canadian Territorial waters
Figure	32.	Internal structure of AISSat-1
Figure	33.	Coverage of AIS Sat outside Norwegian Territorial Waters
Figure	34.	USCG satellite network to collect and forward AIS data
Figure	35.	Tubesat Pico satellite
Figure	36.	Tubesat over maritime operations area – STK scenario
Figure	37.	Design Steps of the Tubesat Picosatellite
Figure	38.	Ad hoc network equipment on a picosatellite node
Figure	39.	Parts of MPU4 and Quad microcontrollers that could be place on orbit on board a picosatellite
Figure	40.	Concept of Space Operations in Maritime Interdiction activities
Figure	41.	Maritime Piracy holistic approach

List of Tables

Table	1.	Resources available for collecting real time piracy data for analysis
Table	2.	Small Satellite Literature Survey (partial representation)
Table	3.	Small Satellite Literature Survey – Operational Characteristics
Table	4.	Satellites through pico dealing with Maritime Security from 1995 until 2015
Table	5.	Weight (<100 kgr) and Power (W) of satellites through pico dealing with Maritime Security from 1995 until 2015
Table	6.	Comparison of chemical, nuclear & other types of propulsion for satellites
Table	7.	Overall Electric Propulsion Thrusters Analysis
Table	8.	Dual Electric Propulsion Systems Analysis
Table	9.	General Propulsion Comparison Characteristics based on power, thrust and Isp
Table	10.	Micro / nano / pico electric propulsion thrusters categorization
Table	11.	Microwave Electrothermal Thrusters Types
Table	12.	Categorization of micro/nano/pico microware electrothermal thrusters
Table	13.	Primitive literature survey of available micropropulsion systems available for picosatellites
Table	14.	ESA's radiation standards in accordance with E-ST-1O-12C
Table	15.	How Radiation affects modern satellite systems
Table	16.	Properties of Earth's Radiation Belts
Table	17.	Ionization rates in different altitudes after extensive experimental measurements in multiple satellite missions
Table	18.	Charged particles and associated energies that exist in Earth's Magnetosphere
Table	19.	Summary of the characteristics of Polymers that are used today in satellite shielding industry.
Table	20.	Tabulated Characteristics of microsatellite FO-29 (Fuji Oscar)
Table	21.	Tabulated simulation data of microsatellite FO-29 comms availability – 1^{st} leg of trip (Malabo to South Africa)
Table	22.	Tabulated simulation data of microsatellite FO-29 comms availability – 2^{nd} leg of trip (South Africa to Madagascar)
Table	23.	Tabulated simulation data of microsatellite FO-29 comms availability 3rd leg of trip (Madagascar to Gulf of Aden to Muscat)
Table	24.	Overall tabulated simulation data of microsatellite FO-29 comms availability with MV Georgios during the trip from Malabo Island (Nigeria) to Muscat (UAE)
Table	25.	Satellite Tool Kit (STK) simulation scenario results (22^{nd}- 23^{rd} Oct '14)
Table	26.	Satellite Tool Kit (STK) simulation scenario results (22^{nd} - 25^{th} Oct '14)
Table	27.	Lambdasat link budget calculations

Table	28.	Lambdasat Link budget constants
Table	29.	Analysis of equipment used for the design and implementation of the Ground Station
Table	30.	Lambdasat Decoding Piracy message
Table	31.	Lambdasat message structure
Table	32.	Lambdasat message header
Table	33.	Message Header- Source and Information Type
Table	34.	Message Header - Content Information
Table	35.	Funcube Orbital Characteristics during experiments
Table	36.	Categorization of Small Satellites in accordance with their net weight
Table	37.	Overall MIO scenario results with a use of 4 picosatellites
Table	38.	6th June 2011 - Total gap timeframe in one day
Table	39.	Daily percent time coverage with the use of 4 and 6 pico MIO satellites 4th -12th of July 2011
Table	40.	Tubesat Orbital Decay Characteristics
Table	41.	Lifetime of PICOMIO satellites
Table	42.	Market available mesh tactical equipment
Table	43.	Picosatellite GO/NO GO criteria for orbital node application
Table	44.	Picosatellite Mesh Operational Limitations
Table	45.	Empirical Piracy model based on SME reviews
Table	46.	Categorization of Piracy Incidents based on Time, Speed and Freeboard of attacked vessel
Table	47.	Services via number of Picosatellites that can be provided. Pricing in approximate numbers
Table	48.	A generic representation of satellites with respect to cost and mass

List of Graphs

Graph	1.	Απεικόνιση στοιχείων κινδύνου ως συνάρτηση της ταχύτητας, χρόνου διέλευσης και του freeboard του πλοίου
Graph	2.	Satellites vs weight that are dealing with Maritime Security
Graph	3.	Satellites vs weight (<100 kgr) through pico dealing with Maritime Security from 1995 until 2015
Graph	4.	Satellites vs Power through pico dealing with Maritime Security from 1995 until 2015
Graph	5.	Small satellites propulsion allocation of power vs thrust
Graph	6.	micro MET power vs thrust
Graph	7.	micro MET power vs thrust (below 35 W)
Graph	8.	micro MET thrust vs Isp
Graph	9.	micro MET thrust vs Isp (below 10mN)
Graph	10.	Overall efficiency of micro MET globally (%)
Graph	11.	Overall efficiency of micro MET vs Power
Graph	12.	Overall efficiency of microMETs vs Power (below 10 W)
Graph	13.	UOSAT-2 anomalies (black dots) that were recorded during a polar orbit
Graph	14.	The electron flux from 1 to 12 radii distances from the Surface of Earth
Graph	15.	Proton Flux from 1 to 12 Radii distances from Earth's Surface
Graph	16.	Existence of monatomic oxygen into Earth's magnetosphere from 100 – 900 km
Graph	17.	ESA's experimental measurements about which charged particles exist in different altitudes from Earth's surface
Graph	18.	Depiction of the durability of different materials for different incoming proton energies
Graph	19.	Combined Microsatellite Coverage Results
Graph	20.	Daily access times to ship from 22nd to 25th of Oct 2014
Graph	21.	Lambdasat elevation angles access to ship's voyage 22nd to 25th Oct '14
Graph	22.	Daily coverage with 1 to 6 picosatellite available on orbit
Graph	23.	65 Data lines received Analysis
Graph	24.	Actual Duration of Received Signal per day in Minutes
Graph	25.	Minimum Elevation that the Actual Communication with Funcube satellite observed per day
Graph	26.	Expected vs Actual Duration of Pass of the cubesat Funcube during measurements period
Graph	27.	Interrelation among three different levels of Space Orbital Mesh Competence Model
Graph	28.	Reliability function in human machine interaction
Graph	29.	Orbital Mesh Network Competence Model
Graph	30.	Risk level % analysis of our 130 piracy incidents based on speed, time and freeboard.
Graph	31.	Risk level % for different speed, time and freeboard parameters - linear regression analysis

Page Intentionally Left Blank

Synopsis in Greek

Τίτλος Διατριβής:

«Πλαίσιο εφαρμογής Πικοδορυφόρων στην Πειρατεία και την Θαλάσσια Ασφάλεια»

Σύνοψη

Το θαλάσσιο στοιχείο αποτελεί αναμφισβήτητα το μεγαλύτερο τμήμα του γήϊνου περιβάλλοντος και κατά συνέπεια αυτό το δεδομένο είναι αρκετό ούτως ώστε να έλξει την προσοχή του ανθρώπου στην εκμετάλλευσή του. Από τα αρχαία ακόμα χρόνια η εξερεύνηση και γνώση των στοιχείων του θαλασσίου περιβάλλοντος αποτελούσε αναπόσπαστο κομμάτι της ζωής του ανθρώπου και όποιος πολιτισμός είχε την δυνατότητα να μεταφέρει την πληροφορία δια των θαλασσίων οδών είχε και το πλεονέκτημα διατήρησης και ενίσχυσης των κυριαρχικών του δικαιωμάτων. Σήμερα, η γνώση των θαλασσών είναι δεδομένη, παρόλα αυτά λείπει η μόνιμη και σε πραγματικό χρόνο πληροφόρηση της κινήσεως των πλοίων μέσα από αυτή. Ιδιαίτερα σε περιοχές απομακρυσμένες από στεριές ή ακόμα και σε περιοχές ειδικού ενδιαφέροντος η απόκτηση της πληροφορίας σε πραγματικό χρόνο για την ύπαρξη ενός σκάφους αποτελεί στοιχείο το οποίο αν ληφθεί και επεξεργαστεί κατάλληλα από τον ενδιαφερόμενο μπορεί να του προσδώσει ασφάλεια (maritime security) και πλήρη γνώση των θαλασσίων οδών. Παραδείγματα της σπουδαιότητας αυτών των στοιχείων αποτελούν τα σύγχρονα και οδυνηρά για την ανθρωπότητα συμβάντα πειρατείας και θαλάσσιας τρομοκρατίας (maritime piracy & terrorism) σύμφωνα με τα οποία ο άνθρωπος μη έχοντας πλήρη γνώση και κάλυψη των θαλασσίων οδών δεν έχει την δυνατότητα ελέγχου αυτών με αποτέλεσμα το κενό που δημιουργείται να δίνει το έναυσμα για την δημιουργία φαινομένων πολύπλοκων στην αντιμετώπισή τους. Το κενό αυτό προσπαθεί η επιστήμη σήμερα να το καλύψει με την χρησιμοποίηση του διαστήματος και με μοντέλα υπολογισμού κινδύνου με τέτοιο τρόπο ούτως ώστε να παρέχει σε κάθε ενδιαφερόμενο πληροφορίες πραγματικού χρόνου στην θαλάσσια περιοχή ενδιαφέροντός του και κατά συνέπεια να επαυξήσει την πρόβλεψη της θαλάσσιας ασφάλειας, πράγμα ύψιστης σημασίας για την ναυτιλία και την διαφύλαξη των πλοίων.

Η ιδέα του Picosatellite

Η επιστήμη τα τελευταία χρόνια μας έχει κάνει κοινωνούς μιας νέας διαστημικής τάσης που κατακλύζει τις επιστημονικές κοινότητες. Ο όρος «picosatellite» περιγράφει ένα διαστημικό αντικείμενο το οποίο έχει σχεδιαστεί με σκοπό να επιτυγχάνει τις απαιτούμενες εργασίες (π.χ. συλλογή πληροφοριών θαλασσίων περιοχών) καλύπτοντας τις ελάχιστες δυνατές διαστάσεις του διαστημικού χώρου και με βάρος που σπάνια ξεπερνά το ένα κιλό (1 kgr). Έτσι έχουν κατασκευαστεί οι μικροί προσωπικοί δορυφόροι τύπου κύβου (Cubesats) ή δορυφόροι κύλινδροι (Tubesats). Οι δορυφόροι αυτοί είναι τόσο μικροί (μέγεθος ποτηριού) που αποτελούν το μικρότερο δείγμα γραφής δορυφόρου μέχρι σήμερα ενώ υπηρεσίες που είναι δυνατόν να προσφέρουν στον ιδιοκτήτη τους είναι οι κάτωθι:

- Εικόνα video σε πραγματικό ή σχεδόν πραγματικό χρόνο.
- Υπηρεσίες έρευνας και εντοπισμού αντικειμένων στη Γή.
- Προσωπικό email - τηλεφωνία
- Διαφήμιση από το διάστημα
- Πειράματα με βάση τις απαιτήσεις του χρήστη.

Εικόνα 1: Σκαριφηματική απεικόνιση του προσωπικού δορυφόρου Tubesat .
(Courtesy Interorbital: www.interorbital.com)

Η παραγγελία ενός τέτοιου τύπου δορυφόρου (Tubesat) κοστίζει περίπου 8000 - 10.000 $. Τα επιχειρησιακά πλεονεκτήματα που καλύπτει ο εν λόγω δορυφόρος είναι τεράστια αφού δίνει την δυνατότητα στον χρήστη για το χρονικό διάστημα λειτουργίας του να λαμβάνει εικόνες πραγματικού χρόνου και να έχει ανεξάρτητο δίαυλο επικοινωνίας. Έτσι αν κάποιος θέλει να καλύψει μια συγκεκριμένη θαλάσσια περιοχή επιχειρησιακά θα πρέπει να αγοράσει τον εν λόγω δορυφόρο και να λαμβάνει εικόνες και πληροφορίες θαλάσσιου περιβάλλοντος. Συνεπώς, αν σε ένα πλοίο ανατεθεί να διέλθει από περιοχή πειρατείας (πχ Ινδικός Ωκεανός ή Malacca Strait ή Δυτική Αφρική κτλ) το πλοίο θα λαμβάνει ή θα στέλνει τα σήματά του και εικόνες / πληροφορίες πραγματικού χρόνου αυτόνομα και με μηδενικό επιπλέον κόστος.

Κίνητρα Έρευνας

Μέχρι σήμερα η χρήση του διαστήματος στο θαλάσσιο περιβάλλον περιορίζεται στην χρήση συστημάτων τηλεπικοινωνιών τα οποία διατίθενται από μεγάλους και κοστοβόρους δορυφόρους τύπου Inmarsat. Με δεδομένο ότι η ναυπήγηση και εκτόξευση ενός τέτοιου δορυφόρου είναι πλέον ασύμφορη για την παγκόσμια οικονομική πραγματικότητα, αλλά και λόγω του γεγονότος ότι δεν υπάρχει άμεσο “redundancy” για την επίλυση ζητημάτων που ενδέχεται να προκύψουν κατά την 14ετή θητεία ενός μεγάλου διαστημικού οχήματος στο διάστημα, για τον λόγο αυτό η έρευνα στρέφεται, όπως άλλωστε σε όλους τους τομείς, σε πιο ευέλικτες και οικομικά συμφέρουσες λύσεις.

Στο Πανεπιστήμιο Αιγαίου αποφασίσαμε να χρησιμοποιήσουμε ένα νέου τύπου πολύ μικρό πραγματικό δορυφόρο (picosatellite) τον οποίο και θελήσαμε να εντάξουμε στην διαδικασία υποστήριξης της θαλάσσιας ασφάλειας μέσω των αρχών του space maritime tracking που εφαρμόζεται για τους μεγάλους δορυφόρους. Η προσπάθεια μας ήταν να εκτιμήσουμε / αποκαλύψουμε τα δεδομένα και τους περιορισμούς σύμφωνα με τα οποία ένας πολύ μικρός και φθηνός δορυφόρους τύπου picosatellite θα μπορεί σήμερα ή στο άμεσο μέλλον να εξυπηρετήσει την παγκόσμια Ναυτιλία και όχι μόνο και να φέρει εφαρμογές που θα είναι εφάμιλλες των παραδοσιακά μεγάλων συστημάτων που φέρει ένας δορυφόρος τύπου Inmarsat.

Για τον σκοπό αυτό δημιουργήθηκε ένας μικρός δορυφόρος τύπου “cubesat” με το όνομα “Lambdasat” (www.lambdasat.com) και μια πραγματική αποστολή εκτόξευσης και συλλογής πληροφοριών έλαβε χώρα στην **NASA** με απόλυτη επιτυχία. Επίσης δημιουργήθηκαν και δύο σταθμοί εδάφους, ο ένας εκ των οποίων στο Πανεπιστήμιο Αιγαίου και ο άλλος στην Σχολή Ναυτικών Δοκίμων, μέσω των οποίων είναι δυνατή η ανταλλαγή μηνυμάτων καταπολέμησης της πειρατείας από τον σταθμό εδάφους προς τα πλέοντα εμπορικά πλοία στις όποιες ωκεάνιες περιοχές αυτά κινούνται και αντίστροφα.

Υπολογισμός Κινδύνου Πειρατείας - Θαλάσσιας Τρομοκρατίας

Επίσης στα πλαίσια της ανωτέρω ερευνητικής προσπάθειας δημιουργήθηκε ο δικτυακός τόπος (www.maritimerisk.gr) ο οποίος παρακολουθεί πιλοτικά τα συμβάντα πειρατείας και υπολογίζει τον κίνδυνο που προκύπτει από αυτά, ενώ ταυτόχρονα έχει δημιουργηθεί και ένα πρωτόλειο μοντέλο το οποίο ανάλογα με στατιστικά στοιχεία, (ανάλυση παλινδρόμησης συμβάντων πειρατείας), καθώς και με επίσημα στοιχεία συλλεχθέντα από τους διεθνείς ναυτιλιακούς οργανισμούς, παρακολουθεί και υπολογίζει το επίπεδο κινδύνου που ένα πλοίο μπορεί να έχει σε περίπτωση που σήμερα διέλθει από μια περιοχή πειρατείας ή μια θαλάσσια περιοχή με ύπαρξη κάθε μορφής θαλάσσιας τρομοκρατίας. Η εφαρμογή αυτή έχει εφαρμοστεί πιλοτικά και έχει αποδείξει απτά αποτελέσματα στην καταγραφή και υπολογισμό του κινδύνου και σήμερα είναι σε θέση να χρησιμοποιηθεί ως επίπεδο πρόβλεψης ασφάλειας 24 - 36 ωρών (ή και μεγαλύτερο) σε επικίνδυνες θαλάσσιες περιοχές της Γης. από την ναυτιλία. Για την ακριβέστερη εύρεση συμβάντων και θέσεως πλοίων χρησιμοποιούνται στα πλαίσια της έρευνας μας και οι picosatellites που αναπτύξαμε, οι οποίοι δίνουν με ακρίβεια σχεδόν πραγματικού χρόνου δεδομένα επιπρόσθετα από τα ήδη διαθέσιμα από άλλες διεθνείς πηγές.

Σκοπιμότητα και Στόχοι της Διατριβής

Αποκλειστική σκοπιμότητα της παρούσας διατριβής είναι η δημιουργία ενός αρχικού αλλά πραγματικού πλαισίου, στο οποίο θα είναι δυνατόν να αποκαλυφθούν τα δεδομένα και οι δυνατότητες υποστήριξης της θαλάσσιας ασφάλειας και γενικότερα της ναυτιλίας μέσω της χρήσης πολύ μικρών δορυφόρων. Απαραίτητη προυπόθεση είναι οι δορυφόροι αυτοί να έχουν συμμεθέξει σε πραγματικές διαστημικές αποστολές και να έχουν ληφθεί πραγματικά διαστημικά δεδομένα. Κατά συνέπεια οι τρεις βασικοί στόχοι της εν λόγω διατριβής είναι:

1. Δημιουργία ενός πραγματικού δορυφόρου μικρών διαστάσεων (τύπου «cubesat) και αποστολή του στο διάστημα.

2. Λήψη πραγματικών δεδομένων από το διάστημα μέσω αυτού του δορυφόρου και αξιολόγηση τους.

3. Δημιουργία μοντέλου κινδύνου, βασισμένο σε ανωτέρω πραγματικά στοιχεία, που θα αφορά την διασύνδεση της θαλάσσιας ασφάλειας με το διάστημα.

Συμβολή της Διατριβής (Added Value)

Όσον αφορά στην συμβολή της διατριβής αναφέρονται τα ακόλουθα:

Αρχικά εκτελείται εκτενής βιβλιογραφική έρευνα βάση της οποίας αποκαλύπτονται όλες οι πτυχές / κενά στην παγκόσμια έρευνα που αφορούν στην χρήση των πολύ μικρών δορυφόρων στον τομέα της πειρατείας και της θαλάσσιας ασφάλειας **(Κεφάλαιο 1 και 2).**

Υπολογίζονται τα χαρακτηριστικά που υπάρχουν στην παγκόσμια αγορά και αφορούν στην χρήση ειδικών χαρακτηριστικών προώθησης των πολύ μικρών δορυφόρων ούτως ώστε αυτοί να μπορέσουν να διατηρήσουν την παρουσία τους στο διάστημα για χρονικό παράθυρο μεγαλύτερο του ενός έτους και συνεπώς να γίνουν πλήρως επιχειρησιακά αξιοποιήσιμοι από την εμπορική ναυτιλία αλλά και από κάθε είδους εφαρμογή που απευθύνεται σε αυτό τον χώρο **(Κεφάλαιο 3).**

Αναλύεται η επίδραση του διαστημικού καιρού και των διαστημικών παραμέτρων / περιβάλλοντος στους πολύ μικρούς δορυφόρους μέσα από την ενδελεχή βιβλιογραφική έρευνα και την πιστοποίηση της ως επίσημο report του πανεπιστημίου NPS στο Μοντερέυ της Καλιφόρνια **(Κεφάλαιο 4).**

Αναπτύσσεται ακολούθως μεθολογία χρήσης των διαστημικών παραμέτρων για την Ναυτιλία και ειδικότερα μέσα από την αποκλειστική χρήση μικρών δορυφόρων των κατηγοριών pico και nano satellite. Η έρευνα αυτή δεν έχει μέχρι στιγμής εφαρμοστεί στην Ναυτιλία για τον υπολογισμό στοιχείων που είναι δυνατόν να μεταφέρουν οι ανωτέρω δορυφόροι από και προς τα πλοία **(Κεφάλαιο 5).**

Δημιουργείται και κατασκευάζεται ένας πραγματικός μικροδορυφόρος (Lambdasat – www.lambdasat.com) ο οποίος συμμετέχει σε πραγματική αποστολή της NASA και αποσπά την πιστοποίηση επιτυχούς διαστημικής αποστολής (**successful NASA mission** http://www.nasa.gov/mission_pages/station/research/experiments/1865.html) . Ο δορυφόρος αυτός εφάρμοσε για πρώτη φορά τις αρχές του maritime security σε διαστημικό όχημα τέτοιου μεγέθους και μετά την λήψη διαστημικών δεδομένων προέκυψαν πολύ χρήσιμα συμπεράσματα τα οποία δημοσιεύθηκαν σε αντίστοιχα journals στο εξωτερικό τα οποία και αναφέρονται στο τέλος αυτής της παραγράφου συνολικά **(Κεφάλαιο 6).**

Εκτελείται προσομοίωση με την χρήση διαφορετικών υπολογιστικών προγραμμάτων για την χρήση πολύ μικρών δορυφόρων (τύπου Tubesat) στην Ναυτιλία και την θαλάσσια ασφάλεια βάσει της οποίας εξήχθησαν συμπεράσματα για την χρονική διαθεσιμότητα των πολύ μικρών δορυφόρων με βάση τα επιχειρησιακά χαρακτηριστικά της τροχιάς τους. Υπολογίστηκε το ελάχιστο μέγεθος ενός constellation που θα πρέπει να χρησιμοποιηθεί για να καλύπτει 24 ώρες / 7 ημέρες την εβδομάδα τον εκάστοτε χώρο ενδιαφέροντος. Δημιουργείαται για αυτό το σκοπό online επισκόπηση του αλγόριθμου κινδύνου σε μορφή demo ως απαραίτητο εργαλείο επισκόπησης του κινδύνου κατά την διάρκεια της πειρατείας (www.maritimerisk.gr) **(Κεφάλαιο 7).**

Αναπτύσσεται μεθοδολογία υπολογισμού κινδύνου στην πειρατεία με περαιτέρω εύκολη και γρήγορη εφαρμογή σε οποιονδήποτε ουσιαστικά πυλώνα της θαλάσσιας ασφάλειας όπως για παράδειγμα αυτόν του Border Security ή του Illegal Immigration. Υπολογίζεται το εμπειρικό μοντέλο κίνδυνοςυ της πειρατείας στην θαλάσσια ασφάλεια μέσα από διαδικασία interviews και συλλογής πληροφοριών από subject matter experts. Ακολούθως αναλύονται τα δεδομένα που συλλέγονται από εκτενή βιβλιογραφική έρευνα και υπολογίζεται ένα αναλυτικό ποσοτικό μοντέλου κινδύνου με την χρήση βασικών τεχνικών γραμμικής και λογαριθμικής παλινδρόμησης (regression analysis) για την εξαγωγή συμπερασμάτων **(Κεφάλαιο 8).**

Συλλέγεται και αναλύτεται η υπάρχουσα πληροφορία που έχει προκύψει από την χρήση των πραγματικών μικροδορυφόρων Lambdasat και Tubesat αλλά και από βιβλιογραφική έρευνα της σχέσεως κόστους και οφέλους χρήσεως μικροδορυφόρων στην θαλάσσια ασφάλεια **(Κεφάλαιο 8).**

Αναζητείται και συλλέγεται η πληροφορία μέσω συνεντεύξεων σε ειδικούς (κατά την διάρκεια ενός συνεδρίου) του πόσο επηρρεάζεται το κίνδυνος από την ικανότητα των ανθρώπων που επανδρώνουν τα εμπορικά πλοία. Ως αποτέλεσμα αυτής την έρευνας προκύπτουν δείκτες ικανότητας (competence) οι οποίοι για πρώτη φορά διασυδένονται με την θαλάσσια ασφάλεια και το διαστημικό περιβάλλον **(παράρτημα 7).**

Δημιουργούνται και εξάγονται πολύ σημαντικά συμπεράσματα για το όφελος χρήσης των πολύ μικρών δορυφόρων στην θαλάσσια ασφάλεια και γενικότερα στην Ναυτιλία **(Κεφάλαιο 9).**

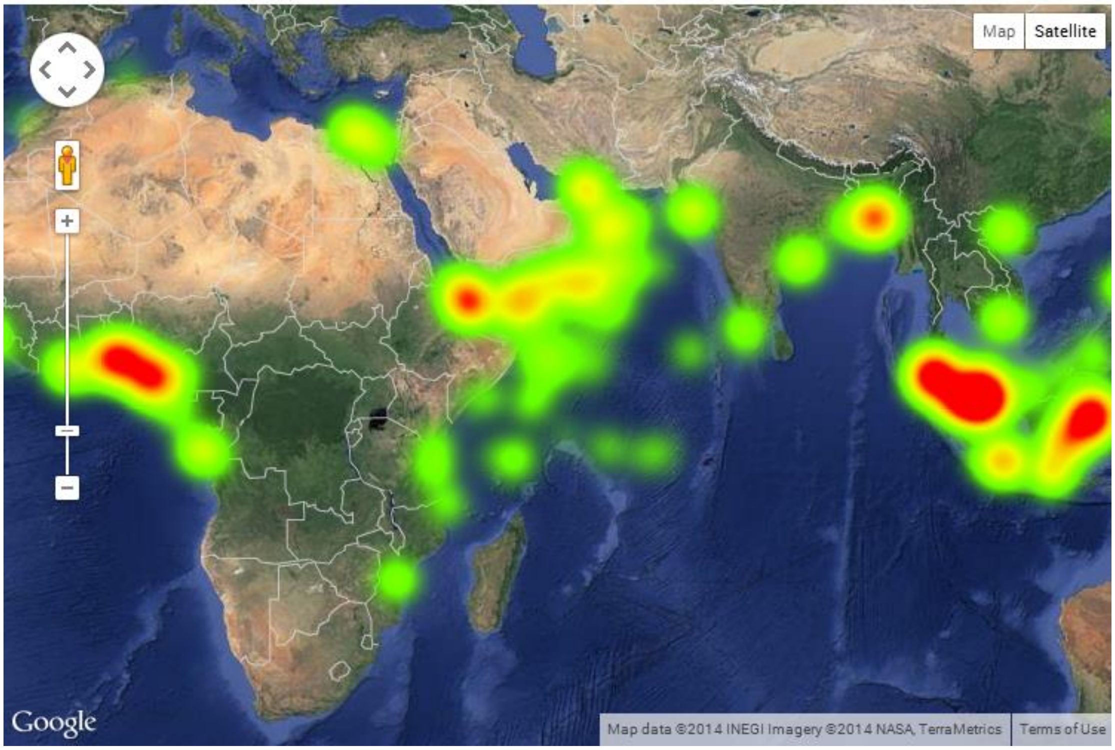
Ως απόρροια και επίρρωση των ανωτέρω δημιουργείται η ιδέα και κατασκευάζεται ο δεύτερος μικροδορυφόρος με την ονομασία UOA/MythPelSat (www.mythpelsat.com) ο οποίος τον Αύγουστο του 2016 παραδίδεται επιτυχώς στην ΝΑΣΑ. Με τον δορυφόρο αυτό, ο οποίος πρόκειται να εκτοξευθεί τον Φεβρουάριο του 2017 από τον Διεθνή Διαστημικό Σταθμό (ISS), αναπτύσσονται οι αρχές του "orbital mesh networking" σε αρχικό επίπεδο, δηλαδή το πως ένας πολύ μικρός δορυφόρος είναι δυνατόν να χρησιμοποιεί αλγορίθμους και τηλεπικοινωνιακές οδούς «αγνώστων διαδρομών» για να υποστηρίζει τηλεπικοινωνιακά την θαλάσσια ασφάλεια με πάρα πολύ μικρό κόστος.

Παράλληλα, είναι σε διαδικασία ολοκλήρωσης και ανάπτυξης ο τρίτος μικροδορυφόρος, ο οποίος θα λειτουργήσει ως εργαστηριακό μοντέλο και θα διασυνδεθεί με το Πανεπιστήμιο NPS και το San Jose State Universities, ούτως ώστε και με τους αντίστοιχους σταθμούς εδάφους να διασυνδεθούν ρομποτικά και να υλοποιήσουν την έρευνα που αποσκοπεί στην αποκάλυψη των αρχών του "space orbital mesh networking", όπως επιγραμματικά αναφέρονται στο κεφάλαιο 7.

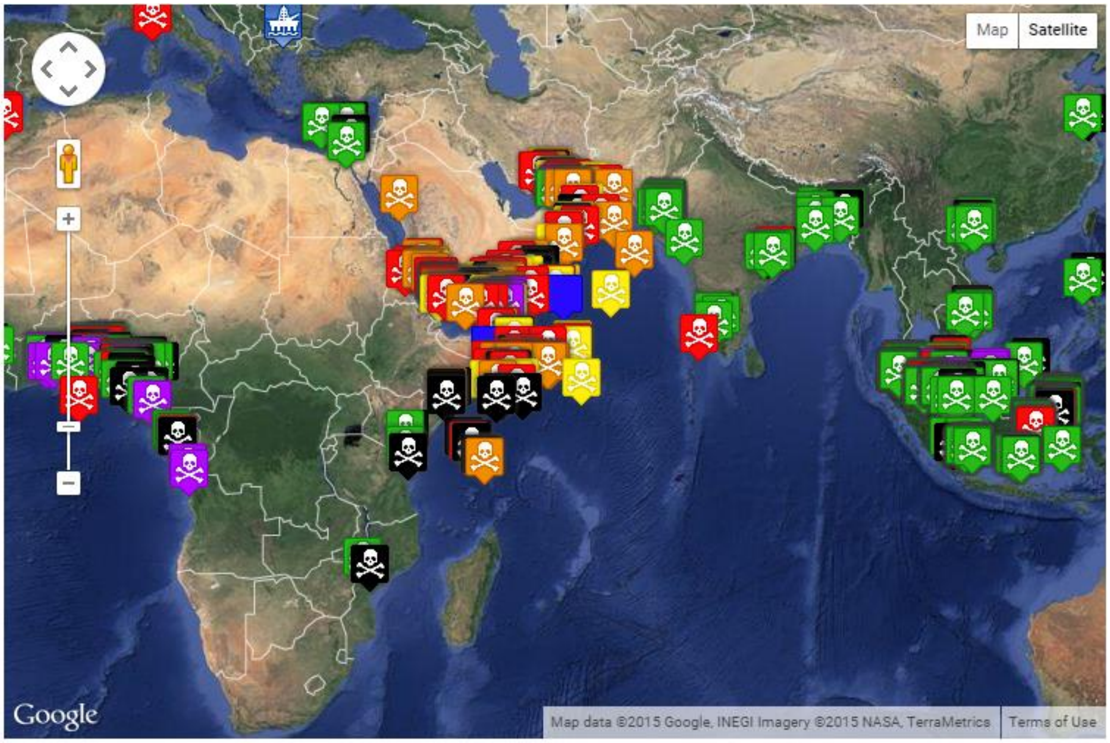
Επίλογος

Από την ανωτέρω ιχνηλάτηση και εφαρμογής της ιδέας των picosatellites και του υπολογισμού κινδύνου θα αντιληφθούμε ότι με το πέρασμα του χρόνου επιτυγχάνεται δραστική μείωση του κόστους στην χρήση του διαστήματος σε εφαρμογές στην Ναυτιλία. Είναι επίσης εμφανές ότι ο υπολογισμός κινδύνου μέσω και της χρήσης των σύγχρονων μικροσκοπικών διαστημικών εφαρμογών (miniature satellites) θα αποτέλέσει τα επόμενα χρόνια τον θεμέλιο λίθο των εφαρμογών, ούτως ώστε η ναυτιλία να είναι δυνατόν να ανταποκριθεί στις αυξημένες απαιτήσεις μέσα σε ένα περιβάλλον ύψιστης ασφάλειας στο θαλάσσιο περιβάλλον.

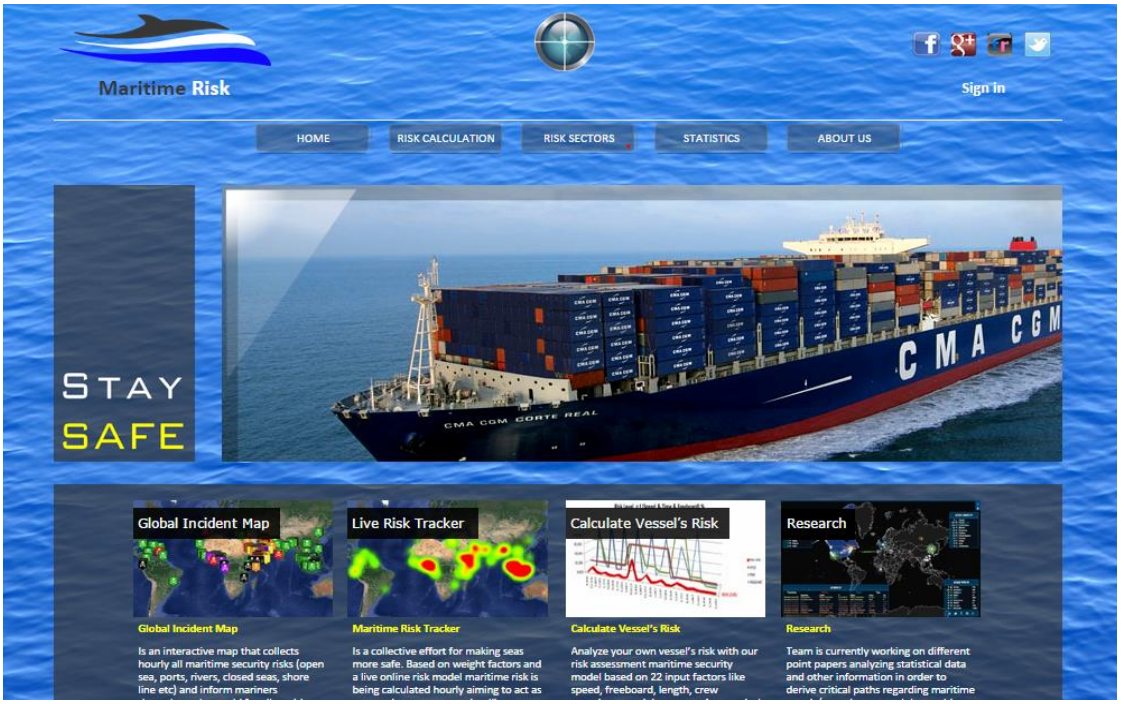
Με την παρούσα διδακτορική διατριβή αποκαλύπτεται μέσω των πειραμάτων που διεξήχθησαν και ανακοινώθηκαν σε διεθνείς συνεδρίες και περιοδικά ότι, σύμφωνα με τα πραγματικά δεδομένα, οι picosatellites θα διαδραματίσουν προεξάρχοντα ρόλο στην ανταλλαγή των πληροφοριών στην Ναυτιλία κάτα την επόμενη εικοσαετία.



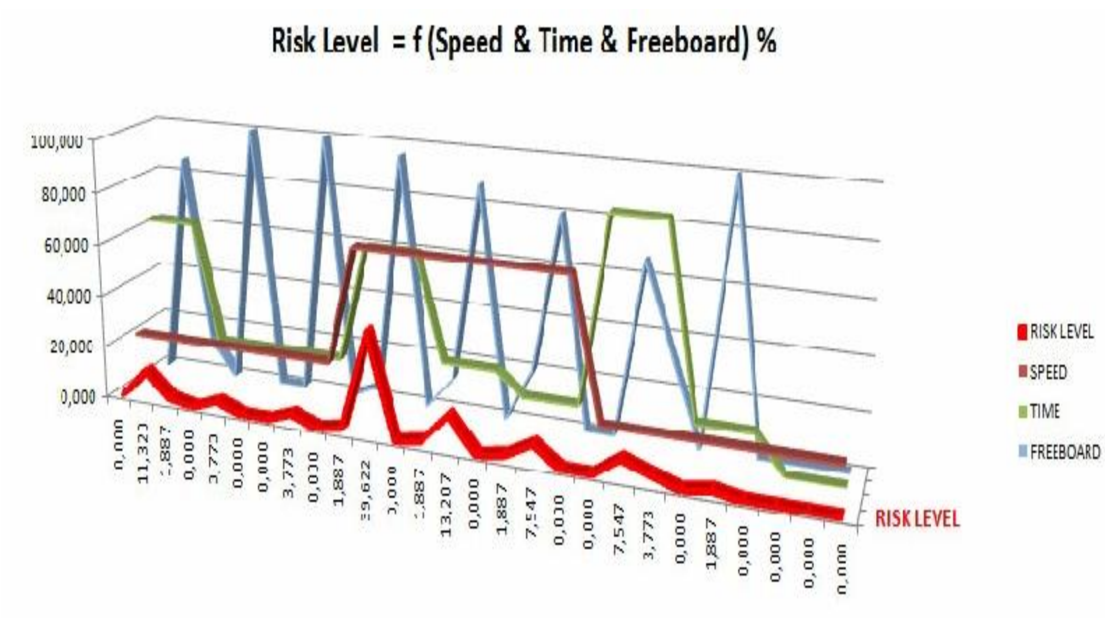
Εικόνα 2: Άποψη Υπολογισμού Κινδύνου Πειρατείας και Θαλάσσιας Τρομοκρατίας (Real Time απεικόνιση - courtesy www.maritimerisk.gr)



Εικόνα 3: Εναλλακτική απεικόνιση συμβάντων πειρατείας και θαλάσσιας τρομοκρατίας σε περιβάλλον πραγματικού χρόνου (courtesy www.maritimerisk.gr)



Εικόνα 4: Απεικόνιση του δικτυακού ιστότοπου που δημιουργήθηκε με σκοπό την καταγραφή και ανάλυση των συμβάντων πειρατείας σε περιβάλλον πραγματικού χρόνου (courtesy www.maritimerisk.gr)



Graph 1: Απεικόνιση στοιχείων κινδύνου ως συνάρτηση της ταχύτητας, χρόνου διέλευσης και του freeboard του πλοίου που εξήχθησαν από την εφαρμογή των δεδομένων της διατριβής.

Page intentionally left blank

Ph.D. Dissertation Synopsis

Research Aim and Vision

Exclusive objective of this dissertation and "Design Science" research study is the creation of a realistic framework in which we are trying to reveal links among pico or nanosatellites and the maritime security. Necessary condition to follow was the fact that we should collect real space data from real nanosatellites on orbit that their design, launch and operation would be held in this research. After successfully satisfying the above mentioned fact we quote below the three basic pillars:

1. Design and construction of a real picosatellite with an assorted ground station in order to finally participate in a real NASA mission.

2. Reception of real satellite data and analysis of them to produce prototype results.

3. Creation of a maritime security risk model based on the above received real space data, linking maritime area to picosatellites and their effectiveness in the field.

Significance of Research - Added Value

Regarding the contribution of the dissertation to "Design Science" a brief chapter analysis is being referred as follows:

Initially we execute an in depth literature survey analysis revealing all aspects / gaps in the global research and specifically to the field of using picosatellites as a mean of data transportation to maritime security situations / operations **(chapter 1 and 2).**

Characteristics of picosatellites with regards to orbital propulsion is also being collected and analyzed taking into account that one of the most important facts for a cubesat to operate is the timeframe that stays on orbit. Under this notion and having sacrificed a good amount of time and research we investigate future trends and understand through rigorous analysis what it needs to be taken in the future in order for picosatellites to become fully operational in the maritime arena **(chapter 3).**

Analysis of the space weather to cubesats is also an important part of our data analysis, taking into account that space environment is often not friendly enough to picosatellites. After a literature survey in the area an official report is being created (NPS report to United States Air Force – funded study). The study assists our analysis to fully understand and create a 360 degrees vision to the field of using picosatellites in the maritime arena (requirements and limitations) **(Chapter 4).**

A space based methodology for the use of picosatellites to maritime security is being developed by creating different scenarios based primarily on piracy effects. This research methodology is also applicable to any maritime security situation / pillar, taking into account that suitable parameters / factors have been inserted to the system **(Chapter 5).**

Design and creation of the first ever built Greek nanosatellite for maritime security (and one of the very few globally – less than three with different objectives) (Lambdasat – www.lambdasat.com), which participated in a real NASA mission and certified accordingly:

Successful NASA mission: http://www.nasa.gov/mission_pages/station/research/experiments/1865.html

This satellite applied for first time the principles of maritime security on a miniaturized satellite bus, by transferring among other messages Automatic Identification System data and creating communication paths available to merchant mariners in the middle of the ocean. From this space mission valuable data generated which published in international journals with one of them to be awarded as a remarkable contribution to European picosatellite conference in Germany **(chapter 6).**

At the same time simulation with the use of another picosatellite (Tubesat type) for maritime security applications is being conducted and results for the use and availability of picosatellites on orbit recorded. This research area uncovers what are the real operational characteristics of a miniature satellite in order to be able to communicate on a 24/7 timeframe by using a constellation type cloud of picosatellites on orbit. For this reason a web demo tool has been created (referring only to 1000 piracy events) which is being accessible through www.maritimerisk.gr . This risk tool is an effective way to one understanding how risk is being transformed throughout different areas of the world **(chapter 7).**

As the research evolves a risk methodology calculation is being created following and comparing empirical and basic regression models (linear and logarithmic) that reveal finally how risk is being altered throughout time, speed and freeboard factors. For this analysis interviews to subject matter experts have been executed as well as analysis of literature survey data in order to finally create an algorithm to approximate maritime security reality in piracy events **(chapter 8).**

Lambdasat real picosatellite and Tubesat testbed satellite feed us with real and simulation data and from the above collection analysis is being executed we conclude on how effective (taking into account cost figures) is the use of miniaturized satellites to maritime security operations. Valuable results have been reported **(chapter 8).**

On an assorted appendix (No 7) we are trying to reveal (at least on an initial level) what is the quantifiable metric of humans in the use of picosatellites in maritime security and specifically on piracy applications. For this reason and during a workshop subject matter experts have been asked and their reports analyzed to produce real metrics. This effort has been called the competence method and for the first time there is a linkage of space to maritime security through human factor analysis **(appendix 7).**

Finally broad and important detailed results have been derived from the above analysis on how effective are picosatellites to maritime security applications and how much decrease risk in merchant mariners **(chapter 9).**

As an aftermath of our "Design Science" research we build also a second picosatellite (cubesat type) which already delivered to NASA for launch. The name of the satellite is UOA/MythPelSat (www.mythpelsat.com) and is going to be placed on orbit by Feb 2017. On this satellite we have tried to use the results and experience from the above research and to execute for first time on the picosatellites the principles of "orbital mesh networking" as it is being presented at the end of this dissertation. This idea basically refers on the use of multiple picosatellites on orbit to contribute to low cost but effective maritime global comms, without knowing exactly through the use of smart algorithms which "communication path" to use.

In parallel it is under completion the design of a third picosatellite, which is going to be the robotic counterpart of the space asset to ground and with the use of our ground stations, mesh networking principle of operation is going to be executed, so as for the research to move forward. More researchers are going to be entangled to the project aiming to unravel the facts, characteristics, requirements, advantages and disadvantages of space mesh networking in global maritime arena (procedure is being analyzed briefly in chapter 7).

The idea of this Ph.D. started back in 2007 when after graduating from my Master thesis in US Naval Postgraduate School my thesis advisor Professor Kolar Ramesh guided me to start thinking about my Ph.D. research. A year later Dr. Alex Bordetsky accepted to be one of my Ph.D. advisors and we started together (under his unwearied guidance and supervision) to draft papers and present ideas on conferences. This work was the cornerstone for the Ph.D. work. Below we quote all this work dividing it into two different areas. One is the publications' section prior to the official start of Ph.D. and the other is the section where papers generated from the research during the Ph.D. timeframe on the University of the Aegean.

Awards

1. **Chief of the Hellenic Navy Research Award**

G. Mantzouris, “Interdiction of small low earth orbiting satellites from on board military crafts”, Hellenic Navy Review, Sep 2009 (in Greek), peer reviewed Journal**.**

2. **Chief of the Hellenic Navy Research Award**

G. Mantzouris, “MIO Satellite Interdiction Operations”, Hellenic Navy Review, Nov 2010 (in Greek), **(**Journal).

3. **Chief of the Hellenic Navy Research Award**

G. Mantzouris, “Micro and Pico satellites in Maritime Security Operations”, Journal of Naval Science and Engineering, 2012, Vol.8, No 2, pp. 1-30, peer reviewed Journal.

4. **Awarded paper as remarkable contribution to small satellite applications (among 64 European papers)**

G. Mantzouris, P. Papadopoulos, N. Nikitakos, “Lambda UoA Pico-Satellite for Maritime Security”, 8^{th} Pico and Nanosatellite Workshop, 15-16 September 2015, Wurzburg, Germany. International Academy of Astronautics (IAA) Book Series, ISBN/EAN IAA: 978-2-917761-49-6, pp 67-75 (International Aerospace peer reviewed Journal) (Session 2b – Technology for Small Satellite Research)

Publications prior to official Ph.D. start

(Peer Reviewed Journals/ Conferences / Invited Lectures)

1. G. Mantzouris, K. Ramesh, “Low Earth Orbiting Satellites - Radiation and Shielding”, NPS official report, May 2008. (Peer review).

2. G. Mantzouris, “Microsatellites in maritime interdiction operations”, Hellenic Navy Review, Oct 2008 (in Greek).

3. G. Mantzouris, “Interdiction of small low earth orbiting satellites from on board military crafts”, Hellenic Navy Review, Sep 2009 (in Greek), **(Chief of the Hellenic Navy Research Award -** peer reviewed Journal**).**

4. G. Mantzouris, “Picosatellites in MIO tracking WMD materials”, NMIOTC MIO Journal Inaugural Issue, Feb 2010 (Journal).

5. A. Bordetsky, G. Mantzouris, “Picosatellites in Maritime Interdiction Operations”, 15th ICCRTS Conference Proceedings, Santa Monica, LA, CA, 22-24 June 2010.

6. A. Bordetsky, G. Mantzouris, “MIO Experimentation at NMIOTC: Networking and Collaboration on small craft maritime sourced nuclear radiological threat detection and interdiction”, NMIOTC MIO Journal 2nd Issue, November 2010 (Journal).

7. T. Dobbins, G. Mantzouris, “Modelling Human performance in MIO”, NATO RTO-MP-HFM-202, NATO RTO Conference, Brussels, October 2010.

8. G. Mantzouris, “MIO Satellite Interdiction Operations”, Hellenic Navy Review, Nov 2010 (in Greek), **(Chief of the Hellenic Navy Research Award -** Journal).

9. A. Bordetsky, G. Mantzouris, “Modeling of Picosatellite Network Applications to Maritime Interdiction Operations”, 16th International Command and Control Research and Technology Symposium / Proceedings – ICCRTS, Quebec, Canada, 21-23 June 2011 (peer reviewed conference).

10. A. Bordetsky, G. Mantzouris, “SPACE MIO: Modeling of Picosatellite Network Applications to Maritime Interdiction Operations”, NMIOTC MIO Journal 3rd Issue, June 2011 (Journal).

11. G. Mantzouris, A. Bordetsky, “Modeling of Pico Satellite Network Applications to Maritime Interdiction Operations”, 2nd International Conference on Space Technology, Athens, 15-17 Sept 2011 (peer review Journal).

12. G. Mantzouris, A. Bordetsky, "Joint NPS – Lawrence Livermore National Lab Experimentation", Georgios Mantzouris and Dr. Alex Bordetsky, NMIOTC MIO Journal 4th Issue, November 2011, (Journal).

13. N. Nikitakos, G. Mantzouris, "Picosatellites in support of Maritime Safety Awareness while transiting high risk areas. A preliminary analysis and design", Journal on Southeastern European Security Strategy and Transatlantic Leadership, Vol. II, November 2011, (peer reviewed Journal).

14. G. Mantzouris, N. Nikitakos, "Geostrategic Value of Using Picosatellites in support of Maritime Security awareness while transiting high risk areas", Empiricum, Middle East Forum, Issue 10, June 2012.

15. G. Mantzouris, "Micro and Pico satellites in Maritime Security Operations", Journal of Naval Science and Engineering, 2012, Vol.8, No 2, pp. 1-30 **(Chief of the Hellenic Navy Research Award -** peer reviewed Journal).

16. G. Mantzouris, "Operational Effectiveness of Maritime Surveillance Systems. A primitive study towards picosatellites to support MIO", NMIOTC Conference, June 2012.

Publications in Ph.D.

(Peer Reviewed Journals/ Conferences / Invited Lectures)

17. G. Mantzouris, N. Nikitakos, "Picosatellites and Counter Piracy Research in the UoA - Maritime Security Risk Tracking", the digital ship conference, Athens, 26-27 Nov 2013.

18. G. Mantzouris, "Armed Guards Contribution in Maritime Security - Horizon 2020", 1st Executive MARSEC conference, Athens, 12th Dec 2013 (Invited Lecture).

19. G. Mantzouris, P. Papadopoulos and N. Nikitakos, "Picosatellites and Maritime Security - Lambdasat Mission", European Union Maritime Security Conference, Hellenic Navy Defense General Staff, NMIOTC, Souda Bay, March 2014 (Invited Lecture).

20. G. Mantzouris, "Picosatellites and Counter Piracy Research in UoA - Maritime Security Risk Tracking", SMI Conference Invited Paper, Singapore 14-15 May 2014.

21. G. Mantzouris, N. Nikitakos et al "Counter Piracy Training Competencies Model", International TRANSNAV 2015 conference, May 2015, Session Terrorism and Piracy (peer reviewed Journal)

22. G. Mantzouris et.al. "Exploring the Application of Picosatellites for Maritime Security", 20th International Command and Control Journal / Conference, California, June 2015 (peer reviewed conference and Journal).

23. G. Mantzouris, N. Nikitakos, I. Koukos, "LEO Picosatellites in Maritime Security Distress Operations - Modeling Space Index Factor Risk Analysis", Athens, 8-11 July 2015

24. G. Mantzouris, P. Papadopoulos, N. Nikitakos, "Lambda UoA Pico-Satellite for Maritime Security", 8th Pico and Nanosatellite Workshop, 15-16 September 2015, Wurzburg, Germany. International Academy of Astronautics (IAA) Book Series, ISBN/EAN IAA: 978-2-917761-49-6, pp 67-75 (International Aerospace peer reviewed Journal) (Session 2b – Technology for Small Satellite Research) – **Awarded paper as remarkable contribution to small satellite applications (among 64 European papers)**

25.

26. G. Mantzouris, N. Nikitakos, P. Papadopoulos, A. Bordetsky, K. Kourousis, "Picosatellites for Maritime Security Applications - The Lambdasat Case", Journal of Aerospace Technology and Management (JATM), Editions V7N4, pp. 551 (peer reviewed Journal)

27. G. Mantzouris, N. Nikitakos et.al. "Recommendations on realising the benefits provided by enhanced counter - measures", Report on Counter Piracy, funded by Seventh Framework Program EU under SEC-2013.2.4-2, GA No. 607685. (EU peer reviewed report)

28. G. Mantzouris, P. Papadopoulos, N. Nikitakos, "Picosatellites and Maritime Security - Lambdasat Mission", General Directorate of Defence Research and Innovation (GDAEE) conference, Athens, 20th October 2015 (Invited Lecture).

29. T. Sakkas, G. Mantzouris, N. Nikitakos, "Multidimensional Use of UAVs in global scale", Academy for Strategic Analysis Conference, Athens 16 Nov 2015. (Invited Lecture).

30. I. Koukos, G. Mantzouris, K. Karanagnostis, "UAV program Vellerofontis in Hellenic Naval Academy", Academy for Strategic Analysis, Athens 16 Nov 2015. (Invited Lecture).

31. G. Mantzouris, creation of the site and Risk Tracker tool in www.maritimerisk.gr

Thesis Advisory (Επίβλεψη Εργασιών)

During Ph.D. the following postgraduate and graduate studies / thesis have been primarily supervised:

1. G. Tsiotsios, "The use of Ground Station for Picosatellites in Maritime Security Operations", Hellenic Naval Academy undergraduate thesis, June 2014.

2. P. Doukas, "Design and Use of UoA Ground Station for picosatellite applications in Maritime Security", Hellenic Air Force Academy undergraduate thesis, June 2015.

3. T. Sakkas, "UAVs in Maritime Security – A design and methodology approach" Master thesis, University of the Aegean, June 2013.

4. I. Bazinas, "The use of Picosatellites in Maritime Security Operations – An operational approach", Hellenic Naval War College postgraduate thesis, Sep 2014.

5. G. Dedousis, "Design of a Picosatellite for Maritime Security – A to Z approach toward launching a new satellite", Hellenic Naval War College postgraduate thesis (under drafting – graduation in Feb 2017).

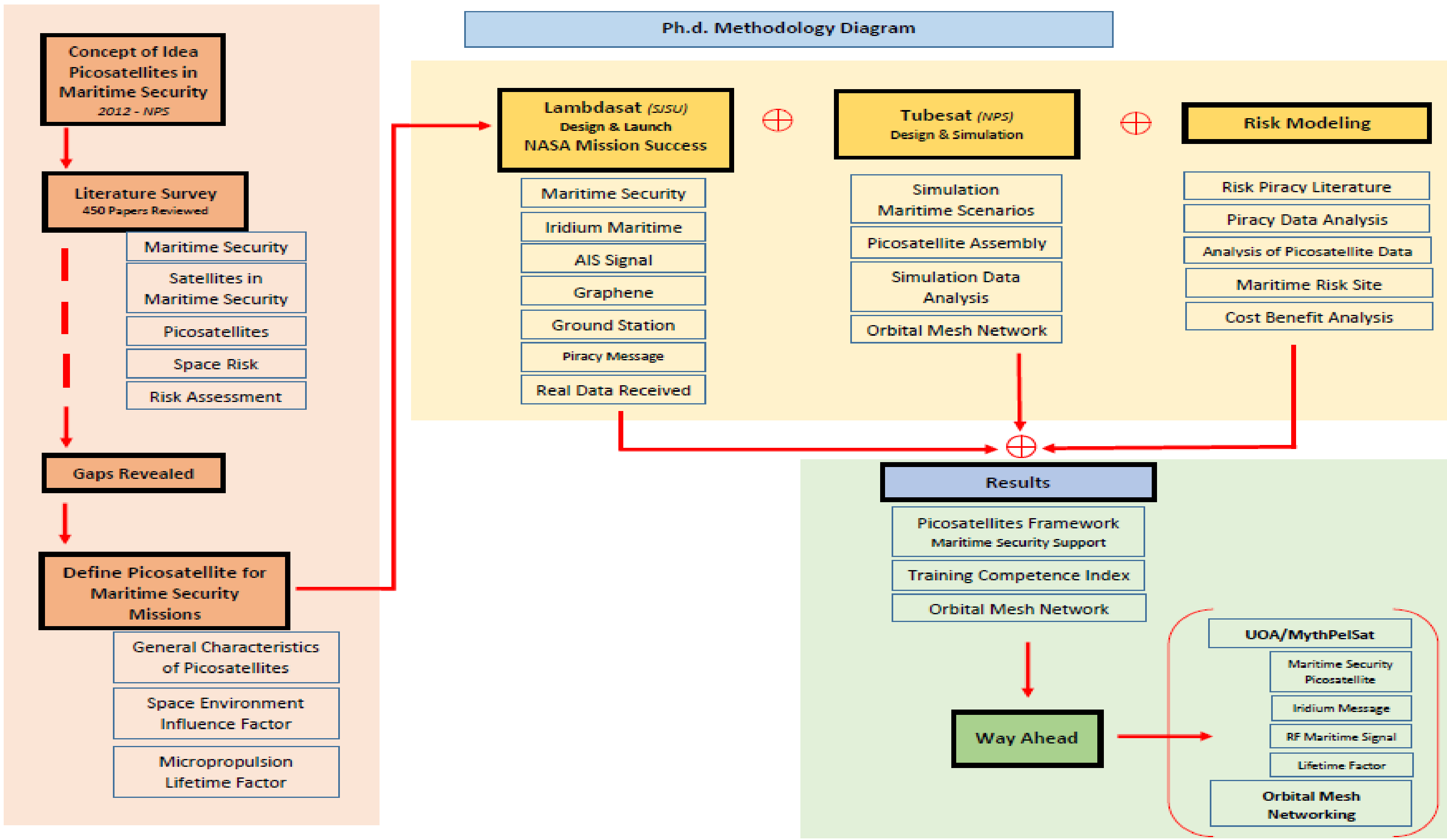
6. G. Toutoutzidakis, "The use of Picosatellites in Maritime Security – Ground Station Applications and Design", Hellenic Naval Academy undergraduate thesis, June 2016.

Grants

Starting from 2007 (date of Ph.D. conceptualization and through today the following grants and positions have been awarded:

1. **2007 - 2009:** LEO satellites vulnerabilities (US Air Force funded study)
2. **2009:** Research Associate in Naval Postgraduate School Information Sciences Department, Maritime Security Networking applications – solutions (NPS - ONR Global funded Study)
3. **2011 - 2012:** Research Associate in Naval Postgraduate School Information Sciences Department, Maritime Security Networking applications and Picosatellites (NPS – ONR Global funded Study)
4. **2013 - 2014:** Research Associate in Naval Postgraduate School Information Sciences Department, Maritime Security Networking applications and Picosatellites (NPS – ONR Global funded Study)
5. **2015 - 2016:** Research Associate in Naval Postgraduate School Information Sciences Department, Tubesat testbed integration and results (NPS – ONR Global funded Study)
6. **2013 - 2015:** Design and creation of the first UAV mini advanced helicopter for Maritime Security Applications (in last phase) (team project) Hellenic Navy (HN funded project)
7. **2013 - 2016:** EU FP7 - Vessel's Protection from piracy - University of the Aegean (EU funded project - General Assembly member)
8. **2012 – present:** Research Scholar in San Jose State University. Design and building of the Lambdasat – picosatellite and ground station supporting merchant shipping in counter piracy. Satellite now in orbit. www.lambdasat.com Now developing the second picosatellite for launch through NASA.

PhD Methodology Graphical Representation



CHAPTER 1

INTRODUCTION

Chapter 1: Introduction

Aim

The use of microsatellites and even smaller space assets in the verge of pico and femto carriers in the last decade have induced important changes on the way that mankind uses space. These alterations have been definitely affected by the global economic recession (and/or crisis) but at the same time this parameter has worked in parallel as a benefit towards the miniaturization of space assets and therefore in providing same or similar services as in the past, but with less amount of money.

Sole aim of this dissertation research is the current mapping of the characteristics of small and very small satellites, mainly in the dimension of pico assets (less than 1 kgr) and in their future application readiness level for space commercial and military missions. More importantly the case of maritime security and merchant marine navigation is going to be investigated thoroughly taking into account that marine highways (as they used to be called in the international navigation community) are throbbed from corners full of uncertainty and high risk level "opportunities" (e.g. terrorism). Different levels from the commercial to economic and military fields are going to be researched in order to prove how effective is nowadays the use of picosatellites in the maritime arena. The main research question which we are seeking to answer is how the use of Picosatellites is able to support current maritime security trends and to lessen in the maximum possible degree phenomena of terror like piracy or generally marine terrorism that infest many maritime geographical areas of the world. Also, which is going to be finally the influence to the future of marine navigation and maritime security in general.

Pico satellites (picosats) are small size short lived satellites that operate at low earth orbit. Their use is becoming popular given their relatively low cost to develop and deploy together with the fact that, having shorter lifecycles than traditional satellites, they can incorporate the latest cutting-edge technology. Numerous communities are currently exploring the use of picosats for various applications, including security and defense.

This dissertation work explores the application of picosats to assist maritime security operations, including surveillance, anti-piracy and search and rescue (depending on the use of AIS sensor or photography on board the satellite bus) [2]. We have conducted a set of experiments that resort mainly, but not only to the Lambda picosat, being one of its main objectives the transmission and dissemination of information globally between shore fusion centers and ships underway. The experiments encompassed sending messages (preformatted, free text and pictures) pertaining to e.g., suspicious activities, piracy alerts and help requests to ships in the Mediterranean Sea. Conversely, (in a simulated way through ground stations use) ships sent messages (e.g., help request, message acknowledgement) to the satellites and consequently to ground stations (simulating advisory centers ashore). Establishing short voice calls, also tried in some cases.

In order to facilitate the execution of the experiments we have built a ground station in the University of Aegean, Athens, capable to receive messages from the Lambda satellite and 54 different amateur / active satellites that are on orbit. Also, with the Tubesat picosatellite testbed in Naval Postgraduate School in Monterey California and especially in CENETIX Lab we have exchanged messages simulating supporting military oriented missions under the maritime interdiction operations (MIO) field [3].

Having in mind the sole aim of this dissertation on how the use of Picosatellites may affect future shipping and maritime security operations, we have built a set of prototype experiments with Picosatellites or microsatellites available on orbit or in available testbeds in order to acquire useful results and finally design a counter piracy model algorithm calculating risk assessment parameters, which is being enhanced with the use of picosatellites by inserting a risk space index, measuring - quantifying the overall effect of the use of picosatellite in a maritime security oriented operation. Is the risk being diminished with the use of a picosatellite or it is an independent variable playing no role in the risk algorithm? Trying to answer the above question we are hoping that this research will enlighten a new route by learning on how to use very small satellites (less than 1 kgr) in the support of a maritime security operation. Study of the critical parameters, limitations and requirements of the picosatellites as well as the maritime security problem has been thoroughly studied and important results have been accumulated indicating what are the gaps, benefits, advantages and disadvantages as well as the capabilities and requirements field up to the time of our research.

The Operational Maritime Dimension

It has been traditionally proven that surveillance in real time framework and parameters in the maritime environment attracts the most interest from communities when an operation is being planned on the strategic or operational level. The command and control procedures and command schemes needs to succeed in order for the operation to be executed in a smooth way. At the same time efforts have been made throughout the last decades to minimize assorted costs and make the intelligence command and control designs affordable and robust.

In maritime operations the factors that affect the conduction of a mission are so many that sometimes the planners follow only the most important ones and finally they do not care about side effects. It is imperative for a successful and cost effective operation to take into account all parameters that will finally lead us to a desired effect. Maritime environment is an area where real time intelligence support is of primary importance, especially when advising from ashore fusion centres is needed and implemented.

Contemporary maritime security operations are covering a full range of different missions starting from countering piracy to countering goods of mass destruction illegal proliferation, as well as human trafficking and embargo situations. All these operations cannot be followed or covered with one intelligence acquisition scheme, but usually different applications and technological frameworks are being utilized in order to effectively support them. A real time information infrastructure that will cover all of the aforementioned operations and combine them in one and cost effective intelligence scheme is still absent from today's operational and tactical maritime environment. Addressing this problem we may encounter many obstacles, but at the same time it is worth pursuing a solution like this, since if at the end we succeed, then we will have merged the cost effectiveness with the real time operational requirements covering almost all aspects of maritime security operations.

Pico-satellite Approach – State of the Art Review

In this short reference we are trying to propose to international maritime community a small but smart satellite command and control system that will be effectively used from every platform and will convey all information from the area of operation to a fusion centre ashore minimizing the assorted costs and giving to interested community (e.g. a country, a non-governmental organization, an international organization) the desired effect, which is intelligence superiority and dominance over a specified area of interest. This system needs to be cost effective in such a way that by comparing it with systems that are now in use will give 50% more surveillance capabilities and it will be at least 50% financially more effective from any other asset in use. This should be our initial goal, yet very difficult to accomplish.

Our attempt is to use the inner space area (very low earth orbits [1]) for implementing such a solution by incorporating very small satellite technologies in order to drive us to the required solution. The pathway to this end result and goal is not easy, needless to say that at the same time during an era of global economic crisis it is imperative for us to prove to international maritime community that a very small satellite system can be a viable solution and decrease the amount of spending money daily in operations. Accomplishing all the above a new business model should arise with less personnel capacity to be used in maritime security operations than it is used today, such as the participation of military personnel on board military ships on very long sea tours in the high risk areas of operation (e.g. Gulf of Aden).

In this case and being more specific we propose the so called pico-satellite system which usually refers to a standalone satellite bus (with two or more ground stations) with weight smaller than 1 kgr, capability of earth from space video imaging and simple on board processing. Flying on very low earth orbits, near the outer atmosphere at around 300 to 400 kilometres from earth's surface, these toys can convey viable information to any fusion centre ashore or to vessels underway by using basic communication schemes that are not subaltern from any other modern communication application used in space. If we are able to have up to 1.5 Mbps bandwidth and at the same time capability of transferring audio, data and even video (current level of technology) at all times through satellite passes, then we would definitely say that this application is worth mentioning and being researched. A system like this (standalone pico-satellite), which is flying at so low orbital paths can communicate on earth and transfer information covering 12 to 15 % of daily time (around 1.5 to 2 hours). Also using more than one small satellite, let's say a cluster of a dozen of those we cover almost the whole daily timeframe on top the area of our operations, leaving the only thing still to consider the cost. But the cost for a small pico-satellite is not high. With less than few thousands of dollars you can have one of those little "toys" flying over the earth (all inclusive) for the duration of your operation and as the technology now stands with maximum satellite lifetime to reach three to four months. Therefore the situation now is that this pico-satellite system can stay up only for a mission oriented operation with a timeframe of three to four months (orbital decay parameters are being implemented). Still we do not have the capability of applying micro propulsion systems on board, but it is a fact that for sure is going to happen in the near future. With the application of small but effective microwave electrothermal thrusters these satellites will have the capability of increasing their flying lifetime over the earth for almost 7 years or so and they will provide us with services that current satellites are providing with very high costs including maintenance and flight sustainment. To sum up and set the technological limit we should say that although the concepts of pico satellites have been experimented with for over two decades now, stable and successful designs in the 1 kg class area are rare, and are virtually non-existent. The design and manufacture of very small satellites is not simply a matter of miniaturization but as the experience has proven several technical hurdles such as space qualification of materials and systems, power system design, and orbital control and ground control assume enormous significance in the design process. The solution though to the application of a pico-satellite to a real operation is now closer to reality than ever before.

Comparing the figures, we can say that if you have small cluster of picosatellites (let's consider tentatively six of those) and each one of them costs around 10.000€, then with 50.000€ [4] you can have adequate coverage of an area of operations 24/7 and at the same time the amount of money you have spent for the next seven years or so is nothing to be compared with the one being spend today. Imagine that a medium size ship (e.g. corvette or frigate) costs per day around 100.000€ (approximate figure) containing the amount of money that is being spend for oil, maintenance, salaries of personnel and other side costs. Additionally this operational planning (with surface ships) does not give you the capability of covering a vast or even a large sea area, since a ship is deemed to be positioned on the surface of the earth and the capability of providing accurate info is limited to some decades of miles. With small picosatellites the coverage is complete (day and night) and the cost will be approximately 150 to 200 € per day [5], which compared to the amount of money that a ship is spending per day to the high risk area is nothing.

The difference in cost is very large and the advantages are at the same time innumerable. In maritime security situations like illegal trafficking of goods, embargo operations, counter piracy operations, human trafficking, slave trade, illegal fishery, illegal environmental pollution, drug trafficking and other illegal activities that may happen in the maritime environment we need robust surveillance or real time intelligence support and the proposed system can help confront them efficiently. It is our belief that any conventional or unconventional illegal activity in the maritime domain can be diminished effectively with the use of these small technological assets. It is not an exaggeration to say that by applying this technology we could search and cover the critical maritime environment areas throughout the world's Sea Lines of Communications with relative easiness and primarily with the use of few national or international assets. The only thing that needs to be done is for the academic society to undertake the risk, make relevant research and combine the effective, efficient and affordable parameters into one small pico-satellite device (research is currently ongoing). The creation of a really miniaturized plasma propulsion thruster (in the range of some grams) is a part of this solution of the problem helping to extend the life of the pico-satellite from months to years. Also miniaturized cameras or any other commercial sensor could be used to increase the operational effectiveness of the satellite itself with less additional cost. If these could happen then a breakthrough to the international maritime industry and community worldwide would occur. The will is here. It only remains to be executed through well-formed combined academic and industrial initiatives.

The above mentioned potential solution could be a savior and having a major operational impact for a number of different actors that make their living in the maritime environment (e.g. merchant mariners). Let's consider a merchant marine company that needs fast, reliable and cost effective intelligence data in order to transit the Gulf of Aden or an area where piracy is the main problem. The pico-satellite conveys the real time data information from the area of operation to the fusion centre or to the merchant vessel itself. By this way, all info is relayed to the merchant vessel, prior to their transit of the area of elevated risk. The pico-satellites could transfer 24/7 real time information (data, images) to the merchant vessel. Therefore the captain of the ship knows well in advance what is happening around his ship in a vast area and that gives him the capability of taking fast and proactive active or passive measures in order to tackle any illegal action towards his ship.

On another potential risky area, like human trafficking, a realistic example is that we may need to verify if small vessels transiting near the shore are conveying illegally people from one country to another (transferring illegal immigrants). The above mentioned standalone maritime surveillance system could be used and provide 24/7 real time images to a command and control centre helping to cease this problem or at least arrest the illegal conveyers on the act.

It may seem futuristic or utopian that a very low cost solution from space could solve so many problems happening every day in the maritime environment. It is not though difficult to apply such a solution, but of course political and legal wills will remain critical factors. Covering with images an area on top of a country has legal limitations in the international community and this is something that needs to be examined before proceed to the execution level. It is worthy though to apply such an endeavour and find solutions that will help humanity to stop the emerging problems that occur in the maritime environment and impede the safety of transportation via the navigation lines.

Geostrategic Effect

Having analyzed the operational environment and the positive implications that the pico-satellite system could have to the real maritime dimension, it is now appropriate, but also imperative to shift to the strategic effect that a very low cost system like this could have globally. International relations, political implications, transport, shipping companies, global maritime organizations, international maritime law, maritime bureaus and most importantly the countries themselves, with so many other actors or end users would be affected from a simple application like this. Consider that today’s world is based on near real time information sharing. Whoever holds the most accurate, fast and reliable information is the one that acts more prudently, minimizing finally the effects in an area of operation. This operation could be transport via Sea Lines of communication and since our goal here is to support these efforts, one can understand that changing or affecting the way that today’s world is acting then this effect is going to finally change the way of conducting our daily business and traditional schemes[6]. The maritime industry is spending millions of dollars daily and is seeking viable and logical solutions to support merchant marines on the move. One example is the well-known use of Inmarsat satellites, where the cost to use them is so high that practically one pays hundreds of euros per minute sometimes only for simple phone calls. At this point some critical questions arise:

What is going to be the strategic effect in the shipping industry and generally in the shipping world and the maritime environment if someone could use only a very small personal pico-satellite to execute all his personal needs (audio, video, phone calls, talking to his family for free for example, plus having all his operational data handy and updated every four to five hours) with practically very low cost?

What is going to be the change in the way of executing shipping operations if a very low cost cluster of pico-satellites are going to provide you all that you had in the past and many more, but only with very few amount of money?

What is going to be the approach of international organizations like EU or IMO to maritime security operations if there is no need any more to spend EU's citizens money to analysis of imaging data that seems now inappropriate or exaggerative excessive for the mission performed?

If we can provide merchant mariners with a solution enough to sustain their operational needs then, **why** we have to spend millions of euros for having something that in most cases does not support them on a way that they want?

All the aforementioned questions are seeking their answers through this small very low cost system of pico-satellite application. It is more than evident that after implementing an idea like this to current maritime environment, huge changes are going to appear on our conventional ways of executing operations.

Therefore the **geo-strategic importance** of value of a very small system like this will be tremendous in the near future. A pico-satellite can act as a critical enabler to the area of shipping industry and mainly in the different and multiple ways that global transportation is being executed in our era. It will provide the capability also to smaller industries, countries, organizations or other key actors that today rely on others, to plan their own way ahead. This is indeed a major impact on the geostrategic links and balances and it is for sure that shipping trade and routes are going to change dramatically, hopefully in a fairer and stable manner. As always happening, the cost drives almost everything and with this logarithmic decrease in cost figures and facts, operational, transport and shipping dependencies will be evoluted to another scale. It remains to be seen though how the implementation of a pico-satellite application to maritime community is going to transform our maritime thinking of executing business, in the near future, and this is what we are trying to implement through our research.

Maritime Security Data Survey

Maritime Security Data is available throughout the internet on commercial and/or confidential databases. In order to conduct our research and evaluate above thinking, we needed real raw data in order to start analyzing them and create results that could lead us to positive results. We followed a procedure of collecting all available commercial or confidential data on internet and then by using taxonomy and categorization we used them as to conclude to useful for our research results. The method of collecting all this data was either by static traditional aggregating techniques or by "software robots" gathering auto uploaded information through the internet. Maritime security data had to do primarily with piracy events, happening basically all over the world (Gulf of Aden, Malacca Strait, Gulf of Guinea etc). The operational characteristics of those data that we were interested on were:

- Border Security and Surveillance
- Maritime Security
- Detection and tracking of small unseaworthy vessels
- Piracy related data - Attacks etc. and found through the following links (table 1):

No	Site Name	Maritime Security Field Link	Comments
1.	**NSC** NATO Shipping Center	Daily Piracy Alerts info http://www.shipping.nato.int/Pages/AllAlerts.aspx	extract from table
2.	**ICC** International Chamber of Commerce	Daily Alerts for Piracy – Armed Robbery incidents http://www.icc-ccs.org/piracy-reporting-centre/live-piracy-report	extract from database or map
3.	**MSCHOA** NATO Maritime Security Center Horn of Africa	Daily Piracy Alerts http://www.mschoa.org/on-shore/home	needs registration
4.	**OCEANUS** Commercial Database	Daily Piracy - Armed Robbery Alerts http://www.oceanuslive.org/main/index.aspx	registering to dashboard page
5.	**EUNAVFOR**	Daily Piracy Incidents	extract information

	European Naval Force	http://eunavfor.eu/latest-news	from news text as it appears
6.	**MANW** NATO Maritime Component	Daily Piracy Incidents http://www.manw.nato.int/	extract from news text as it appears
7.	**IMO** International Maritime Organizations	Daily Piracy and Armed Robbery incidents http://gisis.imo.org/Public/PAR/Default.aspx	need username and password which I have them available
8.	**ONI** US Office of Naval Intelligence	Daily Piracy and Armed Robbery http://www.oni.navy.mil/Intelligence_Community/piracy.htm	extract from weekly report (text) once every week
9.	**RECAAP**	Daily Piracy and Armed Robbery in Asia https://portal.recaap.org/OpenMap	extract info from database
10.	**GIM** US Global Incidents Map	Daily Terrorism Incidents all over the world http://www.globalincidentmap.com/	extract from map or news text. needs login
11.	**Somalia Online**	Daily Piracy and Terrorist attacks http://somaliaonline.com/	Extract info from text news as it appears
12.	**ODIN** Maritime Bulletin	Daily Piracy, Armed Robbery and Terrorist reports http://www.news.odin.tc/index.php?page=view/categories/2/Piracy	extract info from text news where Lat and Lon are being referred
13.	**Noonsite**	Daily Piracy, Armed Robbery events for yachts http://www.noonsite.com/General/Piracy	large amount of data all over the world
14.	**Maritime Magazine**	Daily Piracy reports http://www.maritime-executive.com/piracy-news/attacks	extract from text - news
15.	**Reuters**	Daily Newspaper http://www.reuters.com/article/2013/07/02/us-somalia-arms-un-idUSBRE96101E20130702	seize of armed vessels

Table 1: *Resources available for collecting real time piracy – maritime security data for analysis*

The above sites were used primarily to collect available data regarding daily piracy events. Those data collected were being prioritized in a logical sequence and critical information was extracted. The above sites are only first priority data sources among a list of 60 approximately collected, second and third priority databases, for piracy and armed robbery, such as (newspapers, articles, maritime security companies' reports etc.) Those data gathered color coded initially on an excel spreadsheet and 1000 lines approximately of information collected from 2011 until 2014, where piracy actions flourishing in the Gulf of Aden. In this procedure, patterns of life created, categorization of all incidents occurred and first results were exploited in order to acquire the first big picture of the research that was going to be conducted. Finally, risk assessment indexes and heat maps produced in order to first tabulate results and make decisions on how to proceed with risk assessment analysis. Below, a brief explanation of the sites used is given for a broader understanding of the amount of data used, collected, composed in order to check truthfulness and fidelity.

Maritime Piracy Resources

For the collection of maritime piracy and generally maritime security data the following references have been used and analyzed. In each of the following sites / links one can access open and closed source databases and applications where critical and crucial information for our research was collected. Instead of referring those sites directly to references, we believe that it is better to quote here separately.

1. Piracy Guidance from International Maritime Organization (IMO) – Circulars, codes, and resolutions by IMO.
2. IMO Piracy Resources – Resources on Maritime Piracy by IMO
3. NATO Shipping Centre – Information from NATO Naval forces for maritime security.
4. Live Piracy Report from ICC – Information on piracy events as and when they happen.
5. Maritime Security Council – The non-profit organization for security of maritime industry.
6. Save Our Seafarers – The campaign to save seafarers from sea piracy.
7. RECAAP – The regional cooperation agreement on combating piracy and armed robbery against ships in Asia.
8. INTERCARGO – Piracy – Piracy Briefing from INTERCARGO.
9. MENAS – Middle Easy navigation aids services.
10. Maritime Piracy – Humanitarian Response – Program to help seafarers and their families affected by piracy attacks.
11. EUNAVFOR – Project Atlanta – The operation to protect vessels operating near Somalia.
12. International Chamber of Shipping – Piracy resources from International chamber of shipping.
13. NAVAREA III Warnings (Mediterranean Sea) – Piracy warning in Mediterranean Sea.

14. NAVAREA VIII Warnings (North Indian Ocean) – Piracy warning in North Indian Ocean.

15. NAVAREA IX Warnings (Red Sea/ Arabian Sea/ Persian Gulf) – Piracy warning in Red Sea/ Arabian Sea/ Persian Gulf.

16. BIMCO (Members only) – Piracy information for BIMCO members.

17. Pirat – A Project on Piracy and Maritime Terrorism as a Challenge for Maritime Trade Security.

18. International Maritime Crimes – Great resources from International Maritime Crimes – Center for International Law.

19. Agent C – Employing Computational Modelling, Simulation, and Optimization to Fight Maritime Piracy.

20. MERLN – Piracy resources compiled by The National Defense University.

21. Piracy- Europe – Conferences on combating piracy.

22. Civil Military Fusion Center – Anti-piracy reports.

23. Piracy Reports (paid) – Paid reports on maritime piracy from RAND Corporation.

24. Best management practices for protection against Somalia based piracy – A report by International chamber of commerce (ICC).

25. 24 Hours Maritime Security hotline – 24 hours maritime security hotline from ICC.

26. Maritime Security Centre – Horn of Africa – Provides service to mariners in piracy affected areas.

27. Sea Sentinel – Lloyds Register Fairplay service for ports, security & risk information (paid).

28. UK – P&I Club Piracy Resource – Piracy resource from UK P&I Club.

29. Marsec Review – Maritime Security Review - Provides news and expert reviews on maritime security.

30. OCEANUSLive - Offers maritime situational awareness to enhance safety and security at sea.

31. Neptune Maritime Security - Features latest maritime news and articles. Also offers maritime security services.

References

1. G. Mantzouris, Kolar Ramesh, “Low Earth Orbiting Satellites - Radiation and Shielding”, NPS official report, May 2008.

2. G. Mantzouris, “Microsatellites in maritime interdiction operations”, Hellenic Navy Review, Oct 2008 (in Greek).

3. G. Mantzouris, “Interdiction of small low earth orbiting satellites from on board military crafts”, Hellenic Navy Proceedings, Sep 2009 (in Greek).

4. G. Mantzouris, “Picosatellites in MIO tracking WMD materials”, NMIOTC MIO Journal Inaugural Issue, Feb 2010.

5. A. Bordetsky, G. Mantzouris, “Picosatellites in Maritime Interdiction Operations”, 15th ICCRTS Conference, Santa Monica, LA, CA, 22-24 June 2010.

6. A. Bordetsky, G. Mantzouris, “MIO Experimentation at NMIOTC: Networking and Collaboration on small craft maritime sourced nuclear radiological threat detection and interdiction”, NMIOTC MIO Journal 2nd Issue, November 2010.

Page intentionally left blank

CHAPTER 2

MARITIME PICOSATELLITES

LITERATURE SURVEY

Chapter 2: Maritime Picosatellites - Literature Survey

Picosatellites Operational Characteristics

In this chapter, maritime picosatellites have been collected diligently through thousands of pico and microsatellites available globally. By conducting a thorough literature survey our aim was to understand how many of the available picosatellites are dealing with maritime security or generally with maritime applications. In order to manage this, the operational characteristics of picosatellites have also been collected and analyzed. This approach will uncover initially all the requirements, advantages, disadvantages and limitations of these micro space vehicles and will guide us to our future applied research [1].

Therefore a short list of operational characteristics of picosatellites are being reported through literature, in order a more digestive and detailed comprehension of the system to be fed to the reader. All these characteristics [2] may seem highly tactical or operational, but if one analyzes the effects that are going to affect the execution of operations then the results can be consider strategic. Later, we will refer more to the strategic implications of such a small very low cost system to the global maritime community. Therefore some of the most important characteristics are [4, 6]:

- Provision of fine resolution images from the area of operations.
- Real time transfer of information to merchant mariners for the existence of suspect peripheral traffic.
- Real or Near Real time Tracking Capability depending on the selection of orbital parameters and the area of operation.
- Audio - Voice and video communication to a fusion center ashore for the specified window that a satellite is passing on top of the area (on the move networking capability).
- Feasibility of a two way communication implementing reachback techniques.
- Coverage of a vast geographical sea area and provide partial or total situational awareness based on the number of satellites to be used.

- Lifetime consideration: 1 to 3 months depending on solar weather. If increased to more than a year, then this system will definitely have a strategic effect on the execution of missions.

To sum up though the operational part one has to have in his mind the following attributes of the pico-satellite system. The approximate total time that we have during a whole day to communicate through a system that has four satellites (the cost will be around 50000 € approximately) is 120 minutes (2 hours during the day). Therefore the total gap time between satellite passes during one day is approximately 22 hours. However, with this amount of timeframe we have the capability to exchange the needed information with a merchant vessel underway and feed the important information required for a safe and secure transit from a high risk area. Modern maritime threats, as they appear on the international scene today, do not require 24/7 hours of communication with fusion centers ashore, but only a logical timeframe sufficient to transfer critical information back and forth and secure future courses of action.

We reviewed more than 100 small satellites (amateur and commercial) and we found out that 53 of them have similar characteristics with Lambda satellite. Furthermore, three of them were very close orbital characteristics, transmitting frequency and signal modulation and that is why we selected them for our experiments. Due to transmitting limitations of the satellites though and even if we received them properly, we finally executed our experiments with FO-29, Funcube and others in order to reliably acquaint useful data and results.

Satellite	Operator	Launch	Weight (kg)	Power (W)	Transmitting Power (W)	Orbit (km)	Experiment
LO-19 (LUSAT)	Amsat Argentina	1990	13.76			Sun Synchronous Near Polar	Camera CCD for Earth Photography
FO-29 (JAS-2)	Japan Aerospace Agency	17 Aug 1996	50	10	1	Polar Orbit 1200	Sun Sensor, Geomagnetism Sensor
RS-22 (Mozhayets 4)	Moscow Military Academy	2003	64			670	Glonass Navigation & Laser Geodetic Measurements
RS-40 (MiR)	Siberian State Aerospace University	28 Jul 2012	65			1500 LEO	AOCs for small sats & Earth Observation Camera
CO-57 (XI-IV)	Intelligent Space Systems Lab (ISSL) Tokyo	30 Jun 2003	1	8	800 mW	800	
CO-58 (XI-V)	Intelligent Space Systems Lab (ISSL) Tokyo	27 Oct 2005	1	8	800 mW	700	New types of Solar Cells
CO-65 (CUTE1.7+APDII)	Tokyo Institute of Technology	28 Apr 2008	2	4	80 mW	630	Photo Diode Sensor Module
COMPASS-1	University of Aachen	28 Apr 2008	0.85	1		600	GPS, Camera Color Images
CO-66 (SEEDS-II)	Nihon University Japan	27 Jul 2006	1	1.6	90 mW	620	
RS-30 (Yubileiniy)	Moscow Military Academy	23 May 2008	45				GPS, Glonass combination
PRISM (HITOMI)	Intelligent Space Systems Lab (ISSL) Tokyo	21 Jan 2009	8.5	8	800 mW	660	Remote Sensing
STARS (KUKAI mother)	Kagawa University	23 Jan 2009	4.2	8	3.8	666	Space Tethered Robotic Satellite
STARS (KUKAI daught)	Kagawa University	23 Jan 2009	3.8	8	3.8	666	Space Tethered Robotic Satellite
KKS-1 (KISEKI)	Tokyo Metropolitan College	23 Jan 2009	3			636	Microthrusters and Camera to Earth Imaging
SwissCube-1	University of Lussane	23 Sep 2009	<1	1.5		720 Sunsynchronous	Onboard Telescope
ITU-pSat1	Istanbul Technical University	23 Sep 2009	0.99	1	20 mW	723	Onboard CMOS Camera
HO-68 (XW-1)	China Amateurs	15 Dec 2009	50	21	200 mW	1200 Sunsynchronous	Onboard CMOS Camera
TIsat-1	University of Southern Switzerland	12 Jul 2010	<1			635	Atomic Oxygen Experiment
Jugnu	Indian Institute of Technology	12 Oct 2011	3	3.8		860	MicroImaging and GPS
MaSat-1(MO-72)	BME Hungarian Univeristy	13 Feb 2012	<1	1.2 - 2.2	400 mW	Circular 574	ESA Comms Exps & on board camera
Horyu-2	University of Kyushu	17 May 2012	7.5	2.7	1	Sun Synchronous 680	300V photovoltaic power generation in LEO
AIST-2 (RS-43)	Russian Samara Aerospace University	19 Apr 2013	39	15			Measure Geomagnetic Field
SOMP	University of Dresden Germany	19 Apr 2013	1	2		550	Atomic Oxygen Experiments
BEESAT-2	Technical University of Berlin	19 Apr 2013	1	0.5		550	Reaction Wheels for Picosatellites
EstCube-1	Estonian Tartu University	7 May 2013	1.05	3.6	0.5	660	Micropropulsion
ZACube-1	French South Africa Institute of Technology	21 Nov 2013	1.2		1	620	
Triton-1	ISIS BV Dutch	21 Nov 2013	2.5	4		650	AIS Sensor
Humsat-D	University of Vigo Spain	21 Nov 2013	1	3		610	Arctic Details
UWE-3	University of Wurzburg	21 Nov 2013	1			650	Attitude Determination for Pico
IPEX	NASA JPL Cal Poly	5 Dec 2013	1.5	10	1	700	Validate Exps for Future Earth Obs
AIST-1 (RS-41)	Russian Samara Aerospace University	28 Dec 2013	53			575	
SPROUT	University of Nihon Tokyo Japan	24 May 2014	7.1		450 mW	628	Orbital Membrane - Sail
NanosatC-Br1	South Regional Space Research Center Brazil	19 Jun 2014	1			615	South Atlantic Anomaly Measure
POPSAT-HIP1	Singapore Nanosatellite	19 Jun 2014	3			620	
ANTELSat	Uruguay University	19 Jun 2014	2			650	
PolyITAN	National Technical University Ukraine	19 Jun 2014	1			620	
AISSat-1	German Aerospace Center	30 Jun 2014	14	15		660	Maritime Tracking
VesselSat1	ORBCOMM	20 Oct 2011	29			810	Maritime Tracking
VesselSat2	ORBCOMM	09 Jan 2012	28	6		440	Maritime Tracking
IO-26 (ITAMSAT)	Italian	26 Sep 1993	11.2			800	Amateur Comms
CO-55 (CUTE-I)	Tokyo Institute of Technology	30 Jun 2003	1	1.5	350 Mw	800	
O/OREOS	NASA	20 Nov 2010	5.5			630	
AENEAS	USA	13 Sep 2012	4			600	
CubeBug-1	Argentinian Ministry of Science	26 Apr 2013	1			600	
CUSat-1	Cornell University	29 Sep 2013	23			600	
PhoneSat2.4	NASA Ames Research Center	Apr 2013	1			600	
CubeBug-2 (LO-74)	Argentinian Ministry of Science	Dec 2013	2			600	

Table 2: Small satellites literature survey (partial representation)

Satellite	No	Uplink	Downlink	Beacon	Mode	Operator	Launch	Weight (kg)	Power (W)	Transmiting Power (W)	Orbit (km)	Inclination (°)	Period (min)	Comms	Experiment
CW microsatellites															
LO-19 (LUSAT)	20442	145.840-145.900	437.125/150	437,127	CW carrier	Amsat Argentina	1990	13.76			Sun Synchronous Near Polar LEO	98	100.3	Sending in Beacon 8 telemetry channels	Camera CCD for Earth Photography
FO-29 (JAS-2)	24278	145.900-146.000	435.900-435.800	435,795	SSB CW (DigiTalker)	Japan Aerospace Agency	17 Aug 1996	50	10	1	Polar Orbit 1200	98.5	112	CW Beacon is working	Sun Sensor, Geomagnetism Sensor, Magnetotorquer and Data Processor & GaAs solar cells exp
RS-22 (Mozhayets 4)	27939			435,352	CW	Moscow Military Academy	2003	64			670	98.06	98.4	CW Beacon is working	Glonass Navigation & Laser Geodetic Measurements
RS-40 (MiR)	38736			435,365	CW	Siberian State Aerospace University	28 Jul 2012	65			1500 LEO	82.4	113.5	CW Beacon and Packets	AOCs for small sats & Earth Observation Camera and others
CO-57 (XI-IV)	27848		437,490	436,848	1200bps AFSK CW	Intelligent Space Systems Lab (ISSL) University of Tokyo	30 Jun 2003	1	8	800 mW	800	98.7	101	CW only Telemetry only above Japan	
CO-58 (XI-V)	28895		437,345	437,465	1200bps AFSK CW	Intelligent Space Systems Lab (ISSL) University of Tokyo	27 Oct 2005	1	8	800 mW	700	97.8	98.5	Active CW	New types of Solar Cells
CO-65 (CUTE1.7+APDII)	32785		437,475	437,275	1200bps AFSK CW	Tokyo Institute of Technology	28 Apr 2008	2	4	80 mW	630	98	96.9	Active CW	Photo Diode Sensor Module
COMPASS-1	32787	145,980	437,405	437,275	1200bps AFSK CW	University of Aachen	28 Apr 2008	0.85	1		600	97.7	96.7	Active CW & Packets	GPS, Camera Color Images
CO-66 (SEEDS-II)	32791		437,485	437,485	1k2AFSK CW DigiTalker	Nihon University Japan	27 Jul 2006	1	1.6	90 mW	620	97.9	97.2		
RS-30 (Yubileiniy)	32953		435,215	435,315	CW	Moscow Military Academy	23 May 2008	45				88.5	115.8	Active CW	GPS, Glonass combination

PRISM (HITOMI)	33493		437,425	437,250	1k2AFSK 9k6GMSK CW	Intelligent Space Systems Lab (ISSL) University of Tokyo	21 Jan 2009	8.5	8	800 mW	660	98.3	96.6	CW AFSK	Remote Sensing
STARS (KUKAI mother)	33498	144,000	437,485	437,305	1200bps FM CW	Kagawa University	23 Jan 2009	4.2	8	3.8	666	98.2	97.5	Active CW	Space Tethered Robotic Satellite
STARS (KUKAI daught)	33498	144,000	437,465	437,275	1200bps FM CW	Kagawa University	23 Jan 2009	3.8	8	3.8	666	98.3	97.6	Active CW	Space Tethered Robotic Satellite
KKS-1 (KISEKI)	33499		437,445	437,385	1200bps AFSK CW	Tokyo Metropolitan College of Industrial Technology	23 Jan 2009	3			636	98.2	97		Microthrusters and Camera to Earth Imaging
SwissCube-1	35932	145,000	437,505	437,505	1200bps BFSK CW	University of Lussane	23 Sep 2009	<1	1.5		720 Sunsynchro nous Near Circular Polar	98.4	99.3	Active CW	Onboard Telescope
ITU-pSat1	35935		437,325	437,325	19200bps GFSK CW	Istanbul Technical University	23 Sep 2009	0.99	1	20 mW	723	98.4	99	Active CW	Onboard CMOS Camera
HO-68 (XW-1)	36122	145,825	435,675	435,790	FM_tone67 Hz CW_only	China Amateurs	15 Dec 2009	50	21	200 mW	1200 Sunsynchro nous	109	100.4	Active CW	Onboard CMOS Camera
TIsat-1	36799	145,980	437,305	145,980	FM AFSK PSK CW	University of Applied Sciences of Southern Switzerland	12 Jul 2010	<1			635	97.8	97.4	Active CW	Atomic Oxygen Experiment
Jugnu	37839		437,505	437,276	CW	Indian Institute of Technology	12 Oct 2011	3	3.8		860	19.96	102		MicroImaging and GPS
MaSat-1 (MO-72)	38081		437,345	437,345	625/1250b ps 2FSK CW	BME Hungarian Univeristy	13 Feb 2012	<1	1.2 - 2.2	400 mW	Circular 574	69.4	92.6	CW Beacon is working & Packets	ESA Comms Exps & on board camera
Horyu-2	38340		437,375	437,375	1200bps FSK CW	University of Kyushu	17 May 2012	7.5	2.7	1	Sun Synchronou s 680	98.3	97.7	CW Active	300V photovoltaic power generation in LEO

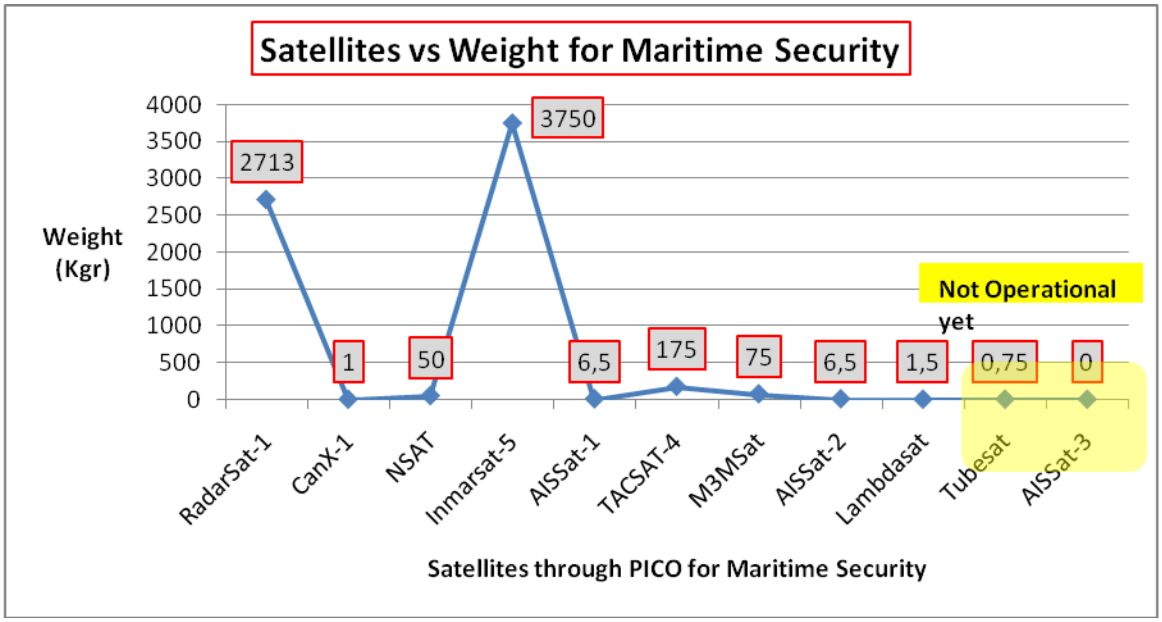
AIST-2 (RS-43)	39133		435,215	435,265	FM CW	Russian Samara Aerospace University	19 Apr 2013	39	15			64.9	95.9		Measure Geomagnetic Field
SOMP	39134		437,485	437,503	1200bps AFSK CW	University of Dresden Germany	19 Apr 2013	1	2		550	64.8	95.6	Active CW	Atomic Oxygen Experiments
BEESAT-2	39136		435,950	435,950	4800bps GMSK CW	Technical University of Berlin	19 Apr 2013	1	0.5		550	64.9	95.6	Active CW	Reaction Wheels for Picosatellites
EstCube-1	39161		437.505/24 01.250	437,254	9600bps GMSK CW	Estonian Tartu University	7 May 2013	1.05	3.6	0.5	660	98.1	98.2	Active CW	Micropropulsion
ZACube-1	39417	145,860	437,345	14,099	1k2AFSK 9k6GMSK CW	French South Africa Institute of Technology	21 Nov 2013	1.2		1	620	97.8	97.4	Active CW	
Triton-1	39427	435.xxx	145.822/14 5.860	2408,000	1200bps RC-BPSK CW	ISIS BV Dutch	21 Nov 2013	2.5	4		650	97.7	98.2	Active - Not possible Receive it is only VHF	AIS Sensor
Humsat-D	39433		437.325/43 7.525	437,325	CW	University of Vigo Spain	21 Nov 2013	1	3		610	97.8	96.8	Active CW	Arctic Details
UWE-3	39446		435.000/43 6.395/437. 385		9600bps FSK CW	University of Wurzburg	21 Nov 2013	1			650	97.7	97.5	Active CW	Attitude Determination for Pico
IPEX	39471		437,270	437,270	9600bps GMSK CW	NASA JPL Cal Poly	5 Dec 2013	1.5	10	1	700	120.5	98.1	Active CW	Validate Exps for Future Earth Obs
AIST-1 (RS-41)	39492			435,265	CW	Russian Samara Aerospace University	28 Dec 2013	53			575	82.4	96.9	Active CW	
SPROUT	39770		437,525	437,525	1k2AFSK 9k6GMSK CW	University of Nihon Tokyo Japan	24 May 2014	7.1		450 mW	628	97.9	97.1	Active CW	Orbital Membrane - Sail
NanosatC-Br1	40024	435.xxx	145,865	145,865	1200bps BPSK CW	South Regional Space Research Center Brazil	19 Jun 2014	1			615	98	96.9		South Atlantic Anomaly Measure
POPSAT-HIP1	40028		437,405	437,405	1k2 9k6 CCSDS CW	Singapore Nanosatellite	19 Jun 2014	3			620	98	96.9		

ANTELSat	40034		437.575/2403.000	437,280	1k2 AFSK GFSK/MSK CW	Uruguay University	19 Jun 2014	2			650	98	97		
PolyITAN	40042		437,675	437,675	9600bps 2FSK CW	National Technical University Ukraine	19 Jun 2014	1			620	98	97	Active CW	
AISSat-1	**40054**		**437,250**	**437,511**	**CW**	**German Aerospace Center**	**30 Jun 2014**	**14**	**15**		**660**	**98.2**		**Active CW**	**Maritime Tracking**
VesselSat1				434.5	Equatorial orbit	ORBCOMM	20 Oct 2011	29			810	20			Maritime Tracking
VEsselSat2			είναι εκτός δέκτη μας	400.645-401.000MHz	AIS RDS	ORBCOMM	09 Jan 2012	28	6		440	97.6	93.3		Maritime Tracking
PACKET microsatellites															
IO-26 (ITAMSAT)	22826	145.875-145.950	435.822/435.867	435,791	1200bps JAS PACKET	Italian	26 Sep 1993	11.2			800	98.7	100.7	Active	Amateur Comms
CO-55 (CUTE-I)	**27844**		**437,470**	**436,838**	**1200bps AFSK**	**Tokyo Institute of Technology**	**30 Jun 2003**	**3**	**3**	**350 Mw**	**800**	**98.7**	**100.7**	**Active**	**LAMBDASAT SIMILAR**
O/OREOS	37224		437,305	437,301	1200bps AFSK	NASA	20 Nov 2010	5.5			630	72	97.3		
AENEAS	38760		437,600	437,600	1200bps AFSK	USA	13 Sep 2012	4			600	64.7	94.7		
CubeBug-1	**39153**		**437,445**	**437,438**	**1200bps AFSK**	**Argentinian Ministry of Science**	**26 Apr 2013**	**1**			**600**	**97.4**	**98.3**	**Active**	**LAMBDASAT SIMILAR**
CUSat-1	39266		437,405	437,405	1200bps AFSK	Cornell University	29 Sep 2013	23			600			Active	
PhoneSat2.4	**39381**		**2401.200-2431.200**	**437,425**	**1200bps AFSK**	**NASA Ames Research Center**	**Apr 2013**	**1**			**600**			**Active**	**LAMBDASAT SIMILAR**
CubeBug-2 (LO-74)	39440			437,445	1k2AFSK 9k6FSK	Argentinian Ministry of Science	Dec 2013	2			600			Active	

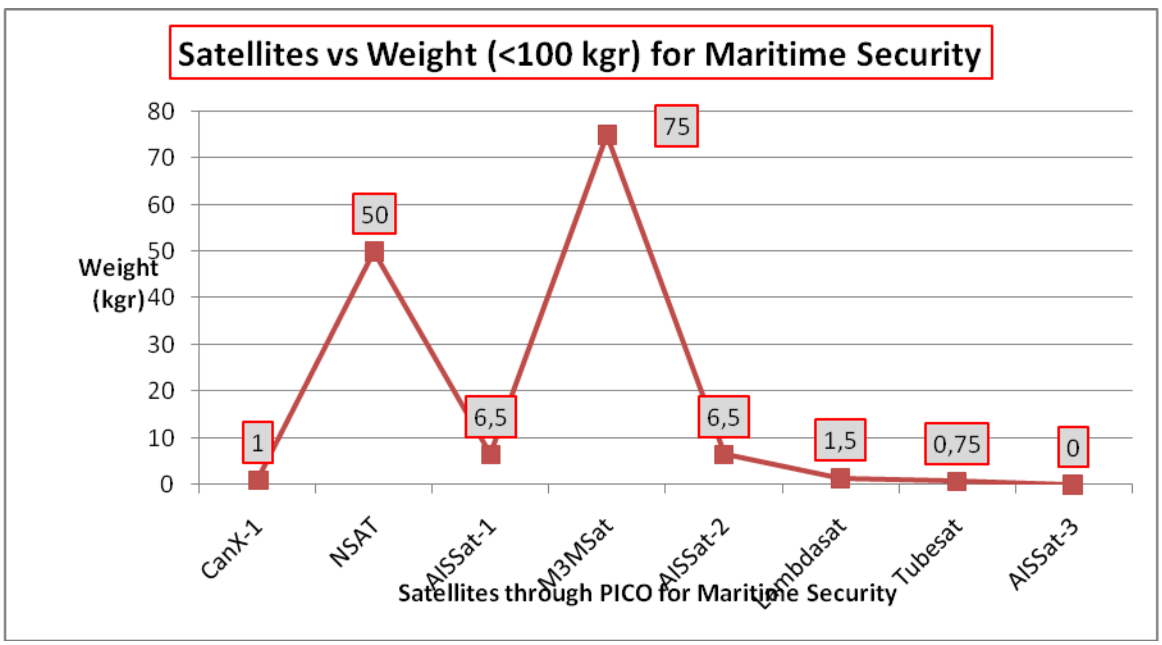
Table 3: Small Satellites Literature Survey – Operational Characteristics

Tables 2 and 3 are showing all the available collected [3, 5] microsatellites, as of start of 2015, where some of them accumulate similar characteristics to our Lambda satellite (green part of Table 3). The above tables have served as a generic guide in order to understand the broader use of microsatellites tabulating not only names and dates of construction or launch, but also other characteristics like uplink and downlink frequencies, experiments on board them, as well as a full range of orbital characteristics. From our analysis (indicating in table with green shaded areas) there are four satellite missions with similar characteristics to our mission satellite Lambdasat that is going to be analyzed thoroughly on a next chapter. Collected microsatellites have been distinguished in two categories. In those that are using continuous wave modulation (CW) and those that are using Packet wave modulation. **AISSAT** is a CW microsatellite whereas **CO-55**, **Phonesat** and **Cubebag** are packet oriented satellites similar to Lambdasat. Even though these microsatellites have very similar orbital and communication characteristics to Lambdasat and even though we established partial (in open channels) communication through UoA ground station, however those satellites had intermittent downlink due to their concept of operation. Therefore we followed our experiments with the use of FO-29, the Japanese microsatellite (this is an old one but still very active and clear in its beacon when passing on top of the University of the Aegean) and the Funcube one. Thus we used this as a base satellite for our research, when communication from Lambdasat was not always possible (more details are being referred to Lambdasat chapter analysis below).

Another important discrimination that we did in microsatellites, as of summer 2015, is to those able to support maritime security operations / missions. They have been collected and shown in graph 2 as a graph vs weight. As one can see the first satellite to dealt with maritime security was RadarSat with 2713 kgr back in 2000 and now satellites that are going to be on orbit dealing with maritime security are in the verge of picosats weighting only 1 kgr or less like AISSAT and Lambdasat.



Graph 2: Satellites vs weight that are dealing with Maritime Security.

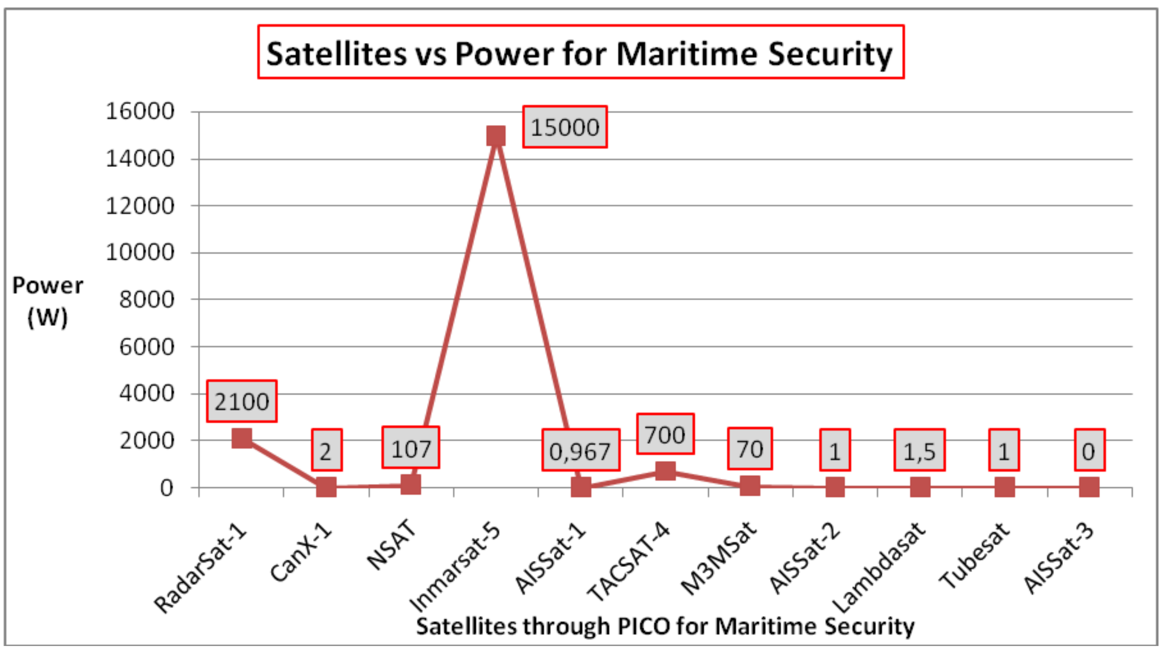


Graph 3: Satellites vs weight (<100 kgr) through pico dealing with Maritime Security from 1995 until 2015

Satellites through Pico for Maritime Security

Name	Launch Date	Weight (Kgr)	Power (W)
RadarSat-1	1995	2713	2100
CanX-1	2003	1	2
NSAT	2005	50	107
Inmarsat-5	2005	3750	15000
AISSat-1	2010	6,5	0,967
TACSAT-4	2011	175	700
M3MSat	2011	75	70
AISSat-2	2013	6,5	1
Lambdasat	**2015**	1,5	1,5
Tubesat	**2015**	0,75	1
AISSat-3	**2015**	0	0

Table 4: Satellites through pico dealing with Maritime Security from 1995 until 2015



Graph 4: Satellites vs Power through pico dealing with Maritime Security from 1995 until 2015

Satellites through Pico for Maritime Security <100 kgr

Name	Launch Date	Weight (Kgr)	Power (W)
CanX-1	2003	1	2
NSAT	2005	50	107
AISSat-1	2010	6,5	0,967
M3MSat	2011	75	70
AISSat-2	2013	6,5	1
Lambdasat	**2015**	1,5	1,5
Tubesat	**2015**	0,75	1
AISSat-3	**2015**	0	0

Table 5: Weight (<100 kgr) and Power (W) of satellites through pico dealing with Maritime Security from 1995 until 2015

Doppler Shift in Picosatellites

During our experiments we encompassed the well-known Doppler shift phenomenon. This phenomenon affects picosatellite's connectivity and is one of the biggest problems in establishing stable communication and transfer of quality information to ground [8]. Here we will cover only briefly the theoretical background of it focusing on picosatellites, giving the reader an insight of the situation.

As known, picosatellites are small live objects that are flying from 320 up to 500 km from earth. They fly in a very low orbits, outside of Van Allen belts, but they have huge speed, in comparison with medium earth orbits or higher. Their speed is approximately 8 km/sec and thus, one of the parameters that affect the communication with them is Doppler Effect. That was also the case with our experiments with amateur satellites for uplink and downlink frequencies effective connectivity.

To a general extent, the downlink frequency will appear to be higher than normal and therefore the receiver frequency at the ground station must be adjusted higher in order to continue receiving the satellite. The satellite in turn will be receiving the uplink signal at a higher frequency than normal so the ground station's transmitted uplink frequency must be lower in order to be received by the satellite. After the satellite passes overhead and begins to move away this process reverses itself. Generally speaking, it is known that the downlink frequency will appear lower and the uplink needs to be adjusted higher. The following mathematical formulas relate Doppler shift to the velocity of the satellite [8].

Where

f_d	=	Doppler corrected downlink frequency
f_u	=	Doppler corrected uplink frequency
f	=	original frequency
v	=	Velocity of the satellite relative to ground station in m/s. Positive when moving towards, negative when moving away.
c	=	The speed of light in a vacuum (3×10^8 m/s).

Change in frequency	**Downlink Correction**	**Uplink Correction**
$\Delta f = f \times \frac{v}{c}$	$f_d = f(1 + \frac{v}{c})$	$f_u = f(1 - \frac{v}{c})$

Fast moving satellites can have a Doppler shift of dozens of kilohertz relative to a ground station and this observed during Lambdasat mission. The same observation though was seen in FO-29 Japanese satellite, when it was being tracked through Orbitron software. The speed, thus magnitude of Doppler Effect, changes due to earth curvature. Dynamic Doppler compensation, where the frequency of a signal is changed multiple times during transmission, is used so the satellite receives a constant frequency signal. This dynamic Doppler compensation was also used during Lambdasat mission with the use of MiXW software, where the satellite was being tracked and we were trying to have a stable downlink communication, without noticing the Doppler Effect. This procedure was extremely difficult, happened only when the satellite had enough elevation degrees (more than 45).

To give an indication of a Doppler shift we can now see figure 5, where the Japanese microsatellite communicates downlink in 435.800 Mhz whereas due to Doppler Effect before passes overhead we were able to communicate in 435.809 Mhz, which means in a difference of 1 Khz (The satellite is approaching the ground station and so the frequency increases).

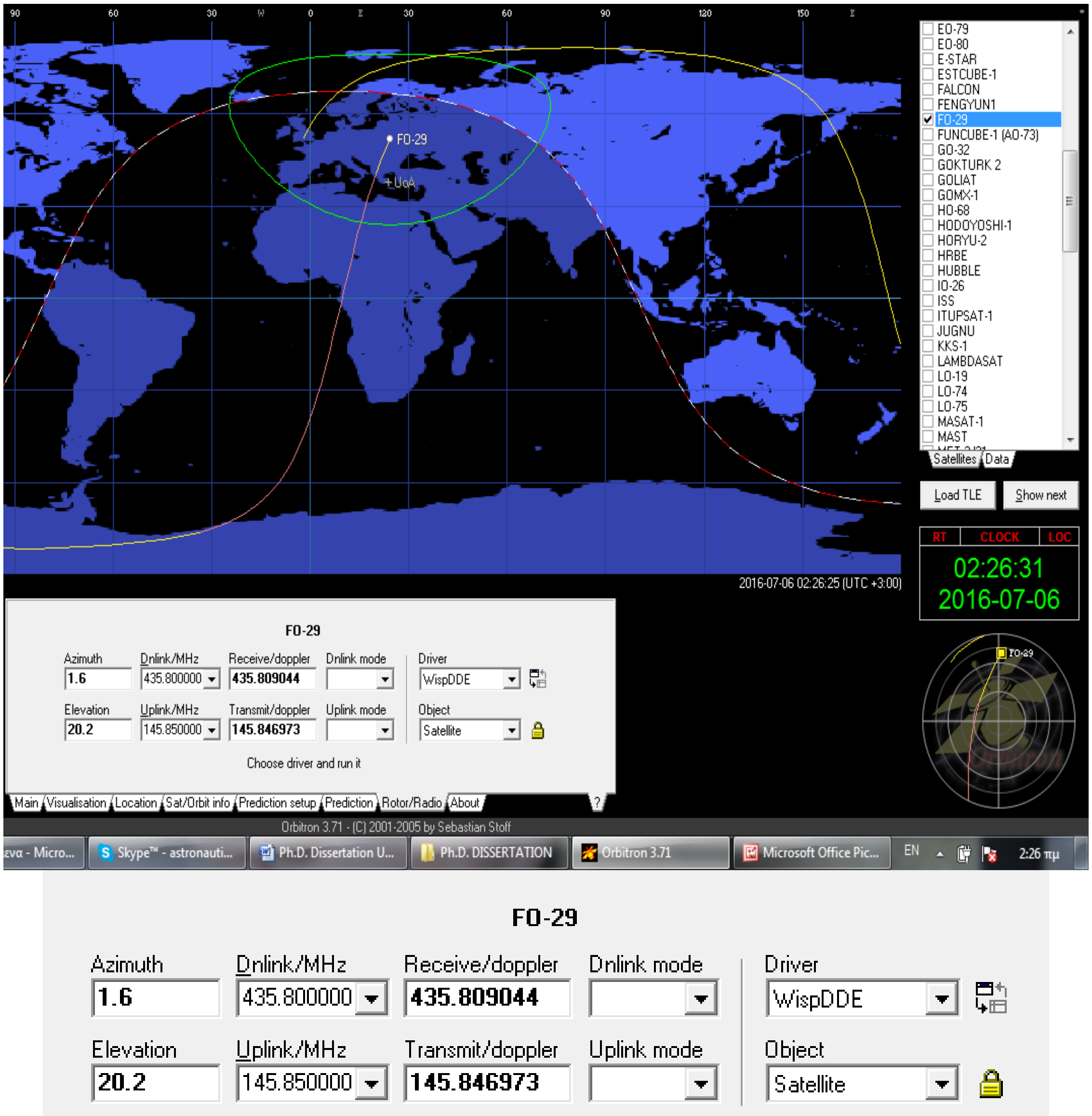


Figure 5: FO-29 Japanese microsatellite Doppler shift

References

1. A. Bordetsky, “Celestial Data Routing Network”, Proceedings of SPIE Book Series, Vol 4136, pp 02777-786x/00, 2000.

2. R. Khullar et.al. “Picosatellite Mission and Applications”, 55th Astronautical Congress, Vancouver, 2004.

3. D. Griffith et.al. “Optimal Microsatellite Cluster Design for Space Based Tracking Missions”, AIAA Guidance Navigation and Control Conference, 20-23 Aug, Hilton, South Carolina.

4. M. Knopp and A. Schramm, “Manned-Unmanned Systems Situational Awareness using Galileo Satellite Constellation and Small Satellites”, Diploma thesis University of Bundeswer, Jan 2009.

5. J. Bouwmeester, J. Guo, “Survey of worldwide pico and nanosatellites missions, distributions and subsystem technology”, Acta Astronautica, vol. 67, pp 854-862, 2010.

6. G. Mantzouris, A. Bordetsky, “Modelling of Picosatellite network applications to Maritime Interdiction Operations”,

7. D. Selva, D. Krejci, “A survey and assessment of the capabilities of Cubesats for Earth Observation”, Acta Astronautica vol 74, pp 50-68, 2012.

8. L. Qingchong, (1999), Doppler measurement and compensation in mobile satellite communications systems, Military Communications Conference Proceedings / MILCOM 1: 316–320,doi:10.1109/milcom.1999.822695

***** *The above references are only a small indicative part of the amount of papers reviewed. More than 130 papers collected and analyzed in order to perform a realistic literature survey and has been stored in a separate database for future use.*

CHAPTER 3

ORBITAL PROPULSION

for PICOSATELLITES

Chapter 3: Orbital Propulsion for Picosatellites

Introduction

Before we move on to the gist of our research we need to investigate some areas that are going to affect the use of picosatellites in orbital motion / operations. One of those important parameters (evident from chapter 2 orbital characteristics of picosatellite) is the fact that a very small satellite in order to stay long enough on orbit needs power. Having completed the literature survey and having in mind and tabulated well enough the miniature satellites used for maritime tracking or generally for maritime applications, we revealed that a picosatellite in order to be fully operational and tactical useful for years needs power. Power right now to picosatellites is another huge problem that companies and universities worldwide are trying to overcome. Right now instead of staying 14 years on orbit (as the classical Inmarsat satellites do because they are having the capability of storing power onboard) the picosatellites have the ability of staying only 1 year on orbital motion using usually passive means of stabilization, as mini magnetotorquers. Our research is based on the picosatellite use to maritime security applications. Lifetime of the picosatellite is one of the most important factors affecting any operation. For this reason we performed an extensive research / survey in order to firstly verify the current status in miniature propulsion systems worldwide, but at the same time and most importantly our research below uncovered all the gaps exist in modern propulsion schemes for picosatellite operations. In order for the reader to understand the concept we start with a brief theoretical introduction and then the analysis is being performed. Useful and important results will be generated at the end of this chapter and our mindset regarding the ability of picosatellite operations will be shaped up on this study.

It is well known that the use of Electric Propulsion in space applications is not a new concept. It emanates its roots back in 60’s when Ernst Stuhlinger, Von Braun’s student, wrote the first book for Ion propulsion in space. Later L.R. Shepard and A. V. Cleaver along with I. Langmuir and Child extended the ideas on more sophisticated experimental solutions and practically opened the way for a new concept regarding the utilization of electricity in space for propulsion purposes. No one can claim that they invented the “silver bullet” or “squared the circle” but with electric propulsion new applications, new ideas and most importantly new solutions found that can be used today in space applications and help miniaturize space systems. This is the main advantage that we acquired from this electric propulsion heritage, along with a way to think and design on a more green and friendly way to our environment.

Electric propulsion uses the same theoretical principles that Newton discovered with his third law centuries ago. “For every action there is an equal and opposite reaction”. This propulsion concept goes also back to the 7^{th} Century, when the Chinese fired their first rocket. The difference here, in electric propulsion, comparing to conventional rocket systems, is the use of electrons instead of chemical propellants, in order to generate the desirable thrust. Electric propulsion thrusters push the spacecraft in one direction using the basic principles that all other propulsion thrusters use. They accelerate a mass quantity and following they expel it like a catapult from the thruster with very high velocity, so as the action and reaction forces to finally deliver to the craft the desirable velocity and consequently the movement forward. This usable mass is charged particles – ions which have been produced from selected materials and accelerated accordingly through electron – ion collisions. With this configuration we can acquire very high velocities, but in comparison with other types of thrusters this velocities can be achieved in large time envelopes. This fact is called the electric propulsion penalty and it is because the mass of the available ions is relatively small and thus it takes more time to accelerate the craft than in chemical, nuclear or other traditional systems. This is a known limitation from the very beginning of the apprehension of electric propulsion idea and it is based purely on mathematics and physics that until this point has not been changed. Finally, all these electric thruster concepts that we are going to discuss in a later stage can be used for different missions such as stationkeeping, ΔV, attitude control or any other secondary missions and applications in space but are not enough to overcome Earth’s gravitational factor and propel a rocket or spacecraft from Earth’s surface directly to the space. That is why up until today all electric propulsion space crafts are deemed to be sent to space mainly through chemical rockets and then use their own designed systems to accomplish their missions.

Background Theory

Electric Propulsion theory is not a new vision. As it is stated above it stems its roots seventy years back, but at the same time it is always attractive to thruster designers due to the fact that gives the possibility for miniaturization, a beauty that is always present. Consecutively this means that electric propulsion thrusters are always the best candidates for low cost space applications, which nowadays is one of the most important driven factors in market. In order though to proceed gradually to our review, a brief theoretical analysis is quoted, in the form of stated facts that need to be kept always in mind, indicating limitations, frameworks and the threshold that the designer could overcome to create a novel model.

Thrust

On a spacecraft vehicle, thrust is always analogous to the total energy that is being liberated from the propellant. In this case, we have to include all those energy losses associated with propellant materials, chamber, dielectric etc. Thrust on a fundamental way is the time rate of the change of the momentum, which eventually equals the time rate change of propellant mass times the exhaust velocity of it from the back of the vehicle[1].

$$\vec{F} = \frac{d\dot{m}_p}{dt}\vec{u}_{ex}$$

In electric propulsion thrust is directly associated with propellant particle flow rate (in particles/sec, mg/sec or sccm) depending thoroughly on the selection of the propellant mass itself. Consequently, thrust equations always relate charged propellants, currents, applied voltages and the electron mass. As it is shown below for example, for ion and hall thrusters the generalized correlated equation of thrust, for a single charged particle, combines particle mass (M), acceleration net voltage (V_b), beam current (I_b) and is given by[99]:

$$F = \sqrt{\frac{2M}{e}} I_b \sqrt{V_b}$$

This equation needs every time to underlie corrections, such as to account for monoenergetic or polyenergetic ions, for beam divergence factors and other small factors that are only relevant to the thruster itself (such as the microwave electrothermal thruster case).

Specific Impulse

Another fundamental factor for space propulsion applications is Specific Impulse. When we refer to specific impulse (a well-known factor in space propulsion for years) we must have in our mindsets that it is called that way because it represents per weight unit, the propellant mass itself. It is directly associated with propellant mass and it is the measurement that totally indicates how much propellant we need to burn / use in order to reach "that" distance. To make it more realistic it is the same as we refer to a car's gas consumption of liters in a specific number of kilometers. The higher the I_{sp} the higher effectiveness of the thruster itself and the longer lifetime we can acquire for the space mission. Thus, the question one must pose every time is for example that with x number of kg of propellant mass how much distance is available for travelling. Concluding we should always keep in mind that as referred explicitly from Dan Goebel and Ira Katz[2] "Cars with high gas mileage typically do not provide much acceleration, just as thrusters with high specific impulse do not provide as much thrust for a given electrical power. Of course Isp is always associated with all other factors that a thruster incorporates, but it is one of the most important design parameters and when linked appropriately is giving the desirable and effective mission results. I_{sp} is being measured in seconds, but these seconds are not actual time. It is time representing that we manage to use lower amounts of propellant mass in order to acquire the same applied force in order to cover more distance. Therefore, if we manage to decrease the usable propellant mass, the size of the thruster decreases at the same time. This specific impulse always needs also to be associated with the exhaust velocity and as a general rule we remember that the bigger the exhaust velocity the most effective is our thruster and eventually I_{sp} is also becoming bigger. Thrust, Specific Impulse and exhaust velocity are being related with the following functions[99]:

$$F = I_{sp} \frac{d\dot{m}_p}{dt} g_0 = \frac{u_{ex}}{g_0}$$

Concluding we must always remember:

The higher the specific impulse is, the lower the propellant flow rate is required for a given thrust.

In case of a rocket, less propellant is needed to perform a given ΔV.

A rocket with high specific impulse does not burn so much propellant as a rocket with low specific impulse

Two engines have two different values of specific impulse. The engine with the higher specific impulse is more efficient because it produces more thrust for the same amount of propellant.

One rocket travelled 2 sec distance and burned only x mass of propellant. A second rocket travelled 1 sec distance and burned 2x mass of propellant. First rocket's Isp=2sec indicates that first rocket is more efficient since it burned less propellant and travelled more distance.

Propellant Mass

Another governing factor in electric propulsion concept is the selective use of a propellant and its linkage to the total mass that will finally provide us with the desirable effects and fulfill our mission requirements. The propellant mass (in the form of ions) is being expelled from the back area of the thruster itself (e.g. nozzle) and create the overall thrust by action and reaction forces. From the conservation of momentum we already know that the expelled propellant mass multiplied with its velocity is equal to the mass of the spacecraft with the change of its velocity over time. The applied force to the space vehicle is then equal to the mass of the spacecraft multiplied by the change of velocity over time. It is well known that the spacecraft thrust is being determined almost solely by the rate of change of the propellant mass and the acquired exit velocity. These two factors can play significant roles and together can increase a spacecraft's thrust figure, which is finally “the” challenge for electric propulsion engines designers.

Below, we can see the governing equation for the consumption of the propellant mass in an electric thruster, which basically shows that for a given mission with specified characteristics and requirements in velocity change ΔV and final mass m_p , the initial mass of the vehicle can be decreased if we increase the specific impulse I_{sp}. This is a way that we can finally manage to decrease the total weight of the mission and eventually the total cost, which is one of the most important factors, especially in an era of global economic crisis.

$$m_p = m_d \left[e^{-\frac{\Delta v}{v_{ex}}} - 1 \right] = m_d \left[e^{\frac{\Delta v}{I_{sp} * g}} - 1 \right]$$

Propellant mass is increasing exponentially when the mission requirements for velocity changes are very high. In chemical thrusters the propellant mass exhaust velocities are being determined and limited by the chemical bonds of the propellant used. Velocities up to 4 km/sec can be easily achieved. In contrast in electric propulsion thrusters we do not have similar limitations. Modern electric propulsion thrusters (e.g. ions) can reach exhaust velocities up to 40 km/sec and to complete difficult ΔV missions that otherwise would be cost limited. The penalty though in electric propulsion is time limitation.

Efficiency

Having said the above on Thrust (F) and Specific Impulse (Isp) parameters it is imperative to link those with the overall dominant principle of a thruster that attracts finally the most interest in the design process. This factor is called efficiency and it combines all associated known and unknown parameters that one must take into account in order to verify if the thruster finally is able to perform the desirable mission or not. This parameter was created from the necessary requirement of having one common number of measurement to refer to, when comparing the overall functioning of a space electric machine. It is not used only in space market, but broadly in engineering community. As it is obvious though, this number is a percentage and associates all parameters under one common shade trying to establish a positive answer to all researchers question. Is it feasible to perform this mission and how?

As mentioned in G. Sutton and O. Biblarz[1] “Thruster efficiency, n_t is defined as the ratio of the thrust – producing kinetic energy (axial component) rate of the exhaust beam to the total electrical power supplied to the thruster, including any use of evaporating or ionizing propellant”.

$$n_t = \frac{P_{jet}}{P_{electrical}} = \frac{\frac{1}{2}\dot{m}_p u^2}{P_{electrical}} = \frac{F * I_{sp} * g_0}{2P_{electrical}} = \frac{F * I_{sp} * g_0}{2\sum(IV)}$$

Where $P_{electrical}$ is the electric power input to thruster in watts, usually the product of all electrical currents and all associated voltages (hence the Σ sign).

Similarly[2] it describes the fraction of the input propellant mass that is converted into ions and accelerated in the electric thruster. It is the beam power out of the thruster divided by the total input power and associates the electrical cost of producing ions, cathode heater or keeper power, currents in the thruster and any other discharge losses that can play their role to the overall performance.

Total efficiency is being represented by a generic function as is shown above. However when one is trying to accurately evaluate the performance of an electrical thruster (in this case a microwave electrothermal thruster) it is a tedious procedure to finally establish a well-structured function that will represent in the most accurate and effective way all the loss parameters that coexist in that design. This process has an initial theoretical step, but thorough experimental procedures need to be implementing in order to finally encompass all those losses linked directly to the specific thruster design. Some of those losses can be wasted electrical power, improperly activated propellant particles, dispersion mechanisms, heat losses, nozzle shape etc.

Ratios

Thrust / Weight

One of the ratios that are important and are being referred often in literature is the thrust to weight ratio for an electrical thruster. This ratio represents the acceleration of the engine and is being measured in regular units of m/sec^2. In the electric propulsion case it is being used taking into account the ion / particle mass. By comparing this ratio, associating all related factors, we compare the acceleration of the available engines and extract valuable conclusions for usage of them in specific mission profiles.

$$\frac{F}{W} = \frac{Nt}{kgr} = \frac{kgr\,\frac{m}{\sec^2}}{kgr} = \frac{m}{\sec^2} \text{ (Acceleration)}$$

Thrust / Power

The most important factor in an engine's performance, which is used to characterize the efficiency, is the thrust over power ratio being expressed in Nt/Watts. It provides the final indication of the thrust that an engine can produce by consuming 1 watt of energy. It is one of the figures that designers take into serious account especially in small satellites designing process where a single watt in efforts to miniaturize space applications is maybe all the available power that your system can handle.

$$\frac{F}{P} = \frac{Nt}{W} = \frac{kgr\,\frac{m}{\sec^2}}{W}$$

Surface / Volume

Another important ratio which is extensively used in propulsion literature is surface to volume ratio of a chamber (denoting as S/V). It indicates the amount of surface area per unit length of an object and is measured in inverse distance units (m^{-1}). Generally, when the length of an object is increasing (e.g. combustion chamber) the S/V decreases and vice versa. In other words, when the length increases the volume increases faster of the surface area and this is an important aspect in designing procedures especially in microsatellites applications where the chamber is very minimal. When surface to volume ratio is large diffusion losses are more possibly to happen.

Propulsion Categorizations

In the following tree diagram (figure 6) we have depicted / categorized all available propulsion engines in accordance with literature review. Apart from chemical and nuclear types, we have represented electric dual stage, no propellant and other types of propulsion engines that are available on current literature, such as Helicon PPT and Hall Quad Confinement (Surrey University[166]). Also, Hall thrusters have been added under electrostatic and electromagnetic modes, since scientific community depicts them on both sides. Dual Stage electric thrusters are being analyzed below on a different section.

Additionally, a comparisons table 6 has been created, reporting figures of all propulsion engines in power, thrust, Isp, efficiency etc. On this table electric propulsion engines are omitted since they analyzed separately on a later stage.

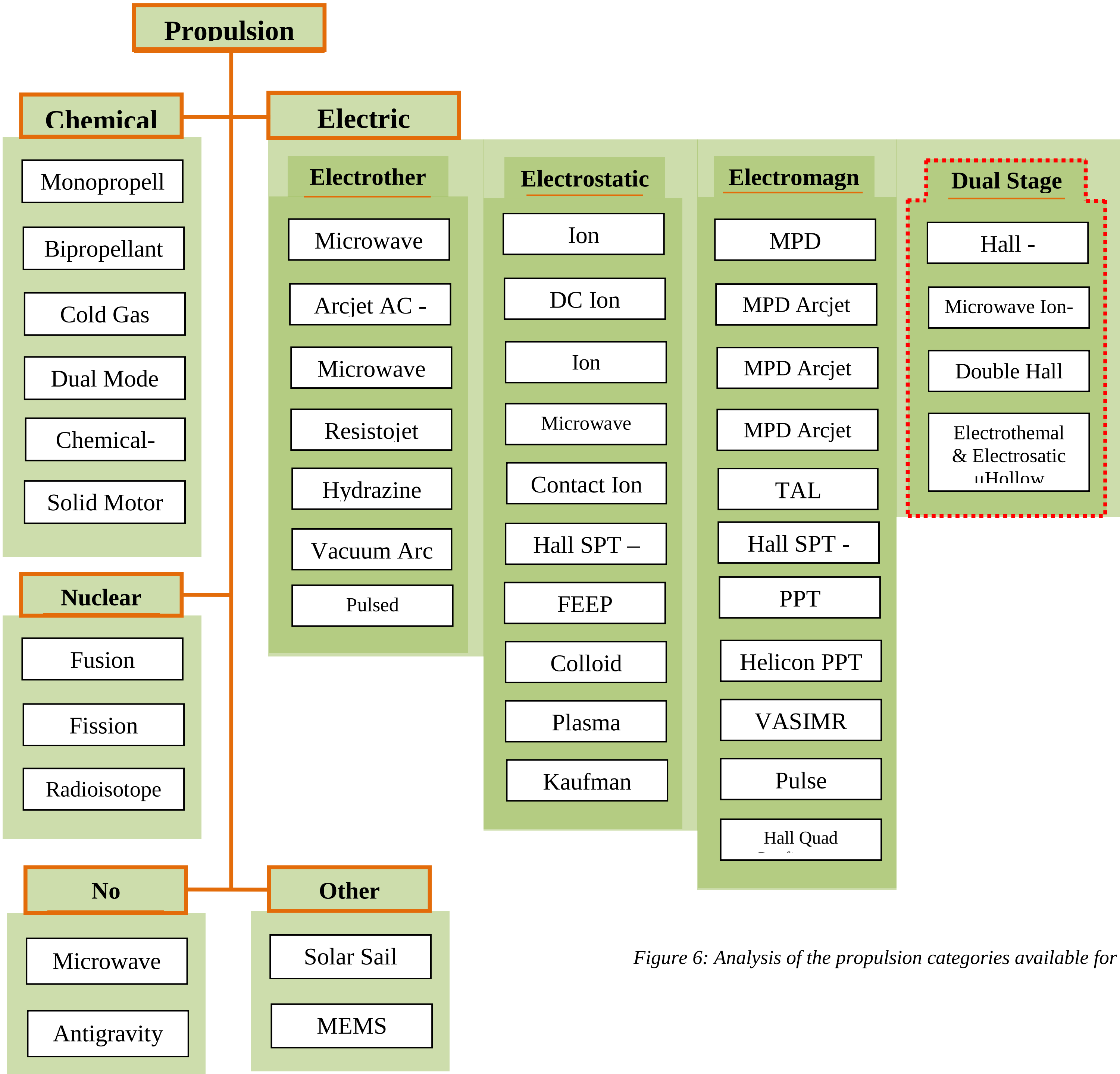


Figure 6: Analysis of the propulsion categories available for satellites and picosatellites

Chemical, Nuclear & Other types of Propulsion Thrusters Comparison										
No	**Type**	**Propulsion Engine**	**Power W**	**Thrust mN**	**Isp sec**	**Thrust Efficiency %**	**Gas**	**Weight kg**	**Lifetime N-s**	**Flown in Space?**
1.	**Chemical**	Cold Gas High Pressure	<1[153]	50-20000[100] 0.5-50[153]	50-75[99,100] 40-80[153]		Various	0.01-0.5[153]		dozens[95]
2.		Monopropellant	kW[95]	30-100000[95] 50-500[100]	200-250[95] 150-225[99,100]	87-97[95]	N_2H_4[99]		hours of minutes[95]	dozens[95]
3.		Bipropellant	kW[95]	N – kN[95]	200-410[96] 300-450[99,100]	50-90[95]	liquid or solid propellants[96]		seconds to minutes[96]	flight proven[96]
4.		Dual Mode	kW[95]	3000-20000[100]	330[100]	high	N_2O_4 / N_2H_4			flown[100]
5.	**Chemical / Electric**	Water Electrolysis	kW[95]	$5x10^4$-$5x10^5$[100]	340-380[100]	high	$H_2 + O_2$			not developed[100]
6.	**Electric**	Dual Mode	<10[153]	0.00001-1[153]	50-6000[153]			0.01-0.5[153]		No[153]
7.	**Nuclear**	Fission / Fusion	MW[95]	40 kN[95]	500-680[96]		H_2[96]		seconds to minutes[96]	stopped[96]
8.	**MEMS**	MEMS	0.01[4]	0.001[4]	100-300[4]					Yes
9.	**Solar Sail**	Electric	700[208]	1000[208]						experimental[208]
10.	**No propellant**	Emdrive[207]	850[207]	16.6[207]				15.5[207]		No[207]
11.		Antigravity[161]								No[161]

Table 6: Comparison of chemical, nuclear & other types of propulsion for satellites (ref in appendix 4)

Electric Propulsion Characteristics

Robert Jahn defined Electric Propulsion as follows: “The acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces”. From that time we begun to study the electric propulsion concepts and we understood concurrently that it is not the solution to every space environment and mission insoluble propulsive issue. It incorporates great advantages but at the same time it has significant disadvantages over a range of space missions.

The last decade researchers are trying to push the envelope to its outer limits and create solutions that will maybe revise the basic physics concepts known today and over the last centuries, by producing applications aiming to be more effective, efficient and affordable for future space missions. Electric propulsion has arisen from the need to be implemented to new classes of missions that have been investigated, such as formation flying, where precise control is required. Subsequently, we submit a concise review of the most significant characteristics of electric propulsion. These are not focused on a specific system, but range over a general manner. One must fully understand that some of the following facts are functioning as advantages to some missions while others, at the same time, offer a great disadvantage and must be avoided. This depends solely on the mission requirements themselves.

Electric propulsion provides lower thrust levels than conventional chemical systems.

Provide higher specific impulses. Therefore, the space vehicle can execute the mission carrying less propellant and is able to build up a high final velocity but in longer period [1].

Create more thrust for a longer period to produce a desired change in trajectory or velocity [1].

It has simpler electric power supplies compared to chemical [2].

High performance with simple feed systems but moderate thrusts is available.

It is propellant efficient but slower due to power limitations [2].

Low inherent thrust to weight ratio. Chemical engines thrust to weight ratio sometimes reaches unity and helps for take-off from ground. This is not a case with electric propulsion which reach numbers of thousands times smaller than this.

With electric propulsion you are only limited by the available power source and its efficiency in generating plasma[8]. It needs always more power than chemical systems.

Pose contamination concerns due to the propellant uses, such as cesium, Indium, Glycerol or Teflon[100] propellants. These propellants may condense on surfaces of sensitive surface components, such as lenses of optical instruments, inflatable antenna surfaces, solar arrays etc and subsequently interfere with the proper function of them [10].

Risk of contamination backflow when thruster is firing. It may influence the functions of a neighboring craft or thruster increasing contamination risks. Use of benign propellants should be used[10].

More complicated interfaces (especially in thermal modes).

They are low thrust and low noise devices with high specific impulses (> 500s) [12].

Energy is delivered from an energy source different from the engine [17].

Convert electric energy into kinetic energy to accelerate the propellant.

Propellant mass is limited.

Provide large mass savings because of the higher propellant exhaust velocity.

Rich diversity of mature engines with flight experience.

Suitable for low thrust and long duration missions.

The tendency nowadays is to reduce the power requirements (less than 100W) in order to find applicable solutions for micro – pico and nano spacecrafts [17]. Electric propulsion thrusters can easily accommodate this need.

Have been widely accepted for stationkeeping and final orbit insertion of commercial satellites.

Suitable for high post launch Δu missions, such as return missions, deep space rendezvous etc.

Include the ability to use available power, increased total throughput capability, lower costs and integration [19].

Electrical power available to spacecraft on board has been so far a heavy limitation for the development and implementation of plasma propulsion. Fortunately the solar array power is growing quickly having attained already 24kW availabilities [18]. Therefore electric propulsion thrusters will materialize more mission requirements in the near future.

Plasma thrusters (where the electric propulsion is acquired) are challenging the monopoly of chemical thrusters in space propulsion by offering much higher specific impulses and a huge reduction in propellant mass and the assertive launch cost of the missions. They depend heavily though on the behavior of the plasma discharge for each particular device.

Encompass a broad variety of strategies for achieving very high exhaust velocities in order to reduce the total propellant burden and corresponding launch mass of present and future transportation systems [20].

Offer a number of secondary application benefits, except the capability of achieving high velocities. These are precision and variability of thrust levels and impulse increments, generous shut down and restart capabilities and the use of chemically passive propellants.

Their major limitations are the need for sophisticated external power sources, very low to modest thrust density capabilities.

Not applicable for rapid thrust maneuvers due to low thrust densities in strong gravitational fields.

No launch or ascent – descent capabilities near planetary surfaces. Thus, near planet applications can be limited to attitude control, station keeping, drag reduction and modest orbit changing applications – functions [20].

Electric Propulsion Thrusters – Categories

Electric propulsion is unique in that it includes both thermal and non-thermal systems. In parallel and because the energy source is divorced from the propellant itself the guided factors are far more different than those in the chemical propulsion [A4-95].

Electric propulsion thrusters are categorized in accordance with their way of functioning, primarily in accordance to the way they produce the available thrust. Amongst the scientific community all authors do not concur on the same classification of electric thrusters. A classic example is the Hall Effect thruster which is sometimes classified as electrostatic or others as an electromagnetic type device. However and based on the available literature we will try to classify the electric thruster technologies as much as possible depicting some of the major differences and characteristics that they encompass, in accordance with their applications and missions. It is well known that electric propulsion thrusters nowadays are widely disparated over a number of mission profiles and it is not our aim here to refer to them explicitly. The purpose of reminding some basic characteristics and functions of the electric thrusters in existence is to have a comparative measurement, when the concept of the microwave electrothermal thruster is going to be analyzed later on.

Electric propulsion thrusters can be distinguished into four main categories:

- Electrostatic
- Electrothermal
- Electromagnetic and
- Dual Stage / Mode,

Which is a newly appeared concept that basically combines two different ways of producing thrust from the above three main / traditional categories.

Electric Propulsion Thrusters Comparison

Table 7 reports all electric propulsion thrusters and depicts a comparison among electrostatic, electrothermal and electromagnetic systems, based on available literature review. It is understood that there are plenty of electric propulsion thrusters available in flight or in experimental status. We hereby submit only a number of those tabulating only the critical characteristics (wherever they are available and have been reported accordingly). This table does not list micro – nano or pico systems that are also available today. These micro scale type of electric propulsion thrusters are being reported separately on table 10. It is our purpose through this table to record the functioning ranges acquired in power, thrust, Isp, thrust efficiency and some other characteristics that are hereby submitted. Wherever there is not enough information a blank box has been left, instead of the filling information to be an approximate number.

Electric Propulsion Thrusters Comparison										
No	**Type**	**Propulsion Engine**	**Power W**	**Thrust mN**	**Isp sec**	**Thrust Efficiency %**	**Propellant**	**Weight kg**	**Lifetime Ns**	**Flown in Space?**
1.	Electrothermal	**General**	5-100000	1-1000	30-3000	25-90		0.1-1		
2.		**Microwave Plasma (MET)**	30-2000[1] 100-350[118]	10-400[1] <1000[4]	450-650[1] 300-1300[4] 540[118]	30-50[1] 40-70[4]	He[1] He, with heavier molecules less impulses[4] H_2, Ammonia[118], Neon[5]	0.5[118]		No
3.		**Arcjet (AC – DC)**	500-2000[1,107] 50-5000[4] 900-2200[99] 300-100000[106]	100-300[1] 200-1000[95] 1-5000[106]	450-600[1] 280-2300[4] 400-1000[95] 500-600[99] 450-1500[100] 500-2000[106,107]	30-50[4,95] 25-45[99]	N_2H_4, N_2, H_2, NH_3[95] N_2H_4[99,106,107] Teflon, N_2H_4, H_2, NH_3, H_2O, N_2O[4]		860000[4] months[95] 1000-1500h[107]	dozens[95]
4.		**Microwave Arcjet**	250-6000[6] 100[7] 20[8] 5-300[12]	3-6[7,12] 0.2-4.5[8]	30-80[7] 169-197[8] 50-250[12]	50-78[7]	He, Nitrogen, Ammonia[7]	0.1-1[12]		
5.		**Resistojet**	350[2] 500-1000[99,122] 500-1500[107]	5-5000[4] 200-300[95] 5-500[100]	150-170[4] 200-350[95] 300[99,107] 150-700[100]	35-90[4] 65-90[95,99,107]	Teflon, N_2H_4, N_2, H_2, NH_3[4,95]		300000[4] months[95] 500h[107]	dozens[4]
6.		**Hydrazine**	1000[122]	330[4]	299-304[4]	300[4]	Hydrazine[4]		300000[4]	multiple[4]
7.		**Pulsed Electrothermal (PET)**		35[4]	2900[4]		Liquid H_2[4]			never[4]
8.		**Vacuum Arc[10]**	1-100[10]	22[10]	1000-3000[10]		Tungsten[10]			?[10]
9.	tr os	**General**	0.88-6000	0.005-2000	450-10000	30-98		0.1-5		
10.		**Ion**	400-4300[99,122] 50-500[102]	0.01-200[95] 0.005-500[100]	1500-5000[95] 2500-3600[99]	60-80[95] 40-80[99]	Xe, Kr, Ar[95] Cs[100] Xe[99,106]	<1[153]	months[95] 10000h[107]	multiple[95]

			300-5000[106,107] 50-300[153]	2-5[102] 7-18[102] 1-200[106] 1-20[153]	2000-6000[100] 1900-3500[102] 1000-4000[106,107] 1000-3700[153]	45-60[102,107]				
11.		**DC Ion**	400-2000[1]	15-40[1]	3000-3900[1,2]			2.5-5[2]		
12.		**Microwave Ion**	340-2500[1] 3000-4000[4] 350[102] 32[103]	8-25[1] 15[4] 4.8[102] 8[103]	2800-10000[1] 3200[102]	56-75[4] 87[102] 88[103]	Xe[102,103]		18000h[102]	dozens[102]
13.		**RF Ion**	240-1100[1,2]	5-35[1,2] 15[4]	3400-3700[1] 3000-4000[4]	56-75[4]	Xe,Kr[4]	1.6[2]		
14.		**Ion Bombardment**		0.005-500[4]	1200-10000[4]	75-90[4]	Xe, Ar, Ne, Cs, Hg[4]		5x10^6 [4]	multiple[4]
15.		**Contact Ion**		<600[4]	3500-8000[4]	55[4]	Ce[4]			multiple[4]
16.		**Hall**	50-300[3,12] 1500-4500[99] 500-5000[106,122] 300-6000[107] 50-300[153]	1-20[3,12] <220[4] 0.01-2000[95] 0.005-100[100] 1-400[106] 1-20[153]	1500-2000[2] 1200-3700[3] 1000-3700[12] 1500-2500[4,100] 1500-2000[95,99] 500-3000[106,107] 1000-3700[153]	40-60[4] 30-50[95,107] 35-60[99]	Xe[2,99,107] Xe, Ar[95]	<1[3,12, 153]	2.3x10^6[4] months[95] >7000[107]	multiple[95]
17.		**Hall SPT - PPT**	500-1500[1]	40-80[1]	~1600[1]		Xe[4]			dozens[4]
18.		**FEEP**	9-60[2] 1-100[3,12] 10^{-5}-1[107] 1-100[153]	0.1-0.8[2] 0.1-1.5[3,12] 0.001-1000[4] 0.001-1.5[153]	<8000[2] 450-9000[3,12] 4000-6000[107] 450-9000[153]	80-98[4,107]	liquid metal, Cs[107], Ru, In[4]	0.45-3.5[2] 0.1-1[3,153]		multiple[4]
19.		**Colloid**	0.88-2.2[2] 1-100[3,12,153]	0.2-0.5[2] 0.1-1.5[3,12] 0.001-0.5[4] 0.005-50[100] 0.001-1.5[153]	450-700[2] 450-9000[3,12] 1100-1500[4] 1200[100] 450-9000[153]	75[4]	Glycerol[2,4]	0.1-1[3,12,153]	>1000[4]	never[4]
20.		**Plasma Separator**					Ce[4]			never[4]
21.	Electromagnetic	**General**	10-4000K	0.03-200000	200-3000	5-80		0.06-0.5		
22.		**Hall PPT**	50-200[1,99] <10[12] 1-200[107,122]	2-10[1] 0.22-1.1[2] 0.14-1[9] 0.03-2[12] 0.05-10[95]	500-1000[1] 800-1500[2] 1125[9] 200-3000[12] 600-2000[95] 850-1200[99,107]	10[95] 7-13[99,107]	Solid Teflon[2,99,107]	5[2] 0.06-0.5[12]	years[95] >10^7[107]	multiple[95]
23.		**Hall SPT**	100K[101] 350-5K[101,122]	20-300[101]	8000[101] 1100-1750[101]	80[101]			>7000h[101]	
24.		**TAL anode layer**	100-500[101,122] 300-6K[101] 15K-30K[101]	1000-3000[101] 5000-7000[101]	1000-2000[101]	20-40[101] 40-60[101]				
25.		**MPD**	10K-60K[1] 200-1K[106]	0.2-2000[1] 0.001-2000[95] 2-15[106]	1000-7000[1] 2000-5000[95,100,106,107]	30-50[95]	Ar, Xe, H_2, Li		weeks[95]	multiple[95]
26.		**MPD Arcjet Steady State**	1-100K[107,122]	20-200000[4]	1000-11000[4] 2000-5000[107]	10-40[4] 50[107]	Nobles, N_2H_4, H_2,NH_3,N_2,CH_4,Li, K, Na[4]			never[4]
27.		**MPD Arcjet Quasi-Steady State**	200-4000K[107,122]		2000-5000[107]		Nobles, N_2H_4, H_2,NH_3,N_2,CH_4,Li, K, Na[4]			never[4]
28.		**MPD Arcjet Pulsed**	1-400[97]	1.4-4000[97]	600-1000[97]					
29.		**Pulsed Plasma**		0.005-20[4]	1000-1500[4,100]	5-15[4]	Teflon, Xe[4,100]		200-200000	multiple[4]
30.		**Helicon Pulsed Plasma**								never[4]
31.		**Pulsed Inductive**	<1000[122]	2000-200000[4,100]	1000-7000[4,100]	20-60[4]	N_2H_4,CO_2,NH_3,Ar[4]			never[4]
32.		**VASIMR**			3000-30000[4]	<60[4]	Hydrogen[4]			never[4]

Table 7: Overall Electric Propulsion Thrusters Analysis *(references in appendix 4)*

Dual Stage Electric Propulsion Systems Comparison

During literature review one can easily distinguish a new tendency on micro propulsion applications with dual stage / mode characteristics. It is evident that designers trying to acquire and implement the most beneficial characteristics of each available traditional electric propulsion system and are moving towards the application of dual stage engines. Until now NASA Glenn research center, The University of Ulsan in South Korea, the Japanese Aerospace Agency (JAXA) along with Kyushu University and finally CNES (France) and the MIREA Institute in Russia, have reported such applications. It is more than evident though that in the years to come and taking into account that cost is one of the major driven factors in space applications, engineers will go towards this direction. On table 8 we record only application characteristics that have been reported from the assorted research organizations for dual stage thrusters. The rest of the boxes have left empty since there are no listing findings – results that could possibly give us a better understanding on the completeness of work and the overall performance of the combined thrusters.

Dual Stage Electric Propulsion Systems								
No		Type	Power w	Thrust mN	Isp sec	Thrust Efficiency %	Date	Organization
1.	Dual Stage	Hall & Kaufmann	1M	39.2	3744	-	2011	NASA Glenn
2.		Microhollow Discharge Electrothermal & Electrostatic	-	-	-	-	2011	Ulsan University South Korea
3.		Microwave Ion & Hall	200	-	-	-	2007	Kyushu University & JAXA
4.		Double Hall	5K	16.5	3700	70	2005	CNES France & MIREA Russia

Table 8: Dual Electric Propulsion Systems Analysis

Generalized Electric Propulsion Comparisons

Analyzing briefly tables 7 and 8 and having listed all the critical characteristic ranges of the electric propulsion thrusters, table 9 produced, which is a general representation / comparison among the basic "four types" of electric propulsion. It is shown below that each type of electric propulsion it can cover a huge area of applications and ranges vastly in the available spectrum. However, it is noted that depending on the mission and the requirements one can use various combinations of electric propulsion thrusters in order to acquire effectiveness and affordability. One must note that the “fourth type” of electric propulsion is the referred “dual stage / mode” thruster development, which is eventually the combination of some of the traditional electric propulsion types (electrostatic, electrothermal and electromagnetic). Finally, we should keep in mind that nowadays and mainly due to the fact that cost is the most important factor in future space missions, there is a tendency for miniaturization of electric propulsion thrusters and this is the issue we are going to analyze in the following paragraphs.

	Generalized Electric Propulsion Comparisons			
	Power w	**Thrust** mN	**Isp** sec	**Thrust Efficiency** %
Electrostatic	5 – 100K	1 - 1000	30 - 3000	25 - 90
Electrothermal	0.88 – 6K	0.005 - 2000	450 - 10000	30 - 98
Electromagnetic	10 – 4M	0.03 - 200000	200 - 3000	5 - 80
Dual Stage	2.22 – 1M	16.5 – 39.2	3700 - 3744	15 -70

Table 9: General Propulsion Comparison Characteristics based on power, thrust and Isp

Small satellites propulsion

Research and development of small spacecrafts have extensively grown up in the world and a number of small satellites have been successfully launched and operated. Moreover an increasing number of small spacecraft missions are in line for execution and the miniaturization of propulsion systems is a need. In the recent years, there has been a specific growing interest for micro, nano and pico satellites. The overall weight of a micro spacecraft is considered for this project to be less than 10 kgr and the power requirements of it less than 100 watts. Thrust and Isp levels as well as thruster efficiency depends on the overall performance and are ranging from application to application.

In general, micro spacecrafts require micro thrusters for executing the missions. Such devices have to be simple, lightweight, low cost and in low power consumption. It is desirable to use simple forms of propellants and up to now as it is shown explicitly in the following tables strong interest has been in the development of small scale thrusters capable of achieving the same types of missions that old and traditional systems used to execute. A micro spacecraft, in international literature, is considered to have a mass of 100kg and less, whereas scaling further down nano spacecrafts are considered to be below 10kg and pico vehicles 1kg and less. It is obvious from the referred weight figures that the small satellites have much more stringent limits due to their overall compact system in comparison with common satellites. Some of the derived unique technical requirements for a micropropulsion system are:

- Very low power consumption
- Simple or no propellant feeding mechanisms
- Minimal propulsion system mass
- Compact size
- Reduced life cycle cost, including reductions in procurement costs
- Mass reduction technologies
- Scalable technologies
- Spacecraft compatibility (contamination)[A4-170]

A modern type or microsatellite is the so-called cubesat stemming its name primarily from the external cubical shapes. This type of micro spacecraft is one of the fastest growing sector in the space industry allowing for cheap access to space. However, their characteristics are being limited by the available volume mass and the power requirements. Cubesats specifically bring together some very important key features for future space missions as follows:

Low development and mission costs

Ease of construction

Frequent launch opportunities

Successful heritage in the last decade

On the other hand and as everything in space has “two sides of a coin”, they encompass some basic disadvantages over the larger satellites, which can be concluded as follows:

Decrease capability of carrying significant amount of scientific payload due to volume and mass limitations.

Lower system power and lower thrust capabilities.

Lower batteries capacity, hence non continuous thrust during eclipse.

Questionable thermal control [A4-142].

Generally and as extensively referred in the literature the main attributes of a small spacecraft dictate smart design are modularity, maneuverability, lifetime, autonomous operation and launch / hardware costs. Our endeavor is to reduce both voltage and power requirements while ensuring reliable long term performance.

Additionally and trying to build a micro or even nano / pico class space vehicles it is of utmost importance to pursue miniaturization of every subsystem in order to maintain the high degree of onboard capability required to ensure an acceptable scientific return for the mission. One of the subsystems that will be included in such a reduction in weight and size is propulsion and that is why nowadays designers and engineers have given all their potential in creating propulsive concepts that will finally reach the optimum goal of fulfilling a space mission [2].

In order to apply mini propulsion systems for micro / nano and picosatellites we need to take into account the severe power limitation, which is inherit characteristic of those types of spacecrafts. At the same time, we must always keep in mind that higher thruster efficiencies would reduce the mass penalty associated with the power system[2]. The research question that is posed here should be to create a system that is compact, efficient and low cost at the same time. However the impact always is measured by two main attributes. The first is mass value of propulsion system and the other one is technology readiness level rating as defined by the standardized system [A4-109].

Below we have created a table10 that lists all the available characteristics for micro, nano and pico propulsion systems available for cubesats or small size satellite applications (table 10). It has been organized by the date of initial application of the system, starting from 1998 until 2012. We report all available systems that are being concentrated on small power requirements, a factor that drives mostly the decision on which system to implement in a required mission. Thrusters listed here have power requirements of less than 100 Watts, with some exceptions depending on other critical characteristics of the thruster performance. It is generally accepted that small size satellites, in the micro / nano / pico scale, can support power requirements until 10 Watts. However and for the completeness of the work we submit records that reach 100 Watts taking into account that in the recent years, power requirements will decrease drastically.

Additionally, table 10 depicts that more than 37 miniature size propulsion systems are under experimental status only in 2012 (79 in total from 1998) from relevant organizations, which clearly indicates the interest of the international scientific community in the miniaturization of thrust engines. Most of these systems though are on experimental status and it remains to be found if in the future will succeed to be evaluated as flight prototypes and perform space missions. Some of the cells have been left blank in purpose, rather than be filled with erroneous values. The reader should understand that most of the applications are in experimental status and reports on results and findings are not yet completed.

micro / nano / pico Electric Propulsion Thrusters
(available for Cubesats and small size satellites)

No	Power W	Thrust mN	Isp sec	Thruster Efficiency %	Propellant	Gas flow rate sccm	Weight kgr	Lifetime Ns	Flown in space?	Date	Institution Thruster type
1.	32 with magnets	3.8-7.2	>2600	>84	Xe	2.94			No	1998	Hokkaido Institute of Technology[58] Microwave Ion Thruster
2.	13.5	112	1125		Teflon					2000	Dawgstar – Primex[9] PPT
3.	0.0053						0.24		Yes	2001	ST-3 Cold Gas[109]
4.	2.4-15	0.68	400		Polymers		0.75	6.2	No	2004	Photonics Laser Ablation PPT[113]
5.	15	0.6	3800		Xe	5					LionSat Penn State[119] Miniature RF Ion
6.	3	3.3	50		Water		0.188	99			UK-DMC Surrey University[120]
7.	2.1	0.68	400	40-130	Polymers		0.75	6.2			μLaser PPT Photonics New Mexico[158]
8.	50	0.14-1	350-3100	14-50	Xe	0.017-0.057 mg/sec					JPL[60]
9.	45-55	0.25	3800		Xe					2005	Penn State[138] RF Ion
10.	29.6	0.5	1371	12.4		0.42					Hokkaido IT [157] Microwave Ion Discharge
11.	10-110	0.3-3	1700	25			6.5		No		RIAME, Moscow[147] Ablative PPT-50
12.	4	2	136	12	Ar	1.5 mg/sec			No		Kyoto University [148] Microwave Electrothermal
13.	60	0.0001-0.15	5000-8000		Cesium		0.076	600	Yes		FEEP-150[110,145,146] LISA
14.	90-185	3-6	1100-1650								Hall Thruster[151] Princeton University
15.	5	0.41	1371	8.6	Xe	0.4					Hokkaido IT [157] Microwave Discharge Ion
16.		0.15	4000-8000	95	Indium				No	2007	FEEP LISA[112,150]
17.	6	1000-2000	320		Ethanol & H_2O_2		0.4		No		Austrian Research Center, Liquid Ion Green Bi propellant[112]
18.		100-800	140-180		H_2O_2	0.055-0.9 g/sec			No		Austrian Research Center Green Mono propellant[112]
19.	4.25-5.25						<1				Austrian Research[134] Center PPT
20.	0.2-2	4	3420		In						Astrium – Giessen University FEEP Ion[136]
21.	100-450	2-18	2500-3000	55	Xe		<2				JPL-L3[137] Ion
22.	4.2		960	3.1				0.022	No		Tokyo University[149] Micro PPT B-20
23.	8 10 magnets	0.67			Xe high purity	0.018 mg/s			No		Kyushu University[52] Microwave Ion Thruster
24.	8 12 magnets	0.79			Xe high	0.018 mg/s			No		

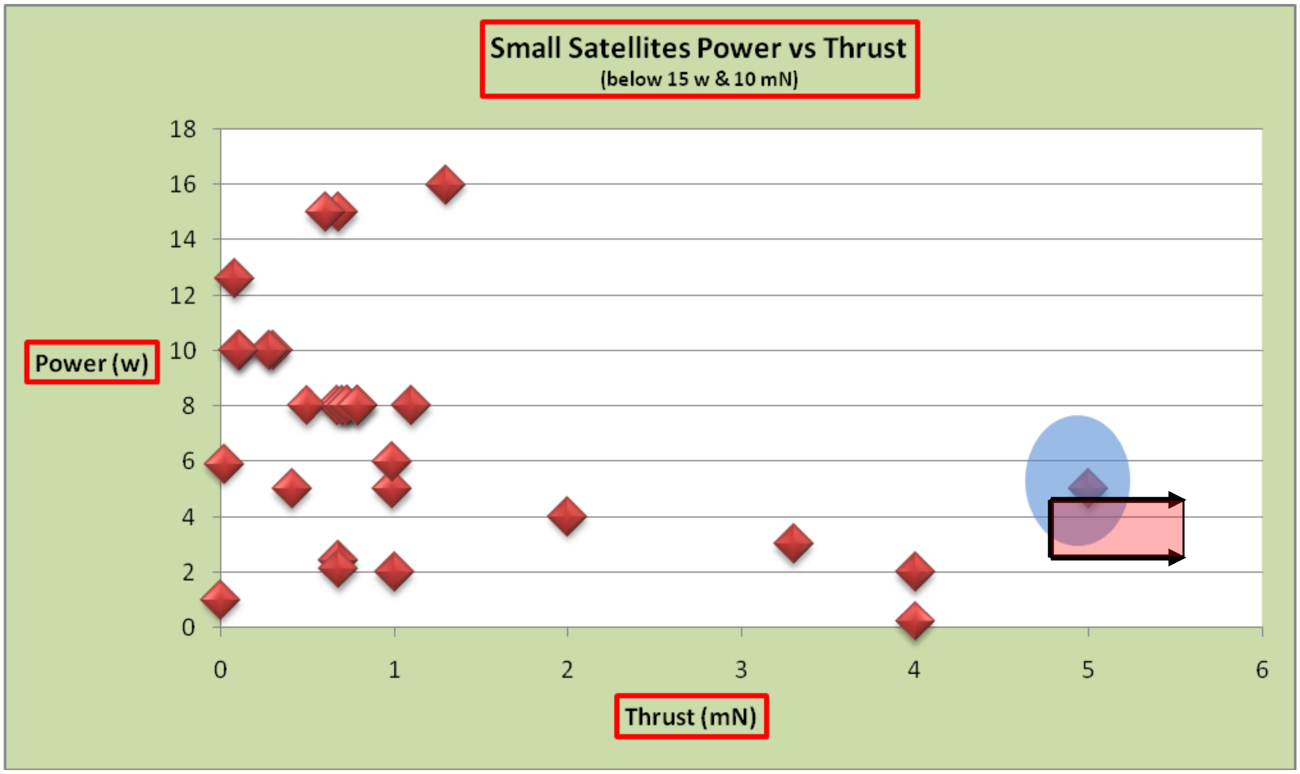
					purity						
25.	8 13 magnets	1.1			Xe high purity	0.027 mg/s			No		
26.	8 14 magnets	0.73			Xe high purity	0.018 mg/s			No		
27.	8 various magnets	0.5 central yoke length 3mm			Xe high purity	0.036 mg/s			No		
28.	8 various magnets	0.7 central yoke length 5mm			Xe high purity	0.036 mg/s			No		
29.	8 various magnets	0.73 central yoke length 7mm			Xe high purity	0.036 mg/s			No		
30.	16	1.3			Xe high purity	0.036 mg/s			No		
31.	8	0.79	4100	57	Xe high purity	0.019 mg/s			No		Microwave Ion Thruster Kyushu University[53]
32.	37	4.9	2100	0.34-0.5	Ar	2.28			No		Microwave Ion Thruster Kyushu University[131]
33.	4.2		1127				1.5	170			Tokyo University [149] PPT
34.		1-10	191		Xe		10				Brazil National Institute for Space Research PION Kaufman[128]
35.	5-300	5	50-250				0.1-1			2008	Purdue University Electrothermal[121] Microwave & Resistojet
36.	-	0.5-50	40-80				0.01-0.5				Chemical Cold Gas[121]
37.	-	1000-200	100-315				0.01-0.5				Chemical Liquid[121]
38.					H_2O_2		0.13	0.6-3.6	No	2009	Plug & Play[114] Cool Gas generators
39.	5-6	0.99	162	7	Hydrazine	0.625 mg/sec					Cheng Kung University[11] MEMS
40.	10	0.11-0.28	450-1500		Xe	0.15				2010*	JAXA Microwave Discharge Ion[159]
41.	50-350	1.3-7.3	400-1940								Hall [160] Princeton
42.		0.18-029	3.5-4.1		Solid propellant		0.05		No		SPM, MEMS[115] York University Toronto
43.		1500	210-230		H_2O_2		0.07		No		CalPoly Cubesat Monopropellant[117]
44.		125	96				<50				Tokyo University[155] Bi - Green Propellant
45.		0.25	5500	32	Ar, Xe	0.15			No		Mini MW Ion, Penn State[180]
46.									No		Cubesat µVaccuum Arc mission NASA Goddard & George Washington University[185]
47.	0.01	9.6	7120		Xe				No		Micro RF Ion, Kyoto University[168]
48.	0.3		600					0.034	No	2011*	Cubesat µPPT, Southampton University[177]
49.	1.5						0.3		No		Cubesat Nano µppt, Austria University[179]
50.	1.5	0.00009	321.8		Te				No		Cubesat µPPT, Surrey University[164]
51.	1-10	0.001-0.1		4.2	Cr						University of Illinois Vacuum Arc[155]
52.	2	1			Butane		0.22	40			Cubesat SSC SPACE[111]
53.	5.9-12.6	0.020-0.080	159-226	1	Xe, Ar	0.31-1	<10				Aerospace Corporation Microwave Discharge Ion[144]
54.	10	0.3-3.5	350	7	Xe	0.1 mg/s			No		Hall Nano satellites Osaka University[169]
55.	10	1-100	-	-	-	-	3	-	No		Cubesat Mission Analysis

											Southampton University[183]
56.	11	0.05-1						1260	No		Cubesat Nano FEEP, Austria University[179]
57.	15.1	0.297	1100		Xe				No		Ion, Tokyo University[173]
58.	19.9	0.379	1410		Xe				No		Ion, Tokyo University[173]
59.	20	0.3-3.5	450	9	Xe	0.2 mg/s			No		Hall Nano satellites Osaka University[169]
60.	20	0.015			CW Laser				No		CW Laser, Tokai University & JAXA[172]
61.	20-92	0.1-1.553	3000	25	Xe		6.2				University of California Lunar Mission Ion[142]
62.	30	2							No		Hall SPT, Ukraine National University[178]
63.	42	0.67			Xe	13.25 mg/s			No		Giessen, Astrium, mini RIT for LISA[171] (replace FEEP)
64.	50	1.5	<1200		N_2H_4	0.2 mg/s			No		Helicon Plasma, Padova University[176]
65.	53	1.61	85		Kr, Xe	20			No		Helicon ,Surrey[182]
66.	66	0.3-3.5	1600	18.1	Xe	0.1 mg/s			No		Hall Nano satellites Osaka University[169]
67.	100	2.1	700		Kr	5			No		Quad Confinement, Surrey [166]
68.	100	3	1200	18		0.3 mg/s			No		Hall SPT, Ukraine National University[178]
69.	100	27.5	170	22.5	Ar				No		Arcjet ,Stuttgart University[175]
70.	100	45	150	34	H_2O				No		Resistojet, Surrey University[175]
71.	100	0.3-3.5	600	6	Xe	0.3 mg/s			No	2011*	Hall Nano satellites Osaka University[169]
72.	100			0.5	PTFE, Te				No		Thermal PPT, University of Stuttgart[170]
73.	130	0.3-3.5	1350	13	Xe	0.2 mg/s			No		Hall Nano satellites Osaka University[169]
74.	196	10	1200	30	Xe				No		Hall, Fakel, Russia[175]
75.	200				Xe, Kr				No		Hall Thruster CNRS France[163] Ion velocity evaluation
76.	200	0.62			Ar	70			No		Helicon Double Layer, Surrey & Australian University[165]
77.	240	0.3-3.5	1200	8	Xe	0.3 mg/s			No		Hall Nano satellites Osaka University[169]
78.	240				Kr	3 mg/s			No		Hall, Harbin IT,China[174]
79.	250	41.1			Kr	16			No		Helicon Double Layer, Surrey & Australian Universities[167]

**Categorization of 2011 and 2010 applications from low to high power requirements (references in appendix 4)*

Table 10: micro / nano / pico Electric Propulsion Thrusters categorization

In the next graph 5 below, small satellites power vs thrust dispersion diagram is depicted, based on literature review that was done in accordance with table 10. Representation has been done only for small satellites that have power requirements below 15 watts. With this limitation in place, best value of thrust acquired is 5mN with only 5 watts of respective power (blue shaded point). Research needs to move towards the red shaded area in order to facilitate miniaturization of satellites and decrease of power requirements (less than 5 watts), suitable case to low cost future missions.



Graph 5: Small satellites propulsion allocation of power vs thrust

Microwave Electrothermal Thrusters (MET)

Theory of microwave concept

Microwave Electrothermal Thrusters have attracted nowadays the research interest on a wide operational envelope. They are an efficient and reliable form of micropropulsion and have been designed and successfully tested under different microwave frequencies, with a variety of propellants and chamber pressures.

MET operates by heating a propellant with a microwave generated free floating plasma. The cold propellant is receiving microwave energy resulting in the production of plasma which in turn gives off radiation and heat energy. The excited species flow away from the plasma while the cold species flows towards it. Finally, the plasma excited propellant is recombined downstream with increased kinetic energy. The thermalized propellant is exhausted through a gas dynamic nozzle to generate thrust.

In an ideal electrothermal thruster all of the input power is converted into stagnation enthalpy, which is subsequently converted into directed kinetic energy in the plume by an adiabatic expansion to infinite Mach number. The ideal thrust efficiency then is 100%. In a real thruster though, some of temperature is lost in thermal radiation by molecular excitation, dissociation, electronic excitation and vibrational excitation [A4-56]. For well-designed thrusters the major energy loss mechanism is frozen flow losses, which are composed of chemical dissociation, ionization energy and excited electronic / vibrational / rotational distributions that are not relaxed during the expansion process [A4-5].

Several different microwave absorption concepts have been studied over the years: The resonant cavity, the coaxial applicator and more recently the waveguide applicator [A4-37]. These are the three most popular candidates.

In a resonant cavity plasma is sustained in the maximum field regions of a standing electromagnetic wave pattern and tuning the system by adjusting the cavity length can yield to coupling efficiencies [A4-37]. The electromagnetic field distributions within the MET cavity can be found by solving Maxwell's equations for a closed cylindrical cavity with perfectly conducting walls. A transverse magnetic mode of resonance (TM) is used to create maximum electric energy density along the axis at the two ends of the cavity [A4-46]. The cylindrical cavity is geometrically sized to create a standing wave focusing the electric field at several locations inside the cavity. The electric field breaks down the gas where the electric field strength is highest forming free floating plasma. The common used transverse mode TM_{011} concentrates the plasma at the ends and midplane of the cavity. The concentration of the electric energy is determined primarily from the frequency of microwave energy and the geometry of the cylindrical resonant cavity [A4-84].

The coaxial applicator is the oldest concept. The plasma here is formed at the tip of the movable center conductor of the coaxial line and is thus well located allowing flexible positioning. The outer conductor serves as the absorption chamber. It is believed though that the formation of plasma to the coaxial tip produces losses and decreases the overall efficiency, creating significant erosion problems [A4-37].

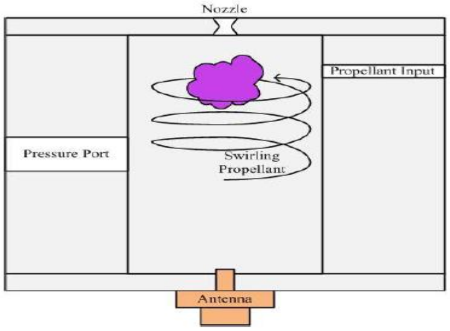
The most recent and promising technique is the waveguide concept, where a waveguide sector is used as absorption chamber. It is able to acquire high temperatures providing higher specific impulses than others [A4-37]. Additionally, the use of traveling microwaves in a waveguide avoids another life limiting factor which is antenna sputtering. Microwaves propagate in the circular TE11 mode while higher modes are cut off. The magnetic field required for ECR heating is established by a ring of samarium cobalt permanent magnets. These magnets are oriented axially and the magnetic field ECR heating zone is established on the centerline of the waveguide. Because the electric field on the center mode TM11 is peaked on the centerline at the location of the ECR zone, microwave power is readily absorbed. The microwaves enter through a quartz window on the upstream end, isolating the plasma from the launching antenna.

The performance calculations that need to be undertaken in order to evaluate the performance of a microwave electrothermal thruster are not limited to but are as follows [A4-69]:

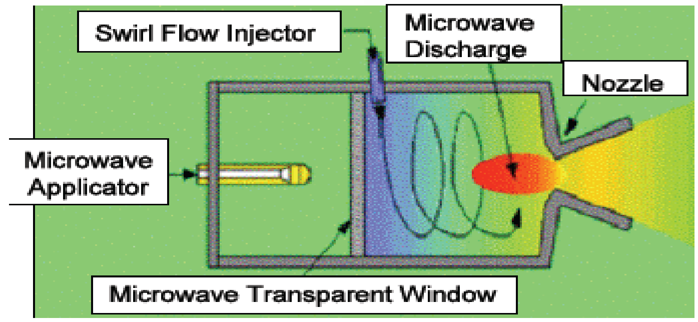
a. Absorbed power
b. Mass Flow rate
c. Plenum pressure
d. Vacuum tank pressure
e. Specific power
f. Thrust
g. Specific Impulse
h. Thermal Efficiency

Extensive experimental studies showed that the most efficient microwave configuration design was the use of a microwave magnetron coupled directly to the thruster [A4-69]. The microwave sustained plasma becomes unstable above a certain threshold of absorbed power and this threshold is a function of mass flow rate and plenum pressure [A4-66]. Because microwave electrothermal thrusters can apply heating locally without electrodes they have the capability of providing extremely high stagnation temperatures with extended lifetimes. Also by increasing the frequency of the thruster, plasma generation size decreasing can occur, at lower input power with increased performance.

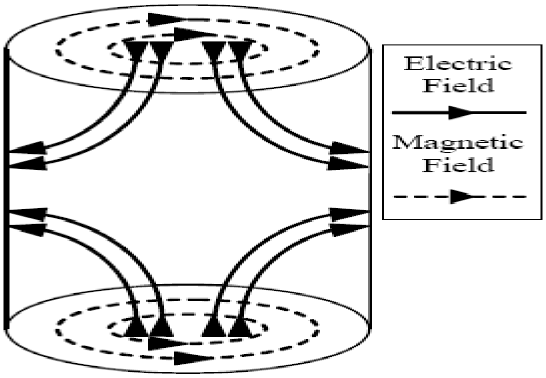
Some of the basic micro MET layouts are depicted on the following figures.



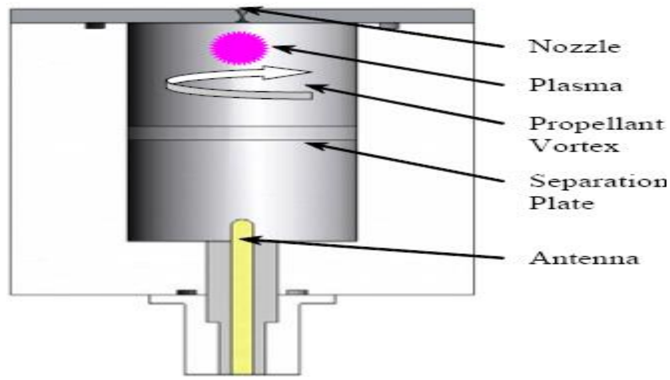
MET basic layout (Penn State University) [181]



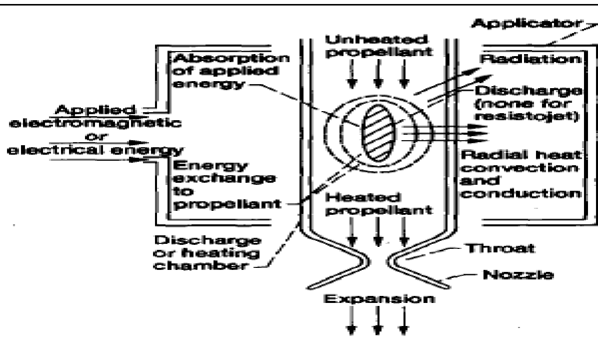
MET schematic (Penn State University) [154]



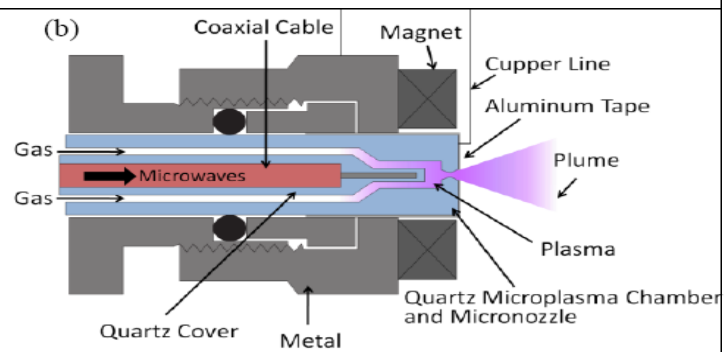
TM^{Z}_{011} mode in a MET[118]



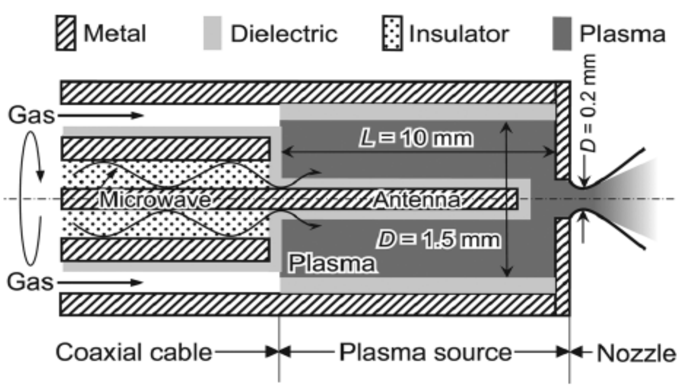
MET schematic (Penn State University) [118]

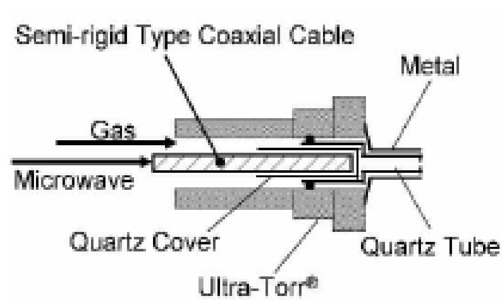


MET processes (NASA Lewis Research)[84]



MET Experimental Thruster (Kyoto University -2011)[22]





MET Experimental Thruster (Kyoto University -2011)[22]	MET Experimental Thruster (Kyoto University -2005)[148]

Table 11: Microwave Electrothermal Thrusters Types (references in appendix 4)

Why MET Propulsion?- Advantages

Microwave Electrothermal Thrusters have distinct advantages over the other electrothermal or generally electric propulsion thrusters. Through literature review it was evident that these advantages can play vital roles in the propulsive mission selection process. The most important advantages of METs are hereby submitted as follows:

By transferring microwave energy via waveguides into the absorption chamber and properly choosing chamber dimensions, coupling methods and electromagnetic field patterns that can be established, sustain the plasma in the maximum field regions away from chamber walls. This allows the plasma to get much hotter [A4-37].

The coupling of microwave energy is extremely efficient into gases at pressures on the order of atmospheric [A4-37].

No use of electrodes (electrodeless technique), neutralizers which means that the structural design is very simple without erosion issues and plasma sputtering. So a microwave thruster would offer a potentially longer thruster lifetime (long life span).

Encompass simple structure, less likely to interfere with adjacent systems on a small satellite.

Higher thrust efficiencies can be obtained due to reduced conductive losses into the engine structure [A4-36].

Concentrate design on compactness and simplicity (2-4 orders of magnitude with respect to other similar systems) [A4-36].

Manufacturing tolerances are fairly loose. Only a simple gas feed is required. All these lead to lower costs [A4-36].

Acquire wide range of thrust.

Manage to have less electromagnetic emissions.

Can replace hydrazine monopropellant thrusters on satellites for N-S station keeping.

Due to the fact that the plasma is created away from the chamber walls can avoid thermal conduction losses on the chamber.

METs can work in both steady state and pulsed mode. (Whiting School of engineering paper).

Heating of plasma can be applied locally without electrodes in the flow and thus they have capacity to generate extremely high stagnation temperatures.

Establishing electrodeless discharge freely supported by electromagnetic fields rather than attached to engine components allow propellants to get much hotter than the engine materials which ultimately lead to higher specific impulse values [A4-36].

By transferring microwave energy via waveguides into the absorption chamber and properly choosing chamber dimensions and coupling methods, electromagnetic field patterns can be selected in order to sustain plasma away from the chamber walls and in the maximum field regions. This allows the propellant to get much hotter.

Microwave thrusters can operate with a variety of propellants such as inert gases, oxidizers and fuels.

The microwave concept is not propellant specific and offers excellent throttling characteristics.

Radiative losses from a microwave created plasma are negligible due to the relatively low temperatures [A4-37]

Using magnetrons, microwave power can be generated at efficiency up to 85% for large amounts of power.

The microwave thruster is safer because it works only when the magnetron or antenna works to ignite the plasma. When you do not need it is off [A4-5].

Microwave discharges are attractive because they are capable of producing high density plasma at low pressures [A4-9].

Low electromagnetic interference (EMI) and an exhaust divergence comparable to chemical thrusters rather than the larger half angles typical of electrostatic thrusters [A4-118].

MET cavity can be constructed with no exotic materials with a very low parts count [A118].

Can be used in a dual mode thruster with hydrazine monopropellant or bipropellant propulsion system with common tanks, ducts and valves for significant cost and mass savings, while enabling missions that nonintegrated electric propulsion and conventional thrusters could not complete [A4-118].

Provide comparable specific impulse values to those obtained with arcjets, while longer lifetime and higher efficiency.

Does not require any power processing to make the transition from plasma formation to stable high power plasma [A4-8].

The fact that microwave thrusters work without electrodes may allow for operation with water vapor as propellant [A4-67]. When an electrode is in presence of the operation oxygen atoms produced from water vapor destroy the electrodes and provoke serious erosion.

Microwave thrusters suffer from temperature limitations when the plasma is generated in the thruster walls. That is why newer researchers are trying to focus on producing the plasma in the center of the cavity and towards the end of the chamber [A4-67,78].

MET Disadvantages

As temperature of the plasma increases nozzle goes to melting and that is one of the problems today.

Not true flight performance up to date due to several factors such as the complex physics involved in microwave heating and the difficulty in using conventional diagnostic techniques to study high temperature molecular plasmas [A4-46].

Diffusion loss is a significant problem for the micro plasma source due to large surface to volume ratio. Applying a magnetic field is a way to reduce diffusion loss to the wall because electrons are strongly affected by the magnetic field and confined along magnetic lines [A4-22].

Maximum temperature in a microwave thruster is limited due to the limitations of the thruster walls. That is why we are trying to create plasmas in the center of the chamber and near the nozzle area.

Because of the successful application of arcjets, for north south stationkeeping and altitude control, and due to the low performance of microwave sources, electrothermal thrusters confined on lab tests only [A4-35].

Micro - MET Literature review - What is available today?

Micro Microwave Electrothermal Thruster (Micro-MET) applications today have started to attract a good amount of interest in the international scientific community. As shown in table 5 there are currently five research organizations that are executing experimental testing in order to acquire beneficial results for the use of microwave electrothermal thrusters. This interest stems primarily from the above mentioned advantages and by the fact that miniaturization in space is a fact which gives a great opportunity to microwave electrothermal thrusters to find their origins for flight applications.

On table 12 we have depicted all the concurrent experimental efforts towards the application of micro microwave electrothermal thrusts flight prototypes. The designers are coming from five different organizations with 28 different experimental configurations under testing procedures. The results clearly indicate that micro METs with very low power requirements can produce an amount of thrust that would be useful for some types of flight missions, like attitude control and very small maneuvering.

micro / nano / pico - Microwave Electrothermal Thruster (MET) Comparisons											
No	**Power** W	**Thrust** mN	**Isp** sec	**Thruster Efficiency** %	**Propellant**	**Propellant flow rate** sccm	**Weight** kgr	**Frequency** GHz	**Flown in space?**	**Date**	**Institution**
1.	3	↑ 1.8 - 5.6%	N/A	N/A	Ar			4	No	**2011**	Kyoto[22]
2.	6	↑ 2.8 - 12.3%	N/A	N/A	Ar			4	No		
3.	3	1.08	62	10	Ar	60 magnet		4	No		
4.	3	1.03	59	9.2	Ar	60 no magnet		4	No		
5.	6	1.23	70	6.8	Ar	60 magnet		4	No		
6.	6	1.11	64	5.6	Ar	60 no magnet		4	No		
7.	6	0.51	250	10.1	He	2-70		4	No		Kyoto[21]
8.	6	0.51	375	10.1	H_2	2-70		4	No		
9.	6	0.2 - 1.4	50 – 80	2 – 12	Ar + 5% N_2 and H_2	10-60		4	No	2009	Kyoto[20]
10.	6	1.4	80	8.7	A r + 5% N_2 and H_2	60		2, 4	No	2008	Kyoto[18]
11.	With 4 GHz, plasma is little affected, with 10 GHz and shorter chamber, improve of thrust performance									2007	Kyoto[17]
12.	3	1.2	66	12	Ar			4	No		Kyoto[16]
13.	6	1.4	79	8.7	Ar			4	No		
14.	6	1.4	80	8.7	Ar + 5% N_2 and H_2	10-60		4	No	2008	Kyoto[19]
15.	10	2.5-3.5	130-180			2 mg/s		1-25	No	2006	Kyoto[14]
16.	5	1.1	73	4.2	Ar	10-50		4	No		Kyoto[15]
17.	4	2	136	12	Ar	1.5 mg/sec		4	No	2005	Kyoto[148]
18.	3.1	4.3	320		Ar	280		4	No	2004	Kyoto[13]
19.	100	3-6	30-80	50-78	He, N_2, Ammonia	2-20 mg/sec			No	2004	Penn State[42]
20.	20	0.2-4.5	169-197		He	2.15 mg/sec		14.5	No	2007	Penn State[8]
21.	200		321-434	6.9-75	Ammonia & Hydrazine		<1	8	No	2010	Penn State[118]
22.	100-250	15-90	190-315		N_2H_3			8	No	**2011**	Penn State[154]
23.	2.94				He			30	No	**2011**	Penn State[181]

24.	100-300	20-120	450-650	34-50	He	4.09-6.14 mg/s			No	2008	Xian[35]
25.	70	15	340		He				No		
26.	120	$25.5x10^6$	5758	61.3	N_2H_4	4.4 mg/sec	1.5		No	**2011**	Xian[152]
27.	1-5	2.5-3.5	130-180		Xe, Ar	80			No	**2011**	Korea Ulsan University[162]
28.	150	40-75	70-200		He & N_2O	0.025 mg/sec		7.5	No	2004	Princeton[69]

**Categorization in accordance with Institution and Date of application (references in appendix 4)*

Table 12: Categorization of micro/nano/pico microware electrothermal thrusters

MET Design Considerations

In the process of designing of a microwave electrothermal thruster the following design considerations need to be taken into account, based always on the available literature review. These are not only limitations, but also objectives in order for a microwave electrothermal thruster to be implemented initially on an experimental testbed status:

- Magnets position on the discharge chamber walls (e.g. vertical or diagonal applied magnetic fields).
- Position of magnets near the plasma in association with the intensity of the applied magnetic field. Effective and efficient positioning in order to acquire the most energy.
- Number of magnets to be used.
- Intensity of the applied magnetic field.
- Intensity of the applied electric field.
- Production of the desirable Isp associated with thrust and power availability.
- Currents in the main discharge area, eventually there are some currents that if they increase their presence and intensity then they decrease efficiency of the thruster itself.
- Position of the magnetic confinement areas – directly associated with the intensity of the magnetic field.
- Beam divergence factor in the exit of the thruster nozzle and impact to thrust equation.
- Multiple charged species factor in association to the beam divergence factor and the overall impact to the thrust equation.

- Increase of Isp, increase of ΔV and the impact to the overall power requirements
- Efficiency of the thruster based on eV / ion measurements energy transfer. The bigger the better.
- Decrease of the cusp phenomenon in the applied magnetic field so as not to decrease the overall intensity of the magnetic field in order not to lose e^- that did not collide with ions and eventually decrease of the efficiency.
- Create a discharge loss (eV/ ion) / propellant utilization efficiency (n) graph in order to compare values and find the most effective area of application for creating the optimum thrust to the system.
- Find Larmor Radius. The smaller the Larmor radius is the bigger possibility we have for an electron to collide with an ion.
- Define the Debye length (how many μm inside the plasma).
- Define the shape of the discharge chamber (cylindrical, conical, rectangular, multi shaped etc).
- Applied voltages.
- Applied microwave frequencies (e.g. 2.45, 4, 10 GHz)
- Selection of outside surface / materials of the thruster.
- Do we need neutralizer? Effect of the plume to the communication scheme on the spacecraft.
- Microwaves are being absorbed from plasma only under specific circumstances. If plasma density is very low then microwaves are being reflected totally. Find the optimum plasma density to maximize the microwave absorption factor.
- Proper selection of the microwave frequency in conjunction with plasma frequency. When microwave frequency is larger than the plasma electron frequency the electromagnetic waves are not propagating due to the fact that wave length tend to infinity
- Travel distance of e^- inside the electric and magnetic fields in order to acquire the most energy and transfer it accordingly after the collision.
- Divergent or convergent magnetic field lines. (Divergent lines are more popular and produce efficient results).

- Weight of the available electromagnets to be used. Small electromagnets produce more magnetic cusps
- Type of the magnets. One candidate is Samarium Cobalt (SmCo).
- Decrease of the ion density in the thruster exit in order to avoid interactive collisions and eventually decrease of the ion exit velocity.
- Space charge limit. What is the availability for the microwave thruster?
- Application of different magnetic fields in intensity. What will be the result? Dual stage application of the magnetic field.
- Creation of the Ion diffusion model for each application.
- Study the microwave phase shift inside the plasma.
- Type of nozzle. Converging – Diverging De Laval nozzle is the design today. Is there any other design available for a microwave electrothermal thruster?
- Cavity resonance design inside the thruster.
- Maximum power density and where it is located inside the plasma. This is the area where the microwave discharge is happening.
- What is the heat transfer mechanism inside the plasma?
- Correlation of resonant frequency, cavity radius and height.
- With the electrodeless design we have the capability of creating very hot plasma, sometimes even hotter than the resistance of the chamber wall materials
- ITU frequency range for Microwave thrusters generally is 2.45, 5.8 and 24.125 GHz in order to minimize jamming. However research is being executed in other frequency ranges such as 4.5 and 10 GHz.
- Decide which Microwave electrothermal concept to use. Up to now there are available three microwave electrothermal thruster propulsion concepts. Coaxial Applicator (flexible positioning), Resonant Cavity and Waveguide applicator (bluff body use to stabilize the plasma). Kyoto’s application is a coaxial applicator.
- Thrust measurement and performance by pendulum or thrust standard methods
- Use of monatomic, biatomic or polyenergetic ions. Consider the factor of vibrational and rotational state distribution.

- Correlation of Isp with gas temperature / molecular weight and specific heat.
- Frozen flow losses – all losses factors except energy transfer
- Mass flow rate, pressure in plenum and relation with plasma parameters. Plasma become unstable after absorbing a specific amount of energy transfer
- Use of TM, TM_{011}, TM_{012} : TM=No magnetic field in the direction of propagation
- TM_{mn} (for rectangular waveguide)
- m= Number of half wavelengths across the width of the waveguide
- n= number of half wavelengths across the height of the waveguide
- TM_{mn} (for circular waveguide)
- m= Number of half wavelengths across half circumference
- n= number of half wavelengths along the radius
- What is the highest temperature to work inside the microwave thruster? Impact to highest specific impulse number.
- Execute all performance calculations for a microwave electrothermal thruster.
- Power / Thrust ratio. The smaller the most efficient is the propulsion thruster
- Surface to Volume ratio of the discharge chamber. The smaller it is the smaller electron losses we have, better efficiency we acquire.
- Microwave antenna. Consider the use of two microwave antennas
- Higher mass flow rates – higher thrust – shorter mission trip times
- Converging and Diverging nozzle angles. Tentatively 30^0 half angle for the converging nozzle and 15^0 half angle for the diverging.
- Electron number density in relation to position in the plume.
- Antenna shape / size / material for the generation of microwave plasma.
- Collision frequency among electron – neutral and electron – ion pairs.
- Excitation frequency to be used.
- Available mission profiles for nanosatellites or miniature microwave excited thrusters.

- Sizing the cavity of the MET correctly and concentrating the electric field at its ends plasma can be created near the entrance of the nozzle[181]. This is the ideal location to be formed because it allows for the most transfer of thermal energy to the propellant by the plasma.
- Investigation of the use of two microwave sources in order to study the plasma characteristics and the effective changes.
- Investigation of the use of two stage microwave thruster where the second stage is located near the nozzle area by adding energy to the propellant.

Critical Analysis

General Findings for microMETs

The following general findings / results (advantages or disadvantages) were obtained from the experimentation with microwave electrothermal micro thrusters in accordance with literature review based on table 6 applications (see also annex tables for detailed analysis on micro MET characteristics separated in accordance with the research organization and the paper that has been submitted):

The shape of the magnetic field directly influences the confinement of energetic electrons[22]. More investigation is needed in order to increase confinement. Kyoto University though reported that with the placement of magnets the thrust efficiency increase by 2.8-12% comparing to operation with no magnets [A4-22].

High diffusivity and thermal conductivity of light mass propellants do not lead to deterioration in performance [A4-21].

The thrust performance found to increase with the discharge on and by increasing microwave power [A4-20].

As power increases thrust increases, as power increases Isp increases and as power increases thruster efficiency decreases [A4-18].

Plasma is little affected by the shape of the plasma source when frequency is 4.0 GHz [A4-17].

Higher electron density and heavy particle temperature was achieved with shorter plasma chamber and frequency of 10 GHz. Thus, in this microwave range and with shorter chamber thrust performance can be improved [A4-17].

Thrust efficiency decreases with increase of the microwave power [A4-16].

Thrust performance is not being severed affected by different throat diameter micronozzles[16]. More investigation is needed in order to verify what exactly influences directly the thrust performance of the microwave electrothermal thruster.

Surface waves tend to be established in the micro plasma source at high frequencies and permitivities [A4-14].

Microwave power absorbed in plasmas increases with increasing frequency and permittivity [A4-14].

Thrust and Isp were improved by discharging plasma and increased with microwave input power [A4-15].

The thrust increased with increasing gas flow rate, whereas Isp had minimum values at around 20-30sccm and then increased at 10sccm in plasma discharging operation [A4-15].

Microwave power absorbed in plasmas increases with increasing frequency [A4-13].

The average gas temperature is increased with increasing microwave power [A4-35].

When the microwave power is increased the electron density increases gradually [A4-35].

First time evaluation of a double stage electrothermal and electrostatic thruster by using MET & Hall configurations. With very low power requirements (< 3 Watt) it seems that thrust is in the order of 2-3 Mn [A4-162].

Thickness of the dielectric causes lack of significant heating to the plasma & increasing mass flow rate thrust was also increased [A4-8].

Increase in flow rate and pressure forces the plasma closer to the nozzle entrance which eventually decreases losses and increases the available thrust efficiency and overall performance [A4-118].

Maximum thermal efficiency is not a function of input power [A4-118].

Utilizing a shorter antenna improves performance of the thruster [A4-118].

By increasing nozzle diameter efficiency was also increased [A4-118].

First time simulation of plasma physics with COMSOL where thermodynamic effects are being coupled with electromagnetic effects [A4-154].

When the resonant frequency was exactly 29.939 Ghz, the power coupling increased by reducing the antenna length [A4-69].

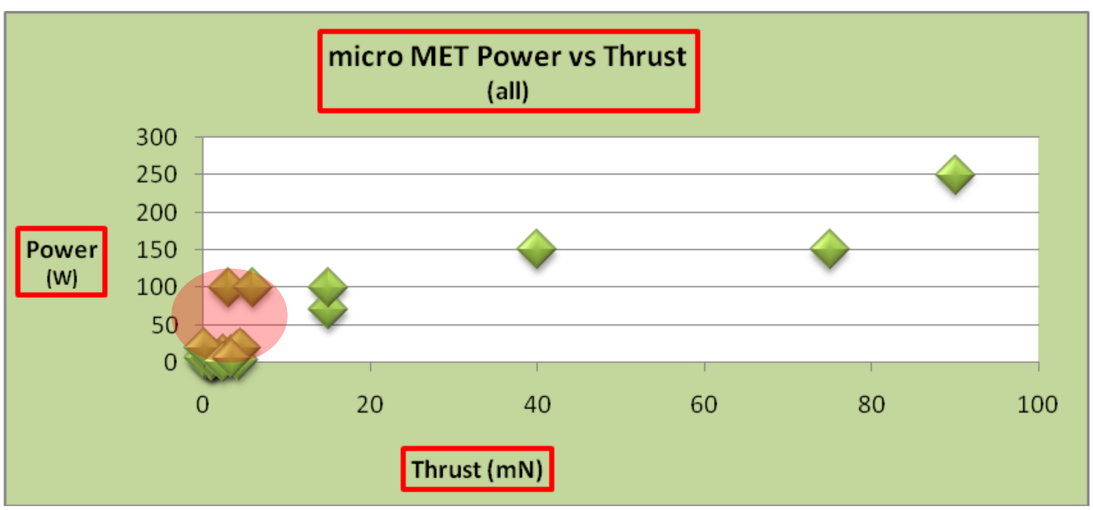
MET are applicable for attitude control and stationkeeping for micro spacecrafts < 10kg [A4-19].

MET can be used for drag compensation, solar pressure cancelation of low earth orbit spacecraft, formation flying, precise positioning of small satellite, repositioning of GEO and main propulsion for interplanetary missions [A4-152].

Comparison Graphs for microMETs

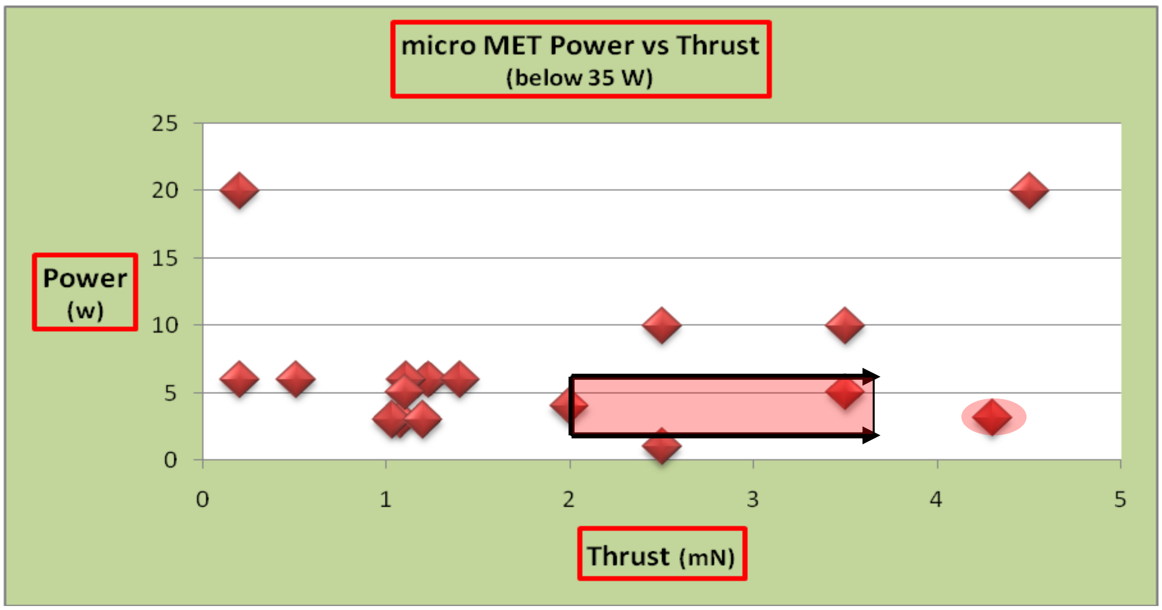
In this section comparison among the experimental microwave electrothermal thrusters is being conducted based on the available collected information from literature review from table 10.

In graph 6 Power is depicted in comparison to Thrust for all thrusters and power levels ranging from 3 to 250 Watt for power and from 0.2 until 90 mN thrust levels. The red shaded area depicts that most of the micro experimental microwave electrothermal thrusters are in the areas below 10 watt with thrust levels ranging from 0.2 until 15mN, trying to accommodate the needs of small and very small satellites that are going to govern the space and scientific environment in the near future, primarily due to very low costs.



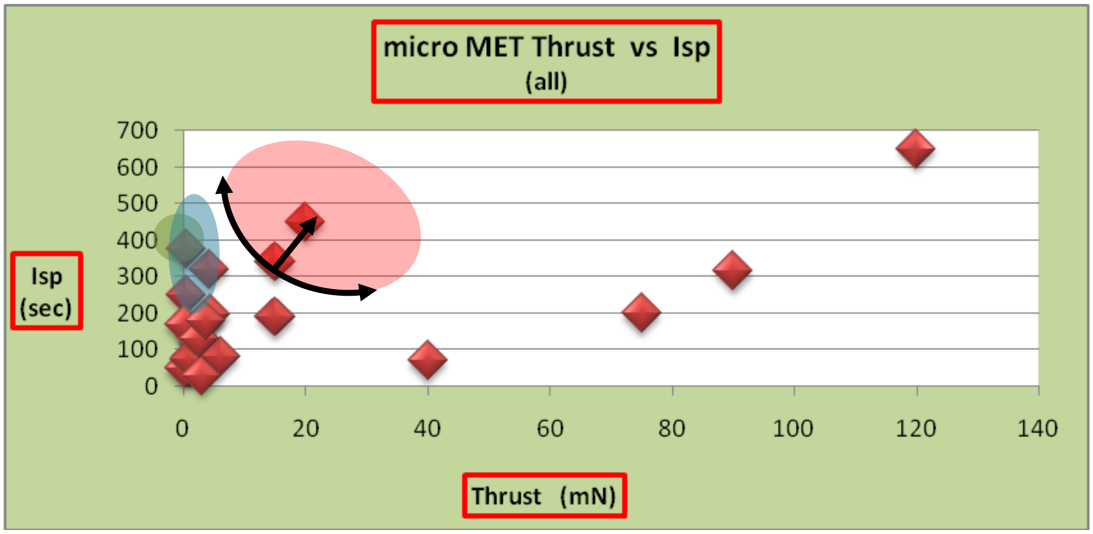
Graph 6: micro MET power vs thrust

Trying to better evaluate the use of very low power levels in microMET research we depict in graph 7 the red shaded area of graph 7 (magnified), which eventually gives us a better grasp of the power levels and the thrust acquired. It is important to notice here that most of the research is centered in the area around 1 – 2 mN of thrust with the power levels to remain near the 5 watts power requirement (representation of these figures have been accomplished by Kyoto University, Japan as it is shown explicitly in table 10). The important fact for researchers to succeed in the near future is the movement of research to the red shaded area, which means to remain on the power levels, 1-5 watts but increase the thrust more than 4.5 mN, which is the best figure for today's applications.



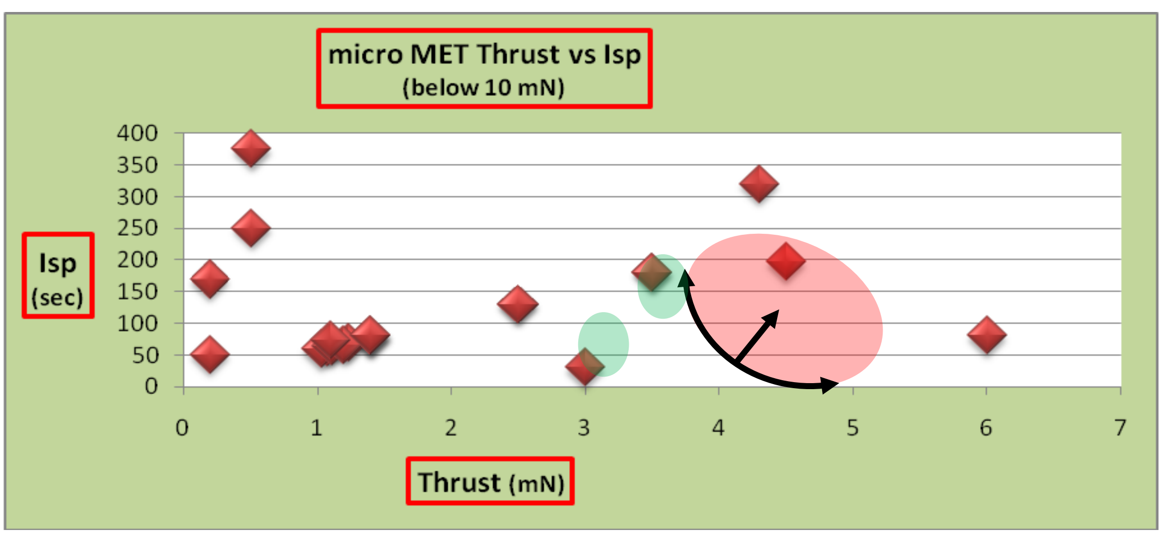
Graph 7: micro MET power vs thrust (below 35 W)

Following our analysis we depict on graph 8 the representation of Thrust with respect to succeed Isp. Best value has been applied by the University of Ulsan, Korea with 3,5 mN thrust and 180 sec of Isp (green shaded area) due to very low power requirements used in the order of 1-5 watt. On the other hand the rest of the research applications are below 100 sec for Isp and below 5mN for thrust (blue shaded area). The red shaded area depicts the way where the research is needed to be focused in order to acquire better results (increase thrust and Isp concurrently if possible – very difficult and very fictitious, but is needed for small satellite applications). The decrease of the Power / Thrust ratio indicates the increase in the performance / effectiveness / efficiency of the engine itself.



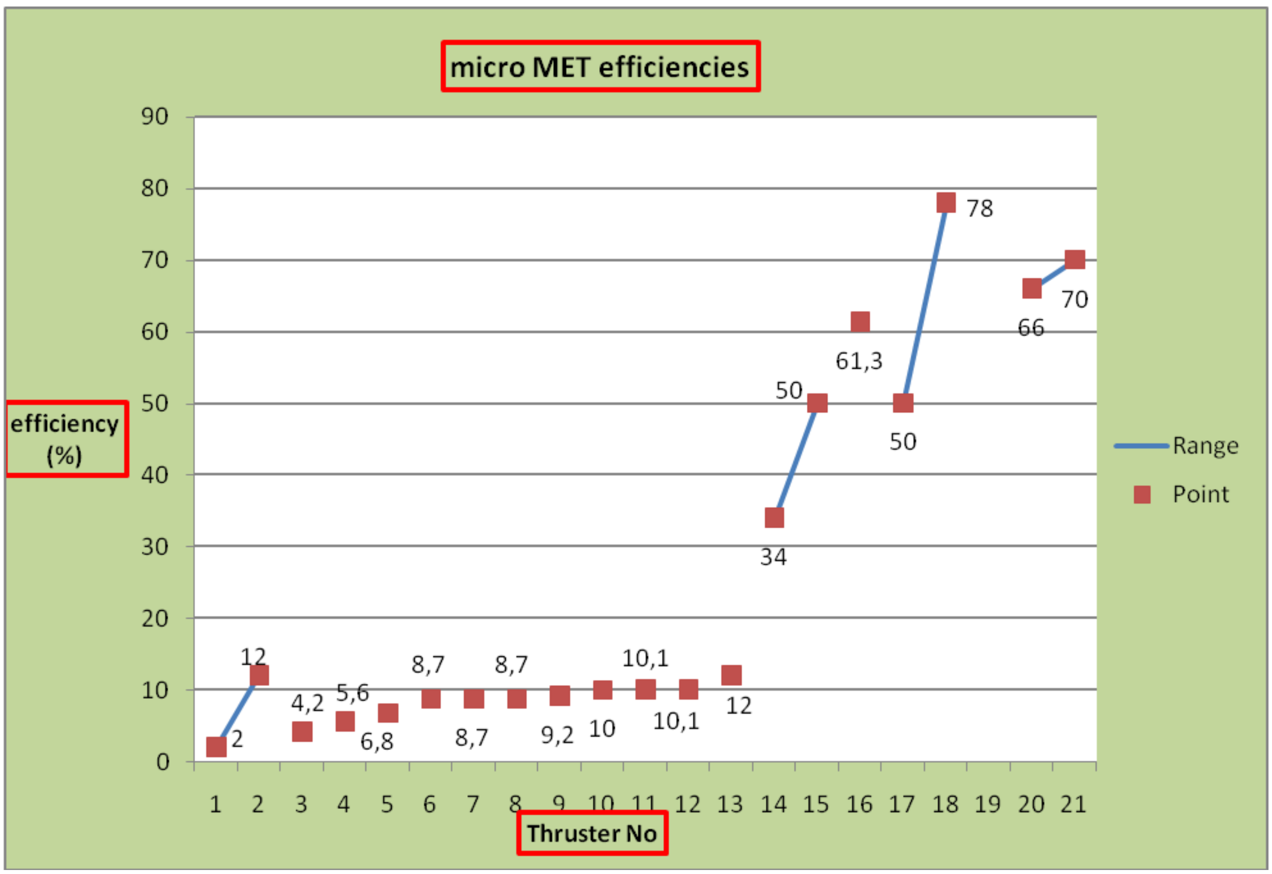
Graph 8: micro MET thrust vs Isp

Regarding Isp and Thrust we depict on graph 9 the blue shaded area of graph 8 in order to analyze it and acquire useful results. As we see in graph 9 (zooming in, the blue shaded area of graph 8) high Isp figures have been acquired for low level thrusts, below 1mN. At the same time the most attractive points are the green shaded ones, where Korea Ulsan University has acquired 3.5mN of thrust and almost 180 sec of Isp with only 1 to 5 watts power availability and Kyoto University has reported 4.3mN of thrust and Isp 330 sec with only 3.1 watt of power. In the future and in order to be more effective the research needs to slip towards the red shaded area trying to acquire higher thrust figures with high Isp range levels and low power requirements, usually low than 5 watts (counting possibly in different types of propellants;).



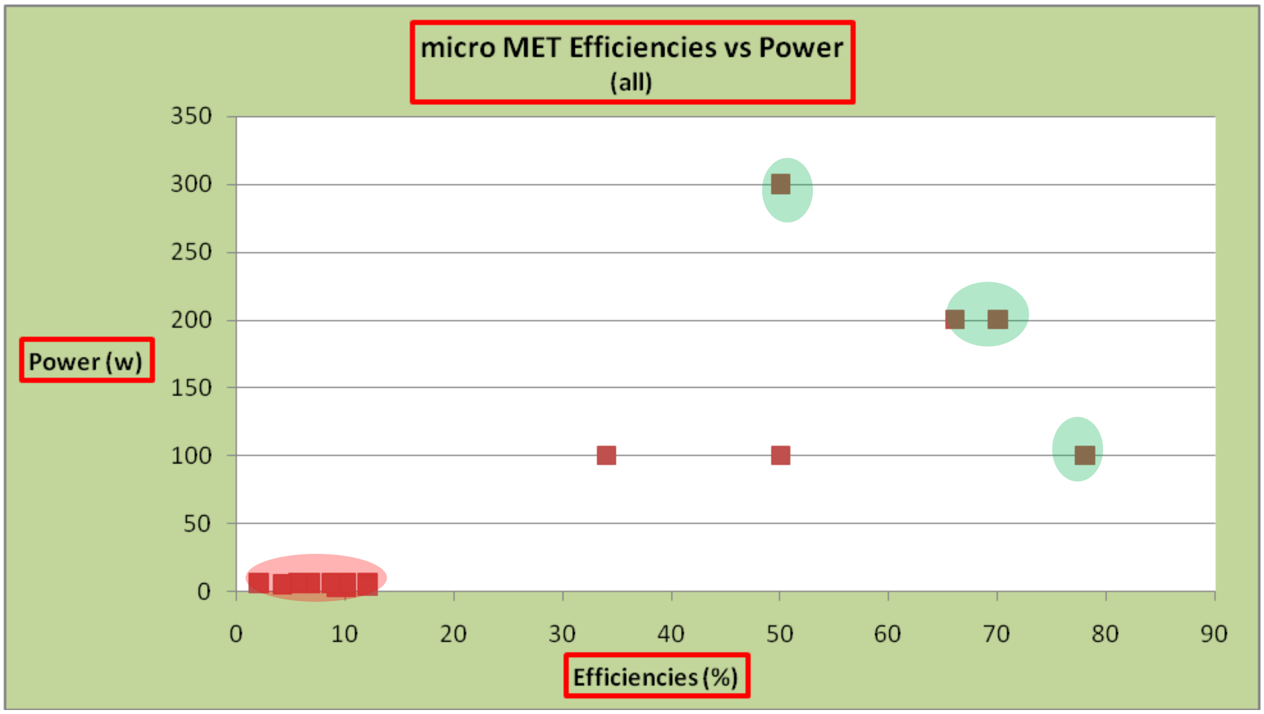
Graph 9: micro MET thrust vs Isp (below 10mN)

On the following graph 10 there is a simple and plain representation of the acquired micro MET efficiencies from the assorted organizations and research communities. The plot has been used in order to tabulate the results on a linear status giving us a very fast idea of what are the efficiency numbers that have been acquired in micro MET thrusters with power requirements less than 250Watt. The blue lines indicate that the whole range of efficiency from one point to the other has been succeeded. The rest, red dots, indicate only single point efficiencies that have been acquired during testing and experimentation.



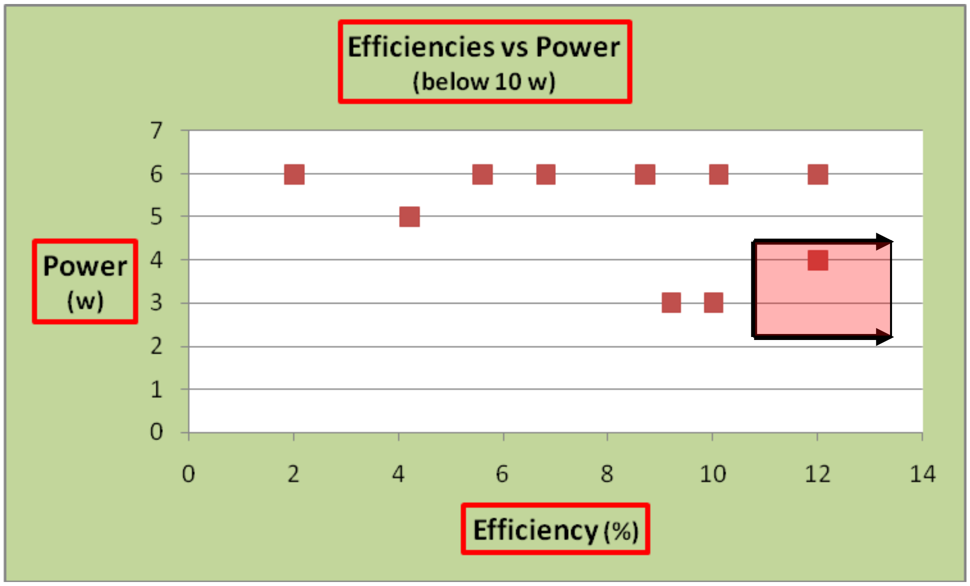
Graph 10: Overall efficiency of micro MET globally (%)

Continuing our analysis graph 11 has been created to plot available thrust efficiencies in accordance with power levels used. It is evident from the representation that very low efficiencies have been acquired for low power level requirements. That means research in micro MET applications on small satellites has very low efficiency as it stands right now. The red shaded area depicts the above mentioned result, whereas the green ones have been used in order for us to better visualize where the research and accomplishments needs to be focused. As we see by decreasing power, efficiency is increased and vice versa. That means basically that up to now well maintained efficiencies have been succeed only with power levels from 50 to 80 Watt (blue shaded points). When power levels lower down drastically in less than 10 watts, thruster efficiency lowers also down under 10% which is not a very acceptable figure for a real mission. Therefore, our intent should be to try further decrease power levels and increase thrust by applying new techniques, materials, propellants and other sophisticated ideas in order to maximize the effectiveness of the use of micro METs to small satellite applications, aiming to produce enough available thrust efficiency levels with very low power requirements, suitable for picosatellite future missions.



Graph 11: Overall efficiency of micro MET vs Power

Finally, the red shaded area of graph 11 has been magnified and is depicted in graph 12. Power levels are maintained around 6 watt whereas the efficiency has been lowered down to 12 % (best available figure – Kyoto University). It should be our endeavor and goal to minimize the power levels and increase thrust efficiency as much as possible. The red shaped area in this case depicts the mission area where research and applications needs to be focused. That basically means that power levels need not to exceed 5 watts (preferably 1watt, although very difficult to accomplish) and thrust efficiencies to be increased to reach at least 30 to 40% concurrently. This is a very difficult task for the scientific research community and it remains to be seen if it will be accomplished in the near future.



Graph 12: Overall efficiency of microMETs vs Power (below 10 w)

Last but not least it is important to mention the following generalized facts:

No miniature microwave electrothermal thruster has been flown to space yet.

Kyoto and Ulsan Universities do not still report thruster efficiencies on microwave electrothermal thrusters, with power requirements less than 3 and 6 Watt.

The propellants that have been used and tested up to now in microMETs with very low power (less than 10 watts) are Ar, He, H_2 and in some cases hydrazine.

Best acquired thrust level was 2.5 mN with only 1 watt (Korea Ulsan University – very primitive results)..

Best acquired thrust efficiency 12 % with only 3 watt power (Kyoto University, Japan).

No institution reports weight of the thrusters, which is a very important figure driving a lot in a mission's profile application.

Prevalent microwave tested frequency is 4 GHz with only Penn State and Kyoto Universities to have used 14.5, 30 and 1-25 GHz ranges respectively.

Conclusion - Commercial on orbit propulsion for Picosatellites

Nowadays and taking into account that cubesats is an emerging technology there are a lot of initiatives in commercial world, where propulsion machines are in existence or under experimental or construction phase. Below in table 13 there is a literature survey for available propulsion types in market, where the only practically available space qualified propulsion thrusters that are flying in cubesats are those noted listed with prices on the table. Practically speaking, Clyde space provides a pulsed plasma thruster that is able to be mounted on an 1U cubesat and the ISIS cubesat shop (cooperating closely with QB50 EU microsatellite program) and costs 81000 € due to the fact that it is MEMS and the associated weight is low. On the other hand ISIS cubesat shop is also providing Nitrogen Cool Gas with very low weight, but at the same time Isp is very low. As a general conclusion though we can infer that in the last years where cubesat technology arose, propulsion for small satellites is an area where research is now at peak. We have to wait in the next 5 or ten years to see cubesats employ propulsion systems and they will be able to stay in orbit with very low power capabilities for years.

Type	Power (w)	Isp (Nsec)	Weight (gr)	Propellant Mass (gr)	Dimensions (mm)	Price	Organization	References
Pulsed Plasma Thruster	**2.7**	**42**	**280**	**7**	**90x90x27**	**18850 $**	**Clyde Space**	**http://www.clyde-space.com/cubesat_shop/propulsion/303_cubesat-pulse-plasma-thruster**
Hydrazine MPS 130	-	2.8	1300	Hydrazine	-	-	Rockedyne	N/A
Nitrogen Micro Cool Gas	-	0.15	2	0.012	12x30	-	ISIS - Cubesat shop	http://www.cubesatshop.com/index.php?option=com_virtuemart&Itemid=98
Nitrogen Micro Cool Gas	-	3	53	3.6	16x90	-	ISIS - Cubesat shop	http://www.cubesatshop.com/index.php?option=com_virtuemart&Itemid=99
MEMS microprop	**2**	**-**	**300**	**-**	**-**	**81000 €**	**ISIS - Cubesat shop**	**http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=74&category_id=21&option=com_virtuemart&Itemid=99**
NANOPS - Canx	4	46.7 sec	500	-	cylindrical tank 3 x 4	-	Canadian Space Center	VKI micropropulsion systems for cubesats

SNAP-1	-	45	422	butane cold gas	170 side triangular x100 mm height	-	-	-
RF ion	0.59	-	1250	-	1 x 1 x 1cm	-	Busek	-
Electrospray colloid propulsion	1	0.1	41	-	Experimental phase	-	Busek	-
Cubesat Ambipolar Thruster	100	-	-	-	Experimental		University of Michigan	http://pepl.engin.umich.edu/thrusters/CAT.html
Ion Electrospray	-	-	-	-	Experimental		MIT Dr. Lozano	http://web.mit.edu/aeroastro/labs/spl/research_ieps.htm

Table 13: Literature survey of micropropulsion systems available for picosatellites

From the above deep collected information and take into account also micro MET's design considerations, advantages, disadvantages and the general findings and results that have been reported from the assorted universities and organizations, with strong experimental interest in the area, we can potentially conclude in the following proposed actions, as a way ahead on micro MET's research subjectal area:

Investigate with the use of micro METs the increase of thrust efficiency more than 10% with power levels lower than 3 watts. Try to increase thrust levels concurrently. Specifically, increase the thrust levels more than 4.3 mN with power less than 3.1 watt (Kyoto configuration 2004). Evaluate Isp and thrust efficiency changes. Additionally, increase the thrust more than 2.5 mN with power less than 1 watt (Ulsan configuration 2011). Evaluate Isp and thrust efficiency changes respectively.

On the other hand, a Dual Stage effort has been reported from Ulsan University in South Korea. Micro MET and Hall thrusters work together, but until now without any significant reports on findings / results. Create a micro MET & Hall dual stage thruster (as proposed by Dr. Vaios Lappas) in order to acquire primitive results on efficiency, thrust, power and Isp.

Combining the above facts and knowing that picosatellites are working usually with power requirements 1 watt or less, evaluate the use of a micro MET to Picosatellites, due to the fact that are very lightweight and encompass simple structural designs. Create a micro MET propulsion system for a picosatellite as this effort has not been reported yet anywhere in the available unclassified literature. Investigate the needed thrust levels for those in order to be able to counter drag compensation. Create mission profiles for picosatellites based on low power, low thrust availability.

Finally and referring to available commercial market products based on our research but most importantly in designing and building Lambdasat and Tubesat missions and picosatellites itself as well as continuous engagement with picosatellite designing in the arena, we can generally conclude that picosatellites and cubesats are having limited propulsion choices. Those that are available on market though and space qualified could constitute reliable solutions for 2 to 5 years missions.

References

**The number of references reviewed in order for the above results to be uncovered are more than 220 from various universities and companies globally. The reference numbers on the chapter above refer to appendix 6 were all references have listed. Here only an indicative and representative papers have been listed. Where [A4-xx] is listed it means that the reference is located in appendix 4.*

1. F.Guarducci etal, “Design and Testing of a Micro Pulsed Plasma Thruster for Cubesat Application”, Southampton University, IEPC 2011-239, 2011.
2. T. Loyan etal, “The comparison of results and tests of low power hall thrusters: SPT and TAL”, Ukraine National University, IEPC 2011-199, 2011.
3. M. Tajmar etal, “Propulsion for Nanosatellites”, University of Applied Science, Austria, IEPC 2011-171, 2011.
4. D. Lubey, “Design of a miniature microwave frequency Ion Thruster”, Michael Micci etal, Penn State University, IEPC 2011-164, 2011.
5. M. Micci etal, “The design and development of a 30GHz microwave electrothermal thruster”, Erica Capalungan, Penn State University, IEPC 2011-162, 2011.
6. J. Gonzalez, “ESA Electric Propulsion Activities”, ESA, IEPC 2011-329, 2011.
7. M. Lozanno et.al., “Powering Cube satellites”, MIT news, 2010, (article) www.web.mit.edu/newsoffice/2010/cubesat-01115.html
8. J. Mueller et al, “JPL Micro Thruster propulsion activities”, JPL, AIAA 2002-5714, Nanotech 2002,12 September Houston, Texas, 2002.
9. Dr. Michele Coletti etal, “Solar Electric Propulsion Subsystem. Architecture for an all-electric spacecraft”, University of Southampton, Chapter 6, Advances in Spacecraft Technologies, 2002.

Page intentionally left blank

CHAPTER 4

PICOSATELLITES RADIATION & SHIELDING

LITERATURE SURVEY

Chapter 4: Picosatellites Radiation and Shielding - Literature Survey

Introduction

After the completion of the literature survey of the picosatellites and the propulsion issues, regarding lifetime, it was evident that the next step was to perform analysis / survey of the environmental characteristics in space in order to verify the conditions in which the picosatellite will fly. In this chapter we will uncover / collect from available literature and finally tabulate in results, all these parameters that will influence the orbital motion of the picosatellite taking into account that the most common flight path is approximately at 350 to 450 km orbital height (apogee or perigee in approximately circular orbit – other orbits may also apply).

Living on Earth is not always easy to understand what are the mechanisms that take place every day in the inner space region. It is not an exaggeration to say that space is not an empty environment but in the opposite there are so many things that take place every second that it would be truth to say, we may not even know the exact composition of Earth's inner space region. Generally though, the region that circles around the Earth is called magnetosphere and is the origin that creates and alter the environmental characteristics in our near Earth environment. In the following paper we describe briefly some of the magnetosphere's parts and characteristics in order to discover how these can affect LEO satellites (orbits among 300-5000 km), when travelling through these areas.

The Earth's magnetosphere can be defined by the area of space around Earth that is controlled by the Earth's Magnetic Field. The space enclosed by the magnetosphere is not empty but filled with trapped particles, mainly ions, protons and electrons. The magnetic forces are much stronger than gravity. The real shape of the boundary of magnetosphere, the magnetopause, is strongly modified by the solar wind and the distance of the magnetopause is:

- On the side facing the Sun 10-12 Re
- Over the poles 15 Re
- On the night side the tail reaches past several 100 Re.

There exists also a neutral gas envelope of the Earth, the Geocorona that extends from 4-5 Re. The different parts of the magnetosphere are:

a. Bow shock: In this front region solar wind particles hit the magnetosphere. With supersonic speeds, over than one Mach, they can create a lot of small and large diversions on the shape of the Magnetosphere.

b. Magnetosheath: The region between the bow shock and the magnetopause, which is responsible for giving into the particles the necessary thermalized-kinetic energy and due to conversion into thermal energy, the plasma is highly turbulent here.

c. Tail Region: The solar wind stretches the Earth's dipole field compressing it on the side towards the Sun and stretching it into a long tail region. The field lines finally close at very large distances (~ 3000 km).

d. Plasmasheet: A sheet of plasma in the tail region dividing the two lobes of the Earth's magnetic field with density for both electrons and protons to be around 0.5 cm^{-3}.

e. Lobes: They are in the magnetotail having opposite direction and separated by the plasmasheet, otherwise they would cancel each other.

f. Plasmasphere: This torus shaped region, surrounding the Earth. It was detected in 1963 and has a very sharp edge at the plasmapause extending to 4-6 Re. It can be regarded as an extension of ionosphere. It is composed mainly from hydrogen.

g. Van Allen Belts: In 1958 Van Allen discovered the radiation belts and they are toroidally shaped. The inner radiation belt extends from 400 to 12000 km above the Earth and the outer one from 12000 to 60000 km [1].

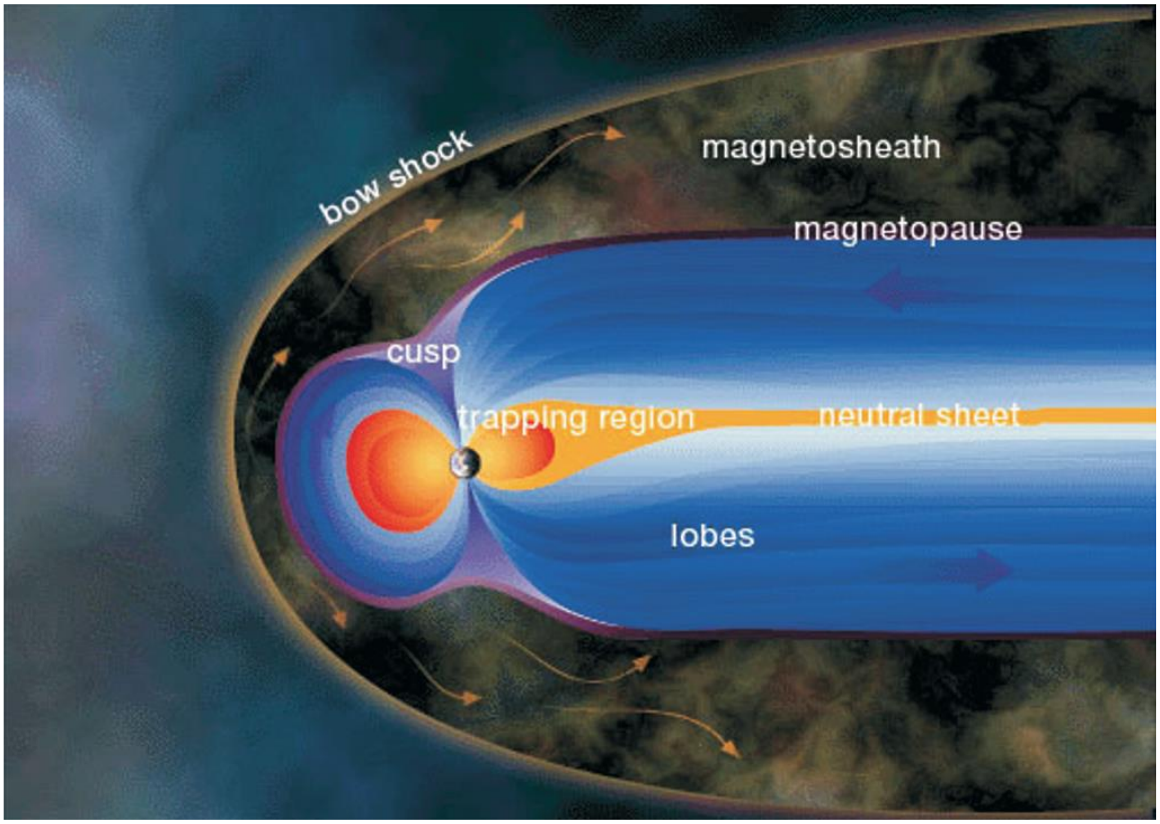


Figure 7: Earth's Magnetosphere and its parts (credit: NASA)

Vulnerability issues of satellites operating in LEO.

The impact of charged particles in Low Earth Orbiting Satellites is a subject that for years the scientists has been engaged on. It is of utmost importance to find out which are those factors that can affect a satellite operating in LEO and following, which are the total damage effects that may cause irreversible situations on satellite's operational lifetime.

The impact of radiation onto a satellite can be divided into two major categories. First, is the total dose that a satellite can be accepted from Earth's Radiation Fields and secondly we have to take into serious account the transient effects that may be created due to the fact that incoming radiation can cause damages to satellite electronics or other systems after some elapsing time frame that would be critical for that process. As a result, we may have total ionization of the material (in the beginning of ionization process there was only surface charging) or atomic displacement of the material in its molecules which is also a very severe transient effect.

The consequences of radiation to satellites (Radiation Induced Anomalies: RIAs) can be divided into the following categories:

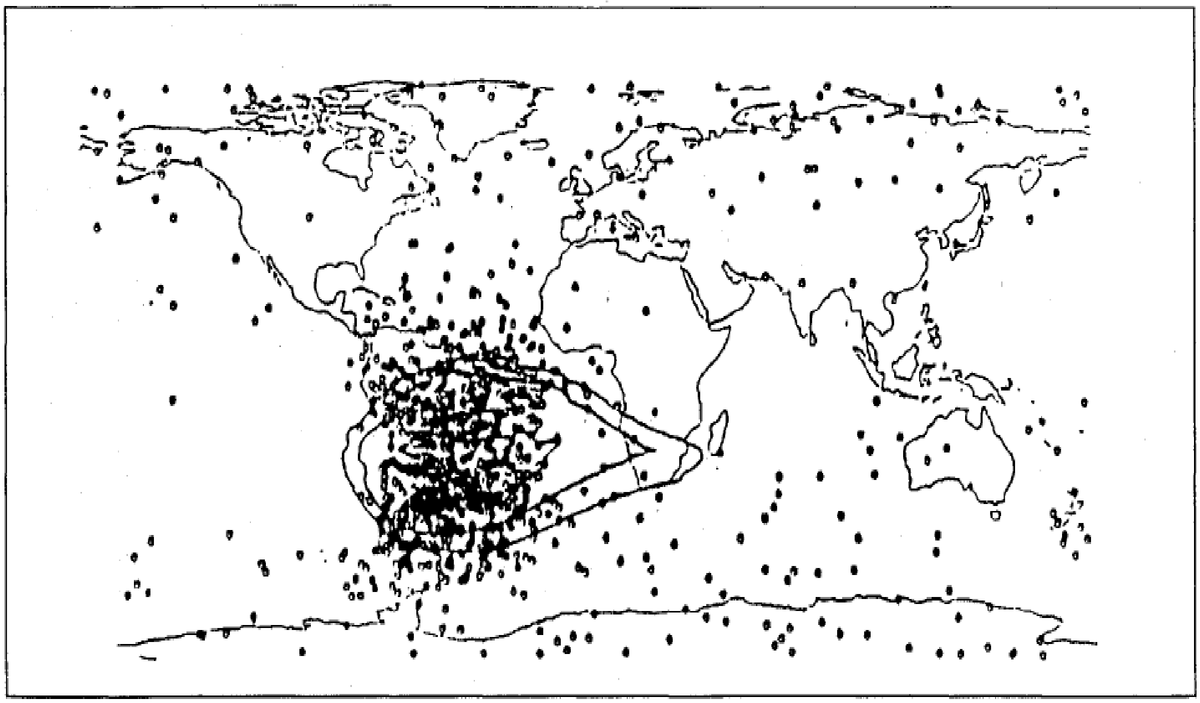
a. Single Event Upsets: This is the effect that is causing to a satellite when a charged particle is hitting directly the satellite bus. This effect can cause problems to operational satellite lifetime.

b. Electrostatic charging and Discharging

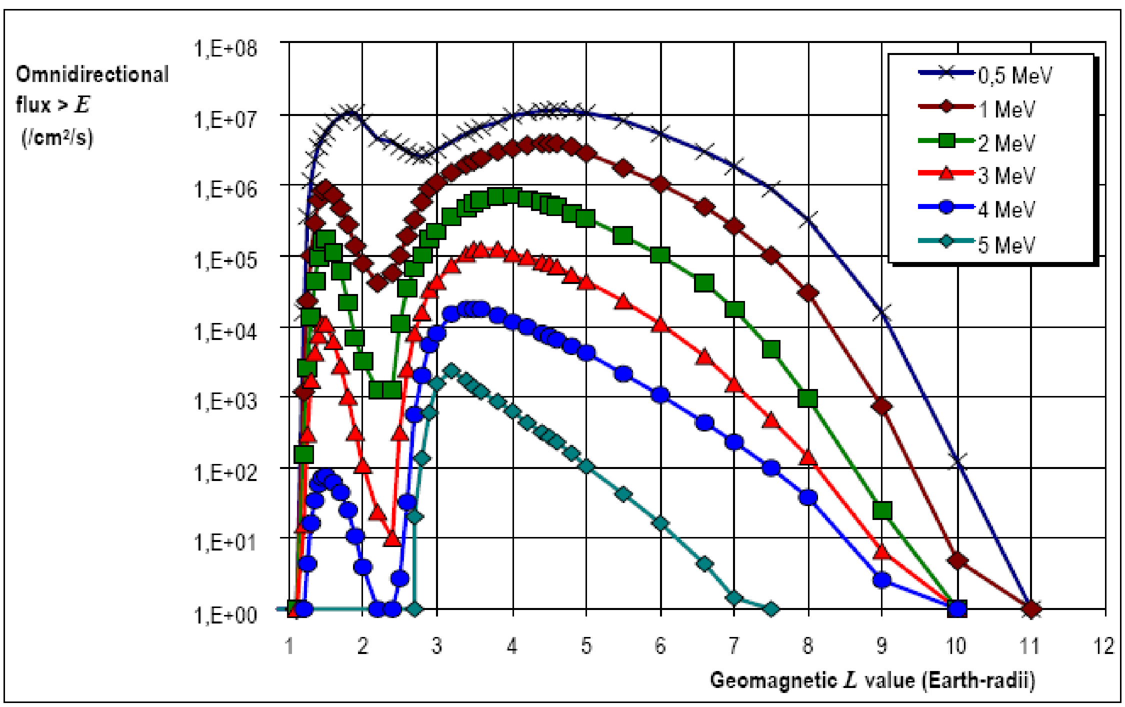
c. Other anomalies of different origins.

It has been proved through extensive researches, that malfunctions which may happen to satellites, during their orbiting periods in LEO or transiting through a high radiating environment are due to the space environment only to a percentage of 20%. It is not a percentage as high as we could have imagined initially, but at the end, it is high enough to cause problems that can affect the operational function of the satellite itself.

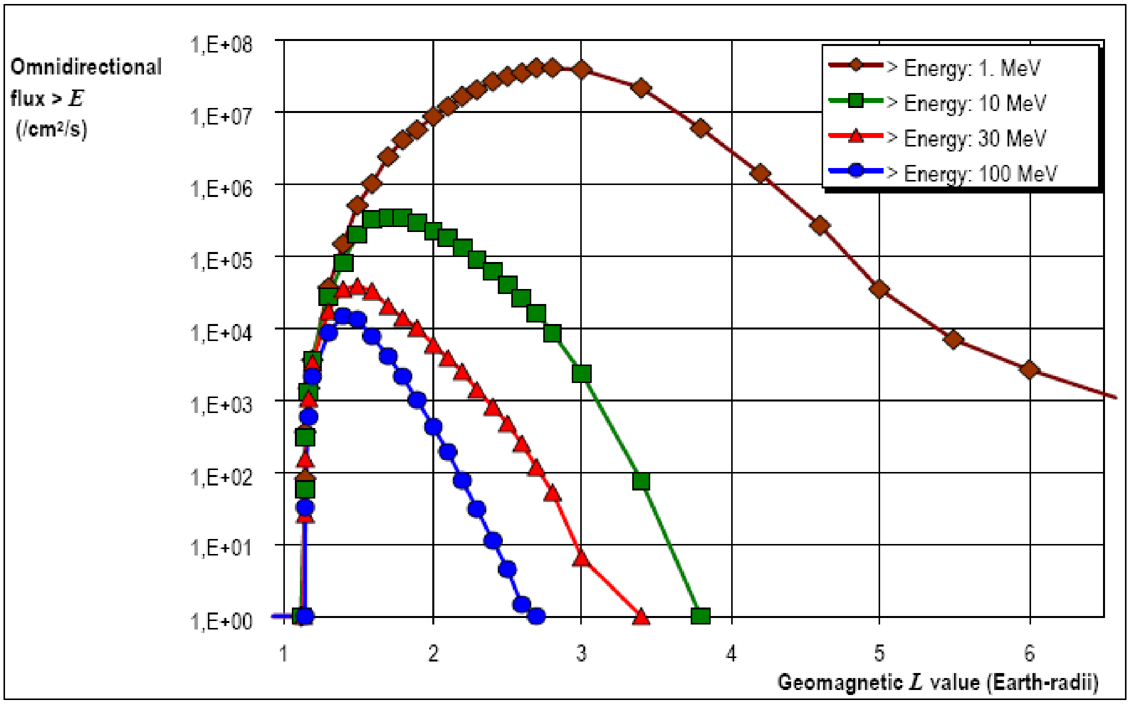
The following graphs 13-15 depict all the anomalies that happened to UOSAT-2 LEO satellite especially in the polar orbit of 500-800 km. The major effects on satellite anomalies happened over the South Atlantic Anomaly area (area with maximum concentration of black dots – every black dot represent one anomaly) and it is due to the fact that in this specific region radiation is extensively high. This confirms the already known fact that anomalies, such those happened to the specific satellite that passed through those areas can turn out to be disastrous for a mission, if they are not taken care of.



Graph 13: UOSAT-2 anomalies (black dots) that were recorded during a polar orbit. We can see that the most of the single event upsets happened above the South Atlantic Anomaly. region. (credit: UOSAT)



Graph 14: The electron flux from 1 to 12 radii distances from the Surface of Earth. For different energies, electron flux hits maximum at distances of 3 Earth's Radii (credit ESA).



Graph 15: Proton Flux from 1 to 12 Radii distances from Earth's Surface. For different energies, proton flux hits maximum at distances of 1.3 Earth's Radii (credit ESA).

Specifically, particles with energies lower than 20 keV can affect the outer surfaces of a satellite and only a few inner materials due to the increase of thermal energy. Particles with energies of 20 keV to 50 MeV are due to the Sun's radiation and can affect only satellites orbiting in GEO area.

Effect	Parameter	Typical units	Examples	Particles
Total ionising dose (TID)	Ionising dose in material	grays (material) (Gy(material)) or rad(material) 1 Gy = 100 rad	Threshold voltage shift and leakage currents in CMOS, linear bipolar (note dose-rate sensitivity)	Electrons, protons, bremsstrahlung
Displacement damage	Displacement damage equivalent dose (total non-ionising dose) Equivalent fluence of 10 MeV protons or 1 MeV electrons	MeV/g cm^{-2}	All photonics, e.g. CCD transfer efficiency, optocoupler transfer ratio Reduction in solar cell efficiency	Protons, electrons, neutrons, ions
Single event effects from direct ionisation	Events per unit fluence from linear energy transfer (LET) spectra & cross-section versus LET	cm^2 versus $MeV{\cdot}cm^2/mg$	Memories, microprocessors. Soft errors, latch-up, burn-out, gate rupture, transients in op-amps, comparators.	Ions Z>1
Single event effects from nuclear reactions	Events per unit fluence from energy spectra & cross-section versus particle energy	cm^2 versus MeV	As above	Protons, neutrons, ions
Payload-specific radiation effects	Energy-loss spectra, charge-deposition spectra charging	counts s^{-1} MeV^{-1}	False count rates in detectors, false images in CCDs Gravity proof-masses	Protons, electrons, neutrons, ions, induced radioactivity (α, $\beta\pm$, γ)
Biological damage	Dose equivalent = Dose(tissue) x Quality Factor; equivalent dose = Dose(tissue) x radiation weighting factor; Effective dose	sieverts (Sv) or rems 1 Sv = 100 rem	DNA rupture, mutation, cell death	Ions, neutrons, protons, electrons, γ-rays, X-rays
Charging	Charge	coulombs (C)	Phantom commands from ESD	Electrons

Table 14: ESA's radiation standards in accordance with E-ST-1O-12C (Credit ESA).

In the above table 14 and in accordance with the characteristics that ESA have as standards (E-ST-1O-12C) in the process of designing a satellite, we can easily see the radiation data that a satellite can receive and how these are capable of influencing in the meantime the functions of the bus.

Additionally, in table 15 below, and in accordance with the same ESA standards we can see how modern technologies that are being used in designing satellites can be affected from the incoming radiation. For example in Microelectronic systems there are leakage problems or shifting voltage levels for the specific system.

Technology category	Sub categories	Effects
MOS	NMOS PMOS CMOS CMOS/SOS/SOI	Threshold voltage shift Decrease in drive current Decrease in switching speed Increased leakage current
BJT		hFE degradation, particularly for low-current conditions
JFET		Enhanced source-drain leakage currents
Analogue microelectronics (general)		Changes in offset voltage and offset current Changes in bias-current Gain degradation
Digital microelectronics (general)		Enhanced transistor leakage Logic failure from (1) reduced gain (BJT), or (2) threshold voltage shift and reduced switching speeds (CMOS)
CCDs		Increased dark currents Effects on MOS transistor elements (described above) Some effects on CTE
APS		Changes to MOS-based circuitry of imager (as described above) – including changes in pixel amplifier gain
MEMS		Shift in response due to charge build-up in dielectric layers near to moving parts
Quartz resonant crystals		Frequency shifts
Optical materials	Cover glasses Fibre optics Optical components, coatings, instruments and scintillators	Increased absorption Variation in absorption spectrum (coloration)
Polymeric surfaces (generally only important for materials exterior to spacecraft)		Mechanical degradation Changes to dielectric properties

Table 15: How Radiation affects modern satellite systems (Credit ESA).

Environmental effects on satellites operating in LEO (e.g. Van Allen Radiation Zones) and consequently on the performance of the satellite.

The Earth's atmosphere is the lower limit of the radiation belts since it causes the loss of all the trapped particles. The upper limit however is less clear and is defined by the minimum intensity in the presence of disturbances of the magnetic field such that the particles are always trapped [6].

	Particle	Energy	Extension (Earth radii)
Earth	e-	1 keV–30 MeV	1–10
	p+	1 keV–100 MeV	1–7

Table 16: Properties of Earth's Radiation Belts

On the above table 16 there is a property summary of Earth's radiation belts. A satellite in LEO will thus be exposed to trapped particles only during certain portions of the orbit. These are the following:

- The polar horns (electrons below 1000 km, electrons and protons above that altitude).
- The South Atlantic Anomaly (protons and electrons at all altitudes).

For example a spacecraft launched from Kourou will pass through a zone with a large flux of energetic trapped protons when being injected into geostationary transfer orbit. This must be taken into account when designing on board electronics which may be sensitive to Single Event Effects produced from protons. Of course we must have in mind that infrequently we can face extreme proton or electron events in the Earth's radiation belts that can affect any space system dramatically with energies much greater than the common ones.

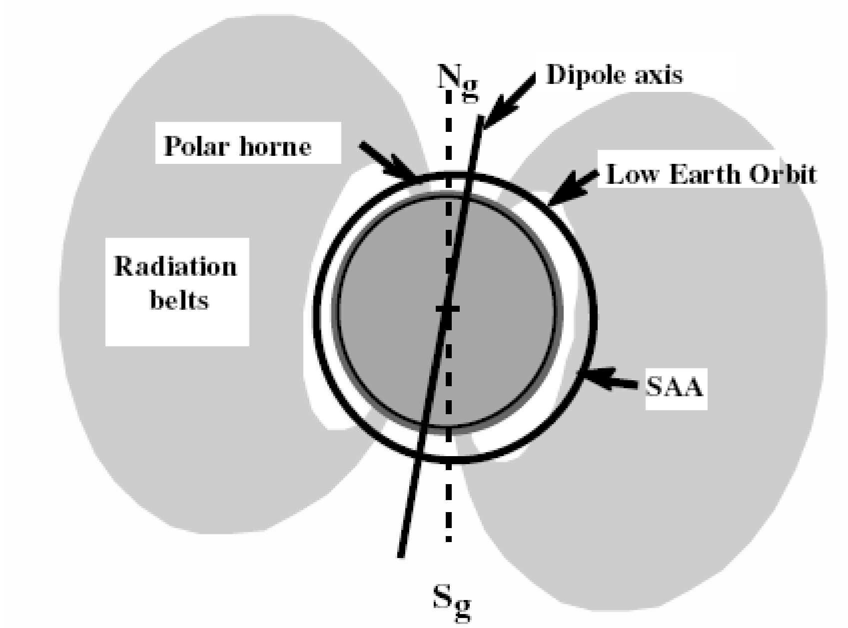


Figure 8: Earth's Radiation Belts (Van Allen Radiation Zones) with the depiction of SAA (South Atlantic Anomaly)

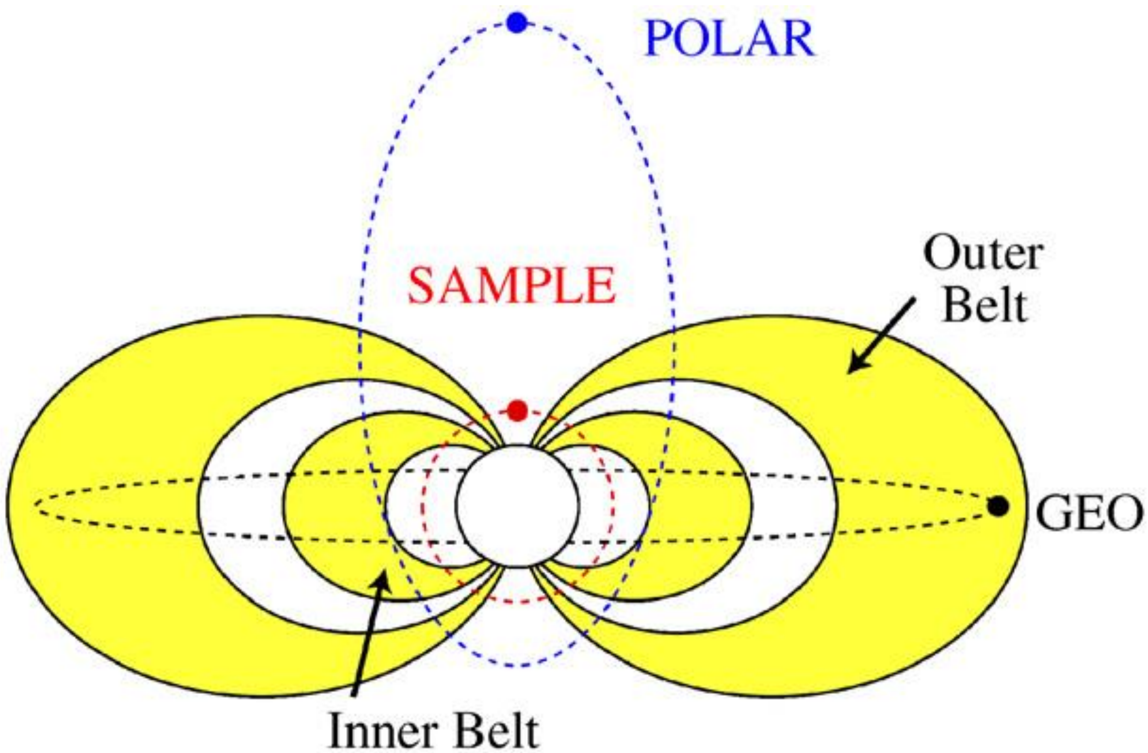
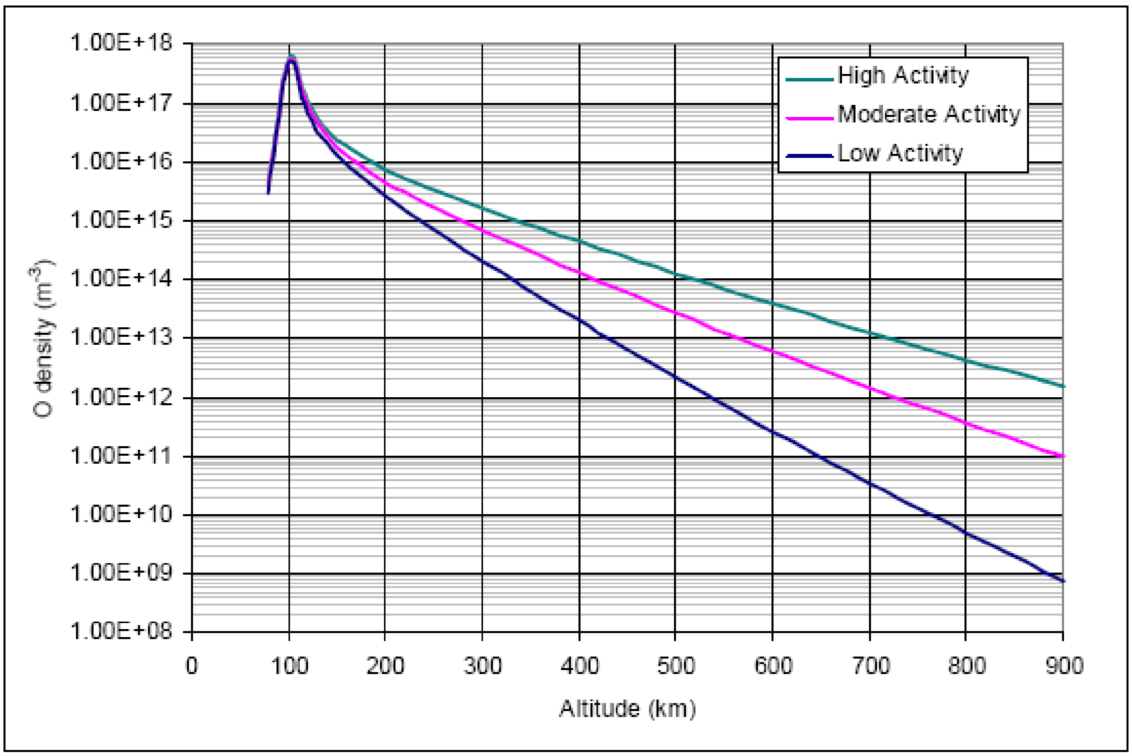


Figure 9: Graphical depiction of Earth's Radiation Belts and the usual orbits that satellites are using to perform their missions.

Additionally, in order to understand how radiation belts are being created, we identify three main particle reservoirs in the magnetosphere: (1) a storage of cool plasma, consisting of protons, heavier ions and electrons of ionospheric origin in the Plasmasphere (2) a storage of warm plasma – protons, electrons and minor proportion of alpha particles and heavier nuclei, of solar wind origin – in the plasmasheet of the geomagnetic tail (3) the population of very hot energetic particles in the radiation belts. During Sun storms and magnetosphere substorms large fluxes of electrons and ions from the plasmasheet can be injected deep into the magnetosphere and left there in magnetically trapped orbits. In this process the particles enter a region of gradually increasing magnetic field as a result of betatron accelerated. Atypical plasmasheet proton of a few thousand electron volts at 10 Re increases its energy by a factor of 10 when is conveyed to 7 Re. The plasmasheet is the main source for radiation belt particles and the substrom that is created the main injection mechanism.

Radiation belt particles (electrons protons and heavier ions) have energies ranging from a few thousand electron volts to hundreds of megaelectron volts [4].

- **Inner Radiation Belt:** It is shaped 1000-5000 km above the equator and 402 km over the South Atlantic Anomaly. It is generally known, that in the inner radiation belt proton's energy is dominating the environment and is approximately 30 MeV and in densities of 120,000 particles per square inch per sec.
- **Intermediate Radiation Belt (Slot):** It is among 12000-13000 km approximately and is an effect that comes from the bow shock in Earth's magnetosphere.
- **Outer Radiation Belt:** 15,000 – 25,000 km above Earth's equator. The energies here are up to 5 MeV and particle densities are 2,000,000 per square inch per second.



Graph 16: Existence of monatomic oxygen into Earth's magnetosphere from 100 – 900 km.

Graph 16 depicts the existence of monatomic oxygen into Earth's atmosphere and magnetosphere from 100 to 900 km. This is mainly a place of orbiting LEO satellites and as we can easily see monatomic oxygen is high at 100 km above Earth's surface and as we transiting in higher altitudes monatomic oxygen's composition is descending dramatically until it reaches to nearly zero above 900 km.

Effects on LEO from solar cycle and magnetosphere of earth

LEO satellites have nothing to do directly with Sun's radiation. It is not true though if we think that everything in Earth's magnetosphere is driving due to Sun's activity in our galactic environment. So it can influence our LEO orbiting satellites because all associated radiation with these orbits is an effect of Sun's radiation cycle and activity.

The solar wind sweeps out the earth's magnetosphere with supersonic speeds ranging from 300 km to 1000 km /sec. It distorts the earth's magnetic field and forms out a comet shaped magnetosphere in which there are numerous fermentations that lead to the movements of the ionized particles through the whole magnetospheric area. The most important part though inside earth's magnetosphere is the formulation of the so-called Van Allen radiation zones which by far constitute the most ionized area in low earth orbits.

As we know there are two different Van Allen radiation zones (the inner and the outer belt). The small inner belt between 1 and 2 Earth radii where protons of energy 50 MeV and electrons with energies of bigger than 30 MeV reside and the outer radiation belt from 3 to 4 earth radii, where less energetic protons and electrons are concentrated [1].

It is generally believed, that earth's atmosphere is ionized up to 0.1 % in distances up to 300 km. The furthest away we travel this percentage raises up to significant numbers that can be finally affect our satellite systems or the bus as a whole entity. In the table 17 below we can see the ionization rates in different altitudes as those became evident after extensive experimental measurements in multiple satellite missions.

h, km	$\bar{c}_e$ m/sec, $T = 500°K$	$\bar{c}_i$ m/sec, $T = 500°K$	$\bar{c}_i$ m/sec, $T = 2200°K$	Principal atoms	v_s, m/sec	Neutral particles, n/m^3	Charged particles, $n_e = n_i/m^3$
300	1.39×10^5	0.79×10^3	1.65×10^3	O	7.7×10^3	2×10^{15}	2×10^{12}
500	1.39×10^5	0.81×10^3	1.7×10^3	O	7.6×10^3	2×10^{14}	2×10^{11}
1000	1.39×10^5	0.81×10^3	1.7×10^3	O	7.35×10^3	5×10^{12}	10^{10}
2000	1.39×10^5	1.6×10^3	3.4×10^3	He	6.9×10^3	10^{11}	5×10^9
3000	1.39×10^5	1.6×10^3	3.4×10^3	He	6.5×10^3	2×10^{10}	2×10^9
4000	1.39×10^5	3.2×10^3	6.8×10^3	H	6.2×10^3	10^9	2×10^9

Table 17: Ionization rates in different altitudes after extensive experimental measurements in multiple satellite missions

We can easily understand that between 300-1000 km altitudes the existence of monatomic oxygen is broad and at the same time for altitudes more than 3000 km we observe monatomic helium atoms that can affect our GEO satellite missions. These monatomic oxygen atoms can affect our satellite systems in such a way that a whole satellite mission can be cancelled or destroyed.

In the inner radiation belt, we can meet protons with energies that come up to 50 MeV and electrons with energies bigger than 30 MeV. In the outer radiation belt, there are fewer protons and electrons concentration but it is obvious from experimental tactics and measurements that can affect critical mission parameters if our LEO satellite pass through this “contaminated” zone. Nevertheless, we can say that between the two Van Allen belts the inner one can be characterized as more stable but at the same time the outer one is unstable and is changing 100 times more than the inner one. These changes are regarding the ionization processes from protons and electrons.

In the table 18 below there is a depiction of all the ionized molecules and particles that can be found in earth’s magnetosphere with their associated energies.

0.03 eV	Molecule of oxygen or nitrogen in the air
0.5	Atom or molecule $T_{\odot}$, surface
0.67 eV	Proton or neutron escape the Earth’s gravity
1000 - 15,000 eV	Electron in the polar aurora
1.4 MeV	Energy of electrons from radioactive potassium major source of the Earth’s heat
10-100 MeV	Proton energies in the inner radiation belt
10-15,000 MeV	Range of energies in solar flares
1-100,000,000,000 GeV	Cosmic ray ions; as their energy goes up, their intensity goes down

Table 18: Charged particles and associated energies that exist in Earth’s Magnetosphere.

Solar Activity and Magnetosphere

There are mainly two factors that influence the most the structure and dynamic processes in Earth’s Magnetosphere. Firstly, is the inner magnetic field of Earth and secondly the solar wind. The inner magnetic field of earth seems to be created in the core of Earth from a dynamic process between the circulation of liquid metal in the core of Earth and also from the thermal energy that is transmitted into the Earth by this procedure. The Earth’s magnetic field form an axis that is tilted 10 degrees approximately from Earth's gyration axis. This magnetic axis can be characterized finally as a magnetic dipole and the magnetic tension in Earth's atmosphere is about 30000-60000 nT.

South Atlantic Anomaly

Since the Earth's dipole is tilted and off-centered by 500 km toward the West Pacific, the radiation belt (protons and Electrons descends to a low altitude over the South Atlantic, the populations of charged particles are attached to the magnetic field. A satellite in LEO will thus be exposed only to radiations on certain fractions of the orbit as far as the trapped particles are concerned when passing through : the polar horns (electrons below 1000 km, electrons and protons above that altitude) and The SAA (protons and electrons at all altitudes) [3].

Magnetic Storms

The Sun heats the Earth's atmosphere. Also the degree of ionization in the ionosphere increases at the dayside and it causes convection in the ionosphere. By this convection charged particles are transported into the magnetosphere by the dynamo action ionospheric electric currents above the equator up to mid-latitudes are generated. These currents produce a magnetic field which moves with the sub solar point. The Sun emits particles and the solar wind compresses the magnetosphere as it has been mentioned above. High Speed particles further compress the magnetosphere and a magnetic storm begins with a storm sudden commencement. The number of charged particles trapped within regions of the magnetosphere is increased. These particles drift around the Earth producing changes in Earth's magnetospheric structure. This accordingly produces auroral electrojets (large horizontal currents that flow in the D and E regions of the auroral ionosphere) which are intense West- East currents. Associated with these currents are intense magnetic fields causing magnetic disturbances and affecting the LEO satellites [1].

Antiproton Radiation Belt

Antiprotons are produced by primary cosmic rays in nuclear reactions with the interstellar matter, when cosmic ray particles move chaotically into the galactic magnetic fields. The same nuclear reactions can happen in Earth's atmosphere especially in the uppermost residual atmosphere corresponding to high altitudes. Part of these secondary articles born in the confinement region of Earth’s magnetosphere will be trapped in Earth’s vicinity by geomagnetic field creating an antiproton radiation belt around the Earth. This belt is a product of nuclear reactions and is located in the equatorial region at altitudes of 1000 km and above [8].

In the absence of sporadic solar particle events the radiation exposure in Low Earth Orbit inside satellites is determined by galactic cosmic rays (protons and heavier ions) and by protons in South Atlantic Anomaly. Also there are electrons of the horns of the radiation belts located at about 60 degrees latitude in Polar Regions. For the majority of LEO missions protons deliver dominant contribution to the radiation exposure. Electrons reach energies of up to 7 MeV and protons up to 600 MeV. The energy of heavy ions is less than 50 MeV and because their limited penetration capacity they are of no consequence for satellite electronics. Almost all radiation received in LEO at low inclinations is due to passages from SAA. For example at an orbit with inclination of 28.5 degrees six orbital rotations per day pass through the anomaly, while nine per day do not. Although traversing the anomaly takes less than 15 minutes and occupies less than 10% of time in orbit this region accounts for the dominant fraction of total exposure [14].

Magnetospheric Currents.

The Sun is the main cause that in Earth’s magnetosphere we observe the existence of currents such as, Chapman Ferraro, Cross Tail and Currents parallel with Earth’s magnetic field.

These currents are associated with Sun’s influence on Earth’s magnetosphere among different processes each time. The main result is that due to Sun’s existence, these currents can influence dramatically the motion of charged particles in the magnetosphere and so the motion of a LEO satellite on orbit has to encounter particles with different tensions and direction. For example the currents that their motion is parallel to the Earth’s magnetic fields lines can cause the phenomenon of auroral borealis in Earth’s North Pole with a major concentration of atomic oxygen in that region.

Solar Flares

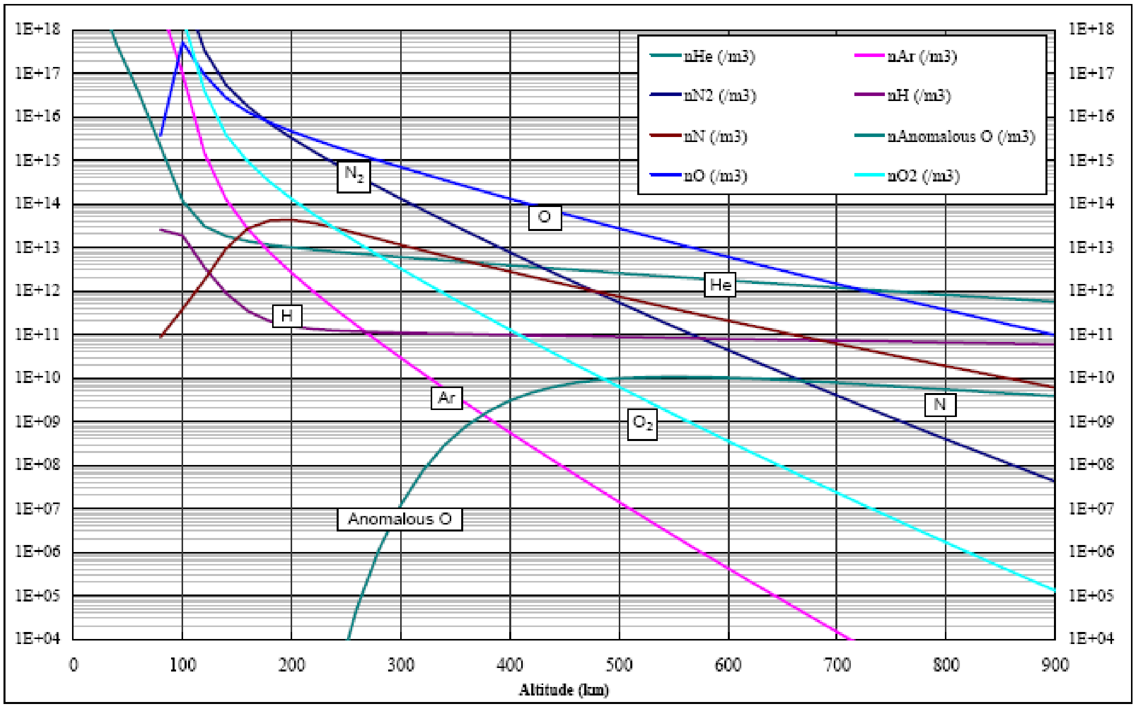
Another phenomenon that is influencing Earth’s magnetosphere every now and then is the existence of solar flares in Sun’s environment. These flare are producing the most dangerous particles (He, O, C, Fe) that can heat up Earth’s magnetospheric environment. Specifically a solar flare is containing 96.4 % protons, 3,5% alpha particles and 0,1% heavy particles such as He and O. We see that solar flare are containing mainly protons but if a satellite at some point comes in contact with a heavy ion then the damage that is going to be produced is very severe. These heavy ions can be transferred into the Earth's inner magnetospheric field through the magnetospheric currents or with a numerous other ways and can cause irreversible damages to LEO satellites. These solar flare effects can be happened during Sun's low intensity period over the 11 year cycle and can last for at least a few days.

Galactic Cosmic Rays

Another factor that is necessary to be mentioned is the Galactic Cosmic Rays (CGR) which is the main origin for the existence of providing particles in Earth's magnetosphere. In a CGR we usually observe particles of 83% protons, 13% He, 3% electrons and 1% of other particles such as heavy ions or other particles of the periodic table (Gallium, Fe or Ca) which have the possibility of arriving into Earth's magnetosphere with fluxes of 2 particles / cm^2 sec. So with all this composition of particles around a satellite the environment can be really harsh and of course not hospitable enough for a LEO satellite. The CGR has been observed to have a main impact in Earth's magnetosphere when the solar flares are at their minimum average percentage in the duration of the 11^{th} year solar cycle. Finally it is important to say that these particles coming from CGRs have found to incorporate energies that can be reaching the levels of some GeV.

Anomalous Cosmic Rays

In the interplanetary medium we can find also some other different particles from the above mentioned dynamic situations. These are mainly particles that have lost one particle from its core and they have energy that ranges from 50-100 MeV. These are He,N,O, Ne, Ar. They have the capability to interact with Sun's system and when they come into heliosphere they accelerated in such a way in order to reach Earth's Magnetosphere. Taking into account their energy distribution they do not have the capability to affect the satellites in a dramatic way but they are usually have minimal effects in charging of satellite bus.



Graph 17: ESA's experimental measurements about which charged particles exist in different altitudes from Earth's surface (credit ESA).

Table 17 derived from the experimental measurements that ESA has put into place during the last years and is depicting the energies of different particles that can be found into earths' magnetosphere and especially from 0 km to 900 km altitudes with their associated particles. It can be seen that in LEO orbits the most significant particle that can affect significantly our missions or satellite systems is the monatomic oxygen.

Effects of the environment on the power supply and electronics

Electrons and Protons are responsible for total dose on satellites. Heavy ions and protons cause a number of specific effects that are grouped under heading SEE (Single Event Effects) [5].

The inner radiation belt contains electrons whose energy is less than 5 MeV. The outer belt contains electrons whose energy may reach 7 MeV. After a magnetic storm on March 24, 1991 a third belt occurred between the first and the second and contains electron with energies that can reach 30 MeV.

The 11 year sunspot cycle can be roughly subdivided into four low activity years and seven of high activity. In this solar flare events solar protons with energies of several tens of MeV to hundreds of GeV per nucleon can be created.

The solar winds cannot easily affect satellites on LEO orbits because they mainly contain particles with energies from 0.5 to 2 KeV. The average density of solar wind is 1 to 30 particles per cm^3 and it contains approximately 95% of protons and 4% of helium atoms with less than 1% other heavier ions.

At Low Earth Orbits the average space distribution of particles is inhomogeneous. The outer electron radiation belt is close to the Earth at high latitudes (polar horns) and the region is centered on the South Atlantic Anomaly which has a high level of electrons and protons. This means that:

- A satellite placed in very low equatorial orbit (300 km) sustains little radiation
- A satellite in low orbit at an inclination of less than 45 degrees is subjected to SAA.
- A satellite in low polar orbit at an inclination greater of 55 degrees is subjected to both SAA and the impact of polar horns.

Today LEO satellites are orbiting usually up to 550 km and with inclinations that reach up to 57,1 degrees. A satellite placed at altitude over 1400 km (e.g. constellation satellite) is heavily impacted by dose effects. The proton belt makes a further contribution that sometime leads to a total dose greater than those received in geostationary orbits (The dose effects there are mainly due to the outer electron belt).

Low earth orbits higher than 1400 km are also impacted by the effects of atomic displacement due to trapped proton. As an example there are displacement effects in optronics and the level of this is almost independent of shielding and thickness.

The **atomic oxygen** is the main specie of the atmosphere from 200 km. The density is 10^9 -10^{10} atoms / cm^3 and in the range of 10^5 atoms / cm^3 at 800 km. The effects of atomic oxygen are various:

In the last decades, a detailed analysis of the problems on satellites shows that the part due to space environment is not negligible. It appears that the malfunctioning are due to problems linked to space environment (9-21 %), electronic problems (6-16%), design problems (11-25%), quality problems (1-8%) and other problems (11-33%) and also problems that are still unexplained (19-53%). It is clear that unexplained problems are either due to space environment or to electronics, design or quality of satellite buses. The space environment is largely responsible for about 20% of the anomalies occurring on satellites and a better mastery of that environment could increase only the average lifetime of space vehicles. This appears more to LEO satellites due to the fact that the environment in this region is harsh due to Van Allen radiation Belts and the South Atlantic Anomaly.

Differential or Internal Charging is another effect that can be caused from incoming radiation. Charging can cause problems to a satellite only when particles have energy greater than 1 MeV. High energy electrons penetrate the outer surface of a satellite and also in dielectric materials, such as the tile on cables. They can cause cracks or damages to satellite materials. In parallel electrons can pass through the thermal coating and then the phenomenon that is creating is called internal charging. In this situation we have to find ways in order to discharge the satellite bus so as to clean up the interior of the satellite from undesirable electrostatic effects.

Deep Dielectric Charging: It is the origin of the most problems that arise inside a spacecraft. It is caused due to impact of harsh radiation (such as Van Allen Radiation Belts) and they can cause severe effects on the charging of the satellite itself or other problems that can't be revoked later on.

Surface Charging: Another effect that usually takes place with disastrous effects, is the surface charging of a satellite when it passes through areas of huge radiation concentration. This effect takes place only in the outer surfaces of the satellite and it can be caused from electrons with low energy (not enough energy to penetrate the satellite bus). It can also be produced from low energy protons which can cause thermal distortion of the satellite.

Solar Particles – Dark Side of Earth: Another adjacent effect is the impact of charged particles to the satellite bus when it is orbiting in the dark side of the earth. Specifically, when plasma from solar wind is in the dark side of the Earth and due to the magnetic fields and currents at that place it is somehow injected to the Earth's surface travelling vertically into the Magnetosphere. This motion can affect the motion of a satellite around the Earth and these impacts with charged particles can also cause problems in satellite systems.

Antiparticle Effect: The existence of antiprotons and positrons depends on the cosmic radiation. This is interacting with Earth's Magnetosphere and we observe that an Antiproton Radiation Belt exists in distances 300-1000 km from Earth's Surface. The density in this area is 5 x 10^{-7} gr/cm^3 or even less 10^{-17} gr/cm^3 but the energy ranges even up to 5629,2 MeV or some GeV. Generally, it has been observed that statistically the existence of positrons in this belt is up to 40 MeV. From the previously referred data we have to take into serious account the existence of these particles in the inner magnetosphere of the Earth and especially in LEO missions.

Effects from radiation on Satellites:

- Effects on thermal coatings of the optics and electronics
- Erosion of materials
- Sporadic effects such as noises on detectors and optics
- Singular events in highly integrated electronic circuits and
- Electrostatic discharges

Shielding

Aluminum Shielding

In current technology there are different levels of aluminum shielding that are used in order to protect our satellite from the above mentioned effects. We have aluminum of 0,025 mm, 2,5 mm and other possible thicknesses that could narrow down significantly the incoming radiation effect. Aluminium is perfect for such uses because it is lightweight and also it has the ability to reduce the incoming energy in a factor of 30% if we double the thickness of it. Aluminium is ideal for satellite orbits from 300-1000 km and for inclinations from 35-75 degrees respectively. Ideal shielding for such cases is at 2.5 mm approximately.

Vacuum Shielding

Another way of shielding electronics and other systems of a satellite is the so-called vacuum shielding. In this case, we position the sensible systems inside specially shaped boxes from aluminum. Inside those boxes the critical materials have a small distance from the outer surfaces of the satellite and inside those there is a small vacuum space which helps to stop the incoming radiation. In parallel we have the advantage of reducing the total weight of the satellite up to 75% due to the fact that we are not using aluminum everywhere but only on the boxes that are vacuum shaped. Finally, with this method we can discharge the satellite easily, if such a case arises.

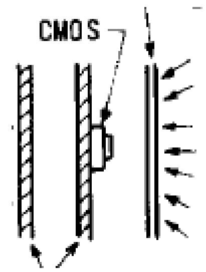


Figure 10: Vacuum Shielding on a CMOS electronic component

Plasma Radiation Shielding

In this method, we create an electrostatic field with a shielding voltage which is remained stable between the satellite bus and the environment. The advantages in this situation is that we have the capability of producing a magnetic field as well as having same and opposite charge which is at the end acting as a capacitor. This shielding system is energetic. That means we can change the tension of the magnetic field each time we have a different operational environment. By this way we achieve to avoid charges and single event upsets that can happen in SAA and also in high radiation environments. In the meantime we reduce the total weight of the satellite which is one of the most important advantages when we are designing satellites.

Discharge Shielding

In this case we manage to discharge the electrons or any other charged particle through a system that acts as conductor. By this method we always have the capability to avoid external charge of the systems of the satellite and thus we reduce the number of single event upsets in the overall mission. The charged particles that are deposited in the surface of a satellite system create a J that is being deposited and through the mechanism that is shown below is conducted and finally deposited to the open space environment.

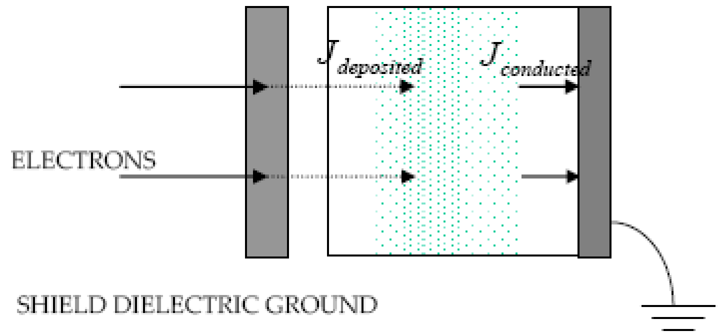


Figure 11: Depiction of the process of discharge radiation shielding on a satellite

Shielding Materials

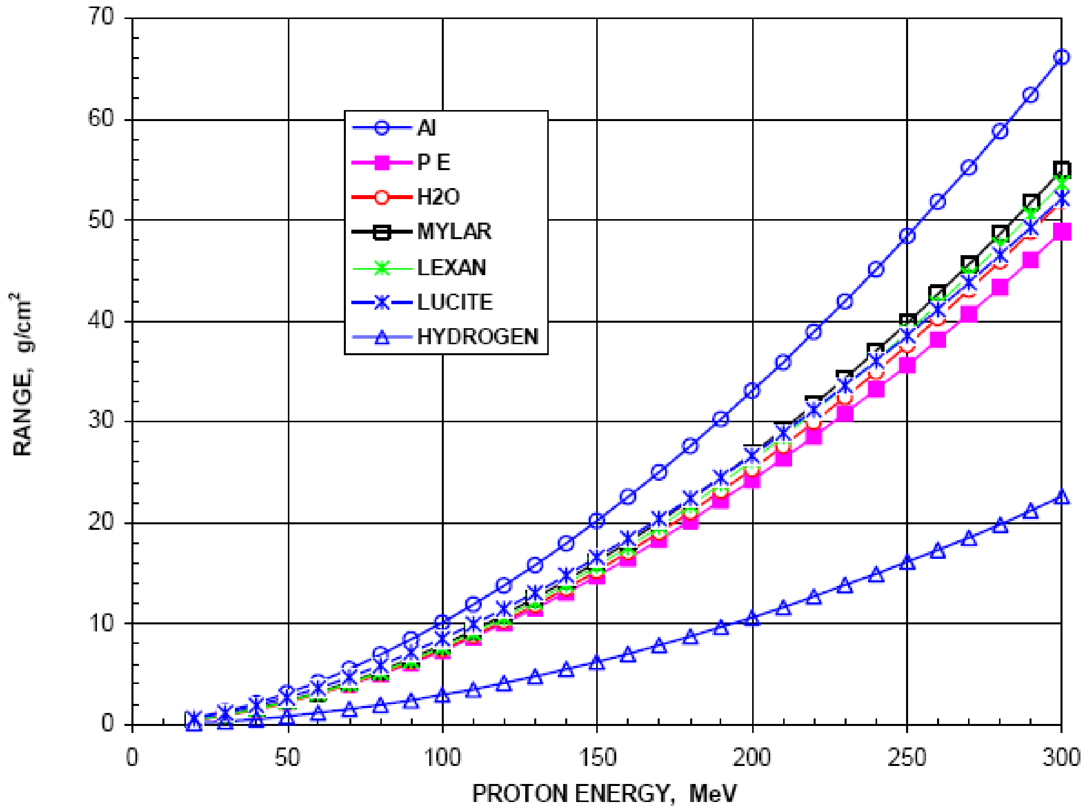
Historically, aluminum and aluminum alloys are the most usable materials in satellite industry. Through the evolution of technology it is today evitable to use materials that their endurance to incoming radiation is much higher than the aluminum itself. By these materials we also have economic effects because these materials are easier to build. Also there is another outcome from this procedure. These new materials are lightweight and so by reducing the total weight of the satellite our mission is finally cost effective.

Seven from these materials are documented as very light and specially designed for satellite applications:

- Polyethylene (ρ=0.92 g/cm^3)
- Polyetherimide (ρ=1.27 g/cm^3)
- Polyimide (ρ=1.42 g/cm^3)
- Polysulfone (ρ=1.24 g/cm^3)
- Polytetrafluoroethylene (ρ=2.17 g/cm^3)

The above mentioned materials have high density in hydrogen which has been experimented as having special characteristics for satellite construction. In accordance with European Space Agency standards Polyimide with thickness of more than 50 mm and epoxy glass with silica cloth are the most unsuitable for use into satellite applications.

Aluminum is capable of receiving up to 300 MeV of incoming radiation and in distances of 65 approximately g/cm g/cm^2 inside the material. In opposite polymers with high density in hydrogen have the above capability but in 35% more percentage in incoming radiation. The best ways of using polymers is by shielding the outer surfaces of the satellite with polymer coatings or by creating a foamy wall between the electronic system and the outside surface of the bus.



Graph 18: Depiction of the durability of different materials for different incoming proton energies. It is logical that for bigger proton energies we have bigger radiation penetration to the shielding material. The most durable materials are Aluminium and Mylar for proton energies that reach 300 MeV.

For solar cells epoxy carbon or aluminum honey comb or film adhesive are the best choices for shielding materials. At the same time we use to shield antennas the epoxy aramid or cyanate carbon or a combination of those two. We use to construct the rest of the satellite from carbon, aluminum honeycomb or other colloid coatings depending on satellites mission and orbit each time. Especially, we mention that epoxy coated materials have extra durability in high radiation environment and they are used extensively in electronic shielding.

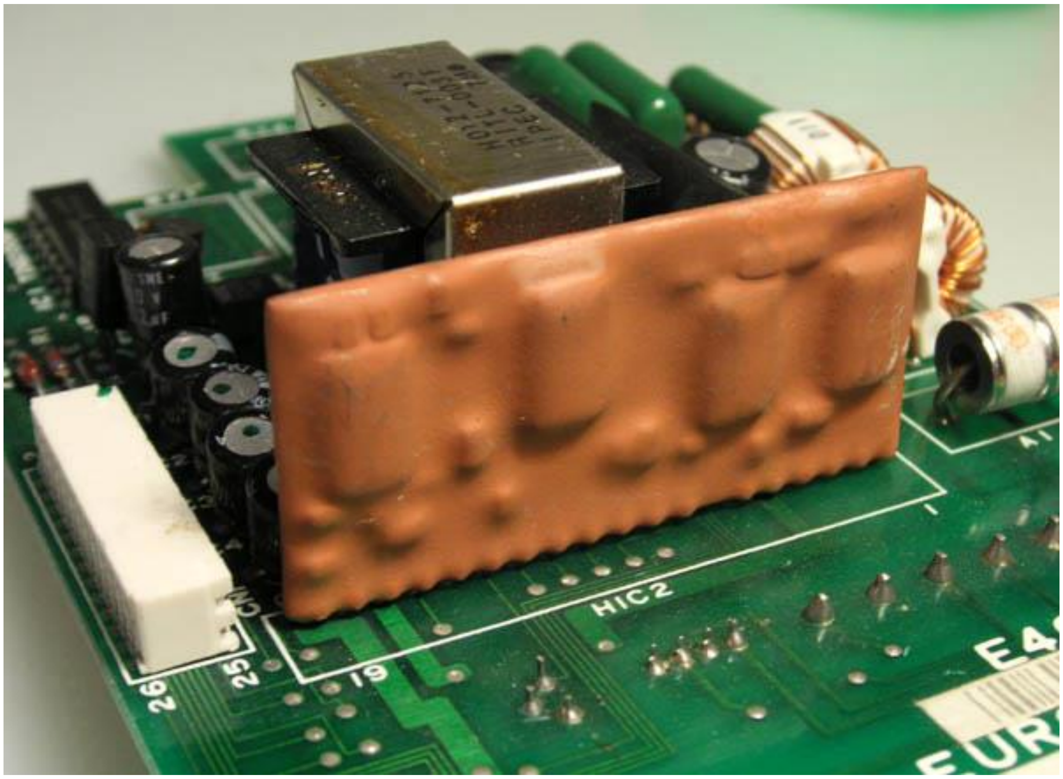


Figure 12: Epoxy carbon is depicted (orange plate) for the protection of a critical hardware part of a satellite electronic circuit (central processing unit).

Additionally other materials that are traditionally used in satellite industry for protection in radiation environments are:

- Aluminum Alloy 2024
- Raw aluminum
- Polished Aluminum
- Steel
- Polished Steel
- Black Paint
- Aluminized Teflon
- Solar Cell Cover
- White epoxy
- Cover glass
- Fused Silica
- Titanium

Polymer Advantages	Still in Research
High Durability	Survival in hostile environment
Durability in erosion	Ignition possibility in an intense thermal environment
Low Thermal Signature	Liberation of toxical wastes on orbit
Design Flexibility	Durability in long time periods
Variety of Characteristics and Types	Maintenance Problems on Orbit
Chemical Stability	Durability in high Temperatures
High Cost Effectiveness	

Table 19: Summary of the characteristics of Polymers that are used today in satellite shielding industry.

Conclusions

1. A satellite orbiting in Low Earth Orbits and close to the equator (300 km) is undergoing through a very low radiation environment.
2. A satellite in LEO with inclination of 45º has to overcome the effects of South Atlantic Anomaly. The incoming radiation is cumulative as it passes through the SAA region. That is to say the more the satellite passes through the SAA region the more is the effect of the radiation that is going to encounter.
3. Another effect that a LEO satellite has to overcome is the polar horns if it is orbiting in a polar orbit. In this specific Polar Regions we have concentration of high energy charged particles until Earth's Surface.
4. A satellite in an orbit of 1400 km (constellation satellites) can be influences the maximum from high dose rates of charged particles that are travelling to reach LEO orbits.
5. From 1400 -2000 km satellites have to encounter monatomic oxygen and other charged particles as protons and electrons.
6. Heavier ions as He, C, N, O, Ne cannot affect satellites electronic systems but can have effect in charging of a satellite.

7. The protons that can affect a satellite are coming from solar flare or from South Atlantic Anomaly.

8. **Monatomic Oxygen** is the only charged particle that can have **severe effect on low earth orbiting satellites**. In 200 km it has a density of 10^9 άτομα / cm^3 and in 800 km it is less than 10^5 άτομα / cm^3. The speed that charged particle have can reach 7 km/sec with energies up to 5 KeV. The results that can have on a satellite if there is a contact are: Material Erosion, very low for aluminum, but high on Arg. Also there is oxidization of the metals and the connections on the electronic circuits. There is also effect on cameras or mirrors that are used on board a satellite.

9. Electrons up to 7 MeV in Van Allen Radiation Zones and protons up to 600 MeV have no impact on satellite's electronics. They can also penetrate the surface of a satellite but only travelling short distances not having the capability to affect the satellite's operation. Aluminum shielding of more than 0.3 mm is used extensively for satellites that are travelling through radiation zones such as Van Allen Radiation Zones.

10. For a satellite in LEO the charged particles that we have to take seriously into account and can affect our mission are energetic protons with energies more than 50 MeV in the inner radiation belt and energetic electrons with energies up to 1 MeV in the outer radiation belt. Finally solar protons (from solar flares) are another charged particle that can have serious effect in our mission.

11. Polyethylene (C_nH_n) is a cheap material, stable and with low atomic number which is used for a resultive radiation shielding in ISS. Experiments have shown that it can reduce by 20% the effects of radiation onto satellite materials.

12. A LEO satellite is exposed to radiation from galactic cosmic rays when it is orbiting near the poles. It is not affected from galactic cosmic rays when is near the equator.

13. Protons in LEO orbits are having energies ranging among 150 – 250 MeV.

14. Future technologies recommend the usage of polymers in new satellite missions.

Acknowledgement

The above work on Chapter 4 has been conducted in US Naval Postgraduate School as part of a United States Air Force program, with Professor Kolar Ramesh from the Mechanical and Astronautical

Engineering Department. It was a funded study and recorded as NPS Official Report 2011, referring to micro satellites under the scope of radiation and shielding on orbit.

References

1. W.G.V. Rosser, “Magnetosphere, Ionosphere, Space Weather”, Proceedings of AIAA, pp 82-89, 2001
2. W.G.V. Rosser, “The Van Allen Radiation Zones, The theory of Trapping and the Inner Radiation Zone”, Physics Department, University of Exeter.
3. S. Bourdarie and Daniel Boscher, “Earth Radiation Belts”, ONERA/ DESP, BP 4025, 2. Av. E. Belin, 31055 Toulous Cedex 04, France
4. J. G. Roedeger, “The International Magnetospheric Study”, Acta Astronautica, Vol.1, pp1-14, Pergamon Press 1974
5. J. Claude Boudenot, “Radiation Space Environment”, Thales Research and Technology, RD 128, 91767 Palaiseau Cedex, France.
6. S. Bourdarie and Michael Xapsos, “The Near Earth Space Radiation Environment”, IEEE Transactions on Nuclear Science, Vol. 55, No 4, August 2008.
7. R. B. Setlow, “The US National Research Council’s View of the Radiation Hazards in Space”, Mutation Research 430 (1999), 169-175, Elsevier.
8. G. Pugacheva, A.A. Gusev, U.B. Jahanthi, N.G. Schuch, W.N. Spejeldvik, K.T. Choque, “Trapped Antiprotons produced by cosmic rays in the Earth’s Magnetosphere”, Advances in Space Research, 34, 2004, 1433-1437, Elsevier.
9. D.N. Baker, S.G. Kanekal, “Solar Cycle changes, geomagnetic variations and energetic particle properties in the inner magnetosphere”, Journal of Atmospheric and Solar Terrestrial Physics 70, 2008, 195-206, Elsevier.
10. T. Sesada, Satoshi Ichikawa, Toshiki Kanai, “In flight Measurements of space radiation effects on commercial DRAM”, IEEE, 2004.
11. E.E. Antonova, N. Yu. Ganushkina, V.F. Bashikov, “Quiet time distribution of plasma pressure in the inner earth’s magnetosphere”, Advances of Space Research, Vol. 25, No 12, pp. 2361-2364, 2000, Moscow, Russia, Elsevier.
12. J.H. Piddington, “The magnetosphere and its environs”, Planet Space Science, 1965, Vol 13, pp. 363-376, Pergamon Press, Sydney Australia.

13. G.I. Pugacheva, A.A. Gusev, U. Jayanthi, I.M. Martin, W.N. Spjeldvik, "Antiparticles and light Element isotope ions in the Earth's magnetosphere", Jounal of Atmospheric and Solar Terrestrial Physics, 64, 2002, 625-631, Elsevier.

14. G. Reitz, "Characteristic of the Radiation Field in Low Earth Orbit and in Deep Space", German Aerospace Center, Koln, Germany, 13 March 2008, Science Direct.

15. P. Rothwell, C. Lynam, "The plasmapause, the plasmasheet and energetic trapped electrons in the earth's magnetosphere", Planet Space Science, 1969, Vol. 17, pp. 447-454, Pergamon Press.

16. G.D. Badhwar, D.E. Robbins, "Decay rate of the second radiation belt", Advances of Space Research, Vol. 17, pp. 151-158, 1996, Pergamon.

17. A. L. Vampola, "The Hazardous Space Environment", IEEE transactions on plasma science, Vol. 28, No. 6, December 2000.

18. E. V. Benton, "Summary of Radiation Dosimetry Results on US and Soviet Manned Spacecraft", Advances of Space Research, Vol. 6, No 11, pp. 315-328, 1986.

19. C.T. Russell, "The solar wind interaction with the Earth's Magnetosphere: A Tutorial", IEEE transactions on plasma science, Vol. 28, No 6, December 2000.

20. W. N. Hess, "Energetic Particles in the Inner Van Allen Belt", Space Science Reviews, 278-312, 1962, Dordrecht, Holland.

21. E.R. Benton, E.V. Benton, "Space Radiaton Dosimetry in low Earth Orbit and Beyond", Nuclear Instruments and Methods in Physics Research, 184, 2001, 255-294, Elsevier.

22. P. Layton, L. Adams, D. Krawzsenek, B. Passenheim, J. Pickel, "Proton Transport, an examination, of model and experimental data for space environment protons", IEEE transactions on Nuclear Science, Vol. 47, No 3, June 2000.

23. E.V.Benton, A.l. Frank, E.R.Benton, T.W.Armstrong, "Absorbed dose measurements on LDEF and comparisons with predictions", Radiation Measurements, Vol 26, No 6, pp. 799-805,1996, Elsevier.

24. Martin Walt, "Introduction to Geomagnetically Trapped Radiation"

25. M. Carlowicz, R. Lopez, "Storms from the Sun", 2002.

26. S. Evans, "Natural Hazards on Space Environment", NASA Marshall Space Flight Center.

27. C. L. Brundin, “Effects of Charged Particles on the Motion of an Earth Satellite”, University of California, Berkeley, AIAA Journal, Vol. 1, No. 11, November 1963.

28. D.R. Hollars, J.F. Janni and M.F. Schneider, “Degradation of Satellite Electronics Produced by Energetic Electrons”, Journal of Spacecraft, Air Force Laboratory, Kirtland Air Force Base, New Mexico, Vol. 14, No. 10, October 1977.

29. W. Atwell, “Spacecraft Design Considerations for Human Radiation Shielding and Protection Issues”, The Boeing Company, AIAA 2005-6650.

30. F. Di Marco (Vega Darmstadt), O. Bergogue (EADS Astrium), M. Schmidt, R. Southworth, L. Harrison (ESOC/ ESA), F. Schmidt (SERCO Darmstadt), “Radiation Environment for Near Earth Mission Phases: The Integral and Lisa pathfinder cases”, AIAA 2008-3549, SpaceOps 2008 Conference, ESA and EUMETSAT.

31. E. G. Stassinopoulos, G. J. Brucker, J.N. Adolphsen, J. Barth, “Radiation Induced Anomalies in Satellites”, Journal of Spacecraft and Rockets, Vol. 33, No. 6, November - December 1996.

32. F. W. French, “Solar Flare Radiation Protection Requirements for Passive and Active Shields”, Journal of Spacecraft, Vol 7, No 7.

33. A. Meulenberg, “Space Radiation Environment and Testing”, SPIE Vol. 2611/31.

34. European Space Agency Standards, ECSS, “Space Environment”, E-ST-10-04C, 14 Νοεμβρίου 2008.

35. European Space Agency Standards, ECSS, “Methods for the calculation of radiation received and its effects and a policy for design margins”, E-ST-10-12C, 15 Νοεμβρίου 2008.

36. European Space Agency Standards, ECSS, “Spacecraft Charging”, E-ST-20-06C, 31 July 2008.

37. Comparative Analysis of Radiation Effects on Medium Earth Orbits Jennifer A. Bolin, 2006.

38. T., A.C., “The Space Radiation Environment: Implications for Spacecraft Design”, Princeton Press, 1995.

39. Lawrence Berkeley National Laboratory, Radiation Shielding Materials NASA Workshop, California Berkeley, August 2000.

Page intentionally left blank

CHAPTER 5

MARITIME SECURITY

SCENARIOS

Chapter 5: Maritime Security Scenarios

Having completed in the previous chapters all aspects of literature survey for picosatellites, starting from microsatellites that support maritime operations all the way to available propulsion for micro/nano/picosatellites and the space environment as well as the operational characteristics of such types of satellites, we can safely now move on to apply our research ideas on scenarios.

In order to safely extract results on how picosatellites can perform tasks as part of a maritime security operation we apply in this chapter different scenarios, using simulation software's available (such as Satellite Tool Kit or Orbitron – commercial satellite orbital software). Under this methodology results on lifetime, duration on orbit, telecommunications capabilities, as well as time coverage on top the area of maritime operation are going to be quoted. The scenarios are more relevant to a maritime piracy operation, but can be safely applied to any maritime security operation converting the designing factors accordingly.

First Scenario: One ship - One Microsatellite (FO-29)

In this scenario we will try to simulate the movement of one vessel from point A to point B while transiting through a high risk area. For example let's suppose that merchant vessel "Georgios" has to travel from Nigeria (point A) to Fujairah (point B) from 15 October 2014. The total distance and the route to follow is seen in the following figures 14 and 15. There is no option to avoid the high risk (regarding piracy) area taking into account that vessel should be berthed in Fujairah in a specific date to load up its cargo areas and move to the next port. Therefore, merchant vessel "Georgios" will travel this distance with a maximum speed of 20 knots. The ship is considered to be a container ship and thus its normal speed in accordance with known data is around 20 knots. What we will try to accumulate through this scenario is the following [1,2]:

a. How many times our picosatellite will find merchant vessel and will communicate text, audio and images in order to keep the vessel informed for the piracy situation in the area.

b. How many times a normal vessel receives a terrestrial message when transiting in the middle of the ocean and what are the general ways of communicating with a vessel from ashore especially for alert messages regarding piracy or other emergency situations.

c. How many times merchant vessel shore station is communicating generally per day with its ship and with what means. What is the associated cost?

d. Find out the areas-distances and associated times that the merchant vessel will not be able to communicate with the satellite (therefore with a shore station). From this information we will finally be able to define how much time per day a merchant vessel is able to communicate with a picosatellite and how much time not. By that we will συμπεράνουμε what is the maximum time and distance covered with communication and how much not.

e. Define the Piracy Risk Index (PRI) of the area taking into account information from available internet sources.

f. Define the Picosatellite Piracy Risk Index (PPRI) and compare them to find out how much decrease in total risk we have accumulated with the use of a very small satellite like Lambdasat - Tubesat or any other picosatellite less than 1 kgr.

g. Create a cost benefit analysis of using a standard satellite service provider to succeed 24/7 exchange of information with a merchant vessel underway and at the same time find out in accordance with the above scenario how much is the cost with the use of Picosatellite. What are the implications (advantages or disadvantages) in this case?

h. Perform multiple scenarios with the use of different Picosatellites available on orbit and provide a mean final result taking into account all operational characteristics (table 20).

Satellite Name	**FO-29 (Fuji Oscar)**
Code Name	JAS-2
Country	Japan
Launch Date	17-08-1996
Status	Operational - Active
Site	Tanegashima Space Center - Japan
Beacon	435.795 MHz (CW)
Downlink	435.800 MHz – 435.900 MHz (USB, CW)
Uplink	145.900 MHz – 146.00 MHz (LSB, CW)
Orbit type	LEO
Altitude	1300 km polar orbit

Perigee x Apogee	801 x 1322 km
Revolutions per day	13.529
Period	106.43 min
Inclination	98°
Drag Factor	0.000002448 1/ER
Info	Packet Satellite with Analog Comms and Digitalker, Telephony
Size	44 cm wide x 47 cm high - Sphere polyhedron consisting of 26 panels
Weight	50 kgr
Power Supply	GaAs solar cells 2cmx2cm and 11 cells of Nickel
RAM	2 MB capable of voice - audio messages

Table 20: Tabulated Characteristics of microsatellite FO-29 (Fuji Oscar)

FO-29 is a Low Earth Orbit (LEO) satellite. LEO satellites orbit around the Earth between 160 kilometers (99 nm) (orbital period around 88 minutes) and 2000 km (1200 nm) (about 127 minutes).

Figure 13: Image of the Japanese Amateur Microsatellite FO-29 (Fuji Oscar) [1]

Having tabulated the characteristics of the above mentioned microsatellite we will now try to formulate our scenario with the use of merchant vessel "Georgios". Let's consider that vessel will start its trip from Malabo (a small island in the Gulf of Guinea) where piracy incidents - oil theft and other illegal activities happening almost every day in accordance with international sources. The vessel will transit through the southern part of Africa and then will head north to the Gulf of Aden and finally will enter Fujairah port. We consider as point A the Malabo Island and point B Fujairah port. The measured distance between point A and B is approximately (taking into account that movement should be performed at least 100 miles away from shore in order for the vessel not be able to communicate with AIS stations) 7700 miles. Having studied and analyzed the general sea lines of communication and routes of merchant vessels through various official sources it is well known that vessels generally transit from outside of Somalia in distances that are more than 500 miles from shore when they are heading to United Arab Emirates (in this case Fujairah). Therefore from the below figure 14 we can see the general route of MV Georgios from point A to point B.

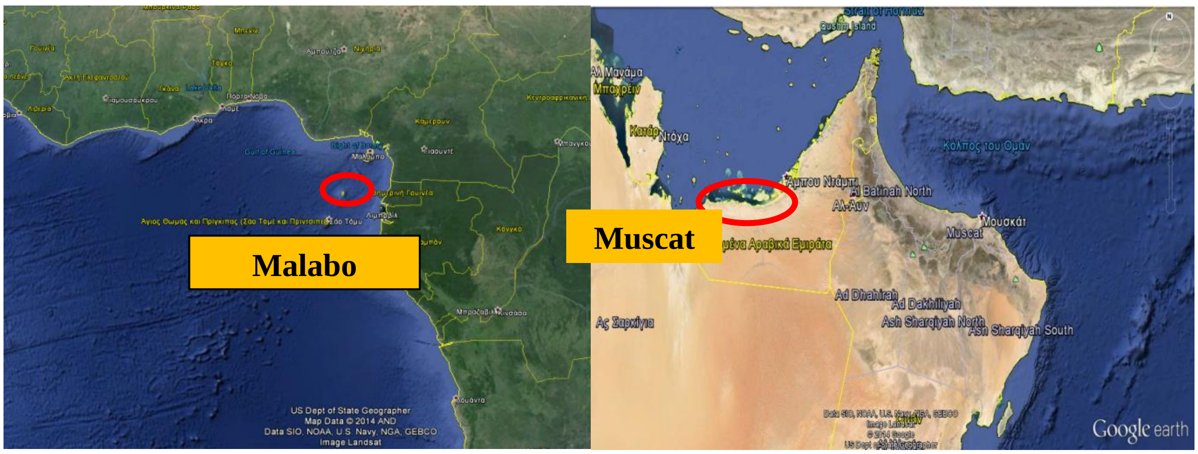


Figure 14: Image of starting Point A (Malabo Island Gulf of Guinea) and ending Point B (Muscat -UAE - Strait of Hormuz) of MV's Georgios trip.

Having identified the starting (Point A) and ending (Point B) points of the vessel's trip we are now able to measure the distances and define specific navigational course during this trip. With the use of an application like Google earth or any other commercial product we can find out the following representation as in figure 15.

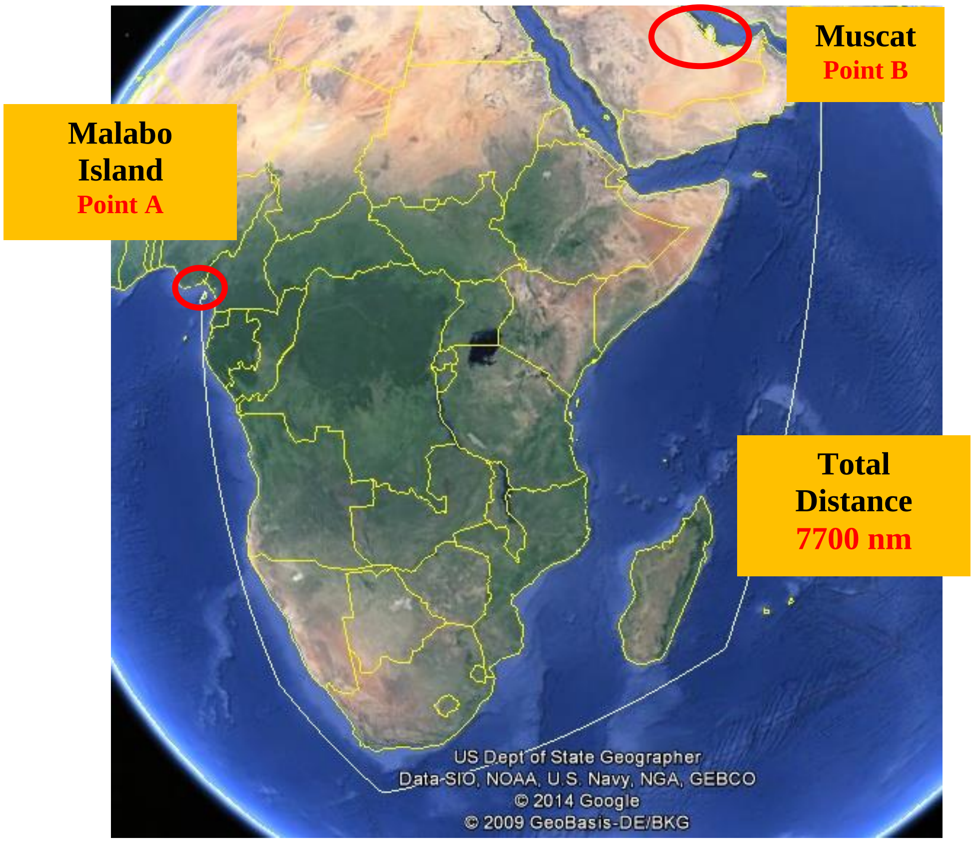


Figure 15: Total distance of trip from Point A to Point B 7700nm

Since we now have calculated the total distance that the MV will travel as 7700 nm and taking into account our hypothesis that this specific MV Georgios is a container ship, its mean speed will be 20 knots per hour. Therefore doing the simple calculation we deduce that the vessel will conduct this trip in:

7700 nm: 20 Knots / hour = 385 hours : 24 hours / day = 16,04 days

Having calculated the total time that the vessel will cover the distance we are now able to shift our scenario to the satellite part of it and calculate how many times FO-29 LEO microsatellite will cover the trip of the above mentioned MV in time and distance respectively. It is always useful to mention that the vessel is travelling at least 100 miles away from the shore and the captain decides on using the route outside of Madagascar island, but near to Seychelles taking into account that Seychelles is a safer place to pass from the strait of Madagascar and near to Somalia shoreline where pirates replete.

Having the given that the ship is moving with 20 knots per day and if start our trip at 14th of October 2014 00:00:00 hours we know that each calendar day (24 hours / day) the ship will move 440 nm distance. We are dividing our trip from Malabo to Muscat in three different legs. From Malabo to South Africa, to Madagascar and finally to Muscat. In each leg we are going to calculate (in approximate figures) how much total time the ship is able to communicate with the microsatellite and finally in how many miles of the total distance of the leg the ship is capable of communicating with the space micro asset. Table 21 summarizes the results (analytical simulated results have been referred to appendix of this chapter for further analysis) and gives an indication for the microsatellite communication availability. Of course one has to bear in mind that FO-29 microsatellite is a LEO orbiting satellite, but it flies in 1300 km altitude, which means that the available footprint of it is much more than a satellite that flies near the International Space Station (approximately or near 400 km). From table 1 we see that the microsatellite is available in the first 5 days for a total number of 12 passes which is being divided into 3 passes the first and one pass the second calendar day. The time coverage during these passages varies from 18 to 20 minutes per passage when there are 3 passes a day and only 5 to 7 minutes, when there is only one pass. In this timeframe of one day with 3 passes the available time is 44 minutes per day approximately with two passes to be in the morning and one passage in the evening. Therefore only 2,37% of the total day and night time is available for communication availability with the microsatellite whereas 97,63 % the ship is not able to communicate. Commenting on that fact we should mention that in any other case (or as it stands today) ships without any subscription to commercial satellite communication (due to heightened costs – and we see it often to happen) are not able to communicate with their shore stations, unless they are near shore. With this case a ship can communicate from one to three times per day and in a timeframe of 45 minutes with the associated office ashore and this time is more than enough to exchange critical information as well as alert messages either for the high risk area transiting or even for the maintenance of the vessel. Not to mention that today piracy alert messages to ships are being transferred in the best case scenario via HF telex messages and are in the form of printed papers. Here with the 45 minutes of total communication per day a ship is able to use internet service at almost no cost. To sum up the overall values for a 5 day leg of the ship’s trip from Malabo to South Africa is 164 min (or 2,7 hours of communication) during a distance of approximately 57 nm through the specific 1st course leg.

Ship Trip - 1st Leg: Malabo to South Africa				
Date	Passage Duration	No of Passes	Coverage min/day	Outage min/day (1440 min = 24h)
14 Oct 14	0618-0636	3	18	
	0800-0820		21	
	2126-2131		05	
Total min in 14th of Oct			44	1396
15 Oct 14	0706-0725	1	19	
Total min in 15th of Oct			19	1421
16 Oct 14	0613-0628	3	15	
	0755-0815		20	
	2121-2127		5	
Total min in 16th of Oct			40	1400
17 Oct 14	0701-0720	1	20	
Total min in 17th of Oct			20	1420
18 Oct 14	0609-0623	3	14	
	0751-0811		20	
	2116-2123		07	
Total min in 18th of Oct			41	1399
Total in 5 days				
Final Averages		12	164	7036
2.37% of total time 7200 min comms availability		2.37% of total distance of 2400 nm comms availability		
164 min satellite comms availability		**57 miles** satellite comms availability		

Table 21: Tabulated simulation data of microsatellite FO-29 comms availability with MV Georgios during the 1st Leg of trip from Malabo to South Africa.

Continuing the analysis to the 2nd leg of the trip from South Africa to Madagascar the results are being tabulated / summarized to table 22. In this case the ship will have moved another 5days*20knots/hour*24hours/day = 2400 nm, which practically means (from a navigational perspective) that the ship will reach the southern part of the island of Madagascar. In this case from the simulation software we receive the below results regarding the comms availability with the microsatellite FO-29.

Ship Trip - 2nd Leg: South Africa to Magadascar				
Date	Passage Duration	No of Passes	Coverage min/day	Outage min/day (1440 min = 24h)
19 Oct 14	0158-0200	3	2	
	0333-0352		19	
	1824-1834		10	
Total min in 19th of Oct			31	1409
20 Oct 14	0241-0255	2	14	
	0423-0442		19	
Total min in 20th of Oct			33	1407
21 Oct 14	0329-0347	2	18	
	1819-1829		10	
Total min in 21th of Oct			28	1412
22 Oct 14	0237-0251	2	14	
	0419-0438		19	
Total min in 22nd of Oct			33	1407
23 Oct 14	0325-0342	2	17	
	1815-1825		10	
Total min in 23rd of Oct			27	1413
Total in 5 days				
Final Averages		11	152	7048
2,11 % of total time 7200 min comms availability		2,11 % of total distance of 2400 nm comms availability		
152 min satellite comms availability		**51 miles** satellite comms availability		

Table 22: Tabulated simulation data of microsatellite FO-29 comms availability with MV Georgios during the 2nd leg of trip from South Africa to Madagascar.

As we can see and for this ship's course leg the results are similar if not the same with the previous one. The communication availability with the satellite is 2.11 % of the available timeframe of the 5 calendar days (which is 7200 min) and for this timeframe the ship will be able to communicate with the microsatellite for 152 minutes in total. It is again the case that the ship will be able to transfer and receive information to shore station - back office for 2 to 3 times per day with one morning and one evening session. This will cover a total distance of 51 miles of communication of the overall covered distance. Similar results we are expecting from the execution of the simulation to the final leg of the trip (Madagascar to Gulf of Aden to Muscat - Table 23).

Ship Trip - 3rd Leg: Madagascar to Gulf of Aden to Muscat				
Date	Passage Duration	No of Passes	Coverage min/day	Outage min/day (1440 min = 24h)
24 Oct 14	0215-0227	3	12	
	0357-0417		20	
	1738-1745		7	
Total min in 24th of Oct			39	1401
25 Oct 14	0303-0321	2	18	
	1639-1653		14	
Total min in 25th of Oct			32	1408
26 Oct 14	0211-0222	3	11	
	0352-0412		20	
	1733-1741		8	
Total min in 26th of Oct			39	1401
27 Oct 14	0259-0316	2	17	
	1634-1649		15	
Total min in 27th of Oct			32	1408
28 Oct 14	0207-0217	3	10	
	0348-0408		20	
	1728-1737		9	
Total min in 28th of Oct			39	1408
Total in 5 days				
Final Averages		13	181	7026
2.51% of total time 7200 min comms availability		2.51% of total distance of 2400 nm comms availability		
181 min satellite comms availability		**61 miles** comms satellite availability		

Table 23: Tabulated simulation data of microsatellite FO-29 comms availability with MV Georgios during the 3rd leg of trip from Madagascar to Gulf of Aden to Muscat

Therefore as we also see from the 3rd leg of the ship's voyage from Madagascar to Muscat we will have another 2.5 % of the total available time of 5 days for communication with the satellite. Each day there is going to be a possibility of 1 to 3 times of exchange of information with the space asset and at the same time the overall calculated distance covered with communication will be 61 nm of the total distance of leg which is 2400 nm. Thus, the characteristics of communication availability here, as it was logical to happen, is following the same pattern as above.

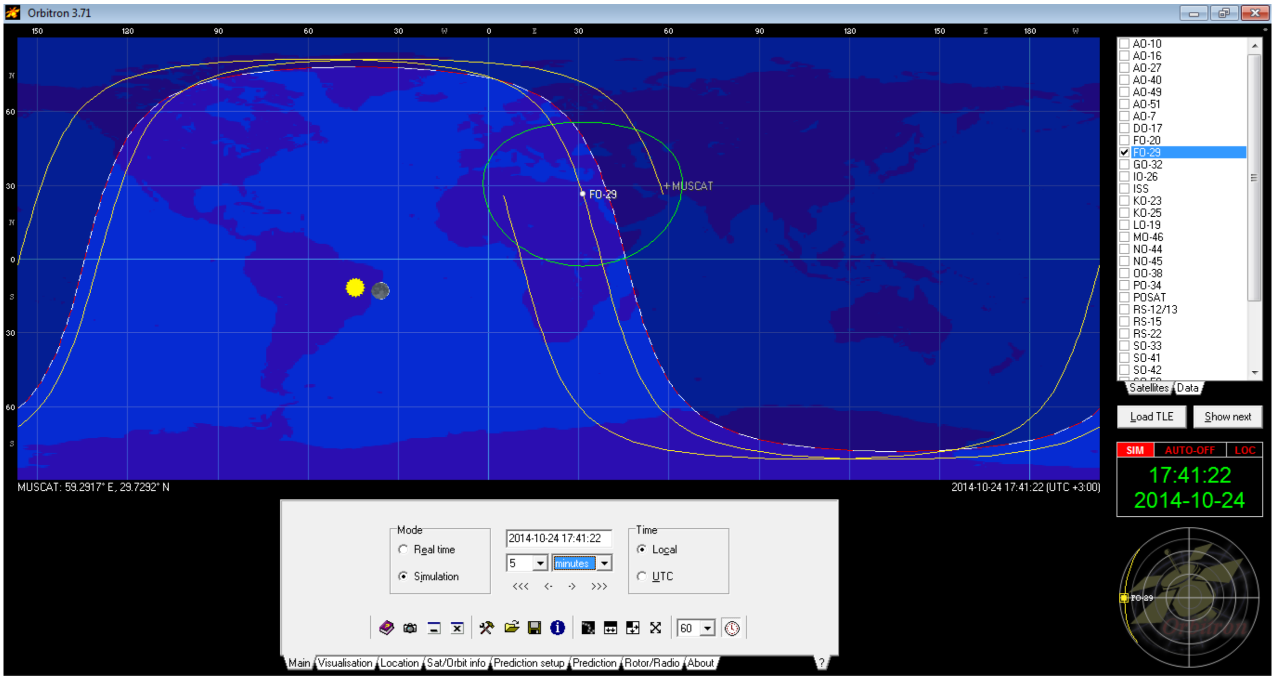


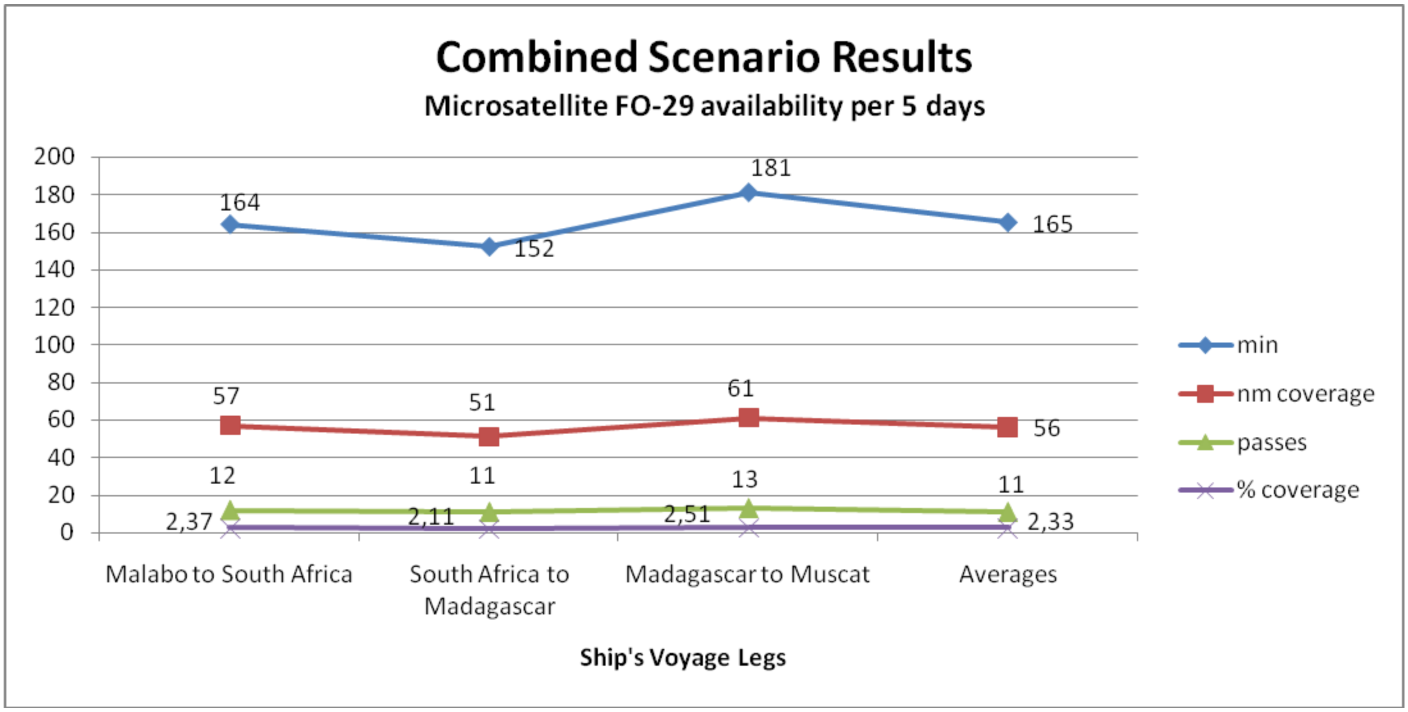
Figure 16: Simulation of FO-29 microsatellite to cover the 3rd leg of the ship's trip from Madagascar to Muscat. FO-29 microsatellite's tracks as well as Muscat location appear on the map (use of Orbiron simulation software)

As we see in the below aggregated information in table 24 the Japanese satellite F0-29 (still active) will access the ship's position during its passage for five days on an average of 165 minutes per 5 days (35 min per day). This is proportional to 56 nautical miles and to 11 passes of the satellite. Hence the total % coverage of the microsatellite to ship's trip is 2,33 % approximately on a daily basis.

Ship's Route Legs	Microsat comms availability (min / 5 days)	Distance with microsat coverage nm (5 days)	Microsatellite passes (in 5 days)	microsatellite coverage (%) (per day)
Malabo to South Africa	164	57	12	2.37
South Africa to Madagascar	152	51	11	2,11
Madagascar to Muscat	181	61	13	2,51
Total Averages	**165**	**56**	**11**	**2,33**

Table 24: Overall tabulated simulation data of microsatellite FO-29 comms availability with MV Georgios during the trip from Malabo Island (Nigeria) to Muscat (UAE). Total averages of connectivity are shown.

If we want now to outline further the whole communication availability with the microsatellite in a linear diagram we would create the below graph 19 which depicts the minutes per day of the microsatellite access to the ship, the nautical miles coverage, the % coverage availability and the microsat passes per day from the area on top the vessel during its transiting from point A (Malabo Island) to point B (Strait of Hormuz - Muscat port).



Graph 19: Combined Microsatellite Coverage Results

Graph 19 above, generated from the first scenario we played with the microsatellite FO-29. We can deduct from it the minutes, nautical miles, passes of the microsatellite over the ship and the % coverage of the satellite during vessel's trip. It is worth mentioning, except the collected data, to see the last "averages" column of information, where list the average of units of the microsatellite accessing the vessel during its trip. 165 minutes, 56 nautical miles, 11 passes on top the vessel and in total 2,33% coverage during the whole trip.

On the above analysis and for easiness of the calculation, each course leg has been calculated for a total distance of 2400 nm in order for the results to be balanced.

This of course does not create any difference in the daily and usual routine that ships follow on real life, since this specific route is very common to Merchant vessels nowadays. Also we should mention here that the above results and simulation data have been acquired using Orbitron 3.71 amateur software and selection of data points have been registered to appendix 1 of this chapter.

Second Scenario: One ship - One Picosatellite (Lambdasat)

In this specific case by using STK we model one different scenario where we have a ship moving from a port in Eastern Africa - Mozambique (just west of Madagascar) and finishes its trip to Oman Southern shore borders. The task here is to find how many times a satellite like Lambdasat (same orbital characteristics like International Space Station - ISS) is going to access the ship during ship’s trip. We should mention here that ship’s speed is 26 knots, which is a typical speed for an LNG vessel. The scenario has been run from 20 Oct until 01 Nov 2014 and has no azimuth or elevation or range constraints. This was done on purpose taking into account that we do not care for communications equipment but we want only to calculate what is the time available that the picosatellite will access the ship during it’s trip. Therefore we will find out the maximum coverage time. This of course is nominal and during real situations where environmental constraints exist we have limitations in communication schemes.

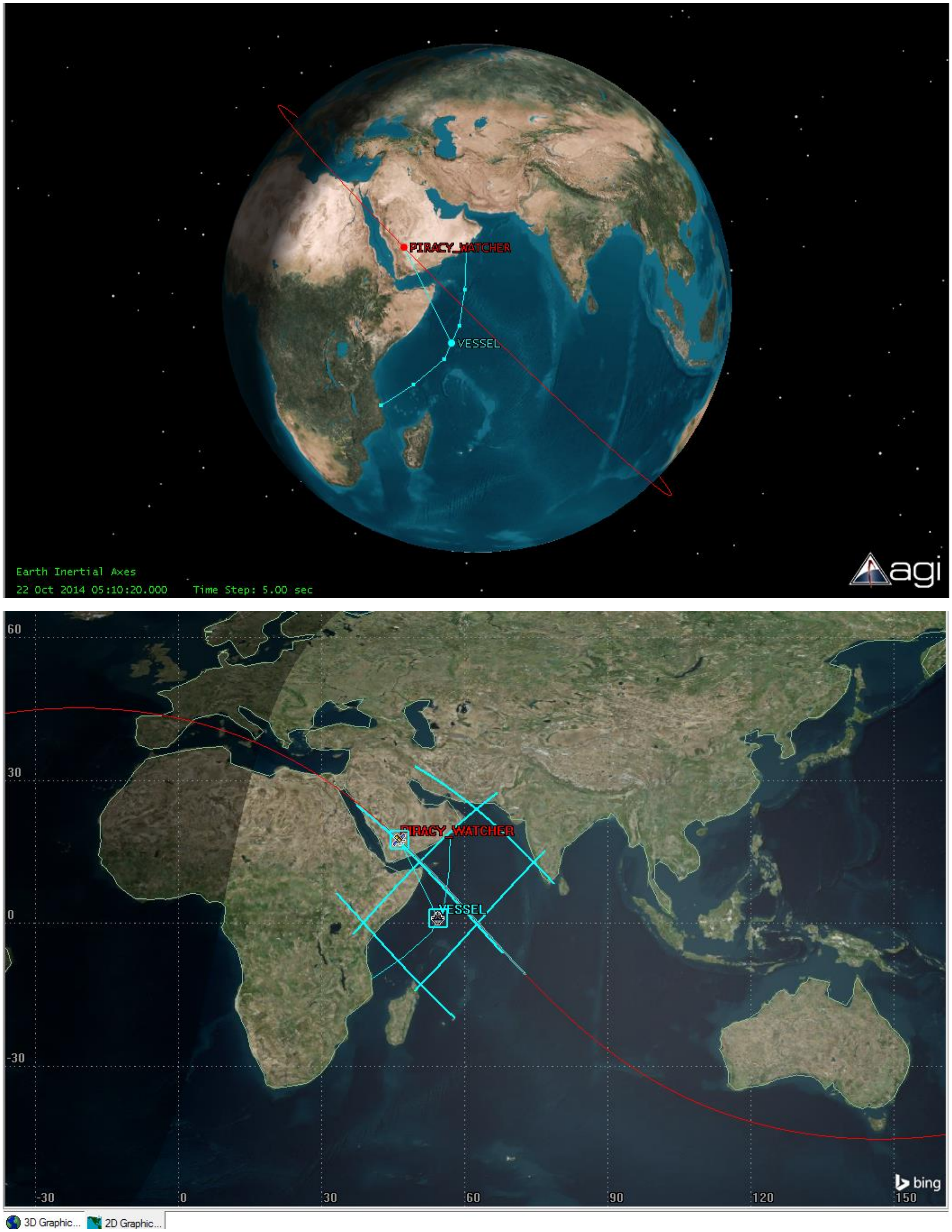


Figure 17: Lambdasat picosatellite coverage to the area of operation (multiple passes) using Satellite Tool Kit (STK) software

Having acquired the results (table 25) from the simulation we see clearly that in two days of the ship's trip there are in total 6 passes over the ship with a maximum duration of each pass to be around 12 minutes whereas the minimum to be 10 minutes approximately. Therefore as we have seen also in the first scenario with FO-29 microsatellite (with slightly different orbital characteristics - the altitude was higher 800 km than here where the altitude is 400 km) the total timeframe that as ship could see a picosatellite during its trip is approximately 65 minutes in 48 hours, which means 2.256% coverage during its trip.

Date	Start Time (h:min:sec)	End Time (h:min:sec)	Passes	Coverage (min)	Min - Max Elevation (°)
22 Oct 2014	05:09:14.040	05:20:57.318	4	11	0 - 35.7
	06:49:02.836	06:58:54.440		10	0 - 11.8
	17:00:14.761	17:11:15.672		11	0 - 20.1
	18:39:12.413	18:50:37.899		11	0 - 25.4
23 Oct 2014	03:06:35.270	03:16:38.069	2	10	0 - 12.4
	04:44:40.521	04:56:30.965		12	0 - 42.3
Min Duration				**9.8 min**	
Max Duration				**11.83 min**	

Table 25: Results from STK simulation scenario for 22nd and 23rd Oct 2014 for access of one picosatellite to one ship (speed: 25 knots) moving from port A (Mozambique) to port B (Oman).

In case now that the vessel is moving not with 26 knots, but with a middle case speed of 12 knots, as most of the merchant vessels move during their trips (economical speed) the coverage table 26 from the satellite would be a little bit different as follows:

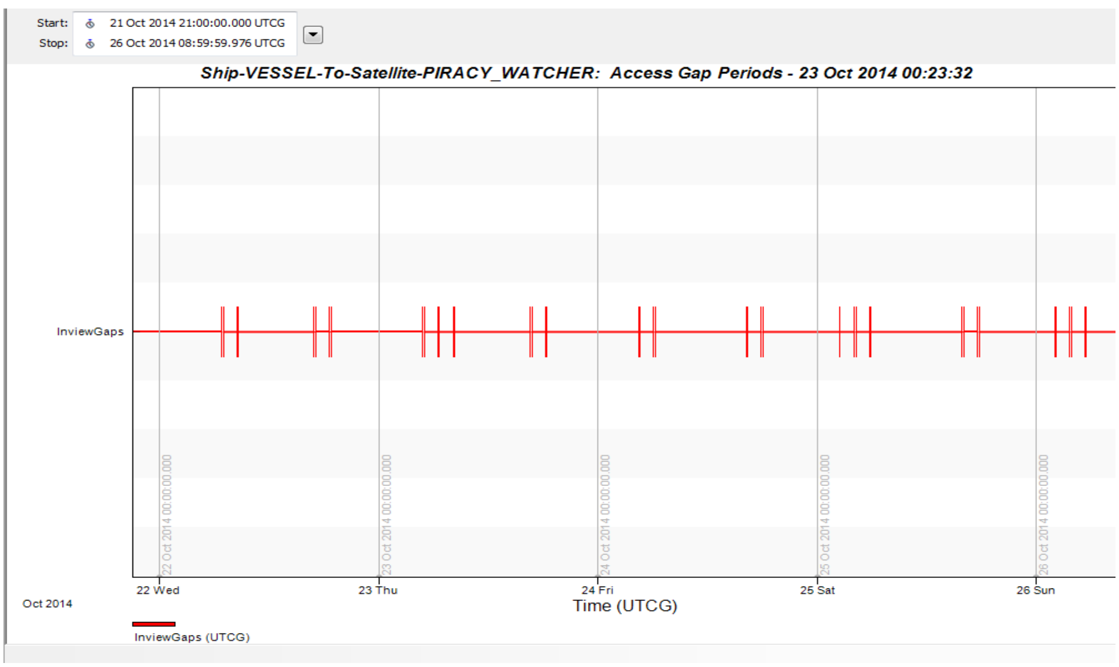
Date	Start Time (h:min:sec)	End Time (h:min:sec)	Passes	Coverage (min)	Min - Max Elevation (°)
22 Oct 2014	05:10:53	05:19:58	5	9	0 - 44.6
	06:48:24	07:00:22		12	0 - 11.6
	08:31:28	08:36:04		5	0 - 27.7
	16:56:40	17:08:20		12	0 - 17.2
	18:36:24	18:46:46		10	0 - 7.1
23 Oct 2014	04:47:13	04:58:27	4	11	0 - 61.3
	06:26:20	06:37:14		11	0 - 2.8
	16:35:41	16:47:19		12	0 - 33.3
	18:15:21	18:25:50		10	0 - 14

24 Oct 2014	02:47:42	02:53:01	5	6	0 - 19.6
	04:23:34	04:35:35		12	0 - 22.2
	06:04:13	06:12:48		8	0 - 36.3
	16:14:45	16:26:01		12	0 - 13.1
	17:53:55	18:05:02		13	0 - 49.7
25 Oct 2014	02:22:13	02:31:33	6	11	0 - 8.9
	03:59:59	04:11:59		12	0 - 17.7
	05:42:53	05:46:47		4	0 - 64.3
	15:53:52	16:04:23		11	0 - 15.4
	17:32:16	17:44:01		12	0 - 22.6
	19:15:25	19:20:28		5	0 - 9.2
Total Coverage Time				**198**	
Total Passes			20		
Mean Duration				9	
Min Duration				4	
Max Duration				13	

Table 26: Results from STK simulation scenario from 22nd until 25th of Oct 2014 for access of one picosatellite to one ship (speed: 13 knots) moving from port A (Mozambique) to port B (Oman).

From Table 26 we deduce that if the ship is moving with lower speed, in this case 13 knots (mean speed of most of the cargo vessels transiting the oceans) then the access time from the satellite is approximately 198 minutes over 4 days which is the time that the vessel will take to move from Mozambique to Oman. Therefore coverage time here is 3.235 % (based on STK exact reporting) of the total available time.

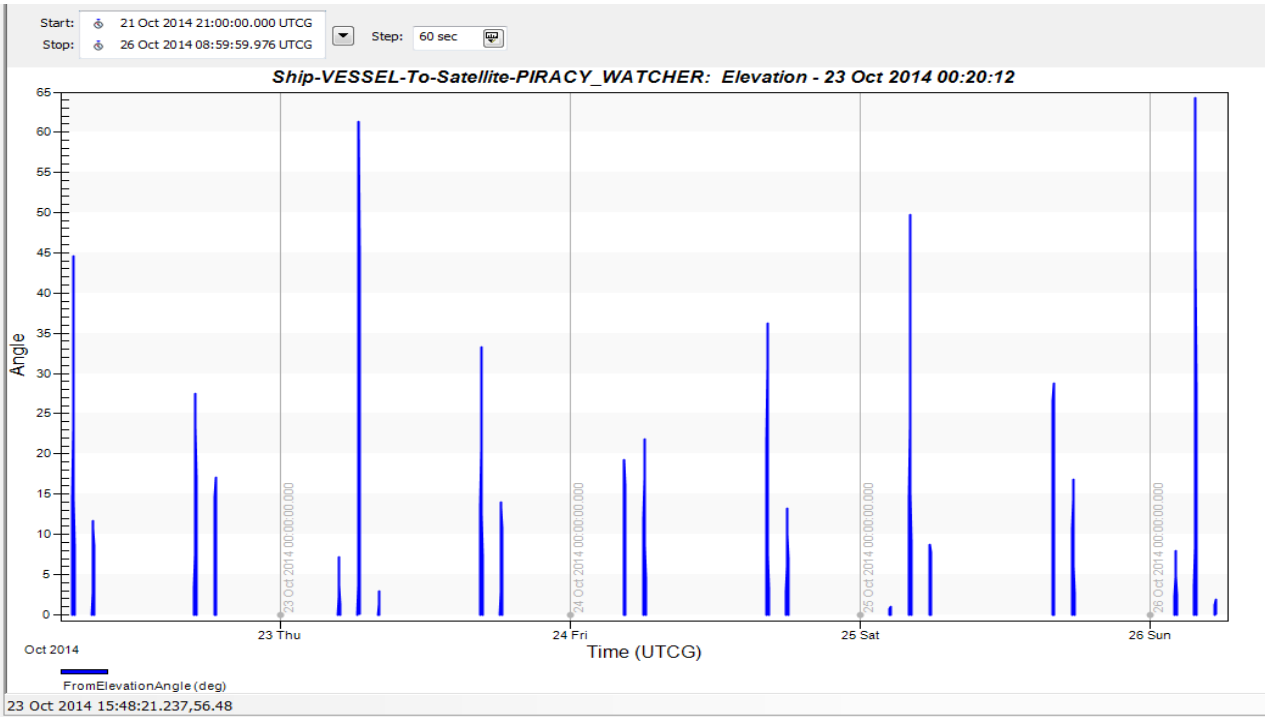
It is not though the overall increase only that we care but if we see in more detail the above table 26 we will see that the satellite passes over the vessel each day from 4 to 6 times and specifically two or three times in the morning and two or three times at night. This is an operational advantage taking into account that the piracy situation can alter from morning to night or from day to day and thus the ground station ashore will have the capability to feed the vessel with all the updated piracy information 5 times per day. This practically means that the satellite footprint which is approximately 800 km feed the vessel all the time with piracy data without leaving any grey area before the vessel moves from one point of route to the other. If the ship moves with 13 knots per hour this is 13 miles per hour distance and so in each calendar day it covers 24*13 = 312 nautical miles distance. So the picosatellite accessing the vessel five times means that every 60 miles the captain of the vessel has new updated information before pirates be able to approach its vessel without him knowing. Even in the worst case scenario where the pirates will happen to be in the area with a directly opposite course of the merchant vessel and with their typical speed of 30 knots then the relevant coverage speed of the area is 13+30=43 knots of approaching the two vessels together. The time in this case if the pirates are 200 miles for example away is 200 miles / 43 knots/hour = 4,6 hours to be near to each other. The picosatellite though will have accessed the merchant vessel either three times in the last 6 hours or 3 times in the last 11 hours (based on the results of the above table 7). This practically means that if pirates happen to be in the first case the merchant vessel will have a very clear and direct information about pirates presence (or at least from all other neutral vessels in the area), whereas in the second case the merchant vessel will have info from 11 hours behind which we will compute in the next chapters how much increase the risk of a vessel being pirated.



Graph 20: Daily access times to ship from 22nd to 25th of Oct 2014

(STK representation).

In graph 20 we represent the number of times and the total number of passes that the picosatellite will access the vessel. It is worth mentioning that a satellite will pass over the area for three to four times in a timeframe of 3-4 hours and then will pass again after 10-11 hours for another 3-5 times. This is the coverage / communication scheme that a vessel will have to follow in order to get updated with counter piracy or generally maritime security information.



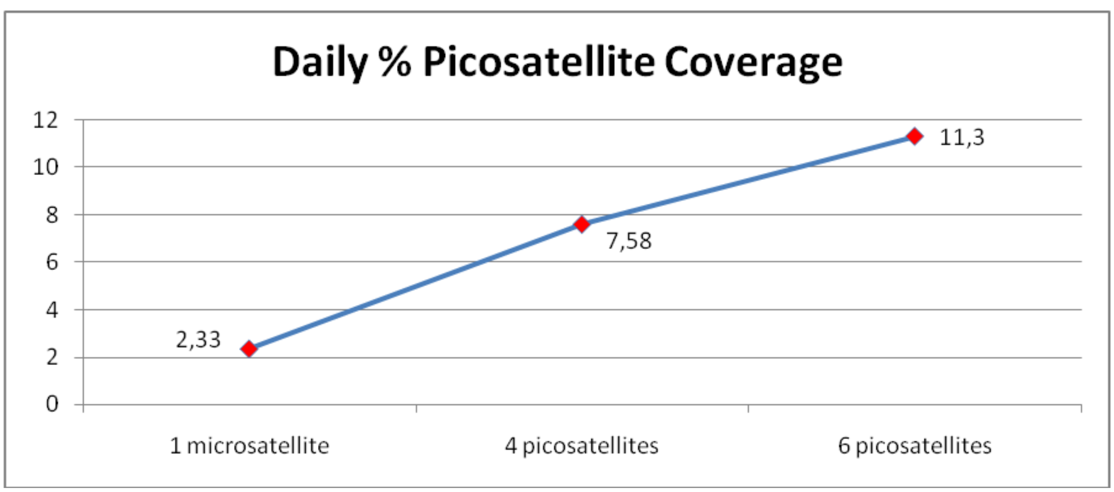
Graph 21: Elevation Angles of the Picosatellite access to ship's voyage from 22nd to 25th of Oct 2014. Max and min elevation angles are being reported.

The above analyzed scenarios have been conducted with the use of STK.10 satellite tool kit software.

Third Scenario: One ship with 4-6 picosatellites coverage

Having executed the previous scenarios it has been perceived from the analysis that a ship moving alone in an oceanic area similar to Indian Ocean could have limited communication capabilities with a picosatellite or microsatellite available on orbit. However this communication capabilities are in some, if not in most, cases adequate of covering the operational requirements and fill in the gap of information to such an extent that merchant mariners will have fresh / updated references on a daily basis two or three times from their centers ashore, whereas nowadays this information is very costly to be received on board a merchant vessel transiting in the middle of an ocean.

On a similar analysis we have used commercial available satellite software tools (STK, orbiter, predictor etc) and we have tabulated below the use of multiple picosatellites on orbit in order to support a maritime oriented mission. As we see in the graph 4 below with one microsatellite (e.g FO-29) the coverage of a single vessel reaches of 2,33 % of daily time as we indicated above. At the same time with the use of 4 picosatellites this percentage increases up to 7,58% whereas the use of 6 picosatellites gives us a timeframe of 11,3% of the available daily access time. Our analysis is being limited to 6 picosatellites (on circular or polar orbit [5,6]) and we are not exploring the fact of using more Picosatellites in orbit taking into account that the cost then reaches high values and we want to avoid those figures. As we have stated from the beginning of this dissertation it is of our interest to see what are the requirements of a mission that we can cover taking into account that the cost is not being increased drastically. If we use more of 6 picosatellites then we are referring to the use of a small constellation and this is out of the scope of this research. Therefore, the use of 6 picosatellites (graph 22) in specifically selected orbital parameters gives us the possibility of communicating with a vessel in the middle of an ocean 11% of it daily time and for our research interest this is an adequate finding to state that 11% * (24*60)/100= 160 minutes availability of communication with the vessel throughout the day.



Graph 22: Daily coverage with 1 to 6 picosatellites available on orbit

Fourth Scenario: One ship - One Picosatellite (Tubesat)

Maritime interdiction operation is being defined as the case where a military vessel is patrolling an area with scope to counter illicit trafficking, pirate activities and hinder unlawful acts. Even if the vessel is not a merchant one this does not mean that the use of picosatellite is going to be on a different philosophy. Similarly, as in the previous scenarios, we would like to know what is the accessible timeframe of the picosatellite (in this case Tubesat) from an area of operation, which in this case is the Gulf of Aden.

Similar results will be obtained with the use of other micro or picosatellites taking into account that the use of a low or very low earth orbit satellite is with the same orbital characteristics as the FO-29 above in table 20. Therefore for satellites with similar orbital parameters and most importantly with orbit altitude of 1000 km or less (down to 320 km) the characteristics / results of the research alter not too much but as enough as around 5 to 10% which is a significant difference. Results have been quoted and obtained from the analysis of the Tubesat [3], which is going to be launched from Naval Postgraduate School under the auspices of interorbital company. In this case we modeled a picosatellite network to support a maritime interdiction operation.

Fifth Scenario: One ship - Continuous (24/7) Coverage

In this case we will simulate the voyage of a cargo vessel from the same point A (Mozambique) to same point B (Oman) taking though into account that we want continuous coverage. What is the number of Picosatellites that we would like to use in order to cover the area 24/7. Performing the simulation for the same timeframe and the same characteristics as in the above scenarios we acquire the following results. Based on references [1,3] and taking into account simulation results that have already been performed and published we need to have 6 satellites on polar orbit or if we are going to use multiple orbits and paths then we need to use the so-called Walker constellation simulation. This simulation though is outside of the scope of this research. An example of this constellation could be in a slightly format Iridium constellation that is already being used in maritime applications (internet, telephony etc.)

References

1. A. Bordetsky, G. Mantzouris "Micro and Pico Satellites in Maritime Interdiction Operations", 15th ICCRTS, Santa Monica, LA, CA, 22-24 June 2010,
2. Wiley J. Larson and James R. Wertz. *Space Mission Analysis and Design*. Third Edition, Space Technology Library, 2005,
3. Dr. Alex Bordetsky, Georgios Mantzouris. *Modelling of Pico Satellite Network Applications To Maritime Interdiction Operations*. 16th International Command & Control Research & Technology Symposium. Quebec, Canada, 21-23 June 2011
4. A. Bordetsky and D. Netzer, Testbed for tactical networking and collaboration. International C2 Journal, 3(4), 2010,
5. "Principles of Communication Satellites", Gary D. Gordon and Walter L. Morgan, Wiley Interscience,1993,
6. "Space Mission Analysis and Design", Wiley J. Larson and James R. Wertz (third edition), Space Technology Library.

CHAPTER 6

THE LAMBDASAT CASE

Chapter 6: The Lambdasat Case

Having performed simulation scenarios with picosatellites and microsatellites in chapter 5 we now move on to the real picosatellites that we designed and sent to orbit in order to receive pragmatic data and analyze their effectiveness on supporting a maritime security operation (compare with simulation results). The first satellite we built was the Lambda picosatellite.

The Lambda satellite team formed in Summer 2012 under the guidance and leadership of Professor Periklis Papadopoulos from San Jose State University in California and with his strong affiliation with NASA Ames Research Center initiated the work in order to design and built a picosatellite under the name of the Greek Letter Lambda (Λάμδα) which historically comes from the "Λ" of Lakedemons from Sparti and the L letter from the Greek word "Έλληνες" (Greeks).

Lambdasat concept

The concept of the mission was to evaluate the use of picosatellites in maritime security operations, supporting especially counter piracy actions (commercial and/or military) and generally provide deterrence to maritime terrorism in the global commons.

The aim of the picosatellite project was to:

1. Evaluate the use of nano and pico satellites (in this case via Lambdasat) to maritime security, supporting especially counter piracy operations and generally provide deterrence to maritime terrorism in the global commons.

2. Promote space innovation and boost space knowledge and new ideas to the Greek space technological arena. Carry out joint research towards the design and launch of "Lambdasat".

3. Exchange general scientific knowledge among partners.

4. Enhance fruitful cooperation among relevant students of the aforementioned University departments, under Professor's supervision and guidance.

5. Train postgraduate and doctoral students in procedures and techniques relevant to the use of microsatellites to maritime security environment.

6. Make publicly available that Maritime Security Operations can be supported from microsatellites with low cost applications and create a framework for

merchant mariners to have a near real time operational support during their transiting through high risk areas.

7. Promote interest in the teaching and research activities of the respective institutions.

8. Deepen the understanding at each institution of the economic, space engineering and cultural and social engineering ethics.

9. Promote faculty and institutional exchanges where feasible by inviting faculty and staff of the partner institutions to participate in a variety of teaching and/or research activities and professional development in space systems field area.

10. Exchange information pertaining to developments in teaching, student development and research at each institution, and publish the results.

11. Sustain the motto that "The real future is the ideas waiting to come true and enlighten the endeavors towards perfection"

The partners of the project (relevant to the scope of this dissertation) were coming from different organizations / Universities as follows:

a. San Jose State University (SJSU): Professor Periklis Papadopoulos – Principal Investigator

b. University of the Aegean (UOA): Professor Nikitas Nikitakos – Shipping - AIS - Counter Piracy

NASA Mission Justification

NASA has supported the whole mission from the beginning and with the sole support of Professor Periklis Papadopoulos (San Jose State University) the justification was to "support merchant shipping in countering maritime piracy in oceanic as well as in littoral sea environment. In parallel, provide merchant mariners with near real time cost effective information such as text, video, audio, images etc. in order to proactively counter the maritime piracy threat during transiting in high risk areas". Under this statement the whole mission started in summer 2012 and the satellite was set in orbit from the International Space Station by the end of February 2015. A mission statement was also produced in order for all to get acquainted with the expectations and this is herein referred as follows:

Piracy Background (Threat)

As it has been seen in the last years piracy is an ongoing phenomenon that has attended global attention. The United Nations Contact Group of Somalia (UNCGPCS), the NATO Operation Ocean Shield , the European Union mission EU NAVFOR Atalanta along with US, Chinese, Indian and Iranian maritime forces (via patrolling vessels in the area of Gulf of Aden) have special interest in contributing to the diminishing of the phenomenon by safeguarding with military vessels the high risk area. High risk areas is considered to be Indian Ocean, Gulf of Aden, Gulf of Oman, West Africa oceanic area and broad area of Gulf of Mexico and the Central America. It is worth noted that even if piracy is diminishing in the Indian Ocean it is being increasing in West Africa areas.

Current Situation (Weaknesses)

The status is now that if a piracy incident happen, the merchant mariners have only one way of communication with operational ashore headquarters, which is UKMTO or national authorities. This is conducted mainly via Inmarsat satellite service which is a very costly mean of communication (1 min of communication costs around 100 dollars or for downloading 1 MB of data it costs 80 €) or via VHF when near shoreline (up to 16 nm).

The most important aspect is though that pirates are travelling throughout a vast oceanic area which is in this case Indian Ocean, Gulf of Aden, Gulf of Oman and Bab El Mandeb straits and the Captain of the merchant vessel has not prominent or instant communication path in order to get informed on a regular basis (on a near real timeframe) for the new positions of incidents or pirates that are in the area.

Currently there is no satellite support to merchant mariners that will feed them with crucial tactical information such as recent piracy incidents or pirate action groups that are active in the area. So with Lambdasat satellite the Captain and the Team Leader (Guard) on board a merchant vessel will eventually know what is happening around his ship not in a range of 40 miles (range of conventional sensors like radars) but at longer distances and with a capability of knowing every 40 minutes what is happening in a circular range around the ship up to the capability of the footprint of the satellite (positive identification of up to 200 miles) and this will give the capability to be proactive and not psychologically stressed for what is going to happen in the next hours of sail. The only information that he has now is only through TELEX from UKMTO which is rare and every 24 hours.

In the last two years NATO is seeking cost effective solutions of dealing with the piracy problem in order to use as few ships as possibly, patrolling in the area of operations. There is a desire of moving into a cost effective network-centric operational scheme in order to utilize patrolling assets only when it is needed and not in a continuous basis. The continuous use of military vessels is costly for the nations as well as not very effective since it has to be at sea for long times waiting to respond to an incident. By giving the capability to the merchant mariners to have updates every 40 minutes they can act proactively and at the same time by using the satellite they can feed us back the real situational awareness data. Therefore military vessels could be stationed on a littoral position ready to deploy their assets, when needed, only patrolling outside pirate camp areas and creating a type of unofficial embargo for their actions.

Way Ahead (Opportunities - Strengths)

First and foremost it is important to note that we try to inform a merchant vessel mariner on board a vessel in the middle of the ocean on a near real time scheme (eventually every 40 minutes that the microsatellite Lambdasat will pass over the same area). This will give him the capability to have on hand information to recent piracy incidents at least every 40 minutes and at very low cost.

Additionally implementing a space AIS capability we deliver to the mariners another very helpful piece of critical information. The merchant mariners now have relevant AIS information which reaches distances of up to 20-30 nautical miles through an earth signal. By providing the capability of receiving space AIS info in the middle of ocean (in distances up to 200 nautical miles around them - potential footprint of the satellite) they have at least a primitive indication which are the non-suspect vessels during the next hours of transiting. AIS is a system that is required from IMO for all vessels above 300 tones. So if the merchant mariner has received AIS information for a vessel (that means it is more than 300 tones) he knows directly that the vessel is not a pirate skiff, dhow or generally a suspect boat. Therefore he does not have to wait to have this verification until he has a visual contact with the vessel (this is the case happening today).

NATO (North Atlantic Treaty Organization) has a special interest on counter piracy operations and it has been reported and noted in the last two years, that even though piracy is decreasing as a phenomenon in the Indian Ocean, it is being increased in other areas like West Africa with recent incidents up to 150 miles from ashore. The support and escorting operations is a status in the Gulf of Aden and Somali Basin area and especially through IRTC. Russia, China, India, US are providing this kind of escort throughout the Indian Ocean, if asked and at the same time they consume a lot of money. It will be much more cost effective if we have systems on board the merchant vessels that would receive information from a center ashore, which would feed them with near real time info in order for them to get prepared and more proactive. Of course this link could be used vice versa for situational awareness. Another aspect is that the merchant vessel has always live and fresh information for suspect vessels that now is being missed. Nobody has the capability of transferring back this information. With Lambdasat capability the merchant mariner will send this information every 40 minutes back to the Center from the middle of the Ocean (either data up to 300 kb, or voice or video or images etc.) The above system will also work in littoral transiting and passages and in territorial waters (less than 40 nm).

Last but not least the use of a micro camera on board a microsatellite would give the opportunity to the Center ashore (e.g. SJSU MOC)to distinguish among large cargo ships and small skiffs, dhows or other suspect vessels that are now invisible in the oceanic areas. With this capability the pirates would be very difficult to hide and at the same time the merchant mariners would have a firsthand response on pirate activities and a much more safe passage through the high risk areas.

Lambdasat Mission Milestones

Lambdasat was a mission where some very few (approximately 6) Greek scientists all over the world meet online and later on in NASA Ames research center facilities to materialize their dream stemming from the leadership of Professor Peri Papas in San Jose State University. The writer of this dissertation was one of them. The formed team created a methodology and later on the design objectives and in 18 months managed to send a microsatellite on the International Space Station ready to be launched.

The milestones of this specific mission included but not limited to:

1. First ever 100% Greek space mission (design, construction, end users with scientific and plain Greek commercial usage)

2. First ever Greek cooperation with International Space Station.

3. First ever Greek materialized cooperation with NASA.

4. First global research effort on how cosmic radiation influence grapheme material in space - a new innovative material for next generation computers (Leading by University of Columbia)

5. First space application for the Greek Shipping Industry (Leading by University of the Aegean – The author of this dissertation was Project Manager)

6. A low cost project driven effort but with high benefit with voluntary scientist participation

7. First international Greek scientist's synergy with tangible and project driven application.

8. Creation of a successful international cooperation model in Greece and abroad.

9. First ever mission to successfully pass all systems testing, verification and integration procedure in order to join International Space Station Launch manifest.

Overall Mission Objectives

During the two years design and construction phase the "L" team worked hard to make Lambda satellite active. Lambdasat was a satellite originally designed to provide space maritime security through the use of space AIS system, as well as the exchange of piracy alert messages within the available footprint of the satellite.

University of the Aegean was the designer of space maritime security risk assessment methods and analysis through the satellite. Specifically the strategic and operational objectives of the satellite with respect to maritime security were as follows:

Strategic Objectives

- Evaluate the use of nano and pico satellites to maritime security
- Provide deterrence to maritime terrorism in the global commons
- Provide Merchant Mariners with low cost near real time operational support during their transiting through high risk areas.

Operational Objectives

- Experiment AIS implementation to maritime security operations
- Support counter piracy – armed robbery operations through various methods of communication to merchant mariners (text, audio, video etc.)
- Create Merchant Marine Risk Assessment Indexes - Methodologies to effectively counter piracy – armed robbery through space micro assets (such as Lambdasat)
- Operational support to armed guards on board the merchant vessel on a near real time frame
- Conduct measure of effectiveness and performance studies and determine way ahead.
- Conduct feasibility study and implement a cost benefit analysis for inserting picosatellites in the maritime security arena
- Utilize a ground station in Greece (University of the Aegean)
- Conduct Studies for MOEs/MOPs/CBA and Risk Assessment
- Exchange data from the satellite ground stations to a Merchant vessel transiting through the High Risk Area
- Measure the operational effectiveness to support counter piracy – armed robbery in the high risk areas (post orbit)
- Measure Risk Assessment factors change with the use of picosats for Merchant Mariners transiting high risk areas (post orbit)
- Give the capability to the Merchant Mariners to receive update piracy or maritime terrorism information that now is limited only to very little info (continuous IMO request).
- Relay of piracy incidents report to merchant mariners in a near real timeframe (every 40 minutes). Today is rare, random and in the best case via TELEX every 24 hours.
- AIS implementation will increase vigilance and alertness in distances up to Lambdasat footprint (tentatively 200 miles)

- Information to Maritime Operations Center from all MVs in the area and give the capability to the MOC to collect critical info that today is being done only via Inmarsat phone by voice or by text emails.
- Diminish the cost of the communication to the necessary and not charge huge amounts of money only for 1 MB of data for merchant marines communication (Inmarsat case).
- Give NATO (and nations) the capability to decrease military vessels in the area by not patrolling continuously on the high seas, but stationed in a dynamic waiting area where assets will be ready to assist upon request from MVs.

Pico-satellite Operational Characteristics

In the following paragraph a short list of operational characteristics of picosatellites are being reported in order a more digestive and detailed comprehension of the system to be fed to the reader. All these characteristics may seem highly tactical or operational but if one analyzes the effects that are going to affect the execution of operations then the results can be consider strategic. Later in this article we will refer more to the strategic implications of such a small very low cost system to the global maritime community. Therefore some of the most important characteristics [3] are:

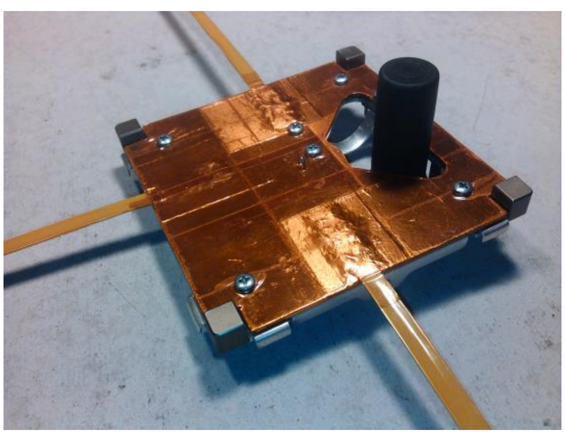
- Provision of fine resolution images from the area of operations.
- Real time transfer of information to merchant mariners for the existence of suspect peripheral traffic.
- Real or Near Real time Tracking Capability depending on the selection of orbital parameters and the area of operation.
- Audio - Voice and video communication to a fusion center ashore for the specified window that a satellite is passing on top of the area (on the move networking capability).
- Feasibility of a two way communication implementing reachback [1] techniques.
- Cover a vast geographical sea area and provide partial or total situational awareness based on the number of satellites to be used.

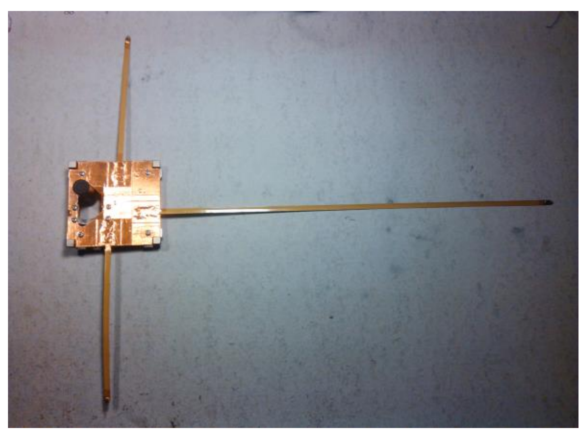
• Lifetime consideration: 1 to 3 months depending on solar weather. If increased to more than a year then this system will definitely have a strategic effect on the execution of missions.

To sum up though the operational part one has to have in his mind the following attributes of the pico-satellite system. The approximate total time that we have during a whole day to communicate through a system that has four satellites (the cost will be around 50000 € approximately) is 120 minutes [3] (2 hours during the day). Therefore the total gap time between satellite passes during one day is approximately 22 hours[3]. However with this amount of timeframe we have the capability to exchange the needed information with a merchant vessel underway and feed the important information required for a safe and secure transit from a high risk area. Modern maritime threats, as they appear on the international scene today, do not require 24/7 hours of communication with fusion centers ashore but only a logical timeframe sufficient to transfer critical information back and forth and secure future courses of action.

Lambdasat Design

The project design was based initially under the general design concept characteristics of TechEdsat (Technology Education Satellite). Total design, construction and launch into space was scheduled to not exceed 18 months. This task was completed successfully by the whole team members.





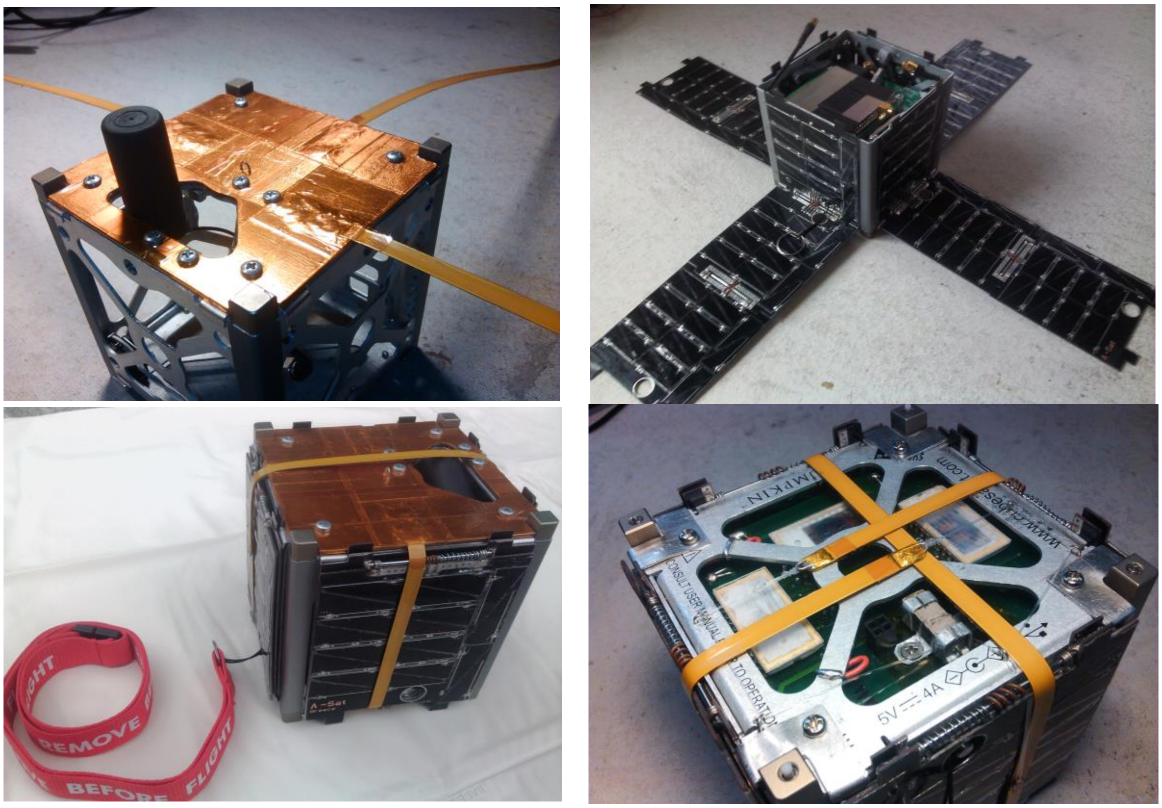


Figure 18: Lambda microsatellite during construction and pre-launch phases.

Lambdasat Operational Characteristics

Lambdasat (Λ-sat) was a Greek small satellite with 1U dimensions (i.e., 10x10x10cm). It was built by Lambda Team, an international group of Greek scientists and students based in Silicon Valley (San Jose), CA, USA [15]. It has deployable solar arrays, which unfold to a 3U envelope for increased power. The space flight will demonstrate the following Scientific, Commercial, Technology and Educational mission objectives [15]:

(Scientific) First of-its kind space qualification of the nanotechnology material "Graphene" and its direct exposure to solar radiation and extreme space environments.

(Commercial) Flight demonstration of a communications platform that monitors, with real-time positioning, Hellenic merchant ships for maritime security. It aims to mitigate risk to Hellenic ships and their crews from piracies at sea.

(Technology) Space qualification of innovative advanced three-fault tolerant spacecraft hardware

(Educational) Address Science Technology Engineering and Math (STEM) educational objectives

The Λ-sat was launched on board of Cygnus CRS-2 to the International Space Station to be deployed from the Japanese airlock and was deployed on 4 March 2015.

Figure 19: Lambdasat picosatellite before launch (Courtesy Lambda Team)

Λ-sat carries several technologies to assist a variety of experiments, including:

- Equipment to measure the radiation effects on Graphene material in real environment in Low Earth Orbit (LEO).
- Experimental AIS (Automatic Identification System) receiver for tracking all the vessels inside its footprint around the globe.
- For communications, it has an Iridium Short Burst Data (SBD) modem that makes use of the Iridium constellation.
- In addition, it has one UHF transmitter and one UHF receiver that will supplement the satellite communications uplinks and downlinks.
- The above mentioned electronics are integrated and operated by one power system and a main computer that have been designed and built for Λ-sat.

The University of the Aegean (UoA) was the designer for space maritime security risk assessment methods and analysis through the Λ-sat [15] as well as for the whole ground station hardware, software and operation regarding maritime security.

Λ-sat was capable to assist maritime security operations through the use of space AIS system as well as the exchange of messages within the available footprint of the satellite. As part of our work, we will use to Λ-sat for the transmission and dissemination of information globally between fusion centres ashore (monitoring piracy activity and assessing risks) and ships.

Orbital and communication characteristics of Lambdasat are as follows:

- Weight: 1 kgr
- Orbital characteristics of ISS
- Perigee 420 km (260 mi)
- Apogee 426 km (265 mi)
- Orbital inclination 51.65 degrees
- Average speed 7.66 km/sec (27,600 km/h; 17,100 mph)
- Orbital period 92.89 minutes
- Orbital decay 2 km/month
- Lifetime: 9-12 months
- Period: ~ 1.5 hours
- Passes per day: 3-5 times from same point / day
- Time per pass: 1-8 minutes depending on inclination
- Footprint : ~ 800 - 1000 km
- Downlink Frequency: 437.462 MHz 1200 bps AFSK (UHF)
- Uplink Frequency: 434 MHz 9600 bps GFSK (UHF)
- AIS Receiver: 161.975 MHz VHF
- Transmission Power : 1W

Lambdasat was a microsatellite incorporating specific transmitter technical characteristics. It was a "Stensat" radio beacon, a small FM transmitter capable of generating AX.25 Unnumbered Information (UI) packets at 1200 bps AFSK and 9600 bps FSK. The 9600 bps FSK signal is compatible with G3RUH modulation. Power level is adjustable from 0 to 1 watt operating on a single 5 volt supply. Other specifications included but not limited to the following:

- Bands available: 2m, 70cm
- RF Output Power: 0 to 1 Watt programmable
- Operating voltage (Vdd): 5.0 volts
- Operating Current: 650 mA when transmitting, 40 ma when idle
- Serial Interface rate: 38.4Kbaud UART 8 bit, no parity, one stop bit
- Dimensions: 1.75 x 3.10" x 1.00" / 44.45mm x 78.74mm

- Mass approx.: 50g
- Digital Input signal specifications: High signal > 0.7*Vdd
- Low signal < 0.3*Vdd, 10 uA
- Digital Output signal specifications: High signal > 2.0 volts
- Low signal < 0.4 volts, 3 ma sink
- Mounting Holes: 0.125 inches, 4-40 mounting hardware
- Frequency Ranges: SRB-51-01 at 420-450 MHz and SRB-51-02 at 144-148 MHz

Lambdasat Link Budget - Communication

In order to set up the Ground Station as well as to communicate with the satellite effectively we analyzed and computed the Link budget of it for the communication scheme. The central frequency that we are using is as indicated and above 437,462 Mhz. Based on this frequency and taking into account orbital characteristics of the satellite as well as losses through the medium and other parameters we have calculated the Link Budget of Lambda satellite in order to figure out how many decibels is the ratio of Energy per bit rate to the Noise Figure. On the satellite a monopole antenna has been mounted that has length from 15 to 20 cm since there are three different very simple monopole antennas on two of the three dimensional axis of the satellite in the planes X and Y. These antennas serve the purpose of communication with the Ground Station in the University of the Aegean.

As it is generally known Link Budget is a calculation that computes Received Power taking into account Transmitter power minus Losses and plus all Gains. This equation is as follows:

Received Power (dBw) = Transmission Power (dBw) + Gains (dB) - Losses (dB)

Based on the above equation we created an excel spreadsheet that accumulates all the above factors containing each detail that is critical for our communication path. The calculation will yield in how much quantity of signal is going to be received on our ground station so as to finally decode the signal of the Lambda satellite and receive AIS message as well as the piracy message.

As it has been noted in references 19 and 20 through the analysis of factors for Link Budget we have calculated using excel spreadsheet the absolute energy per bit rate per noise for the Lambda satellite. We have used as transmitting power the maximum available requirement from the satellite power bus and for satellite antenna beam width we have used 360 degrees since the antenna is monopole. The gain of the antenna is around 6 dB whereas the diameter is only 1 cm (indicative figure). On the other side for transmitting antenna pointing losses from 0.5 degrees up to 180 degrees the communication margin changes only 5 dB approximately which is acceptable. For the slant range of the satellite we have figured out that this is from 1200 km to 600 km approximately and for that reason we have played two different scenarios with minimum and maximum slant range when the elevation of the satellite is more than 5 degrees which practically gives us the capability to start communicating from the ground station in the University of the Aegean. In the first maximum case we have margin of E_b over N_o 26 dB (100 times the signal stronger from the noise) whereas in the second minimum distance of slant range we have E_b / N_o 32 dB which practically means that the signal is 1000 times stronger from the noise. In both cases though we know that our figures are acceptable for the communication of the Lambdasat with the Ground Station. Following our analysis and as known in the equations of Link Budget stemming from references 19 and 20 we have accumulated space losses as well as transmission line losses and System Noise Temperature. All these losses are being subtracted from the final collected Energy Level in order to gives us the communication margin for the satellite. Ground station as it will be analyzed below comprises of Yagi UHF antennas of 42 elements with Gain that reaches 18 db. Pointing losses of the antenna are less than 3 degrees since there is automatic control and tracking of the antenna that follows through automatic software the change in azimuth and elevation of the satellite. Finally and for data rate of 1200 bps which is the Data Rate that our satellite is using in AFSK mode we calculate using the excel spreadsheets available that have been produced for this reason and it is shown in figure. The final Margin for communication with the satellite taking into account real time orbital characteristics as well as worse and best case scenarios are being calculated to be in range of 26 up to 32 dbW with only 1 W of available power.

Lambdasat Link Budget Calculation

#	Item	Symbol	Units	Source	Cmmd	Equation		
4	Frequency	f	Ghz	Input	0,4			
5	Transmitter Power	Pt	Watts	Input	1,0			
6	Transmitter Power	Pt	dBW	10*log(Pt)	0,0			
7	Transmitter Line Loss	Ll	dB	Input	-1,0			
8	Transmit Antenna Beamwidth	θbt	deg	Input	360,0			
9	PeakTransmit Antenna Gain	Gpt	dB	Eq. (13-20)	-6,8	G=44.3-10*log(θx*θy)		
10	Transmit Antenna Diameter	Dt	m	Eq. (13-19)	0,1	D=21/(θ*f*)		
11	Transmit Antenna Pointing Error	θet	deg	Input	0,2			
12	Transmit Antenna Pointing Loss	Lpt	dB	Eq. (13-21)	0,0	L=-12(θe/θb)^2		
13	Transmit Antenna Gain	Gt	dB	Gpt+Lpt	-6,8			
14	Equiv. Isotropic Radiated Power	EIRP	dBW	Pt+Ll+Gt	-7,8			
15	Slant Range	S	km	Input	600,0			
16	Space Loss	Ls	dB	Eq. (13-23b)	-140,8	Ls=147.55-20log(S~m)-20log(f~Hz)		
17	Propagation & Polarization Loss	La	dB	Fig. 13-10	-0,3			
18	Receiver Antenna Diameter	Dr	m	Input	0,07			
19	Peak Receiver Antenna Gain	Gpr	dB	Eq. (13-18b)	18,90	Gpr=n*(pi*Dr*f/c)^2	(where n=0.55 &	
20	Receiver Antenna Beamwidth	θbr	deg	Eq. (13-19)	685,8	θ=21/D/f	c=speed of light)	
21	Receiver Antenna Pointing Error	θer	deg	Input	10,0			
22	Receiver Antenna Pointing Loss	Lpr	dB	Eq. (13-21)	0,0	L=-12(θe/θb)^2		
23	Receiver Antenna Gain	Gr	dB	Gpr+Lpr	18,9			
24	System Noise Temperature	Ts	K	Table 13-10	220,0			
25	Data Rate	R	bps	Input	1200,0			
26	Eb/No (1)	Eb/No	dB	Eq. (13-13)	44,3	Eb/No=Pt*Ll*Gt*Ls*La*Gr/(k*Ts*R)		
27	Carrier-to-Noise Density Ratio	C/No	dB-Hz	Eq. (13-15a)	75,1	C/No=Eb/No+ 10*logR		
28	Bit Error Rate	BER	--------	Input	1,0E-07	Alternate Approach		
29	Required Eb/No (2)	Req Eb/No	dB	Fig. 13-9	11,3	C~dB	-130,1	Pt*Ll*Gt*Ls*La*Gr
30	Implementation Loss (3)	-------	dB	Estimate	-1,0	No~dB	-205,2	k*Ts
31	Margin	-------	dB	(1)-(2)+(3)	32,0	C/No~dB	75,1	C/No
32	Power Flux Density	PFD	dB	EIRP/(4πS^2)	-134,4	Eb/No~dB	44,3	C/No-10*logR
33	PFD/4kHz band	PFD/4kHz	dB	PFD/4000	-170,4			
34	Transmitter Efficiency	ηdc	%	Input	20,0			
35	Required d-c Power	Pdct	Watts	Pt/(ηdc/100)	5	Note: C=10^(-135.3/10)=~0.03 picowatts		

COMMS LINK BUDGET

Table 27: Lambda satellite Link budget calculations

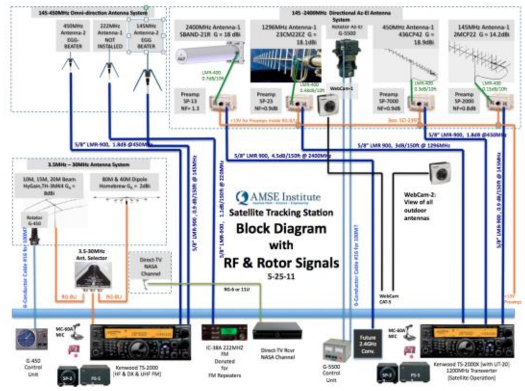
Constants:			
Speed of Light in Free Space		299.79	$x10^6$ m/s
Earth's Equatorial Radius		6378.15	Km
Standard Temperature		300.00	K
G/S Antenna Temperature		100.00	K
Boltzmann's Constant	1.38E-23	-198.60	dB(mW/K*s)

Table 28: Lambdasat Link budget constants

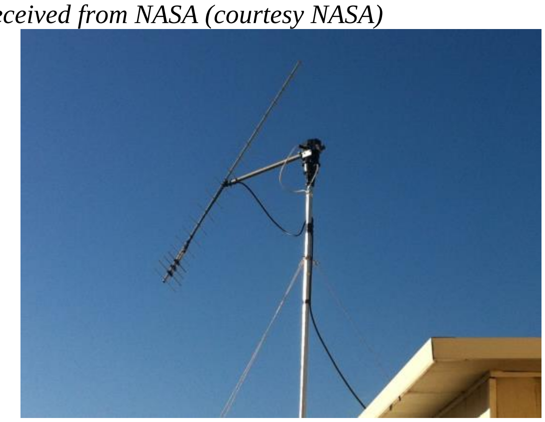
On the above table 28 we summarize all available constants that were being used in Link Budget calculations.

Ground Station Design

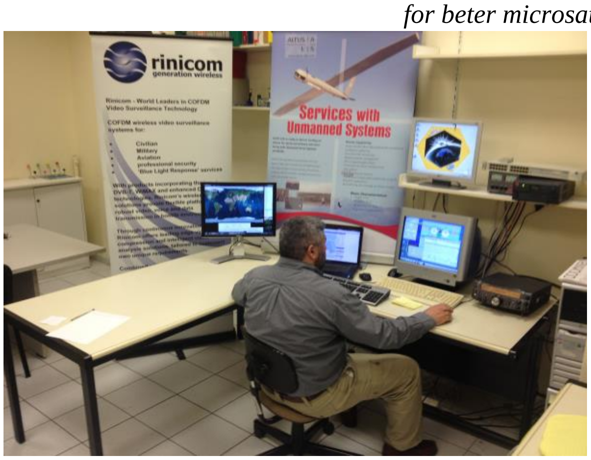
For our experiments two ground stations were designed and created based on NASA specifications for cubesats. In the below figures one can see schematics used as well as our ground station representative images on the University of the Aegean and the Ground station in the Hellenic Naval Academy site.



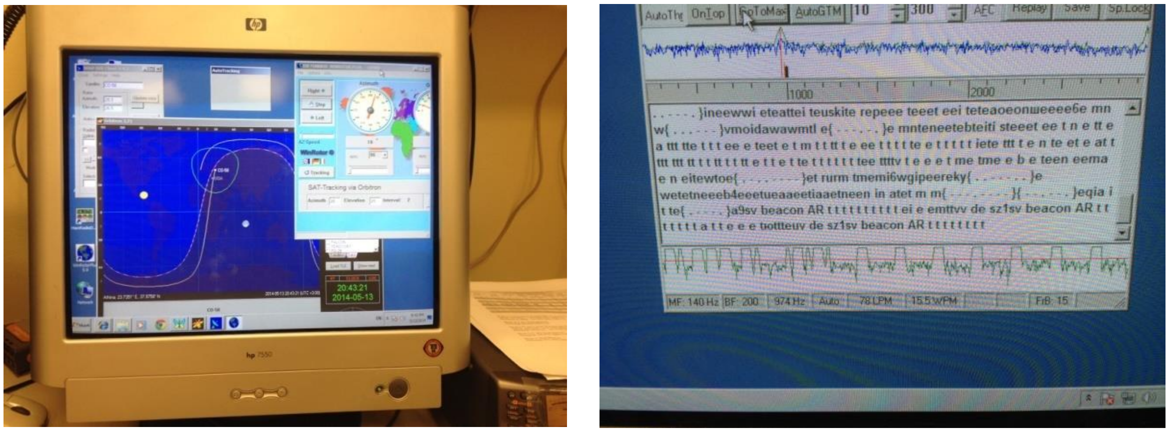
Ground Station design schematics as received from NASA (courtesy NASA)



Old (right) and new (left) ground station antenna allocation. Newer antennas have extended receive profit for beter microsatellite reception



Ground Station set up in the University of the Aegean.



Automatic antenna tracking software, orbital tracking software, transceiver decoding and tranceiver driven software during operation (left) and decoding (right)

Figure 20: Ground Station – University of the Aegean site

Mr John Traikos (president of Greek Radio Amateur society) and Mr Manolis Darkadakis (former president) put a tremendous effort along with writer to materialize the setup of University of the Aegean ground station before Lambdasat launch. Companies, UK Rinicom represented by Mr Marco Manso and Altus Ltd represented by Mr. Zacharias Sarris played a vital role in supporting the full and fast acquisition of the equipment. Based on the above efforts and support the ground station was up and running in two months period of time during the summer of 2014.

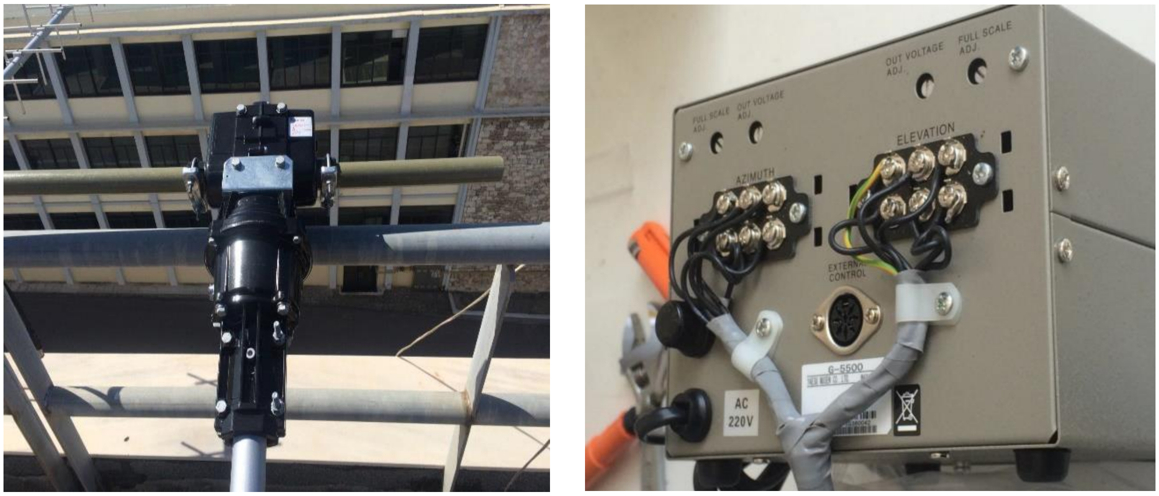


Figure 20: Ground Station – Hellenic Naval Academy site

During the research another ground station was also built in Hellenic Naval Academy on one hand as a redundancy for the ground station connectivity to the satellite and associated support to the mission, but most importantly as a second ground station site to communicate and exchange messages through the picosatellite during the same or consecutive passages of the satellite on top of Athens. This connectivity though was not effective through Lambdasat mission lifetime, but it has been designed to be used as part of the mesh network with the use of the UOA/MythPelSat picosatellite on February of 2017. Responsible Professor on Hellenic Naval Academy site is Professor Ioannis Koukos, Dean of the Academy and former NASA JPL scientist and researcher for years.

Our ground stations have been designed / implemented using the equipment listed in Table 3. The total cost of the Ground station reached almost 5K € including set up and computers.

No	**Equipment**	**Cost (€)**
1.	Kenwood TS-2000 - HF/VHF/UHF All Mode Transceiver	1835
2.	Power Supply	169
3.	Cross Yagi multiple (42 elements) antenna UHF 70cm (430 - 440MHz)	300
4.	Phasing Harness – cross polarization	180
5.	30 meters ECOFLEX 15 low loss coaxial cable	100
6.	N type connectors	50
7.	YAESU G5500 rotor with Az – El	800
8.	Wire for Rotor cabling	30
9.	Support mast for the antenna	100
10.	Tracking satellite software	50
11.	Rotor Software Interface	150

Table 29: Analysis of equipment used for the design and implementation of the Ground Station.

Analysis of the reception signals from microsatellites during the experiments is being reported in the following paragraphs. Also L-sat decoder sequence where the counter piracy message is being shown with respect to the satellite's on board computer cycle transmission is being reported to appendix 6 (The decoding procedure was created from Mr Vaggelis Christodoulou, engineer of the Lambdasat team. Counter piracy message coding and operational mission concept was created for the purpose of the experiments from the writer).

Experiments

This work explores the application of Pico-Satellites to assist security maritime operations, including surveillance, anti-piracy and search and rescue operations. We planned and conducted a set of experiments that resorted to a Pico-satellite to transmit and disseminate information globally between land fusion centers and ships.

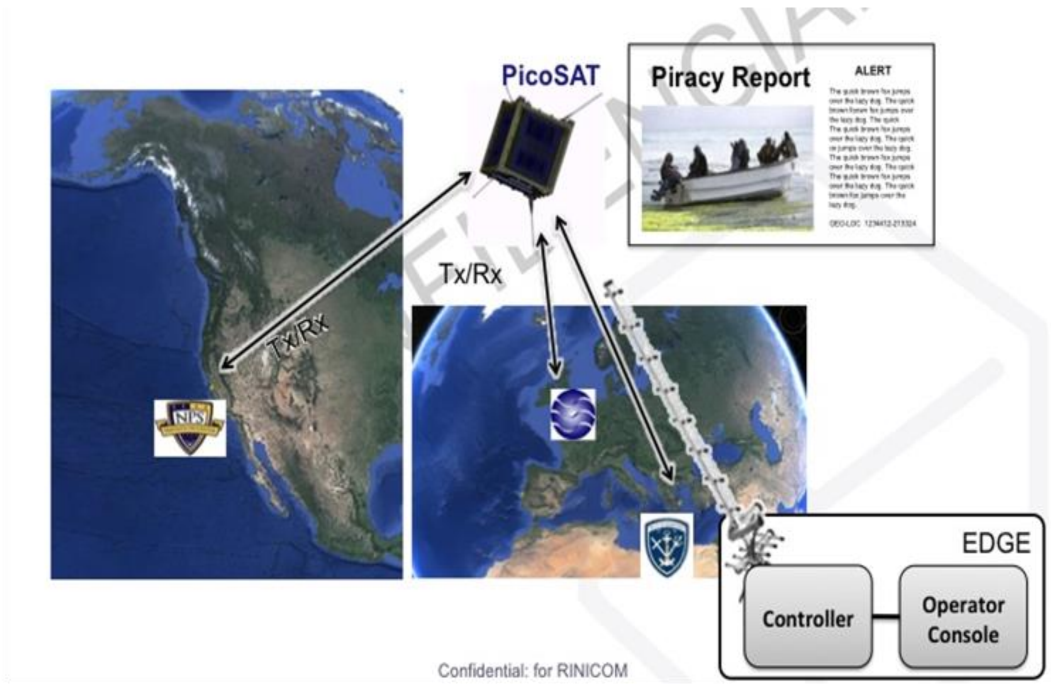


Figure 21: UK Rinicom's representation of the Tactical use of Picosatellites to mission oriented experiments that partially took place

The experiments encompassed sending messages (preformatted, free text and pictures) pertaining to e.g., suspicious activities, piracy alerts and help requests to Ships in the Mediterranean Sea. Conversely, ships will send messages (e.g., help request, message acknowledgement) to the satellites and consequently to ground stations. Establishing short voice calls will also be tried. Below one can see the basic alert message format created in order to be send from the University of the Aegean ground station to the satellite and then to a ship in the middle of the ocean.

The set of experiments was resorting to capabilities provided by the Λ-sat to demonstrate the picosatellites capabilities to support maritime security operations. More specifically, we will cover the following operational capabilities (see full list in Section 2):

- Monitor maritime traffic using on-board AIS.
- Real time transfer of information to merchant mariners for the existence of suspect peripheral traffic.
- Voice (audio) and video communication to a fusion centre ashore for the specified window that a satellite is passing on top of the area (on-the-move networking capability).
- Feasibility of a two way communication implementing reach back techniques.
- Cover a vast geographical sea area and provide partial situational awareness.
- Lifetime consideration: three to four months.

Some example scenarios have been elaborated in order to support our research.

Example 1: Merchant vessel planning transit over the Gulf of Aden

Consider a merchant marine company that needs fast, reliable and cost effective intelligence data in order to safely plan transit over the Gulf of Aden, an area where piracy is the main problem. Prior to its transit, the merchant company planner obtains direct live real-time observation data from the picosatellite pertaining to the area of interest. Furthermore, via the picosatellite, the company receives messages (e.g., piracy alerts) relayed from a remote fusion center (ashore). The planner identifies areas of greater risk and plans the safer routes to take (and when).

Example 2: Merchant marine vessel transiting over the Gulf of Aden

A vessel is transiting over the Gulf of Aden, an area where piracy attacks have been reported. Via the picosatellite, the vessel commander receives a piracy alert, with indication of the likely location of pirates. The commander requests and receives observation data from the picosatellite pertaining the area of interest, identifies suspicious activity and opts for a safer route.

Example 3: Combating human trafficking

Human trafficking occurs frequently in the Mediterranean Sea, where small vessels illegally transport people into Europe. Using the observation capabilities of the Picosat, remote command and control centers monitor the Mediterranean Sea detecting suspicious activity and deploying, where needed, naval means to assist victims and arrest criminals.

Communication Scheme

UOA in conjunction with other partners will provide a real scenario, which is going to be executed during the flight mission. The scenario is going to be built initially on a conceptual basis, SJSU will verify its compatibility with the satellite's characteristics and then the whole scenario is going to be tested via the STK software. The areas to incorporate as experiments to be tested during flight time are as follows:

i. Data will be send from SJSU to Lambdasat and then to a Merchant Vessel. This data should be received via a cell phone on board the merchant vessel (open sea / coastline / port areas).

ii. Send and Receive data from mobile ground station to the merchant vessel, acting as ashore advisory team to the ship (command and control mobile center).

iii. Measure the overall effectiveness of network, communication, latency times among end users, weather data influence and other important factors. All these areas are going to be specified in upcoming meetings to finalize the exact priorities.

iv. Include voice in transmission if possible. (These two factors are extremely helpful and supportive to maritime security issues).

v. If a camera is going to be incorporated then a transfer of a satellite image to the ground station or to the vessel should be of great importance for maritime safety purposes. Analyze the operational use of images received from very LEO satellites. (There is no camera on board the Lambdasat but this feature is going to be implemented in the next picosatellite mission).

vi. UOA ground station team will transmit a text type document of maritime security critical factors to a merchant vessel underway. These critical factors are going to be the major factors that influence the survivability of the ship when transiting through the high risk area. The document has been prepared from UOA and in accordance with the comms specifications given from the SJSU (Appendix 4).

vii. During the analysis and research the following research areas would also considered:

(a) Specifications of the communication equipment on board Merchant Vessel (UOA). This can happen only after receiving the exact communication scheme for the satellite from the SJSU.

(b) Ways (if needed) on how this communication / software can be modified (if needed) in order to transmit the available data to the merchant vessel or to the other ground stations in Greece (SJSU).

(c) Available throughput / Bandwidth of the Lambdasat (SJSU).

(d) Ground station in Greece should be mobile (small antenna and a computer based system).

(e) Incorporate an AIS (Automatic Identification System) approach to the satellite bus. An AIS sensor can be installed in the satellite to receive AIS signals from the ships. All ships with greater tonnage than 300 tones have to have installed on board an AIS transmitter to transmit their positions to an ashore station (IMO regulation). ORBCOMM in US has launched the first satellite with implementation of a satellite AIS sensor on board its satellite bus. Further research is needed if this is an option. UOA is going to implement this type of search and provide more info to the principal investigator, if asked.

(f) Send a message from UOA ground station to a merchant vessel bridge via Iridium communication and the Lambdasat to a mobile telephone (iPhone, blackberry type). The message will be a text with tables, word document and some images.

(g) Ability to communicate back and forth with Lambdasat during one pass timeframe (approximately 8 minutes of satellite available time in each pass).

(h) Available test schemes

(1) Basic: Text

Simple data containing information for piracy activity up to 300 Kbyte. (e.g. Lat, Lon, time, color and name of pirate vessel etc.)

(2) Intermediate: Audio

Capability to talk to ashore stations and convey by voice high risk area picture and situational awareness. Give the capability to the field officers (Team Leaders - Guards on board vessels or Captains to communicate with operational headquarters at no extra or very low cost).

(3) Advanced: AIS

Receive and relay AIS signals from and to other vessels (up to 200 miles).

The experiments involve the following main elements:

- **Lambdasat** described above.
- **Greek Ground Station** at UoA that will be used to exchange (upload and download) maritime security related messages with the Lambdasat (e.g., piracy alerts to be disseminated to vessels).
- **San Jose State University (SJSU) Ground Station** that will be used to exchange information between the Lambdasat and the Iridium satellites.
- **Merchant Vessels** operating at the Mediterranean Sea that will be able to receive messages from Lambdasat (e.g., piracy alerts) and send alerts (e.g., help request) to the Lambdasat (that will be relayed to the Greek and SJSU ground stations).
- **Iridium satellites** that will be used to relay messages from/to Lambdasat when necessary.

The information flows between the above main elements are depicted in the following schematic diagram:

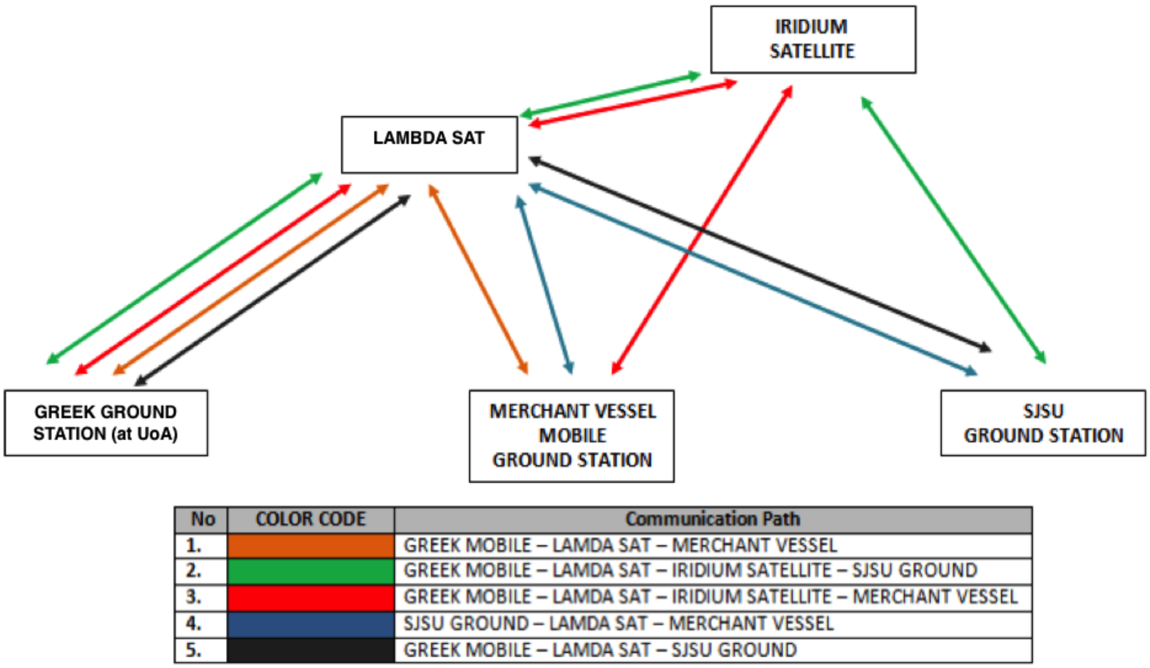


Figure 12: Lambdasat Communications Flow

Both the Greek and SJSU ground stations can upload messages to and receive messages from Λ-sat. Piracy status and alert messages will be uploaded to the Λ-sat and the Λ-sat will disseminate the messages to any receiver below (on land or on sea).

The SJSU ground station has the additional capability to communicate with Iridium satellites, thus being able to receive (and send) messages relayed by the Λ-sat Iridium modem.

Send messages to and receive messages from Λ-sat Iridium modem.

Merchant vessels, equipped with a mobile ground station, will be able to receive messages from (e.g., piracy alerts) and send messages to Λ-sat (e.g., help request) to Λ-sat.

The above setting demonstrates the picosatellite capability to interconnect distant actors - located in Greece, US and vessels over the Mediterranean Sea - and generate situational awareness (piracy risk assessment) among them.

The messages to be exchange through Λ-sat are specified next.

FIELD	CODING	No of digits	COMMENT
Year	xxxx	4	2014 (example)
Month	xx	2	04(example)
Day	xx	2	04(example)

Hour	xx	2	12(example)
Minute	xx	2	22(example)
Latitude	xxxxxx	6	02 22 47(example)
North or South	x	1	1= North 2= South
Longitude	xxxxxxx	7	003 12 27(example)
West or East	x	1	1=West 2= East
Piracy Event	x	1	1= Approach
			2= Hijack
			3= Attack
			4=Suspicious Activity
			5=Armed Robbery
			6=Miscellaneous
Source	x	1	1=IMO
			2=NSC
			3=IMB
			4=RECAAP
			5=EUNAVFOR
			6=ICC
			7=UKMTO
			8=MARITIMERISK.GR
			9=OTHER
Risk Level	x	1	0=Avoid Route
			1= Extremely High
			2= High
			3=Medium
			4=Low
			5=Very Low
			6=Clear - No Risk
			7= Risk from other terror events
			8=Illicit trafficking
			9=Narcoterrorism
Text	xxxxxx…..xxxxx	60	
	Total Sum of Digits	**90**	
3 Message Code Cycle			
Message 1	* **text**		
30 bytes	64 bytes		Time: 0 sec
Message 1	* **Message 2**	* **text**	
30 bytes	30 bytes	33 bytes	Time: + 3 sec from Message 1
Message 1	* **Message 2**	*	**Message 3 * text**
30 bytes	30 bytes	30 bytes	3 bytes Time: + 3 sec from Message 2
Comment: Every time we transform only the ability of writing bytes to the text			

Table 30: Lambdasat Decoding Piracy message.

To conduct these experiments we built a ground station in the University of Aegean, Athens, capable to receive messages from the Pico-Satellites. To upload messages, we send them directly through the Lambdasat using a UHF antenna and then this is being retransmitted on earth on an Omni directional basis and to the satellite footprint available. These data from satellite will then be received from the Ground station for analysis simulating a merchant vessel in the middle of an oceanic area.

Message Specifications

For our experiments, we defined also along with UK Rinicom's Director of Innovation and in accordance with their comms requirements for a picosatellite scenario, a similar message format to be uploaded to Λ-sat that was much more effective and an improved version of the first format.

The messages are relevant for purposes of maritime security (e.g., suspicious activities, piracy alerts and help requests). The messages contain pre-defined fields and optional additional information in free text or multimedia form (e.g., pictures and audio).

Λ-sat gives us a slot of 94 Bytes (per message code cycle) that we can use to upload messages. As such, we defined the following structure for each message:

A **message header part** that contains information identifying its source, type of message, risk level and location information. It also contains information about additional information content (size and type) (if any). This part has a fixed size of 16 Bytes.

A **message content part** that contains additional content (if any). This part has a variable size up to 78 Bytes.

The message structure is illustrated in**Error! Reference source not found.**.

Message Header 16 Bytes	**Message Content Up to 78 Bytes**

Table 31: Lambdasat message structure

We form the message header as follows:

- First 77 BITS correspond to source and type info,
- Subsequent 16 BITS correspond to content information,

- Subsequent 14 BITS are spare bits,
- Final 21 BITS are used for error correction (using the Bose-Chaudhuri-Hocquenghem (BCH) error-correcting code [16]).

The message header is presented in the following table**Error! Reference source not found.**.

FIELD	CODING	Nbr. Bits	COMMENT
Index	2 digits	6	00 .. 63
Type	2 digits	3	0 = none (no content)
			1 = Text
			2 = Picture (JPEG)
			3 = Audio (*)
			4 = Video
Size	2 digits	7	00 .. 78 (Bytes)
SIZE (BITS)		16	

Bits	1 .. 77	78 .. 93	94 .. 107	108 .. 128
	Source and Type Info 77 BITS	Content Information 16 BITS	Spare 14 BITS	BCH 21 BITS

Table 32: Lambdasat message header

Message Header: Source and Information Type (77 BITS)

This part of the message contains the following information:

- **Source:** that identifies the source of the message
- **Event type:** that identifies the type of the event refers to (e.g., piracy)
- **Risk level:** that identifies the risk level (none too high to confirm)
- **Date and Time:** that identifies the date and time (GMT+0) when the message was created.
- **Location:** that identifies the location of the event in lat-lon coordinates.

This message detailed specification is presented in the following table 33.

	FIELD	CODING	Nbr. Bits	COMMENT
	Source	1 digit	4	0 = not specified
				1 = IMO
				2 = NSC
				3 = IMB
				4 = RECAAP
				5 = EUNAVFOR
				6 = ICC
				7 = UKMTO
				8 = MARITIMERISK.GR
	Event Type	1 digit	3	0 = not specified
				1 = Suspicious activity
				2 = Piracy
				3 = Hijack
				4 = Armed Robbery
				5 = Search and Rescue
				6 = Illicit activity
				7 = Human traffic
	Risk Level	1 digit	3	0 = Avoid Route
				1 = Confirmed
				2 = High
				3 = Medium
				4 = Low
				5 = Clear (No Risk)
Date and Time	**Year**	2 digits	6	00 = 2000 ... 63=2063
	Month	2 digits	4	01=Jan..12=Dec
	Day of Month	2 digits	5	01 .. 31
	Hour	2 digits	5	00 .. 23
	Minute	2 digits	6	00 .. 59
Latitude	**Degrees**	2 digits	7	00 .. 90
	Minutes	2 digits	6	00 .. 59
	Seconds	2 digits	6	00 .. 59
	North or South	1 digit	1	0= North, 1=South
Longitude	**Degrees**	2 digits	8	00 .. 189
	Minutes	2 digits	6	00 .. 59
	Seconds	2 digits	6	00 .. 59
	West or East	1 digit	1	0=West, 1=East
	SIZE (BITS)		**77**	

Table 33: Message Header- Source and Information Type

Message Header: Content Information (16 BITS)

This part of the message contains information about the message additional content:

- **Index:** in case the additional content of the message is split over multiple messages (for example, due to its large size), it identifies the sequence number of the content part.
- **Type:** identifies the type of content (e.g., text, picture, audio or video).
- **Size:** identifies the size (in bytes) of the content.

As an example, considering the 94 Bytes message code cycle granted by Λ-sat, we can produce the following sequence of messages:

Messages Cycle (1 cycle = 94 Bytes)		
Message 1 (16 Bytes)	Message 2 (32 Bytes)	Message 3 (62 Bytes)

(*) Opus codec: open-source free low bitrate speech and audio codec - RFC6716 [17]

Table 34: Message Header - Content Information

- A first message of 16 Bytes (no content)
- A second message of 32 Bytes (16 Bytes for header + 16 Bytes of additional content)
- A third message of 62 Bytes (16 Bytes for header + 46 Bytes of additional content)
- We will use these resources to send messages to merchant vessels in the middle of the ocean serving the purpose of supporting mariners with near real time counter piracy data.

Analysis of Acquired Orbital Data

Our experiments were conducted in the mid of 2015 starting after the launch of Lambdasat on 4th of March and up to the end of August of the same year. We collected a series of data from different small satellites telemetry, such as FO-29 (Japanese microsat), the Funcube (AO-73), LO-75, Micromas (MIT microsatellite), Flock 1B and others. Our first audio data (very weak signal reception) from Lambdasat was reality and also iridium constellation proved that our satellite is active and running (figure 24). Taking into account though that our satellite stayed inside the International Space Station (ISS) for more than 9 months, due to ISS Cubesat deployer problems, the battery was drained out and the signal was weak. Even though the signal was easily detectable through audio (Morse code - AFSK modulation) it was very difficult to be received and decoded with amateur radio ground station capability as the one owned in the University of the Aegean. NASA ground stations though acquired the signal many times using state of the art equipment that we did not have the capability to install on our low cost ground station. Therefore and taking into account that our small picosatellite Lambdasat is similar to other cubesats on orbit and not having plenty of signals received from our satellite we decided to perform our experiments with the use of other similar microsatellites on orbit such as Funcube. Even though the signal is not quite similar however the capability of receiving the signals through our ground station is a primitive indication on how a small satellite can send a signal to earth and in what exact quality each time. Based on this fact and having only a few lines of data from the Lambda Picosatellite received, mainly through the Iridium constellation, we performed our experiments using Funcube, simulating that is our satellite signal. By this way, the only fact we were able to measure was the quality of the signal received from our Ground Station and based on this quality we measured the relative capability of a small Picosatellite to support a maritime security operation.

Funcube satellite is flying on 630 km above the ground, approximately 250 km above Lambdasat. That is why there was an increase in signal reception by approximately 4 minutes in each pass. This fact helped our procedure since we were able to receive the signal from the satellite and decode it properly at least once in each pass. Therefore, we tried to create a basis and to prove that a very small satellite, like Funcube, is able to support a maritime operation by sending and receiving signals to and from ships. On board Lambdasat we had placed an Automatic Identification Sensor (AIS), which was built solely from our team. The signal that the sensor has the capability to transmit or receive is similar in many ways to an AFSK modulated telemetry signal. In our research, we estimated that the telemetry signal of the Funcube satellite is similar to AIS signal (similar in modulation but different in some other technical characteristics - one assumption is being made here due to missing of Lambdasat AIS adequate information) and if we would be able to receive this message correctly at least one time per pass, then we would had the capability of receiving a signal from a ship and respectively send it through the picosatellite to support a maritime security operation. Based on received data from Funcube satellite and from Iridium constellation (signals received from Iridium satellites from Lambdasat) we started our research on 12th of June 2015 and for one month - until 12th of July 2015, we were tracking Funcube signals every single day. We acquired 65 recordings in total, enough information to perform our analysis. From this derived data we compared the actual duration of the received signal in minutes, versus the expected duration of the received signal taking into account the position of the satellite over the University of the Aegean Ground Station in Athens, Greece (graph 23). We also recorded the maximum and minimum elevation of the satellite data received in comparison with simulation data acquired from different programs available commercially (like orbitron, gpredict, STK etc.) Finally through the Funcube dashboard (available on internet) we determined the error count (bytes) from the reception of each signal in order to calculate when a signal was accurate and when a signal was not readable and subsequently it could not support a maritime security operation. To put that in plain words every time that we received a signal based on its quality and if more than 70% of the signal bytes were readable we considered that we had acquired communication with the satellite.

Another important fact that we recorded was the minimum elevation that our ground station could communicate with the satellite taking into account that our ground station is located approximately 400 meters above the level of the sea in the middle of Athens nearby and behind to the Lycabetus hill. By this recording we also calculated the receiving capability accuracy of our ground station in accordance with its location.

Overall Facts - Findings - Results

In this section we will report the main findings of our research and it is obvious that only major results are going to be presented. Thus, starting from the acquisition of data we quote the following:

1. The data reception period was extended to one month from 12 Jun until 12 Jul 2015.

2. We managed to collect / receive 65 single data lines from the Funcube satellite for analysis, even though the satellite passed on top of our Ground station almost 160 times (table 36).

3. All passes of the Funcube satellite were late at night (based on our location). It is well known that communication during night from space is better than day.

4. Weather was excellent during the satellite passes. Therefore data was acquired under the best possible reception weather conditions as compared to reception through winter time or other seasons with rains, storms and heavy clouds. Therefore results that are going to be presented are for best case scenario.

5. The mean difference of the expected minus the actual duration of each pass, in minutes, was 6.5 minutes. This practically means that the actual duration of the reception time for the satellite signal was less than 6.5 minutes taking into account the Doppler effect that created irregularities in signal reception, especially if the elevation was low and the azimuth difference was huge (the auto tracking software moves the antenna from 0 to 360 making a full opposite turn from one side to the other - limitation of the auto tracking antenna based on the allocation of the installed wiring).

6. From the 65 different measurements (graph 23) 31 were corrupted. This fact was calculated taking into account that if we had communication where the error count was more than the correct bytes received then the message considered corrupted. Therefore we assumed that communication with a ship - if present - would not be valid.

7. 34 measurements were effective out of 65 received in total. This means that a 52.3 % percentage of valid communication was performed. In this percentage we have not accumulated as a negative factor the fact that in each total pass of the satellite above the ground station you will need to at least communicate with it two times. One time for receiving the assumed signal from a ship in the middle of the ocean and another time for sending up your messages to the ships. The rest of 49.7% of the communication performed with the satellite can be considered as failure. This percentage is an important fact for our research and reveals that the communication capability of a picosatellite (similar to Funcube and assumingly to Lambdasat) passing over an area is almost 50% successful today. In plain words this means that if you are willing to communicate with a Picosatellite to a ship in the middle of the ocean you will have a possibility of almost 50% to transfer or receive your messages successfully.

8. The satellite is passing over the same place of the earth from 1 to 3 times per day but if we accommodate the quality of signal reception then we see that only once per day you have the capability of communicating effectively with the small satellite.

9. When the elevation of the satellite was under 16.4 degrees then the communication was not effective. This means that under this elevation and even if our ground station was high enough to receive in the horizon we were not able to acquire correct data with low error count and decode a signal that was reliable enough to support a maritime security mission.

10. On the above measurements take into account that Funcube and all the other measured satellites are located higher from Lambdasat, which flies on 422 km. This is practically being translated into approximately 3-4 more minutes of communication window each time and with lower Doppler Effect due to less velocity. Therefore communication with Lambdasat would even worse.

11. The duration of each satellite pass difference (expected minus actual) follows a mean line that is stable with a point distance of 6.5 minutes (graph 24). This practically means that we have to accommodate our operational mission in a timeframe of 6.5 minutes approximately.

12. We noticed as an obvious research result, that error count was very low when the elevation was at maximum rates (graphs 25, 26). Therefore when the elevation was more than 30 degrees the error count was very low, under 40 % (of the total message bytes), and the communication was stable enough to receive a message. At this case only one would have the capability to also send a message to the satellite since the communication was successful from the first minutes of the total pass and so one could enough time to upload a message to the satellite and not only receive one.

13. The best possible scenario communication case we achieved was at 21 Jun 2015 where we acquired actual reception data for 10.1 minutes comparing with the expected which was 12.1. In this case good communication started with a min elevation of 9 degrees and maximum communication elevation performed at 60.2 degrees (graph 26).

14. It has been experienced through different receive of amateur pico and cube satellites that if elevation is under approximately 10 degrees then the communication is pretty much incapable. Of course this characteristic has direct relationship with the

communication equipment of the cubesat and the capability of it sending data with high bit rate consuming power more than 1 Watt. In most cases though this situation has not been chosen during design phase taking into account that all experimental / educational small satellites are trying to allocate more experiments on the satellite bus and thus allocate as less power as possible to each one of them. Telemetry is one subsystem that follows this principle.

15. When the elevation was under 9 to 12 degrees we noticed that Azimuth change had a very little effect in the reception of the signal.

16. Funcube Orbital Characteristics during measurements time were:

ALTITUDE [km]:	649.70
ALTITUDE [mi]:	403.7
SPEED [km/s]:	7.62
SPEED [mi/s]:	4.73
AZIMUTH:	146.4 SE
ELEVATION:	-83.4
RIGHT ASCENSION:	21h 47m 34s
DECLINATION:	-44° 28' 31"

Table 35: Funcube Orbital Characteristics during experiments

17. Lambdasat started flying approximately at 405 km. Therefore the audio received signal communication similar to Micromas (MIT cube satellite launched with Lambdasat on 1st March 2015) was at a maximum duration of 7-8 minutes when the elevation was more than 60 degrees.

18. There were no buildings or any other obstacles among the satellite and the ground station. The UoA ground station antenna was able of shooting down and receives signals even from 0 degrees elevation of the satellite. The antenna is located 400 meters above the sea level and on top of a building that is like a hill in the middle of Athens similar to Lycabetus hill. Normally the ground station would be able to receive signals from the horizon all the way up to the maximum elevation (happens numerous times with FO-29).

19. For every elevation less than 16.4 degrees the error count was more than 137 bytes and so we did not manage to receive a good signal for one time. For any other elevation more than 16.4 degrees we received one full good signal in the window we had for communication. However when the communication window was less than 3 minutes

the reception due to Doppler effect was incapable leading us to no practical reception of the signal.

20. Finally we should note that tracking procedure of the Lambda satellite was made via available commercial software (Orbitron and Gpredict) (figures 26, 27). There was an observation via Orbitron that Lambdasat was having a Doppler shift of 8 to 10 kHz when passing inbound and outbound respectively on a positive and negative effect. So when approaching the Doppler Effect was 10 kHz where the outbound was 10 kHz. This situation was further influencing the communication in a maximum degree since normal cubesats and microsatellites like FO-29, Cubebag1 and other similar we have decoded through our Ground Station, have a typical figure of Doppler shift of 4 to 6 KHz. In accordance with the Doppler effect function and calculation this is happening primarily due to the fact that the satellite is orbiting at a very low earth orbit (lower than ISS) in 400 km and the satellite velocity there is 7.669 km/sec in accordance with calculations based on Gpredict software at 11th of March 2015. Date here is critical since the satellite did not have on board propulsion and a standard orbital decay parameter was affecting its motion (see Tubesat calculations on Chapter 7 for Orbital Decay parameter).

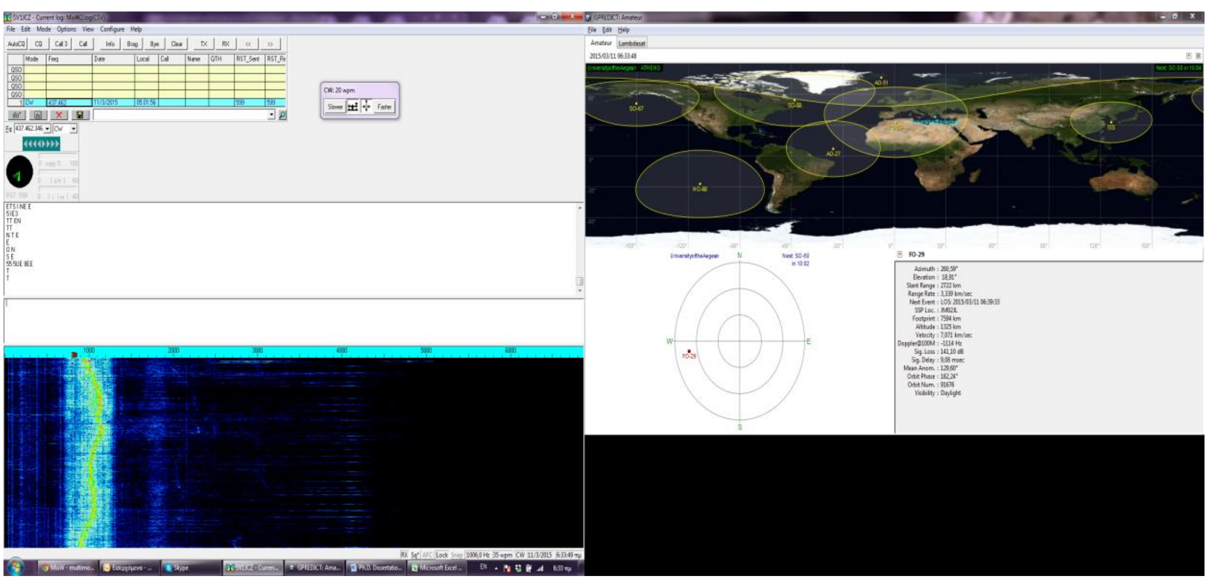


Figure 23: Tracking of Lambdasat and FO-29 Japanese microsatellite using gpredict commercial software and decode data via the open source MiXW software.

After an ISS onboard waiting period of 9 months (due to ISS cubesat deployer malfunctions), the Lambdasat picosatellite was deployed on March 4, 2015. Just 3 hours after the launch Iridium constellation received the first signal from Lambdasat proving the work status of the Picosatellite and the successful launch of it. The satellite acquire mission success status from NASA as the first ever Greek launched satellite from ISS.

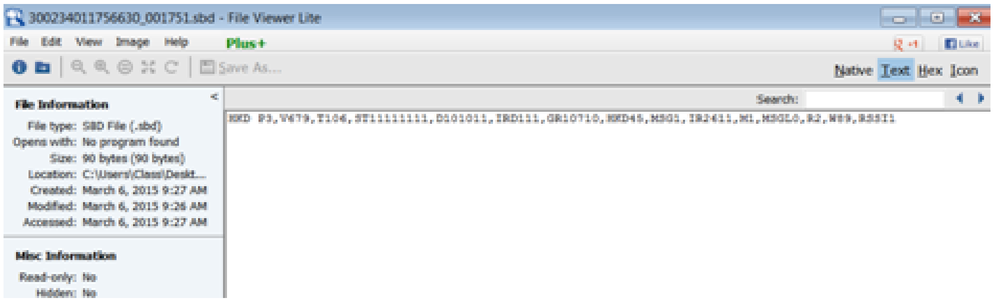


Figure 24: First Lambdasat signal through Iridium proving mission success

```
HI HI AE C7 88 55 08 5D FF 0D 00 16 34 46 95 60 96 90 9F 8D BC BA BC BC BA
HI HI AE 67 88 55 0D 5S FF 0D 00 16 7E 4F 96 60 96 91 B0 8E BC BA BC BC BA
HI HI AE C7 88 55 1A 5D FF 0D 00 16 A6 49 96 60 96 90 B0 90 BC BA BC BC BA
HI HI AE C7 88 55 17 5D FF 0D 00 16 5D 5F 96 60 96 90 B0 84 BC BA BB BB BA
HI HI AE 07 88 51 07 54 1E 0D 00 16 5F 3D 81 4A 96 92 B0 8E BD BC BD BD BA
HI HI AE C7 88 55 0C 54 FF 0D 00 16 56 38 7D 60 93 91 9F 88 BD BC BD BD BA
HI HI AE C7 88 55 11 55 FF 0D 00 16 62 34 7D 60 94 91 B0 8D BD BB BD BD BA
HI HI AE 07 88 51 16 56 FF 0D 00 16 76 31 7E 60 94 91 A0 8E BD BB BD BD BA
HI HI AE C7 78 51 1B 56 0A 9D 00 16 75 33 7E 60 94 91 B0 7B BD BB BD BD BA
HI HI AE 07 88 51 00 57 FF 0D 00 16 55 37 82 60 93 90 B0 9B BD BB BD BD BA
```

Figure 25: FO-29 Decoded message from UoA ground station.

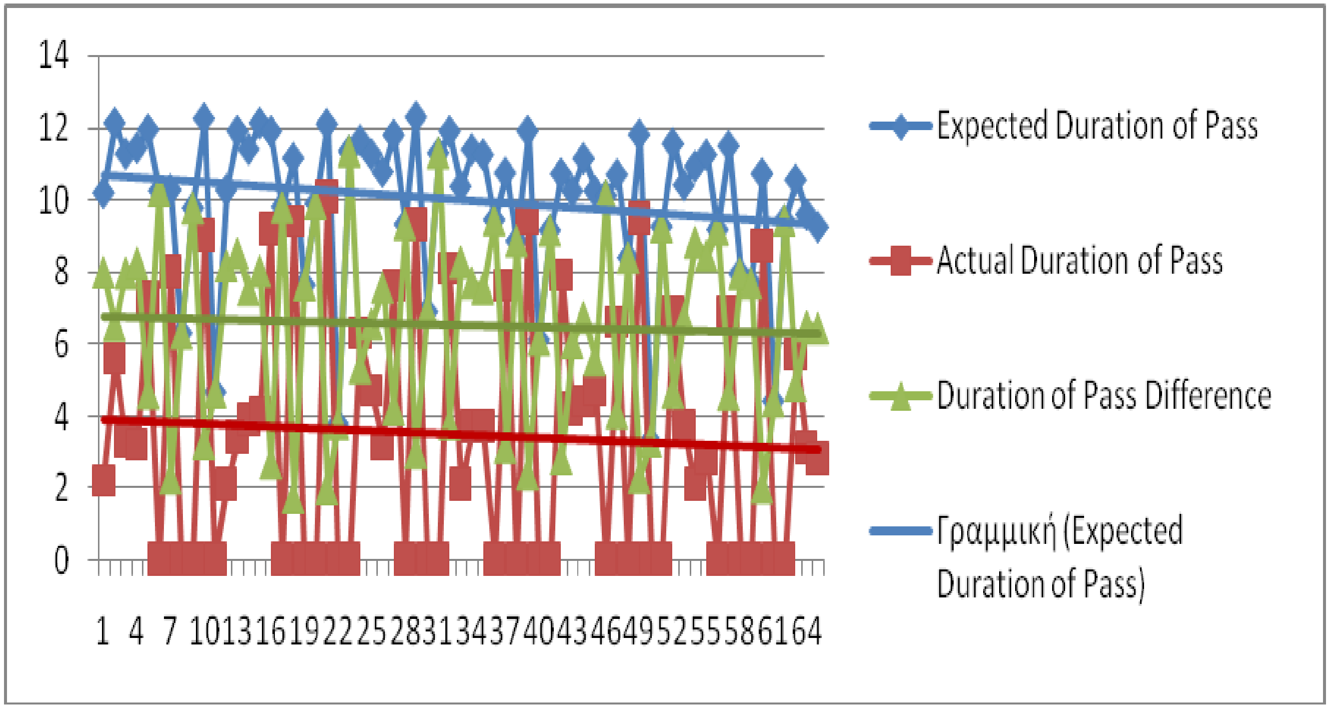
In figure 25 we can see the message received and decoded from FO-29 Japanese microsatellite where we analyzed the bit error count in order to quantify the quality of a message received from the microsatellite. This work was performed various / multiple times and the following table 36 created. It shows 65 received data lines from Funcube and FO- 29 satellites during decoding phase of our experiments. One can notice in green column the bit error rate received. 0 indicates bad reception whereas 100 indicates a readable message. From this work a useful research result was extracted showing us the pragmatic situation of the use of a microsatellite supporting a maritime security operation. 34 out of 65 measurements were readable proving that more than 50 % of the signal can be transferred to the ground station from the picosatellite. In order though to be more accurate we could use error correction algorithms and in that case more than 80 % of accuracy would be performed. This task was not conducted here since it was outside of the scope of the thesis, however if done in future will give much more accurate results taking into account that those algorithms are being used for bigger satellite vehicles and science in already well known behind those methods. The fact that in raw data we received accurately more than 50% gives us an optimistic insight for the future of picosatellites in maritime applications.

Registration of Received Orbital Microsatellite Data													
No of data lines	Date	Time of Pass (Local)	Expected Duration of Pass (min)			Expected Duration of Pass (min dec)	Actual Duration of Received Signal (min)	El min (actual)	El max (real data)	Error Count (bytes)	Message Quality Received (Readable? Yes=100, No=0)	Expected - Actual Difference Duration of Pass
			min	sec								
1	12/6/2015	2132	10	12	20	10,2	2,2	11	16,4	137	0	8
2	12/6/2015	2307	12	8	13,33333	12,13	5,6	9	42,9	80	100	6,53
3	13/6/2015	2151	11	17	28,33333	11,28	3,3	12	25,8	123	100	7,98
4	13/6/2015	2327	11	27	45	11,45	3,2	10	25,7	127	100	8,25
5	14/6/2015	2211	11	57	95	11,95	7,3	8	41,9	55	100	4,65
6	14/6/2015	2348	10	16	26,66667	10,26	0	0	15,6	153	0	10,26
7	15/6/2015	2230	10	17	28,33333	10,28	8	7	72	54	100	2,28
8	16/6/2015	9	6	19	31,66667	6,31	0	0	8,8	148	0	6,31
9	16/6/2015	2116	9	47	78,33333	9,78	0	0	10,7	139	0	9,78
10	16/6/2015	2250	12	16	26,66667	12,26	9	5	66,9	65	100	3,26
11	17/6/2015	31	4	41	68,33333	4,68	0	0	3,7	152	0	4,68
12	17/6/2015	2135	10	17	28,33333	10,28	2,1	8	17,4	159	0	8,18
13	17/6/2015	2310	11	55	91,66667	11,91	3,4	12	38,4	67	100	8,51
14	18/6/2015	2154	11	25	41,66667	11,41	3,9	11	27,7	123	100	7,51
15	18/6/2015	2331	12	8	13,33333	12,13	4,1	11	23,1	134	100	8,03
16	19/6/2015	2214	11	54	90	11,9	9,2	5	45,6	45	100	2,7
17	19/6/2015	2351	9	49	81,66667	9,81	0	0	13,9	168	0	9,81
18	20/6/2015	2234	11	10	16,66667	11,16	9,4	10	78,9	32	100	1,76
19	21/6/2015	13	7	39	65	7,65	0	0	7,5	165	0	7,65
20	21/6/2015	2119	9	55	91,66667	9,91	0	0	11,4	139	0	9,91
21	21/6/2015	2253	12	6	10	12,1	10,1	9	60,2	57	100	2
22	22/6/2015	35	3	5	8,333333	3,8	0	0	2,7	149	0	3,8
23	22/6/2015	2138	11	21	35	11,35	0	0	18,5	154	0	11,35
24	22/6/2015	2314	11	39	65	11,65	6,3	11	34,6	117	100	5,35

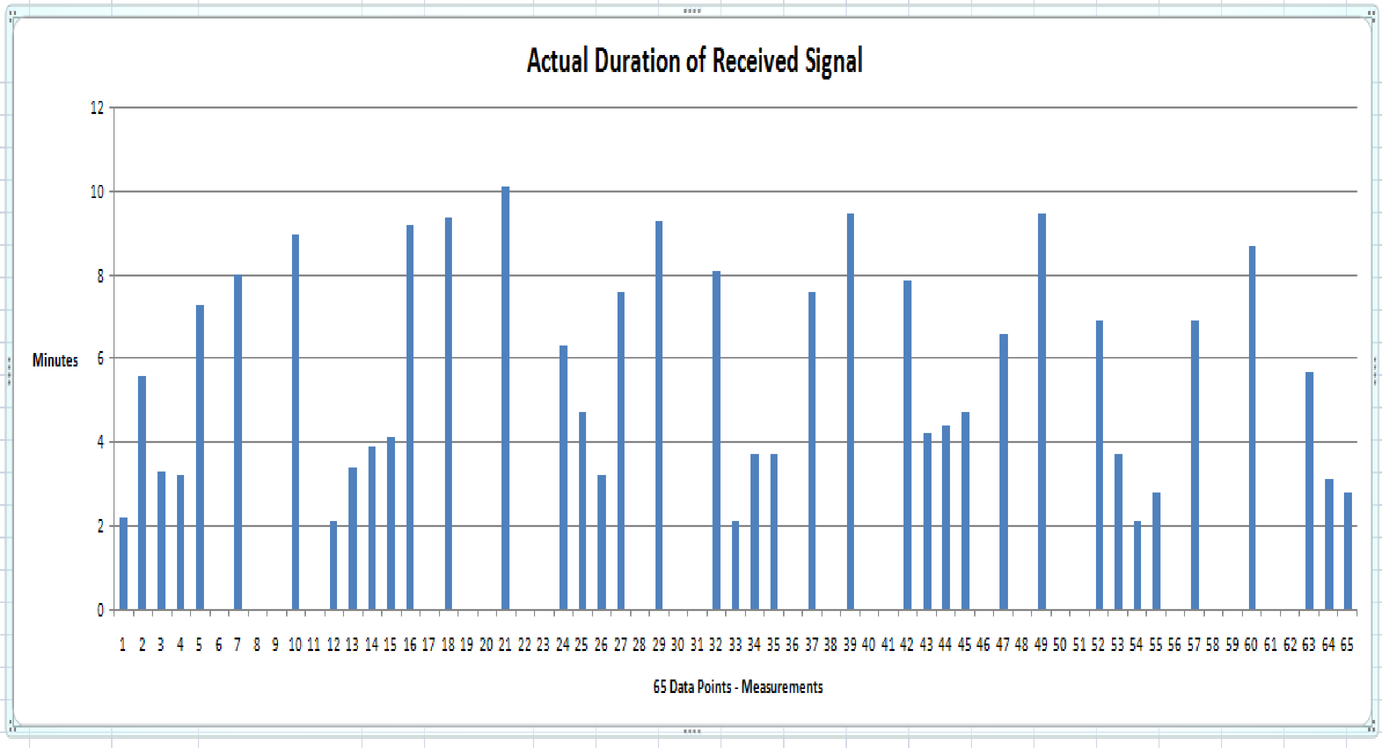
25	23/6/2015	2157	11	16	26,66667	11,26	4,7	9	29,6	112	100	6,56
26	23/6/2015	2334	10	47	78,33333	10,78	3,2	9	20,8	102	100	7,58
27	24/6/2015	2217	11	48	80	11,8	7,6	7	49,5	77	100	4,2
28	24/6/2015	2355	9	20	33,33333	9,33	0	0	12,3	148	0	9,33
29	25/6/2015	2237	12	2	3,333333	12,3	9,3	6	86,1	22	100	3
30	26/6/2015	16	6	55	91,66667	6,91	0	0	6,3	172	0	6,91
31	26/6/2015	2122	11	2	3,333333	11,3	0	0	12,1	167	0	11,3
32	26/6/2015	2256	11	54	90	11,9	8,1	11	54,2	87	100	3,8
33	27/6/2015	2141	10	23	38,33333	10,38	2,1	9	19,6	139	0	8,28
34	27/6/2015	2317	11	24	40	11,4	3,7	10	31,2	110	100	7,7
35	28/6/2015	2201	11	15	25	11,25	3,7	10	31,6	101	100	7,55
36	28/6/2015	2337	9	27	45	9,45	0	0	18,8	158	0	9,45
37	29/6/2015	2220	10	45	75	10,75	7,6	11	53,7	65	100	3,15
38	30/6/2015	1	8	52	86,66667	8,86	0	0	10,9	167	0	8,86
39	30/6/2015	2239	11	55	91,66667	11,91	9,5	7	86,7	21	100	2,41
40	1/7/2015	19	6	8	13,33333	6,13	0	0	5,3	170	0	6,13
41	1/7/2015	2125	9	10	16,66667	9,16	0	0	12,9	151	0	9,16
42	1/7/2015	2259	10	44	73,33333	10,73	7,9	9	49	68	100	2,83
43	2/7/2015	2144	10	15	25	10,25	4,2	7	20,8	121	100	6,05
44	2/7/2015	2319	11	9	15	11,15	4,4	7	28,4	117	100	6,75
45	3/7/2015	2203	10	15	25	10,25	4,7	8	33,8	103	100	5,55
46	3/7/2015	2340	10	7	11,66667	10,12	0	0	17	152	0	10,12
47	4/7/2015	2222	10	42	70	10,7	6,6	12	58,4	77	100	4,1
48	5/7/2015	1	8	24	40	8,4	0	0	9,7	164	0	8,4
49	5/7/2015	2242	11	49	81,66667	11,81	9,5	11	79,8	43	100	2,31
50	6/7/2015	2244	3	19	31,66667	3,31	0	0	4,4	170	0	3,31
51	6/7/2015	2127	9	16	26,66667	9,26	0	0	13,7	169	0	9,26
52	6/7/2015	2302	11	34	56,66667	11,56	6,9	11	44,5	52	100	4,66
53	7/7/2015	2146	10	25	41,66667	10,41	3,7	10	22,1	49	100	6,71
54	7/7/2015	2322	10	56	93,33333	10,93	2,1	12	26	143	0	8,83
55	8/7/2015	2205	11	15	25	11,25	2,8	12	36,2	156	0	8,45
56	8/7/2015	2343	9	11	18,33333	9,18	0	0	15,5	159	0	9,18

57	9/7/2015	2225	11	30	50	11,5	6,9	9	63,4	68	100	4,6
58	10/7/2015	3	7	58	96,66667	7,96	0	0	8,7	164	0	7,96
59	10/7/2015	2111	7	42	70	7,7	0	0	8,6	167	0	7,7
60	10/7/2015	2245	10	44	73,33333	10,73	8,7	8	73,3	37	100	2,03
61	11/7/2015	25	4	26	43,33333	4,43	0	0	3,6	152	0	4,43
62	11/7/2015	2130	9	26	43,33333	9,43	0	0	14,6	143	0	9,43
63	11/7/2015	2305	10	34	56,66667	10,56	5,7	8	40,8	76	100	4,86
64	12/7/2015	2149	9	36	60	9,6	3,1	11	23,5	122	100	6,5
65	12/7/2015	2325	9	15	25	9,25	2,8	12	24	146	0	6,45

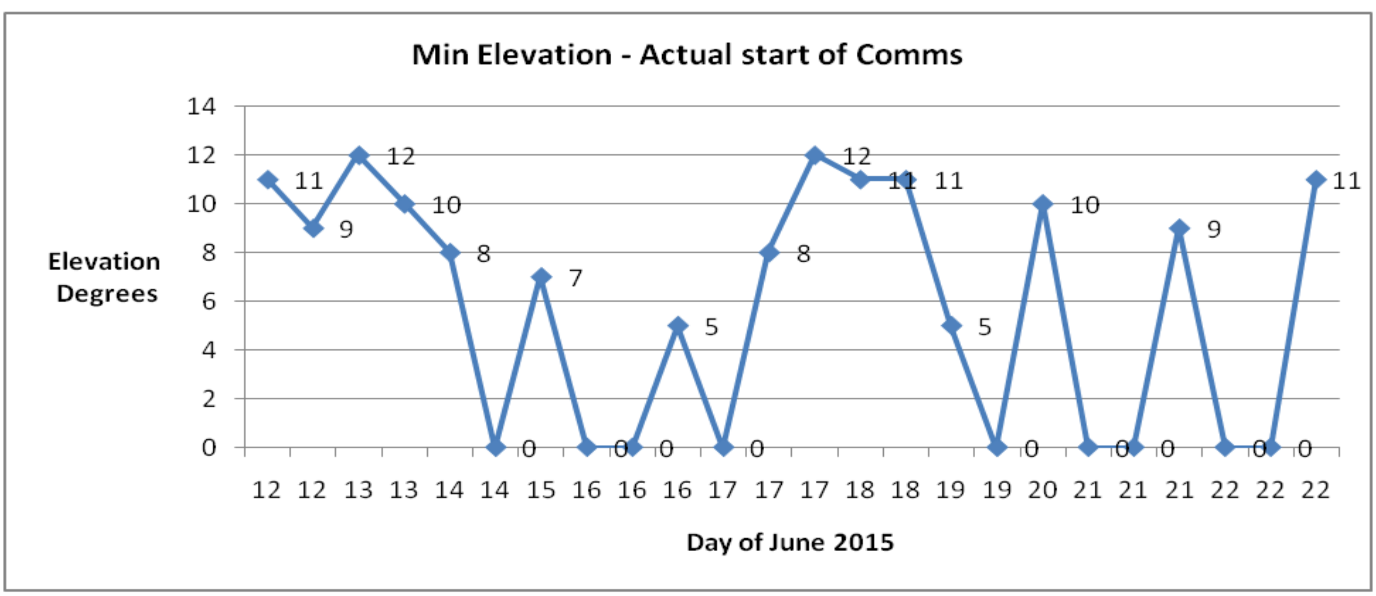
Table 36: 65 received data lines from Funcube and FO- 29 satellites during decoding phase of our experiments.



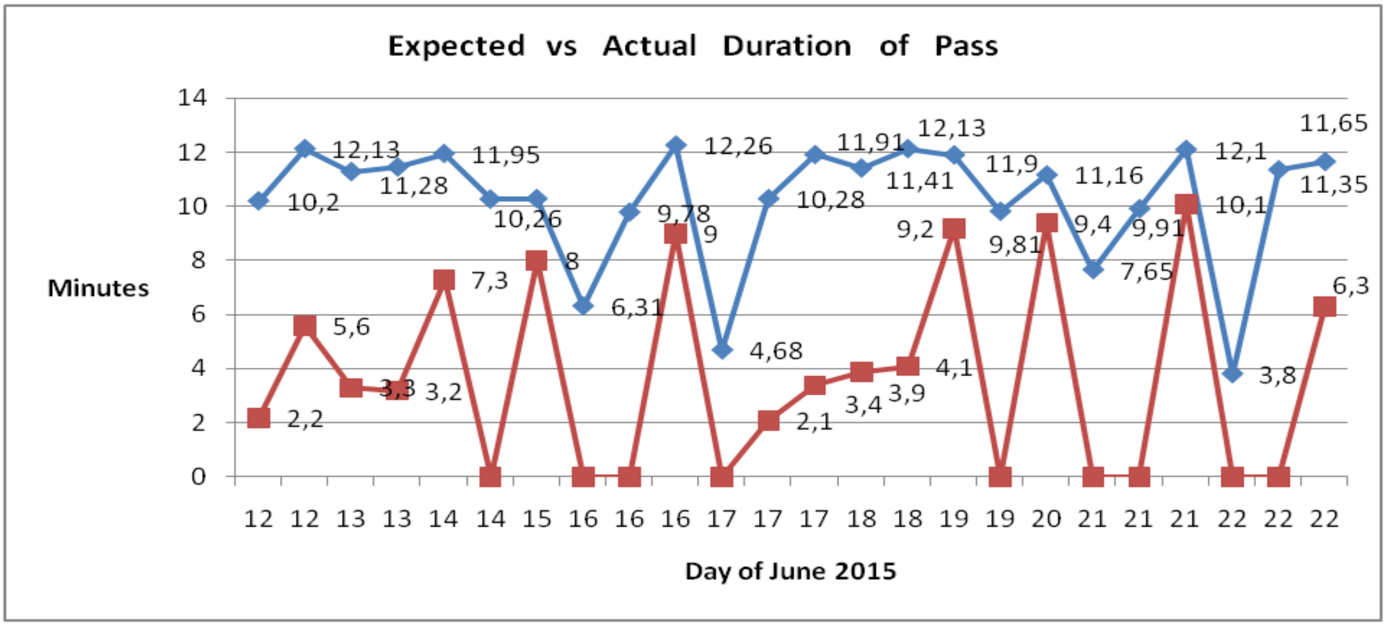
Graph 23: 65 Data lines received Analysis



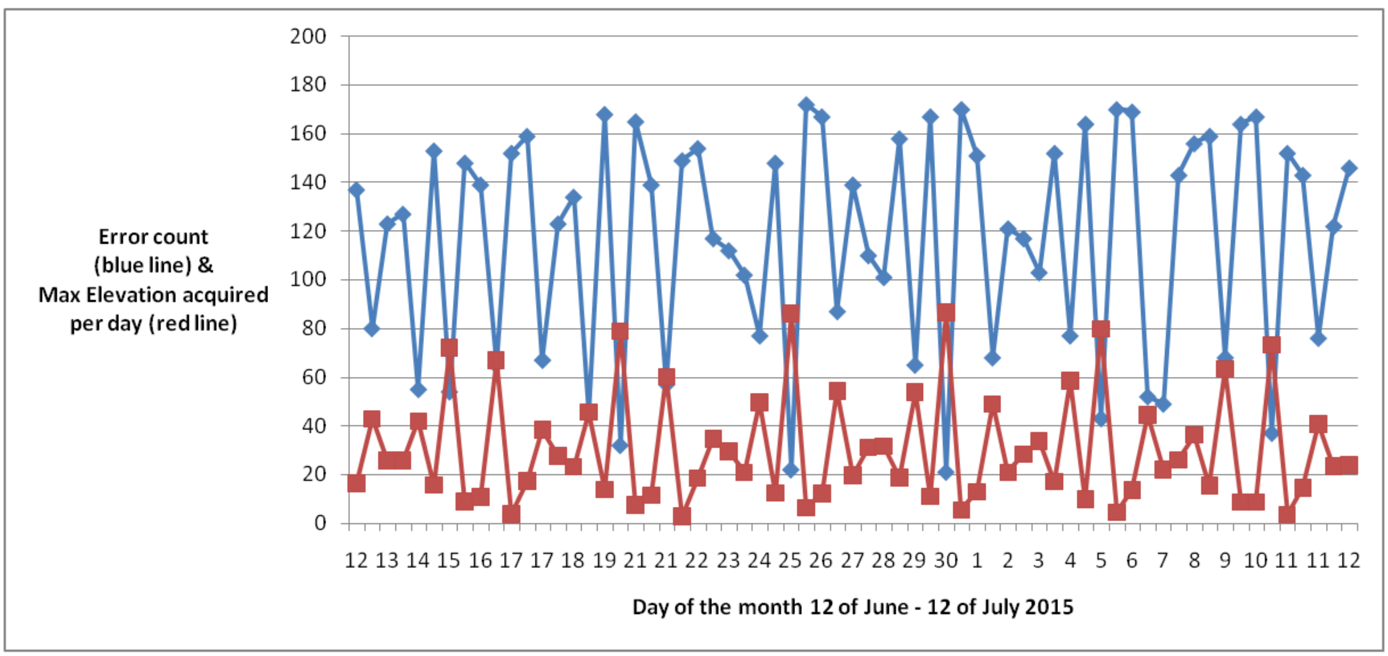
Graph 24: Actual Duration of Received Signal per day in Minutes.



Graph 25: Minimum Elevation that the Actual Communication with Funcube satellite observed per day.



Graph 26: Expected vs Actual Duration of Pass of the cubesat Funcube during measurements period.



Graph 27: Error count (blue line) and Maximum Elevation Communication acquired per day (red line)

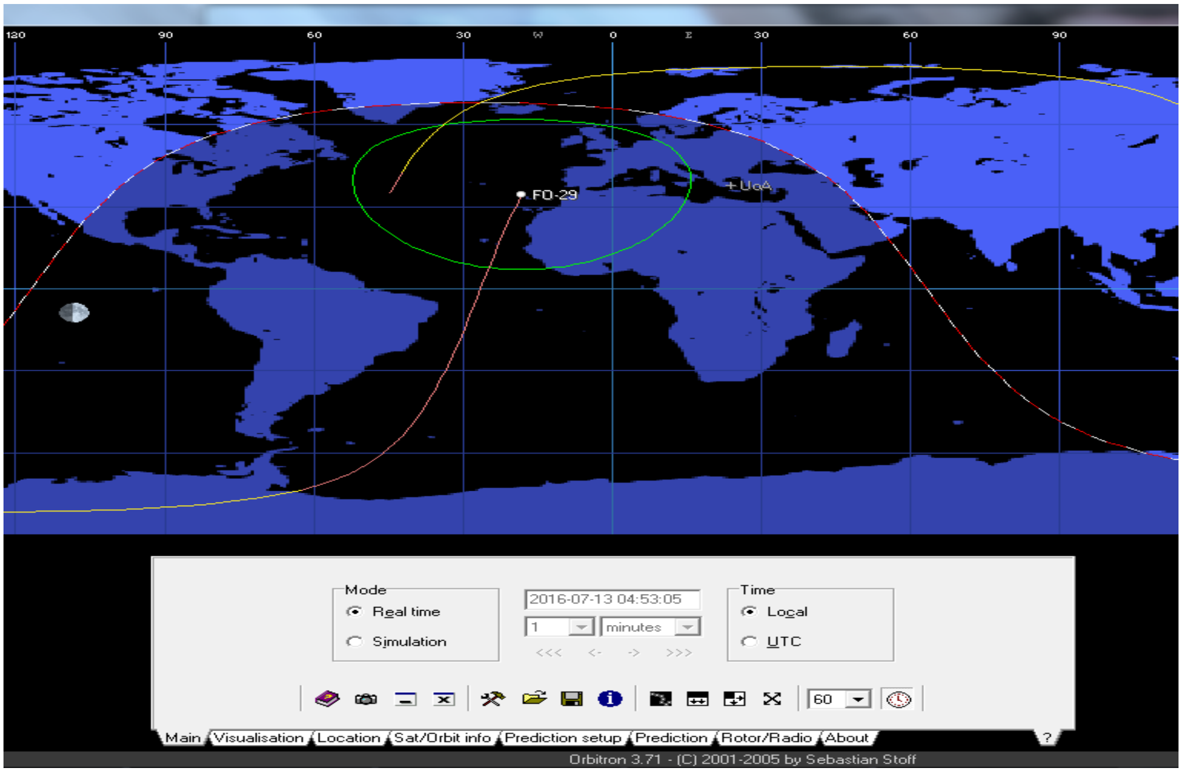


Figure 26: Footprint and Orbit of FO-29 microsatellite during experiments

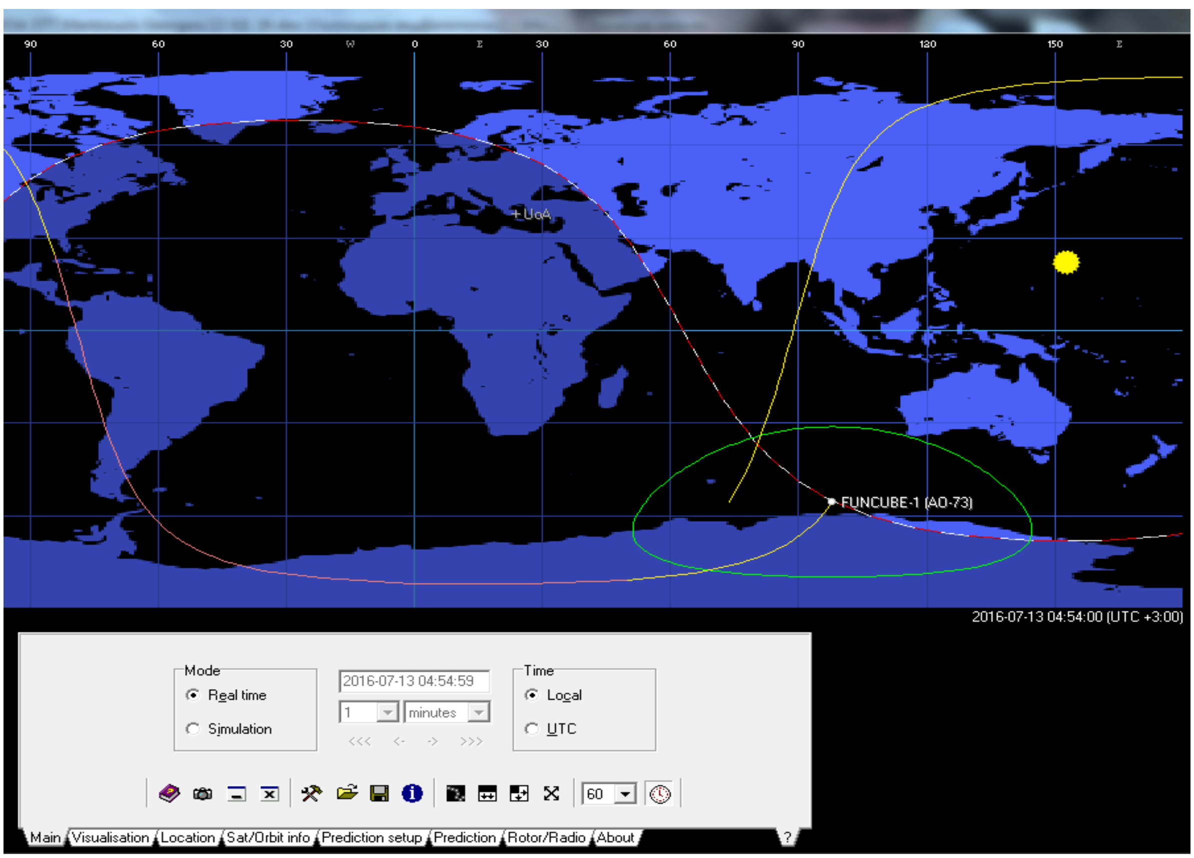


Figure 27: Footprint and Orbit of Funcube picosatellite during experiments

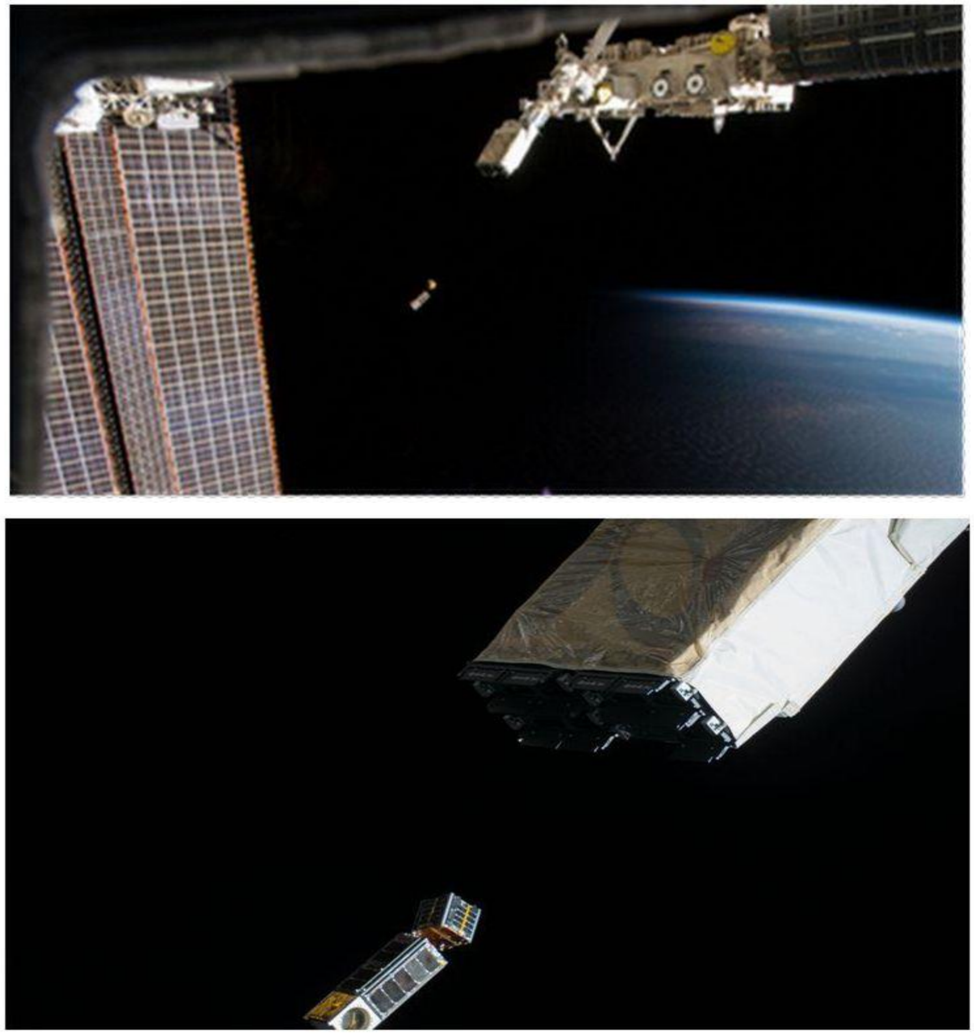


Figure 28: Lambdasat during launch from International Space Station to space on March 2015.

Conclusion

Completing the above analysis and finding we can deduce that with a type Lambda picosatellite communication to a maritime security operation is available by approximately **55%** taking into account only summer weather conditions and Yagi antenna configuration. If the above limitations change then new measurements / experiments need to take place in order to evaluate the use of such picosatellites to maritime operations. With this result though in hands **picosatellites prove their position to be promising for participating in future maritime security operations as part of a whole alert or generally space mesh networking collaboration system.**

Page intentionally left blank

CHAPTER 7

THE TUBESAT CASE

Chapter 7: The Tubesat Case

Micro and Pico satellites are small space assets that have been around for decades. Sputnik, the first ever satellite to fly was considered to be a microsatellite since its weight and characteristics were similar to the ones designed for today's operational environment. These small devices have been considered part of our space lives for years but nobody until now has ever thought if we can use these devices in order to minimize the cost of global maritime security operations. It is imperative in the middle of one of the most severe economic crisis that the world has ever sensed, to reinvigorate all the ideas that deal with space operations, but from a cost effectiveness perspective. Solutions that have been proved successful but require high costs in order to be implemented in space are no longer solutions and no one consider them as being viable. On the other side, solutions that prove cost effectiveness and the cost benefit analysis rates on a very low scale are being analyzed as appropriate for implementing them into our operational environment. In older times everybody was thinking of the smart ideas not including though in the analysis the cost as one of the most important factors. Today, smart idea is considered the one that can fill the operational gaps, but with very little amount of money. This is the modern challenge for the governments, academic institutions, organizations and in this direction the scientific community has turned with all its power and effort.

Following the above mentioned principles and believing that there is still room for great advancements and improvement in the areas of micro, pico and femto satellites applications to the maritime environment, we are going to analyze in the following paragraphs how these types of very small devices can add significantly to the maritime security operations area and most importantly that with these little space "toys" we can sustain effectively an operation, such as counter piracy or to help counter any other type of maritime terrorism operation. Of course there are limitations and restrictions and the research is still ongoing. Through this research though we are hoping to investigate and propose solutions that are going to minimize the cost to the lowest allowed for space operations and in the range of some thousands of dollars, which is an exceedingly crazy figure for today's missions.

Operational Background

It has been traditionally proven that surveillance in real time framework and parameters in the maritime environment attracts the most interest from communities when an operation is being planned on the strategic or operational level. The command and control procedures and command schemes needs to succeed in order for the operation to be executed in a smooth way. At the same time efforts have been made throughout the last decades to minimize assorted costs and make the intelligence command and control designs affordable and robust.

In maritime operations the factors that affect the conduction of a mission are so many that sometimes the planners follow only the most important ones without caring about the side effects. It is imperative for a successful and cost effective operation to take into account all parameters that will finally lead us to the desired result. Maritime environment is an area where real time intelligence support is of primary importance especially, when advising from ashore fusion centres is needed and must be implemented.

Contemporary maritime security operations are covering a full range of different missions starting from countering piracy to countering transportation of illegal goods, as well as human trafficking and embargo situations. All these operations cannot be followed or covered with one intelligence acquisition scheme and usually different applications and technological frameworks are being utilized in order to effectively support them. A real time information infrastructure that will cover all of the aforementioned operations and combine them in one and cost effective intelligence scheme is still absent from today's operational and tactical maritime environment. Addressing this problem we may encounter many obstacles but at the same time it is worth pursuing a solution like this, since if it at the end we succeed, then we will have merged the cost effectiveness with the real time operational requirements covering almost all aspects of maritime security operations.

Satellite Category	Net Weight
Large	> 1000 kgr
Medium	500 - 1000 kgr
Mini	100 – 500 kgr
Micro (Cubesat)	**10 -100 kgr**
Nano (Cubesat)	**1 – 10 kgr**
Pico (Tubesat)	**0.1 – 1 kgr**
Femto (?)	**< 100 gr**

Table 36: Categorization of Small Satellites in accordance with their net weight.

For revision purposes and taking into account that are different categorizations of satellites we need to specify that when we refer to small satellites we imply a bus that is less than 100 kgr in net weight. Table 36 summarizes the existing categories of satellites in the commercial space environment and shows explicitly what the weight differences in these categories are. In our research and experiments we are going to use the notion of micro, nano and pico satellites, with net weight near or less than a kilogram. Up to now there are no commercial very small satellite buses in orbit (in the range of 1 kgr) that are able to reroute information from a maritime warfare operational area back to a network operation center.

Small Satellites in Maritime Situational Awareness

Satellites with Space Maritime Tracking Capability have been around not for many years. The research started from academic institutions and today is available commercially primarily in the applications of space maritime tracking of merchant vessels around coastal waters in the primary sea lines of communications (e.g. Gibraltar). In the following pages we present some of the available commercial small satellite applications that are in orbit or under construction and in the near future they are going to be used for space maritime tracking. It turns up that there are not so many "people" around the world that are using or trying to apply this technology and even more we did not manage to find out any organizations or small satellite applications on orbit or under construction that are dealing with the tracking of merchant vessels or supporting critical maritime security missions. Also and up to now the applications are exceeding the acceptable costs for this research which is some thousands of Euros.

Nanosatellite Tracking Ships (NTS), Canadian Nanospace eXperiment 6 (CanX-6) (University of Toronto – UTIAS - Space Flight Laboratory)[1,2].

The mission of this cubesat (type of microsatellite in rectangle size) is to provide secure space based AIS receiver and secure confidence in space-based ship tracking technology. The challenge is to detect AIS signals from space for global ship tracking and monitoring. It was launched on 28 April 2008[1].

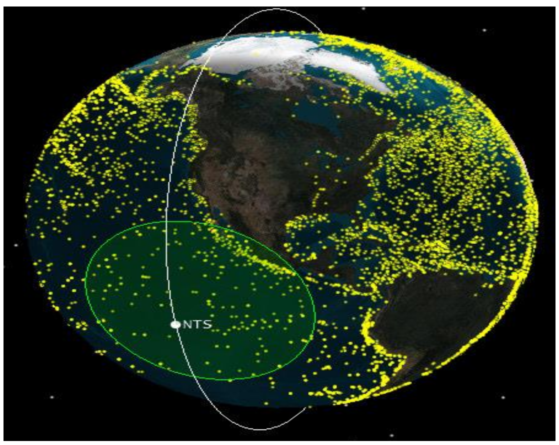


Figure 29: Illustration of the AIS messages recovered from Nanosat NTS.(Courtesy: UTIAS[1])

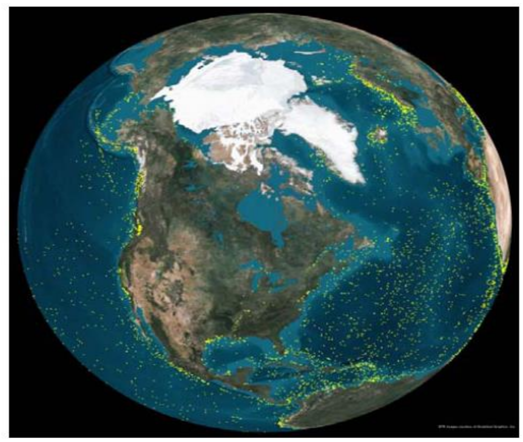


Figure 30: Earth's shipping traffic density as it was acquired from NTSAT (Courtesy: UTIAS[1])

a. Maritime Monitoring and Messaging Satellite (M3MSat

The Maritime Monitoring and Messaging Satellite (M3MSat) is the next miniature satellite from Canadian Space Agency. Its mission will be the Maritime surveillance that will enable an unprecedented global view of the world's shipping traffic. It was planned to be in orbit by the end of 2010 and it will contribute to wide area surveillance coverage of maritime approaches to Canadian territorial waters, in the middle & outer zone coverage (50-1000 nm)[10].

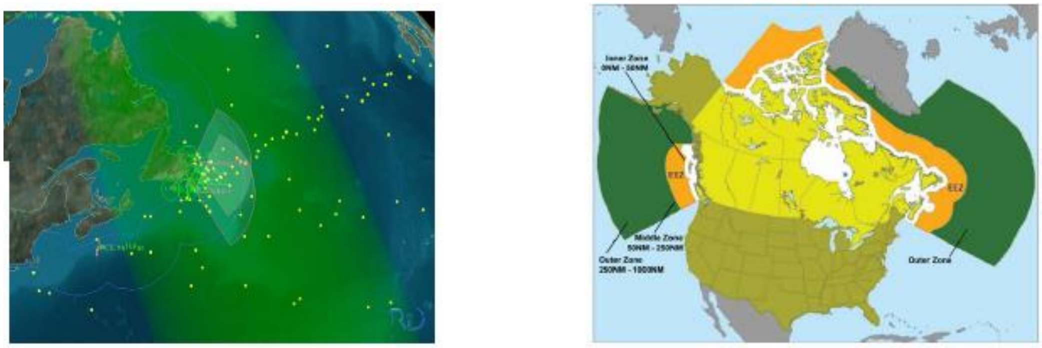


Figure 31: Coverage of M3MSat outside Canadian Territorial waters (courtesy UTIA[10])

b. AISSat -1 Automatic Identification System Satellite [2]

AISSat can receive messages by a VHF receiver in space for wide area observation of maritime activity. Its mission focused on Norway's TTW (territorial waters), an area with long shorelines, large coastal waters and fishing grounds. This work is going to be executed by AISSat-1 during all 15 daily passes over Norwegian ocean areas.

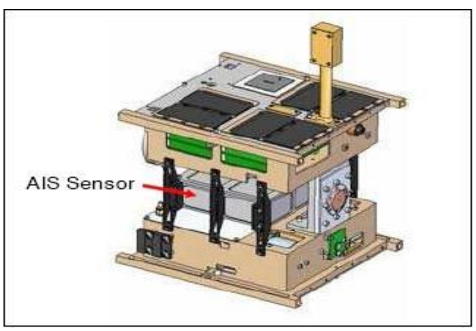


Figure 32: Internal structure of AISSat-1 (Courtesy AISSat)

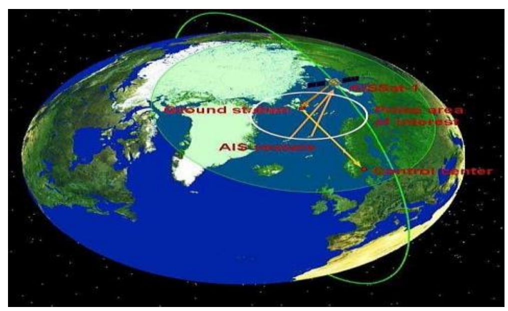
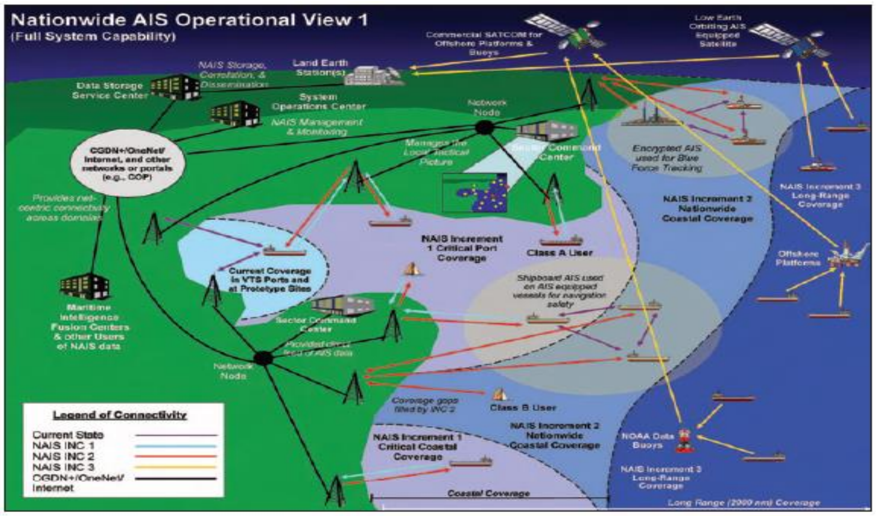


Figure 33: Coverage of AIS Sat outside Norwegian Territorial Waters (courtesy AISSat)

c. TACSAT-2: Maritime Surveillance Satellite for U.S. Coast Guard (USCG)

The Coast Guard hopes to use the technology for its future nationwide automatic identification system (NAIS), which is the service's three-stage plan to extend its ability to track and identify vessels. The first stage will track ships near 55 critical ports and the second stage calls for AIS tracking as far out as 50 nautical miles. Satellites will be added in the final stage, and along with a network of offshore platforms and buoys, are expected to identify ships as far as 2,000 nautical miles. The system is expected to be operational in 2014[4].



A USCG outline of how the satellite network will be expected to collect and forward AIS data

Figure 34: USCG outline of how the satellite network will be expected to collect and forward AIS data.(courtesy TACSAT[4])

Picosatellites in MIO Networks

The successful command and control in Maritime Interdiction Operations (MIO) depends heavily upon an organization's communication and network platform architecture. These platforms must provide effective, efficient, affordable communications in between operational and tactical commanders, globally distributed subject matter expert advisors and finally positive communication exchange among them. Since 2009, the researchers at the Naval Postgraduate School (NPS) together with their Lawrence Livermore National Laboratory (LLNL) and overseas partners started to explore the benefits of using very small, picosatellite based, private orbital tactical networking nodes to support expert reachback and coordination in Maritime Interdiction Operations scenarios. Currently the NPS team has assembled the first set of three picosatellites to be launched in the near future for conducting first field trials of MIO reachback via an orbital tactical node. In order to plan and design picosatellite nodes integration experiments, we've developed the software model of future miniature orbital tactical nodes, using the simulation modeling environment of the Satellite Tool Kit (STK). The research scenario analyzed in the following chapter describes the results of picosatellite networking nodes simulation as well as records the analysis of their implementation in MIO scenarios. Finally a conceptual comparison of how a picosatellite can become part of a node network (MANET) has been created where available commercial types of mesh networking applications have been analyzed, comparisons have been made and a final conclusion has been made on how future picosatellite orbital nodes must be designed in order to be part of a global mesh networking environment.

Therefore, in the emerging reality of network-centric warfare, it is becoming increasingly evident that space-based tactical networking solutions can effectively facilitate synchronous reachback and collaboration between on-scene commanders and subject matter experts in the remote locations. Many researchers and members of multilateral security organizations acknowledge the urgency of finding approaches to provide solutions to intractable threats from the illicit proliferation and use of weapons of mass effect (WME) up to illicit trafficking and piracy. The need is most urgent in the many ungoverned and under-governed regions, and across the global commons, such as Gulf of Aden in the Somali Basin area. Since 2009, the researchers at the Naval Postgraduate School (NPS) together with Lawrence Livermore National Laboratory (LLNL) and overseas partners started to explore the benefits of using very small, Picosatellite based, private orbital tactical networking nodes to support expert reachback and coordination in Maritime Interdiction Operations (MIO) scenarios. Typically picosatellite is defined as the smallest type Cube satellite (< 10 kg) category, with short life-time in orbit (1-3 months) and overall weight of 1 kg or less. Within the framework of ongoing MIO Experimentation Campaign [1], we envision an addition of picosatellite based orbital nodes, as an extension of the existing MIO testbed infrastructure, which has been originally developed by the NPS and LLNL to support the MIO experiments focused on countering maritime sourced nuclear radiation threats. The testbed overseas sites are operated by academic partners from the University of Bundeswehr, Swedish Defense Research Agency and others. They enable the research team to explore challenging solutions for tagging and monitoring small craft sourced nuclear material illicit transfer between the continents. It will be a challenge for all these partners to conduct networking research utilizing picosatellite orbital nodes as part of their broad and global mesh network.

The Tubesat or similar picosatellite based orbital ad hoc networking node will provide vital space element for coordinating detection awareness between the foreign origin layer, transit layer, foreign point of departure, transit-to-target, and so one down to the target vicinity layer of the emerging nine-layer Nuclear Detection Architecture Model (DNDO, 2009). Currently, tagging and global tracking of small craft transported illicit material could be accomplished using a combination of low bandwidth Low Earth Orbiting (LEO) satellite links (Iridium, Global Star), cellular GSM 3G/4G networking for feeding tag GPS location (or similar method in the GPS denial areas) to situational awareness systems. Such methods have multiple limitations due to the high dependency on the LEO constellation access, especially in when such spaces assets become unavailable or taken down. Another important fact is that use of Iridium or Inmarsat or any other commercial type satellite provider has a very high figure in cost parameters. (see chapter below for cost benefit analysis on picosatellites). The Picosatellite based orbital node provides a low cost tactical alternative for processing the detection data and relaying it to geographically distributed fusion centers [4]. It provides for the "private" ad hoc orbital node that sensor operators and experts could use at their discretion to collect data from unattended sensors, follow small craft over the large distances, etc.

MIO Reachback needs and requirements

The robust agile reachback networking solutions enable distributed MIO teams on-the-move to rapidly exchange information updates with assisting tactical or higher level operational and strategic centers. The reachback capabilities have specific operational characteristics which are critical the Maritime Interdiction Operation success. They also include, but are not limited to real time information flow. In the event that a MIO is being conducted on board a suspect merchant vessel, the boarding team commander requires expert analysis and recommendations. For example, a boarding team may request an accurate identification of possible fissile materials based upon alerts from a team member's hand-held sensor on board a merchant vessel. Timely assessment is critical in order for the team commander to determine whether to proceed further for his search on board the vessel or retreat in order not to pose a risk to human life and eventually to the overall success of the mission. In a present day scenario, a MIO team commander communicates via radio with the tactical command afloat (e.g. frigate, fast patrol boat). The tactical command afloat relays the information to a fusion center ashore and awaits responses, which are then forwarded back to the team commander on board the suspect vessel. In this C2 communication channels loop, the action officer must rely on others to accurately relay detailed, time critical information at the tactical command to the ashore fusion center, and so on. This method is neither adequately rapid nor reliable, given the volatility of communications afloat. Nonetheless, it is the current state of the art that is available during MIO operations. Giving the afloat officer the ability to communicate directly with the command operational center (fusion center) and technical experts will afford him with the synchronous collaboration capability that he needs to make rapid decisions and minimize operational risk to his boarding team. An example vignette follows regarding the localization and tracking of illegal WMD materials. During the search of a suspect merchant vessel, a boarding team member with a handheld WMD sensor device receives an indication that he is in the proximity of an unspecified type of fissile material. His sensor only provides information regarding the source's radiation activity. Unable to transmit from his present location, the sensor operator returns to the outside deck of the suspect vessel in order to transmit the readings to his tactical command. The data is then forwarded to a fusion center via satellite or another communication mode beyond the boarding team's range. Delays can and do occur but the benefits of providing the boarding officer with rapid, reliable, efficient communications with the fusion center and technical experts directly are clear. The team is safer and more efficient at adjudicating the situation. Time to make decisions on how to move onboard the merchant vessel, when all the crew is gathered somewhere and delays may create psychological tension, is a serious factor and if time is limited to the minimum extend then it is more productive and safer for the conduction of the mission. By this aforementioned example it is obvious that by giving to the action officer the capability of communicating directly with experts ashore is of critical importance and with the use of Picosatellites over the operational area we will have this capability in place by using command and control networks that will link the action area officer, the tactical afloat command and the fusion center as well. This is one approach that finally will provide effectiveness and efficiency to the completion of the overall operational mission. This approach is nowadays a need for MIO advising upon request which eventually will direct the mission to potential success. At least MIO advising in real time will not clog the evolution of the operation but it will add to it positive dynamics.

Picosatellite characteristics critical to MIO Support

In the described MIO project we use a particular version of the Picosatellite system, which is developed by the Interorbital Co, and is named as Tubesat. The NPS experimentation team has acquired three Tubesat kits, and, under the company's assistance and has assembled two of them using them in MIO testbed (figure 35), which are expected to enter the elliptical low orbit in 2017. Initially the launch was going to be executed by 2012 but a significant delay of 4 years for Tubesat launch has affected the whole design and operational process. At the same time though the usability solutions have increased dramatically and so we are going to use on orbit regarding mesh networking. Delays are due to NASA restrictions based on preparations from the company. To date 52 universities have bought this Tube satellite kits and have assembled them ready to send on orbit or create testbeds for further research and evaluation of space based solutions.

Figure 35: Tubesat Pico satellite (courtesy Interorbital Co [5])

Tubesat is a standalone picosatellite with minor capability of data networking, space imaging and on-board processing. The Tubesat has a total mass of 0.75 kg, including 0.2-0.3 kg available for the MIO experiment payload. It has been designed to operate for up to 3 months, from a 310 km circular polar orbit, with an orbital longevity of 3 weeks to 3 months, depending on the solar weather (the parameter here of orbital decay is in effect). To date, no picosatellite, including Tubesat has any on board propulsion, which is why the orbital decay parameter will affect the lifetime of the orbit. However and based on the analysis of a previous chapter orbit propulsion for picosatellites are available today in order to put them in orbit for more than 5 years.

Tubesat though is a type of picosatellite that can have similar operational characteristics with a cubesat or a microsatellite in general and for a MIO operation to be supported operational capabilities may include:

(a) Satellite Operational Lifetime: 20 days to 3 months, depending on solar activity,

(b) Real or Near Real time Tracking Capability: Real and non-Real depending on the selection of orbital parameters and the area of operation.

(c) Tracking Accuracy: None Real time or asynchronous data action officer on-the-move networking.

(d) Reachback Capability: Yes, with connection to MIO expert or C2 team ashore correspondingly.

In parallel the critical orbital characteristics include:

(a) Types of orbits that small satellites support: Circular polar orbit at 310 km to maximize coverage with 4-6 satellites.

(b) Lifetime consideration: 1 to 3 months depending on solar weather.

(c) Orbital decay parameter impacts lifetime of the picosatellite and the usable time of the picosatellite constellation. (if propulsion is being used this parameter zeroizes),

(d) Time of Revisit: a Picosatellite can be accessed every 1.5 hours, but refer to the STK analysis further down where analytical and detailed results are being mentioned.

(e) Security that is enabled: No security encryption on the picosatellite due to overconsumption in power due to high processing requirements.

(f) Back up satellites: It is relatively easy to place another picosatellite in orbit.

(g) Ability for satellites to crosslink and transfer data in near real time: Future capabilities, not yet implemented but possible.

Therefore, we conclude that for our research the type of parameters that are going to be utilized for our analysis are the so-called “Mission Critical Parameters”.

We are listing hereunder the Mission Critical Parameters that a small satellite (a micro or nano or pico satellite) must collect in order our operational mission to be antagonistic with respect to other already in existence.

“Mission Critical Parameters”:

- Satellite Operational Lifetime.
- Real or Near Real time Tracking Capabilities.
- Accuracy of Tracking.
- Available Data Transmission Techniques.
- Available Data Channels.
- Operating Principles of small satellites.
- Tactical Implications in MIO: Most of the times we do not consider the tactical requirements and discreteness of our mission.

We usually take into account the strategic and operational MIO characteristics of a mission but we leave the tactical level solutions to be carried out from people that finally implement the research. This is a classic mistake and it usually creates insolvable problems. In this experiment we will try to reach the tactical level and find out solutions that will be able to apply in a maritime warfare environment operation, such as trying to send back information while being on board a merchant vessel, searching for illegal WMD materials and at the same time executing an “opposed boarding” mission. If we manage to provide solutions that will be useful also in extreme situations then we have accomplished our primary goal.

Moving forward and for the completeness of our work, it is necessary before we proceed, to mention all the Operational Characteristics that have to be taken care of in order to fulfill a MIO mission. Under the work “Operational” we mean primarily all these specific tasks that need to be satisfied in order our solutions at the end to be realistic. At this point we must study diligently all the details that will finally comprise parts of the MIO scenario. These details are sententiously considered below [6]:

- Types of orbits that small satellites support, as equatorial or polar ones.
- Available footprints.
- Segments that use and provide.
- Lifetime consideration.
- Time of Revisit.
- Services that is able to provide such as SMS / FAX / Teleconference – Video.

- Security that is being enabled.
- Available data rate.
- Probability to establish a call.
- Probability of maintaining a call for LEO – Small satellites.
- Back up satellites for service if needed.
- Ability for crosslink among satellites to transfer data on a near real time environment.
- Ability of global coverage.
- Available power throughput.
- Ability of the signal to penetrate through materials (such as through walls or inside a ship). How weak is the signal to be transmitted during wall networking.
- How the signal is transmitted through oceans and distant sea regions (coverage especially for MIO environment).
- Meteorological situation and how is it affecting the whole transmission operation in microsatellites.
- What is the more applicable solution for blue force (allies) and red force (enemies) tracking?
- Vertical / Horizontal accuracy of the system especially for cargo vessels between searching decks.
- What are the available clock accuracy and the mistakes that can occur if clock accuracy is low?
- Is there any small satellite (such as Tubesat) with some kind of on board processing and what are the advantages that a MIO operation can acquire if this exists?
- Is there any small satellite available with electric propulsion so as to maintain the accuracy or to serve any other usability purposes on orbit?
- Reorbiting a small satellite in order to tag and track the maritime asset. Is there any possibility of doing that?
- Examine if it possible to simulate the mission by using available software, such as STK, in order to understand explicitly, prior to launching, the capabilities and coverage areas that a Tubesat can provide and uncover maybe any grey areas that have not been considered but affect the mission at the end.

- What are the implications in MIO scenario if there are no terrestrial networks to support the whole mission?

Tubesat STK modeling - Support to MIO

The described modeling effort above is based on the assumption that a boarding or field officer needs to communicate via picosatellite orbital nodes in a near real time environment, providing information to experts in data fusion centers and receiving an advice back from them (even in a near real time environment).

On a hypothetical scenario (literally happening daily on the operational world) is assumed that intelligence has been received that a merchant vessel or a small craft are transferring WMD materials in the area of operation. The detection / boarding team is deployed. The boarding officer locates the material but he does not know how to handle it. In this case he needs to send all the information that he has collected back to a fusion center, where a WMD specialist is behind a WMD in MIO cell advising the boarding officer how to react and what are the safety precautions that he needs to undertake. For solving the situation we create a satellite model trying to evaluate the use of orbital nodes during this operation to the tactical network in place.

The Tubesat scenario is based on sending data to a merchant vessel that is underway transiting the high risk area. The available timeframe for communication is 7 minutes four times per day increasing the total communication time to 120 minutes. This time is more than enough for feeding the Captain of a maritime vessel with valuable information supporting his proactive actions towards a maritime illegal act situation that may occur [8,9].

The STK model of Tubesat integration in such type operation was designed based on two options. The first modeling option is based on a four Tubesat type picosatellites integration in MIO Reachback. The second modeling option is based on a six satellites integration capability. The orbital characteristics have been selected so as the satellites to be in polar orbits and the apogee and perigee altitude remains constant at 310 km due to the fact that the Tubesat PICOMIO satellites will orbit in this altitude. The inclination for every satellite has been chosen to be 90 degrees and the true anomaly for the circular orbit is always zero. The two parameters that we are changing is the Argument of Perigee and the Right Ascension for the Ascending Node (RAAN), which are being changed respectively in order to have an optimum coverage in the areas of interest.

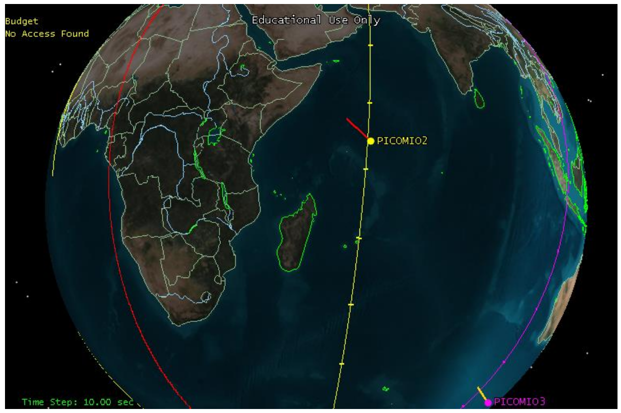
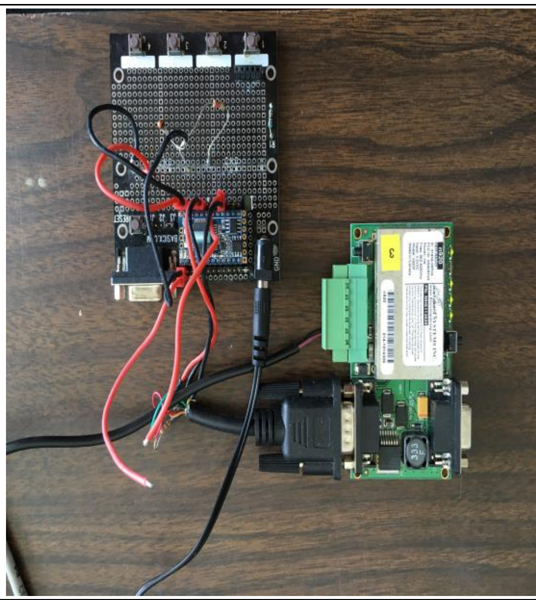


Figure 36: A pico-satellite is passing over the area of maritime operations in the Somali Basin – STK modeling.

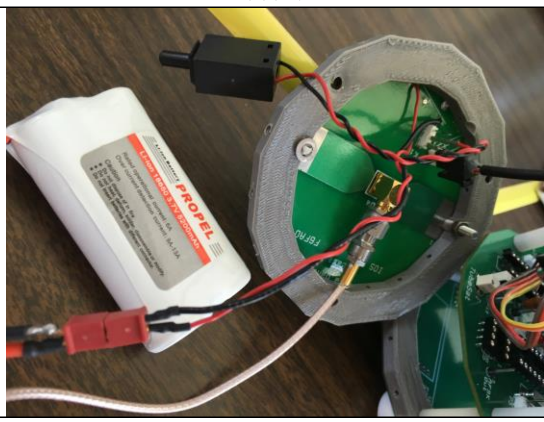
Assembly of the Tubesat picosatellite

During Ph.D. research a Tubesat picosatellite was assembled in order for us to visualize what a real Tube satellite is and what are the capabilities that could encompass on a maritime security mission. Of course this work has been done with the immense support and guidance of Professor Alex Bordetsky, Director of NPS CENETIX Lab and his Chief engineer Mr Eugene Bourakov. During the assembly of the satellite the writer had an in depth access and study to the design and creation of a satellite ready to be launched. On board the satellite a communication equipment installed and tested with the NPS ground station testbed proving that a message of at least 300 bytes of free text can be passed correctly and transfer all data that can be used for a maritime security mission.

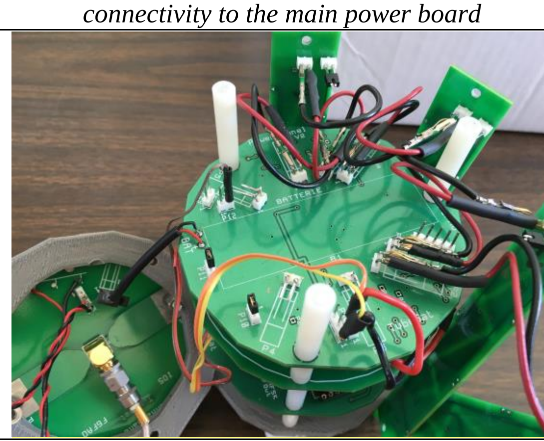
	
Tubesat assembled with solar panels	Side of Tubesat without solar panels showing all different connectivity through the boards
	
Development model of the Tubesat on the testbed	*Model of a Ground Station for communication with Tube satellite*

Solar Panels connectivity and soldering to the board

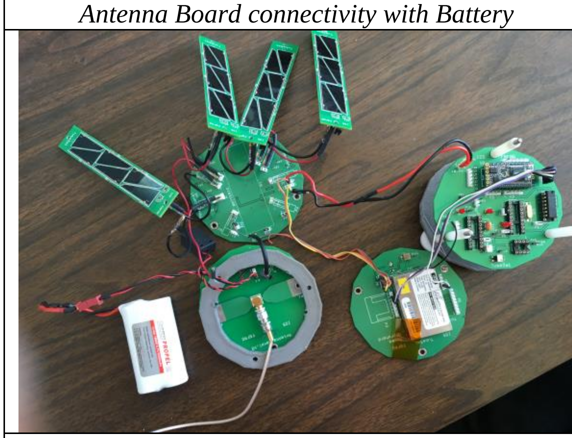
Disassembled solar panels showing the connectivity to the main power board



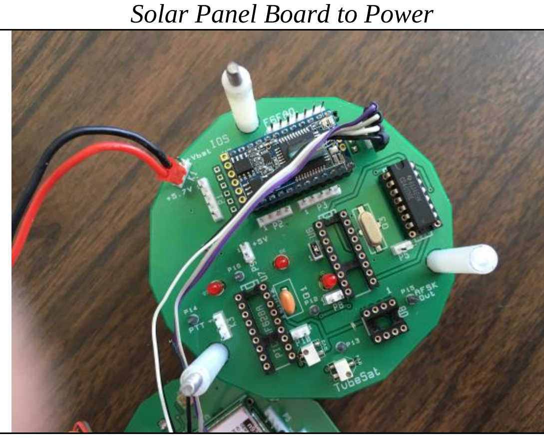
Antenna Board connectivity with Battery



Solar Panel Board to Power

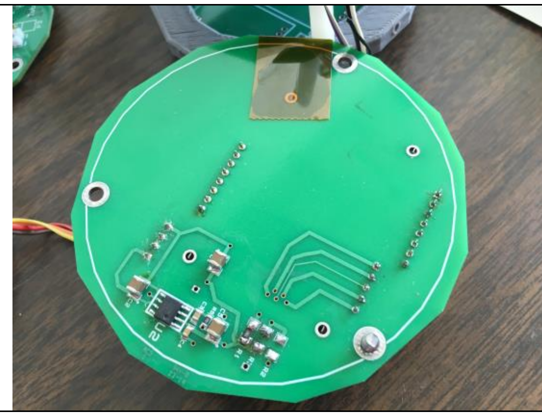


Antenna, Solar Panel and Radio Connection to OBC

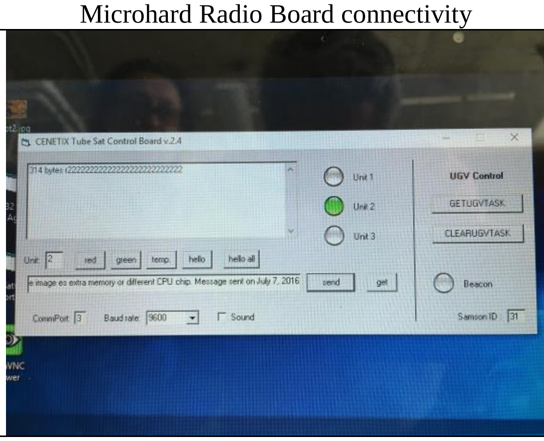


Tubesat OBC board

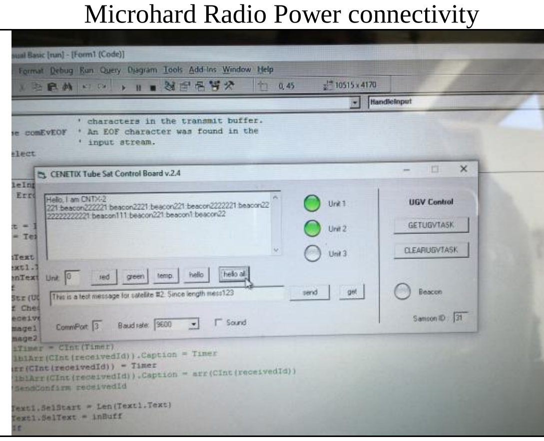
Microhard Radio Board connectivity



Microhard Radio Power connectivity



First message to the Satellite in Testbed



Two satellites (green lights) are working and send a message of 314 bytes in 8 seconds to the Ground Station model (slow response)

Figure 37: Design Steps of the Tubesat Picosatellite

(Courtesy Naval Postgraduate School – CENETIX Lab - http://my.nps.edu/web/cenetix)

Picosatellite integration modeling results

We've conducted the simulation runs for both models based on the NPS scenario for the upcoming MIO experiment in the second half of 2015. Table 37 illustrates modeling results for the Tubesat expected passes on June 6th indicatively. It highlights the fact that and approximate total time that the PICOMIO satellites will be available for communication is 120 minutes per day. The model identifies vital time-delay structure for boarding officer reachback communications. On a given day the total passes of the four Picosatellites are fluctuating from 12 to 18 consecutive orbits. Each time a satellite is orbiting over the ground station or over the operations area, the time duration that we can have access to it is also fluctuating from 2 to 9 minutes. So this is the optimum timeframe that we can use in order to send information back and forth to a ground station or to an operational area. The approximate total time that we have during a whole day to communicate through a satellite is 120 minutes (2 hours during the day). In table 38 we can see for the dates of 6th and 7th of June 2011 that there is a gap of almost one and a half hour by the time that we will have the next satellite in place to communicate. The total gap time between satellite passes during one day using four satellites is approximately 22 hours.

Date	Satellite	Passes / Satellite	Time (GMT)	Duration (min)
6th June	PICOMIO 1	4	05:09:41 - 05:18:35 06:43:08 - 06:47:11 16:14:30 - 16:20:26 17:44:02 - 17:52:40	9 4 6 8
	PICOMIO 2	3	07:49:59 - 07:58:18 09:21:23 - 09:28:11 20:22:44 - 20:31:42	9 7 9
	PICOMIO 3	4	00:33:12 - 00:38:50 10:40:23 - 10:48:15 12:11:05 - 12:18:38 23:12:53 - 23:21:50	6 8 7 9
	PICOMIO 4	4	01:51:42 - 02:00:08 03:22:56 - 03:29:33 13:30:53 - 13:38:10 15:00:54 - 15:08:59	8 7 8 8

Table 37: Overall MIO scenario results with a use of 4 picosatellites

Start Time of Pass	End Time of Pass	Gaps among passes
00:33:12	00:38:50	1 h 10 min
01:51:42	02:00:08	1 h 22 min
03:22:56	03:29:33	1 h 40 min
05:09:41	05:18:35	1 h 25 min
06:43:08	06:47:11	1 h 02 min
07:49:59	07:58:18	1 h 23 min
09:21:23	09:28:11	1 h 12 min
10:40:23	10:48:15	1 h 23 min
12:11:05	12:18:38	1 h 12 min
13:30:53	13:38:10	1 h 22 min
15:00:54	15:08:59	1 h 06 min
16:14:30	16:20:26	1 h 24 min
17:44:02	17:52:40	2 h 30 min
20:22:44	20:31:42	2 h 41 min
23:12:53	23:21:50	-
≈ Total Gap Time in one day		**22 , 5 hours**

Table 38: 6th June 2011 - Total gap timeframe in one day

Table 39 represents the modeling results for expected coverage time in the footprint of MIO experimentation sites, as provided by using four or six Tubesat type Picosatellites from 4th to 12th of June 2011. The results clearly illustrate that by adding two more satellites to the MIO experiment support orbit the total daily time coverage is being increased by 3 - 4 % which is approximately 1 hour and 20 minutes more per day.

Dates in June 2011	Daily Percent Time Covered 4 Pico-Satellites	Daily Percent Time Covered 6 Pico-Satellites
4	7.00	11.32
5	7.17	11.84
6	8.10	11.81
7	7.92	11.66
8	7.96	11.66
9	7.77	10.14
10	7.23	10.15
11	7.52	11.51
12	7.62	11.67

Table 39: Daily percent time coverage with the use of 4 and 6 pico MIO satellites 4th -12th of July 2011

Picosatellite Orbital Decay Effects

Finally we should refer to the Orbital Decay Characteristics of the Pico satellites because the TUBESAT solution that we are using is not having any type of propulsion on board so it will remain on orbit for a period of time depending on the sun activity. In our STK model we insert the parameters that we see in the following table.

Orbital Decay Characteristics	Value
Cd	2.033
Cr	1.33
Drag Area	0.01365 m^2
Area Exposed to Sun	0.01543 m^2
Mass	1 kgr
Atmospheric Density	Jacchia 1970 model
Solar Flux sigma level	0

Table 40: Tubesat Orbital Decay Characteristics

After running the model with the above mentioned orbital decay characteristics (table 40) we acquire the following results. The PICOMIO satellites will remain on orbit for a little over a month, ranging from 30 – 33 days).

Pico Satellite	Date (June)	Time (GMT)	Orbits (one month)	Lifetime (in days)
PICOMIO1	4	07:39:32	527	**33**
PICOMIO2	3	19:28:47	528	**32**
PICOMIO3	2	05:54:02	503	**31**
PICOMIO4	2	07:29:36	504	**30**

Table 41: Lifetime of PICOMIO satellites

Changing in the model Cd or Cr coefficients to be identical as 2 and 1 (best case scenario) are only changing the orbital path for only one orbit. For example, if we change Cd and Cr for PICOMIO1 to the identical values of 2 and 1 respectively, it will change the orbital value only for one orbit, from 527 orbits to 528. The change is neither critical nor serious. The lifetime parameter influences the orbital path and the satellites to be up there for almost a month and this is the important fact for our maritime scenarios. In this short reference we are trying to propose to international maritime community a small but smart satellite command and control system that will be effectively used from every platform and will convey all information from the area of operation to a fusion centre ashore minimizing the assorted costs and giving to interested community (e.g. a country, a non-governmental organization, an international organization) the desired effect, which is intelligence superiority and dominance over a specified area of interest. This system needs to be cost effective in such a way that by comparing it with systems that are now in use will give 50% more surveillance capabilities and it will be at least 50% financially more effective from any other asset in use. This should be our initial goal, yet very difficult to accomplish.

Orbital Analysis and Results

Our attempt is to use the inner space area (very low earth orbits) for implementing such a solution by incorporating very small satellite technologies in order to drive us to the required solution. The pathway to this end result and goal is not easy, needless to say that at the same time during an era of global economic crisis it is imperative for us to prove to international maritime community that a very small satellite system can be a viable solution and decrease the amount of spending money daily in operations. By accomplishing all of the above a new business model should arise with less personnel capacity to be used in maritime security operations than it is used today, such as the participation of military personnel on board military ships on very long sea tours in the high risk areas of operation (e.g. Gulf of Aden).

Following our analysis and being more specific we propose the so called nano or pico satellite system which usually refers to a standalone satellite bus with weight smaller than 1 kgr, capability of earth from space video imaging and simple on board processing. Flying on very low earth orbits, near the outer atmosphere at around 300 to 400 kilometres from earth's surface, these toys can convey viable information to any fusion centre ashore or to vessels underway by using basic communication schemes that are not subaltern from any other modern communication application used in space. If we are able to have up to 1.5 Mbps bandwidth and at the same time capability of transferring audio, data and even video (current level of technology) at all times through satellite passes, then we would definitely say that this application is worth mentioning and being researched. A system like this (standalone pico-satellite), which is flying at so low orbital paths can communicate on earth and transfer information covering 12 to 15 % of daily time (around 1.5 to 2 hours). Also using more than one small satellite, let's say a cluster of a dozen of those we cover almost the whole daily timeframe on top the area of our operations, leaving the only thing still to consider the cost. But the cost for a small nano or pico satellite is not high. With less than few thousands of dollars (all inclusive) you can have one of those little "toys" flying over the earth for the duration of your operation and as the technology now stands with maximum satellite lifetime to reach three to four months. Therefore the situation now is that this system can stay up only for a mission oriented operation with a timeframe of three to four months (orbital decay parameters are being implemented). Still we do not have the capability of applying micro propulsion systems on board, but it is a fact that for sure is going to happen in the near future. With the application of small but effective microwave electrothermal thrusters these satellites will have the capability of increasing their flying lifetime over the earth for almost 7 years or so and they will provide us with services that current satellites are providing with very high costs including maintenance and flight sustainment. To sum up and set the technological limit we should say that although the concepts of nano and pico satellites have been experimented with for over two decades now, stable and successful designs in the 1 kg class area are so rare, that are virtually non-existent. The design and manufacture of very small satellites is not simply a matter of miniaturization, but as the experience has proven, several technical hurdles such as space qualification of materials and systems, power system design, and orbital control and ground control assume enormous significance in the design process[26]. The solution though to the application of a nano or pico satellite to a real operation is now closer to reality than ever before.

Comparing the above figures, we can say that if you have a small cluster of picosatellites (let's consider tentatively six of those) and each one of them costs around 10.000€, then with 50.000€ you can have adequate coverage of an area of operations 24/7 and at the same time the amount of money you have spent for the next seven years or so is nothing to be compared with the one being spend today. Imagine that a medium size ship (e.g. corvette or frigate) costs thousands of euros per day (usually more than 30000€ or even more - approximate figure) containing the amount of money that is being spend for oil, maintenance, salaries of personnel and other side costs. Additionally this operational planning (with surface ships) does not give you the capability of covering a vast or even a large sea area, since a ship is deemed to be positioned on the surface of the earth and the capability of providing accurate info is limited to some decades of miles. With small nano or picosatellites the coverage is complete (day and night) and the cost will be approximately 150 to 200 € per day, which compared to the amount of money that a ship is spending per day to the high risk area is nothing. The difference in cost is very large and the advantages are at the same time innumerable. In maritime security situations like illegal trafficking of goods, embargo operations, counter piracy operations, human trafficking, slave trade, illegal fishery, illegal environmental pollution, drug trafficking and other illegal activities that may happen in the maritime environment we need robust surveillance or real time intelligence support and the proposed system can help confront them efficiently. It is our belief that any conventional or unconventional illegal activity in the maritime domain can be diminished effectively with the use of these small technological assets. It is not an exaggeration to say that by applying this technology we could search and cover the critical maritime environment areas throughout the world's Sea Lines of Communications with relative easiness and primarily with the use of few national or international assets. The only thing that needs to be done is for the academic society to undertake the risk, make relevant research and combine the effective, efficient and affordable parameters into one small pico-satellite device (research is currently ongoing). The creation of a really miniaturized plasma propulsion thruster (in the range of some grams) is a part of this solution of the problem helping to extend the life of the pico-satellite from months to years. Also miniaturized cameras or any other commercial sensor could be used to increase the operational effectiveness of the satellite itself with less additional cost. If these could happen then a breakthrough to the international maritime industry and community worldwide would occur. The will is here. It only remains to be executed through well-formed combined academic and industrial initiatives.

The above mentioned potential solution could be a saviour and having a major operational impact for a number of different actors that make their living in the maritime environment (e.g. merchant mariners). Let's consider a merchant marine company that needs fast, reliable and cost effective intelligence data in order to transit the Gulf of Aden or an area where piracy is the main problem. The pico-satellite conveys the real time data information from the area of operation to the fusion centre or to the merchant vessel itself. By this way, all info is relayed to the merchant vessel, prior to their transit of the area of elevated risk. The pico-satellites could transfer 24/7 real time information (data, images) to the merchant vessel. Therefore the captain of the ship knows well in advance what is happening around his ship in a vast area and that gives him the capability of taking fast and proactive active or passive measures in order to tackle any illegal action towards his ship.

On another potential risky area, like human trafficking, a realistic example is that we may need to verify if small vessels transiting near the shore are conveying illegally people from one country to another (transferring illegal immigrants). The above mentioned standalone maritime surveillance system could be used and provide 24/7 real time images to a command and control centre helping to cease this problem or at least arrest the illegal conveyers on the act.

It may seem futuristic or utopian that a very low cost solution from space could solve so many problems happening every day in the maritime environment. It is not though difficult to apply such a solution but of course political and legal wills will remain critical factors. Covering with images an area on top of a country has legal limitations in the international community and this is something that needs to be examined before proceeding to the execution level. It is worthy though to undertake such an endeavour and find solutions that will help humanity to stop the emerging problems that occur in the maritime environment and impede the safety of transportation via the navigation lines.

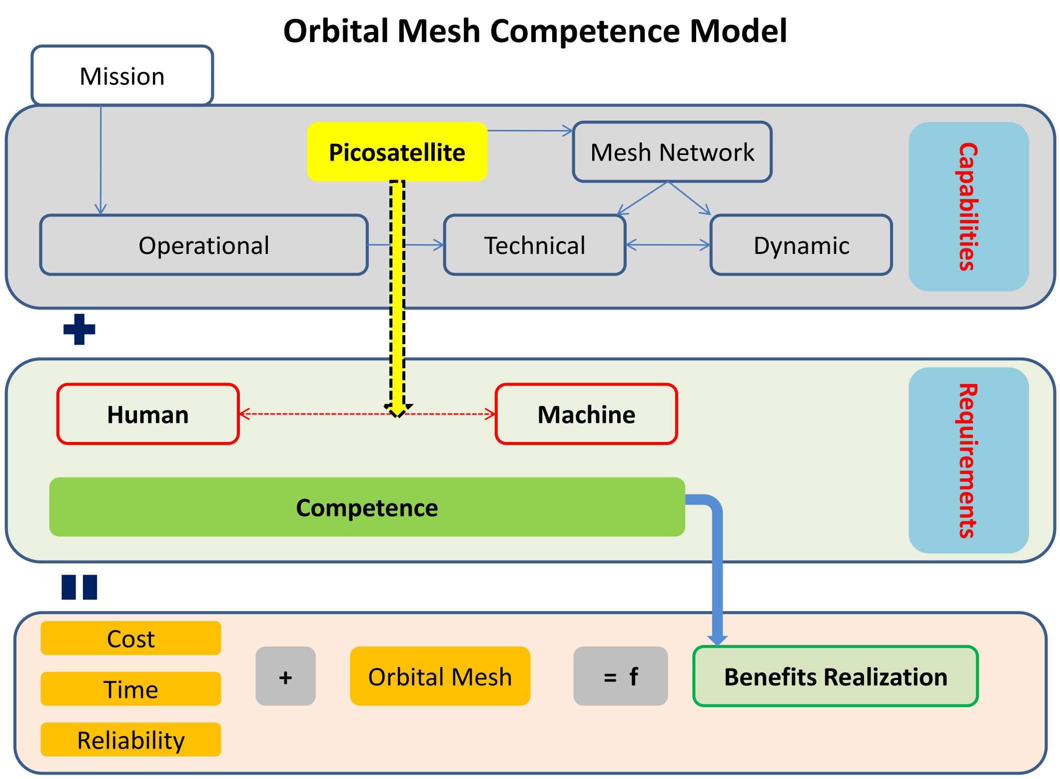
Orbital Mesh Competence Network Model

Consummation of the experiments with Tubesat and Lambasat picosatellites in the last three years has taken us to the point where a future model needs to be created as a whole brightness of our research. Taking into account all limitations, capabilities and requirements that we had encountered in order to run our ideas we have concluded in some serious results and thoughts that constitute the future benefit roadmap and the concept foundation model for future research verification by quantification.

Ad hoc networks have been around for many years trying to make our lives simpler but dynamic. However, their fitting into our traditional environment has revealed science gaps when the application theory comes to reality. These gaps are usually very difficult to overcome and the primary reason is human behavior and interaction. It is evident that people have limits in their capabilities especially on how they react to decision making and to their base knowledge of things, as it was well described in Bordetsky - Niessen’s paper regarding modern theory of information flow. This typical and obvious reality along with cost, time and reliability of systems creates a coarse environment to perform successful tasks. A basic but solid result from our experimentations was the numerous cases observerd where no results or not the desired results were being acquired to the mission, due to the fact that the modern systems design applied theory have inherent limitations to be overcomed under the traditional way of thinking.

Our work with pico satellites revealed those limitations and gaps in time, cost and reliability and through our experiments we faced up problems that lead us to record chasms, advantages and disadvantages from the application of orbital nodes to an ad hoc network. Critical parameters for orbital nodes have been collected dilligently and listed to other and this chapter of the dissertation. In this specific paragraphs we are called upon to envision a concept that is a logical conclusion to our observations. We propose this concept to be quantified in a future reserearch effort through a new set of experiments proposed at the end of this chapter. It is our firm belief that a new era in interconnection of networking capabilities and requirements which will lead us to enlighten and head our efforts in different ways of thinking and acting regarding mobile ad hoc mesh networks.

The created visualized model is called "Orbital Mesh Competence Model" transferring practically the idea of competences to a network decision process taking into account all critical dynamic capabilities and parameters that a network must encapsulate in order to prove itself rigorous, agile, flexible and transgenic.



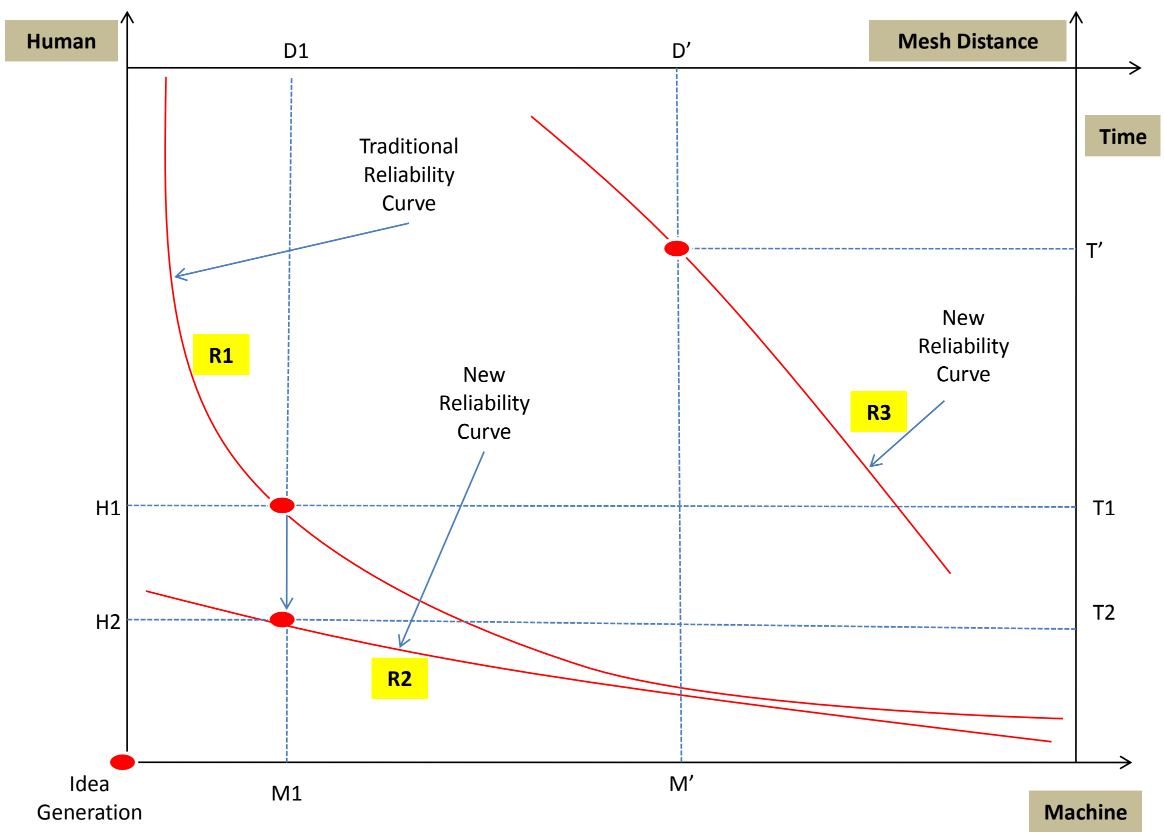
Graph 27: Interrelation among three different levels of Space Orbital Mesh Competence Model.

Let's hypothetical assume a mission to be conducted in a multidisciplinary environment. The word multidisciplinary represents here near and far, close and distant, fast and slow, dynamic and stable, low and high level communication paths as well as many other parameters one would like to add on. The end result of the associated mission should be the provision of services to people needed access to a network and elaborate critical information in order to complete the mission successfully. For that, a 2D graph has been created in order to pinpoint and tabulate on one single icon different characteristics as well as all the different levels of hierarchy and comms that information should go through in order to efficient and effectively reach the end of the mission.

Nowadays in traditional mesh networking environment there are specific capabilities and requirements fullfilled. Operational and technical parameters need to be closely interconnected in order to create an environment that will finally push the information to the next possible level. Below that level another level exists where humans and machines are needed to interact properly (noone has ever investigated the word “properly”) so as for an information route to be completed and transferred through right allesy in the network. This is not though always the case and when it happens it is because a decision has been administered by a suitable person. What happens though when a decision maker has a different knowledge background or competence level from the desired? The decision making process then delays in the best case or stops and the network does not correctly respond. Then the machine creates a partial successful solution and push the information not in the best possible route concerning time, cost and reliability of the whole system. At this point is where the idea of “competence” takes place fetching association of humans and machines not in different but in the same level of interaction and ability.

Competence is a measure of a knowledge level inside a multidisciplinary environment, it has to be associated only with similar knowledge levels (machines or humans) in order to act beneficially and depends upon a lot of factors starting from the psychological situation of the persons up to their total human performance and touches upon training, capability and a number of other factors that need to be recorded properly and carefully. Application of competence to the system has also different levels of response in humans and machines depending again on time, cost and reliability. Quantifying and discriminating diligently levels of competence and linking machines with humans in a way where competence of a human is equal to the competence level of a machine then the best possible result for information flow will occur in a fast and reliable way and at the end the successful completion of the mission will happen, with regards to minimization of cost, time effectiveness and increase in reliability.

Following the above notion a benefits realization roadmap could be created in accordance with provision of services and usability of mesh networks in the future environment. Having set the above conceptual background we then insert orbital node or nodes to our mesh network and manage to minimize time and cost by increasing at the same time reliability of transfer of information. Adding one or a series of pico satellite orbital nodes able to communication during orbital crossroads on the mesh network a fundamental capability is being acquired with two very important principles. First principle is the decrease time of reaction with regards to flow of information by sending info up space and then back to another entity on earth and secondly we give the absolute freedom and ability to the system to overcome places where human and machine interaction is not appropriate. This is doable by the use of intelligently sophisticated methods by overpassing low and not acceptable levels of human - machine interaction. Therefore the human - machine gap of not associated competence levels has been tresspassed by adding an orbital node and have a proper competence flow level of information from another user or entity on a dynamic way.

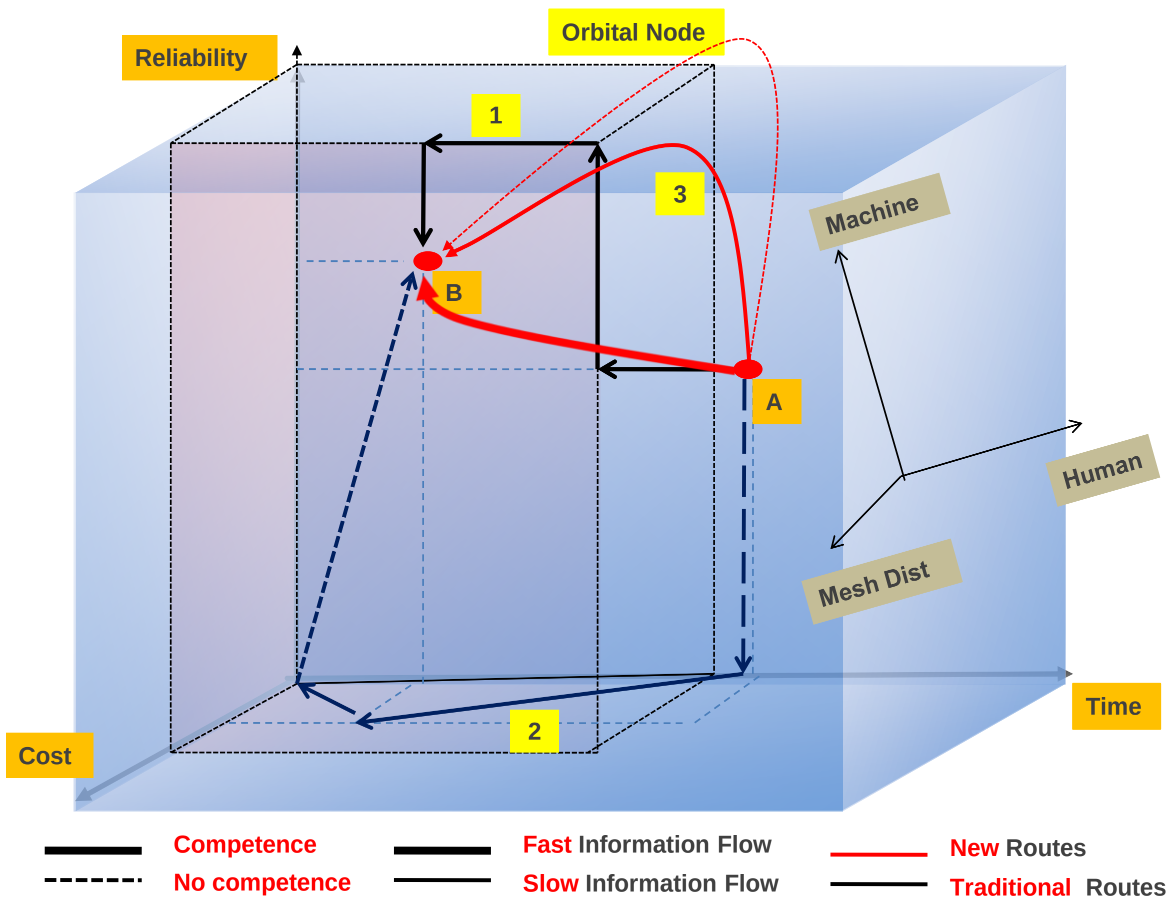


Graph 28: Reliability function in human machine interaction

After the analysis of the the first graphical approach and having set up the conceptual background we then can move onto our next visualized graph (elaborated directly from our set of experiments and experiences collected) where we initially attempt an assignment of relationships among the creation of orbital mesh competence hierarchies (human - machine interaction) with the factors of time and the acquired mesh network distance. Cost is not yet represented since it is associated with reliability and time and is going to be referred explicitly on next analyzed 3D graph representation.

Before we proceed we must make a critical clarification referrring to Human-Machine interaction. When we especially mention human competence levels we not only refer to classical attributes but may also include psychological, economic, political, ethical, legal attributes of the person that could influence the competence level of the mission. The above attributes in literature are ofter reffered as PEESLE. Reliability is now the factor that needs to be analyzed and a curve must be produced to represent realism. Even if this is still conceptual, we already now from empirical and the traditional way of thinking that reliability changes almost linearly and changes its behavior in accordance with time and cost. On the other hand and if human and machine interaction used as parameters in x and y axis respectively then our sole aim would be to create a new reliability curve similar to the one depected as R1, where as machine interction increases, human interaction decreases and reliability either stays the same or is being increased. Conversely, if human interaction increases then machine interaction decreases and reliability shrinks down towards zero. In parallel reliability curve R2 represents the future end result by adding an orbital node to our system and create smart levels of competence among factors. Then as you see even if machine interaction remains the same Time is less and human interaction is also less. Moving to another option of possible reliability (best case scenario) we notice in curve R3 that machine interaction increases, mesh distance increase, time decreases and human interaction also decreases. This different options of course are now empirical and needs to be normalized through careful quantification using mathematical appropriate models.

The ability of the system though to decrease human and time parameters as well as to increase in parallel mesh acquired distances and machine interaction with a positive effect in reliability function is due to the fact that an independent variable, which in our case is called orbital node, has been added to the system. The role of this variable is to police and manage the network with the use of one or a series of picosatellites in a way that if human - machine interaction are hoping on different competence levels to intrude and undertake the effort of information flow to a different more effective route, even solely through space. By that way we manage to sustain reliability status in less time, increasing the reliability avoiding human decision errors based on competence levels and increasing the mesh network distance. Moving to our next and final representation of our model we know in a 3D graph associate Reliability, Time and Cost in a common environment. As we know cost drives significantly the decision making processs today. Our traditional environment is being represented with a cube where a set of coordinates with Reliability, Time and Cost covers our way of thinking. However taking into account a new set of coordinates, of the factors analyzed above, Human, Machine and Mesh Distance, we envision to prove that this two different systems of coordinates we have observed needs to be associated or even better to replace Time, Cost and Reliability in a new cube of Human, Machine, and Mesh Distance interaction. This new envrionment is smaller than the previous one, but only in the axis of Time and Cost. If orbital nodes are being added to the system and so we increase competence levels of information flow, then reliability plane of the inner cube is being observed to the same height whereas the other two planes of Time and Cost must be decreased accordingly. In order though to move from the outer to the inner cube a solution is needed to help us "fly" and close the gap. That is where orbital nodes and competence levels come to play their important role. Traditionally we move through the edges of the cube following a logical road with rectangular way of thinking (black arrows indicate possible routes 1 and 2 of traditional decision making mesh networking). By adding competence levels and dynamic capabilities to the system it means that new ways may arise, such as the red lines, where orbital nodes and competence levels have been enabled. Thick and solid red lines indicates a compence and orbital node hierarchy has been applied whereas intermittent indicate that no competence level is in place. There maybe numerous other ways of moving from the outer to the inner cube, we are just representing only some fictitious ones.



Graph 29: Orbital Mesh Network Competence Model

As mentioned above, the model we propose is called orbital mesh network competence model. This specific approach can also incorporate other innovative dynamic autonomous capabilities in order to be further enhanced. An example to this could be UAVs or generally robots. It is being estimated that if all those new capabilities are being associated properly with the new requirements then a tremendous positive energetic dynamic capability will arise and the results maybe change totally our way of conducting operations. Under a generic view the above mode is part of the so-called systems design science and all the above parameters must be quantified to create a human - machine interaction compeence performance index .

Coming back to where we started in graph 1 a benefits realization roadmap has to always be created in order for this metric to be proven that is accurate. Benefits is the end resulting factor of our model and should be a vector taking into account that represents factors and parameters in at least three dimension. Benefits should be a function of Human, Machine and Reliability,

Benefits = f (Human & Machine & Reliability)

As it has been tested and proven in Chapter 8 Competence is a factor of Knowledge, Understanding and Processing. This work has been conducted in counter piracy training of personnel participating in counter piracy missions. By measuring the level of training one has we could measure eventually the competence level of the human. Broadly using the same technique of multilinear analysis we can use as a starting point the below function of competence where weight criteria must be established and criterion Average (A) must be calculated among interviewed SMEs or information flow routes investigated in different scenarios / set of experiments. Then a metric in competence can be created for all different levels of human machine interaction.

$$C = \prod_{i=1}^{n} w_i A_i$$

Where,

C = Competence Level

w_i= criteria weight

A = Criterion Average across SMEs

n = number of total criteria

The above first quantification approach should start with multidisciplinary analysis of all collected factors that could potentially influence the whole system. For that reason a set of experiments must be performed in order to fulfill the above intriguing task.

A cube or pico satellite is needed to be on orbit with employed mesh network equipment on board. From our analysis above mesh network radios could be employed to a cube satellite taking into account all technical characteristics like weight, temperature, power consumption and all other parameters. As one can see from the below tables there are available mesh network radio equipment that could potentially be employed to a cube satellite taking into account available space and connectivities. Referring also to access times, lifetime and the parameters that have been tested with Tubesat on the development testbed, it is evident that some software programming work needs to be employed in order to interconnect the satellite with down in the earth mesh network machines. However, when mesh network goes into space then we can produce quantifiable measurements of the quality of the messages received from space and how a pico satellite could serve as an orbital node to decide for competence levels and police human machine interaction.

To a second extend these measurements have to be analyzed accurately in order to evaluate the above graphs and create accurate points on how a pico satellite orbital node could affect competence hierarchies and finally work as a policing node to system's design.

Orbital Mesh Competence Model is meant to be one solution to overcome traditional way of thinking and add more reliabiltiy and finally benefits to our systems future design by interlinking humans and machines in a competence based reality.

Picosatellite Orbital Node Networking Feasibility

All the above mentioned and analyzed information is critical, important and concise. However and in order to consider picosatellites working orbital nodes we need to technically evaluate the use of mesh network applications on board a picosatellite and then try to understand what are the limitations we have if we decide to transfer mesh networking capabilities in space. It may not have only limitations but through this research feasible paths could appear that will open new roadmaps to future networking capabilities.

In order to conduct this part of the research the following steps will be followed: First of all we are going to collect all available data for Tactical Mesh Network Radios from commercial applications and tabulate them in accordance with their characteristics (technical and operational).

Secondly, we will compare the collected data with picosatellite operational and technical capabilities and will then create a table with GO/NO GO criteria for those applications that could be used as mesh networking assets in space. This analysis is going to be made using examples of mesh networking radios available in our Testbed.

On the next step of our research we will finally pinpoint all those minimum requirements that a tactical network needs in order to be employed on a Picosatellite or Cubesat. Hence the result would be the above mentioned notion (in the previous paragraph) of how we could possibly could implement a mesh network on orbit taking into account all the above critical design requirements and parameters. All the above are being imprinted in the innovative Orbital Competence Model presenting design parameters and requirements in a common place as well as functionality and operational characteristics.

Tacit results should be extracted directly after the implementation of the experiments, whereas human and machine interlink is be a baseline parameter for it. It is important following the above analysis and work to have a concrete benefits realization map for mesh networking information flow in orbit as well as all the reachback and responsive picture of it by incorporating multilinear dimension analysis for the above mentioned elements as explicitly described above.

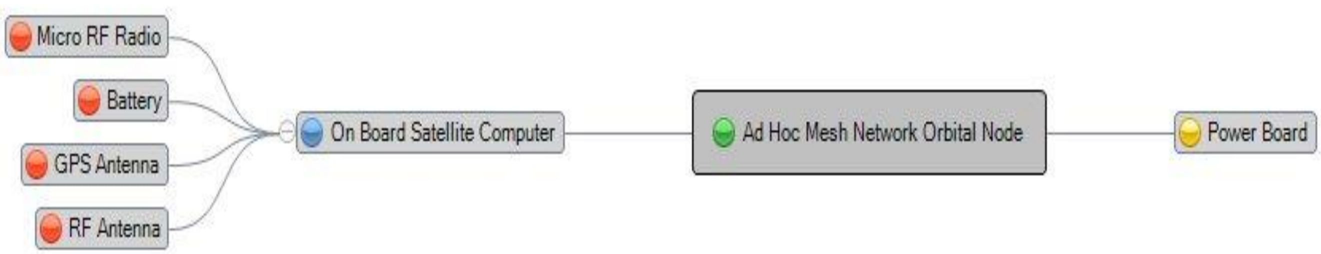


Figure 38: Ad hoc network equipment on a picosatellite node

On the above simple graph one can visualize what are the additions needed on an Ad Hoc Network equipment in order to be placed on orbit on a picosatellite. Below photos shows that neither the weight nor the size are factors that could possibly hinder the application of those mesh controllers on orbit. In fact only power requirements may impose a problem on the satellite power budget allocation, but for a 3U cube satellite power can easily reach 5 through 10 watts and so the operation can be sustained.

Figure 39: Parts of MPU4 and Quad microcontrollers that could be place on orbit on board a picosatellite.

Market Available Mesh Tactical Equipment

No	Type	Output Power (W)	Power Consumption (W)	Weight (gr)	Input Power (VDC)	Antenna Connectivity (V)	Frequency (MHz)	Bandwidth (Mbps)	OBC Compatibility	Size (cm)	Temp (ºC)	Voice /Data
1	MPU 4	0.005 - 1 Depending on pins	4.1	499 without battery	8	Active 3.3	907-4985	41	UDP / TCP	11.7 x 7.6 x 3.2	-40º to 85	Both
2	Quad	0.005 - 6 Depending on pins	8	1451.5 with battery	10	No	907-4985	41	UDP / TCP	21.6 x 15.2 x 5.1	-40º to 85	Both
3	Harris Falcon III RF-7850S	3.2	3.2	775 without battery	N/A	Yes - USB 2.0	225 - 2000	1	USB 2.0	21.0 x 8.0 x 5.0	-30º to 55	Both

Table 42: Market available mesh tactical equipment

No	Picosatellite Technical Limitation	MPU 4	Quad	Harris
1	Power	Yes	No	No
2	Output Power	No	Yes	Yes
3	Frequency	Yes	Yes	Yes
4	Data Compatibility	Yes	Yes	Yes
5	Temperature	Yes	Yes	No
6	Size	No	No	Yes
7	Weight	Yes	Yes	No
8	OBC Compatibility	Yes	Yes	Yes
9	Voice / Data	Yes	Yes	Yes
10	Antenna Connectivity	Yes	Yes	Yes
11	Bandwidth	No	No	No

Table 43: Picosatellite GO/NO GO criteria for orbital node application

Below adequate limitations independently from the technical characteristics of the radio depending on the operations that have to be drawn attention taking into account the operational limitations of the Picosatellite.

No	Picosatellite Characteristic	Influence on MANET	Comment
1	Lifetime	No	Limited comparing to traditional satellites
2	Orbital Decay	Yes	Available only for some months
3	Window of Communication	No	Near Real time communication If more than one satellites on the same orbital path it can work as relay node on orbit
5	Doppler Effect	Yes	Alter the frequency up or down and needs mechanism for compensation
6	Tumbling Effect	Yes	Work only if Omni antenna
7	On Propulsion	Yes	If there is no propulsion then it will have orbital decay
8	Radiation Shielding	Yes	Degradation of electronics on the radio - Need hardening

Table 44: Picosatellite Mesh Operational Limitations

Conclusions

The modeling results clearly demonstrate that having six Tubesats in polar orbit would provide have an operationally effective communication window, as big as four hours per day, depending on the configuration of the satellites. However, based on the described modeling results for four Picosatellites, we are going to have almost 2 and a half hours availability of communication which is enough time for applying reachback methods in operational use. The field officers need this capability in order to enhance their mission success and safeguard their tasks performing work on board suspect vessels through the tactical orbital reach back to fusion or/and C2 center experts. The proposed picosatellite based networking model contributes directly to the emerging concept of Space Operations to Counter Maritime Terrorism (figure 40) by populating the “funnel” part of the diagram.

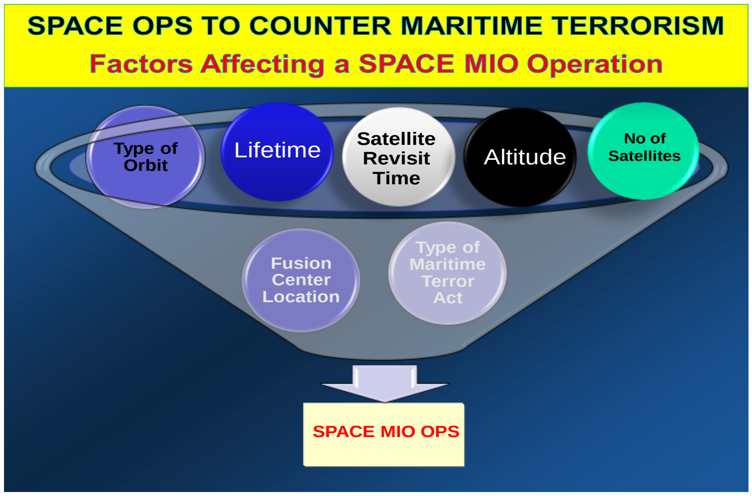


Fig. 40: Concept of Space Operations executed for supporting the Maritime Interdiction activities

It is evident from the simulation of the above three different scenarios (one with one microsatellite - FO-29, and two with four and six Picosatellites - Tubesats) that the daily percent of coverage is changing by a small factor from 2,3 % up to 11,3%. It is important to evaluate the course of a ship knowing that with one or six Picosatellites the difference is almost 11% but it is far more important to evaluate the use of Picosatellites when having 24/7 coverage for providing continuing communication coverage with the vessel. In the next subchapters we are going to simulate the movement of a vessel accordingly which is transiting through a pirate high risk area and we will finally find out how many cubesats / Tubesats or generally Picosatellites (less than 1 kgr) we need in order to cover its movement providing continuous coverage. We also need to mention here that the above satellites should have a type of orbital propulsion such one of those proposed above in chapter 3, so as to be stabilized on orbit and do not decay in the atmosphere like in the case of the Tubesat.

The above short but concrete analysis tried to provide to the potential reader an alternative way of how in the future maritime security operations can be supported and executed with alternative cost effective ways. It is yet to be proven that solutions like micro and pico-satellites will succeed in the years to come and having in mind the advent of microsatellites (space assets less than 100 kg) two decades ago, where it seemed unreal that solutions like those could place themselves in a way that would change absolutely the daily operational world, then is more than evident that nano or pico satellites solutions will ameliorate our world towards cost. Future is not very far and the technology has proven numerous times that can provide solutions better that those we can imagine. It is only a matter of willingness, persistence and hard work that will lead us to another more cost effective future environment. Cost – benefit analysis of the above proposed pico-satellite system is under stuffing and is in the process of being executed in order to acquire the first primitive results on how we can implement solutions like the one above in the maritime daily business without affecting the operational environment's key factors. It is our firm belief though that this analysis and approaches will change dramatically the way of executing maritime security operations. The operational needs will seek demanding solutions and technology will provide them. It remains though unclear how these solutions will affect our world, which to us seems a sure aftereffect and outcome by minimizing the cost, giving us more possibilities to survive in a harsh global economic environment. For us future is the past and the "real future" is our ideas that are waiting to come and enlighten our endeavors towards perfection in the small satellite arena.

The above analysis has been executed in whole in US Naval Postgraduate School in Monterey California under the guidance and direction of* ***Professor Alex Bordetsky* *from the Information Sciences Department. The work has been published in three Conference and Two journal papers accordingly and as per ref [6]. Author would like to deeply than* ***Mr. Eugene Bourakov*** *for supporting his work with all his power, ideas and sacrificing his spare time. Thank you Eugene!*

References

1. Nanosatellite Tracking Ships: Responsive, Seven-Month Nanosatellite Construction for a Rapid On-Orbit Automatic Identification System Experiment, Freddy M. Pranajaya and Robert E. Zee, Space Flight Laboratory, University of Toronto, Institute for Aerospace Studies, 7th Responsive Space Conference April 27–30, 2009 Los Angeles.
2. http://www.utias-sfl.net/nanosatellites/AISSat-1/
3. http://www.utias-sfl.net/nanosatellites/CanX6/
4. http://www.nasa.gov/mission_pages/tacsat-2/main/
5. http://www.interorbital.com/TubeSat_1.htm
6. Bordetsky, G. Mantzouris, Picosatellites in Maritime Interdiction Operations, 15th ICCRTS, Santa Monica, LA, CA, 22-24 June 2010, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA525245
7. Satellite Analysis Toolkit, www.stk.com
8. Nanosatellite Tracking of Ships — Review of the First Year of Operations, Franz Newland, Elliott Coleshill, Ian DSouza and Jeff Cain, COM DEV Ltd., 7th Responsive Space Conference April 27–30, 2009 Los Angeles, CA
9. Bjorn T. Narheim, Oystein Olsen, Oystein Helleren, Richard Olsen, Alexander M Beattie, Robert E. Zee, "A Norwegian Satellite for Space-based Observations of AIS in the High North," Proceedings of the 22nd Annual AIAA/USU Conference on Small Satellites, Logan, UT, USA, Aug. 11-14, 2008.
10. http://www.cnw.ca/ (M3MSat)

CHAPTER 8

RISK ANALYSIS

in MARITIME SECURITY

Chapter 8: Risk Analysis in Maritime Security

Modeling Risk Assessment in Counter Piracy

Maritime Security is definitely nowadays in the forefront of future security at sea. Terrorism in the sea commons is generally accepted as one of the most prominent and hideous occurring act, employing a lot of international resources in confrontation. Piracy, Armed Robbery, Improvised explosive devices from individuals in land or of small boats, weapons of mass destruction or disruption, as well as any other form of simple or complicated terror is going to affect the maritime environment and arena in the near future. Analysts worldwide are skeptical on how to effective counter future maritime terrorism phenomena not only in big merchant vessels, but also in pleasure vessels such as super yachts, yachts, sailing boats underway, berthed in peaceful marinas or in any other place conducting daily routine business.

Proposal

In this research we propose a risk assessment and management model that based on available data fusion will try to simulate reality and be an effective tool for any dynamic counter risk process towards maritime security. The model will be able to implement gathered individual distributions of likelihood from sensors / humans and provide a probabilistic of risk and threat assessment of maritime areas and especially being implemented in the idea / project of marine highways safeguarding the sea commons. It will be based on a mathematical model that will approximate reality based on data already accumulated from maritime security missions. Using deterministic factors it will eventually give answers to the following questions:

What is the risk / security of specific maritime areas and what is the risk ranking of a vessel transiting from port A to port B (probabilistic analysis).

How we reduce the level of the above risk with the effective use of available assets.

What is the minimum risk that our asset can handle in order to perform the mission effectively (sensitivity analysis).

Analysis

In order to start creating our analysis field we firstly decided to use the parameters of time-visibility, speed of vessel, freeboard and wave height as the most critical parameters. This hypothesis has been generated from our literature survey in the previous chapters and coincide with subject matter expert reviews and opinions that we utilize during our research.

Time - Visibility: Time is a factor that all piracy data collecting organizations are reporting. We are using GMT / UTC time in order to have consistent results. Using this factor we are trying to find out which timeframe most of the attacks happened (if any) and follow the pattern in order to execute our analysis in the most possible accurate sense. Therefore accurate timing of the incident will create a pattern for visibility factor.

Speed: To know the speed of the vessel during the attack or the suspicious activity is extremely difficult due to the fact that there are no reports for that anywhere. Organizations, shipping companies and all third party interested partners are not using this as a primary factor in their analysis mentioning that the speed of the vessel is being associated with the capability of it in accordance with its type. For example a traditional merchant vessel has a typical speed of 11 to 15 knots whereas a container ship has an economic speed of 20-25 knots. Therefore, we are going to associate the speed of the vessel with their type in order to be consistent with our analysis. Moreover it is not important to analyze the exact speed but the maximum that a vessel can withstand during an attack or suspicious activity in order to perform evasive maneuvers.

Freeboard: The most important factor based on the analysis of results and with the linkage of wave height becomes critical on how pirates would engage or not to attack a vessel.

Wave height: Specifically there is available historical weather data for West Africa where piracy is lured at least in the last two years, since 2012. These weather data are being collected from the US National Data Buoy Center, a subset of National Oceanic and Atmospheric Administration (NOAA) from buoy station 15007 in position 005.98 S and 008.00 E and the buoy station 13010 in position 0.00 N and 0.01W.

Based on the above categorization and in literature survey executed and refer to the previous chapters an empirical model with 21 different parameters was used that made us calculate a risk factor for maritime piracy based on Subject Matter Expert reviews. This empirical model (table 49) has been created on excel spreadsheet and calculates the risk level a ship undergoes when passing through a maritime piracy region. We will see later on that our empirical model coincide with reality and with the linear / logarithmic regression model results.

COMBINED COUNTER PIRACY RISK ASSESSMENT (CCPRA) (M/V + VOYAGE)

FACTORS	UNITS	ENTER	RISK WEIGHT	WEIGHTING CHOICES					
SPEED	kts	4	6						
FREEBOARD	meters	4	6						
WAVE HEIGHT	meters	2	6						
TEMPERATURE	° Celcius	10	1						
SECURITY TEAM	No of people	1	10						
BMP4	-	2	1	1 = No	2 = Partially	3 = Full			
PAG / Mother Ships	No of them on route	5	3						
FREQUENCY OF ATTACKS	No of attacks in area	5	1						
RELEASED VESSELS	No of released vessels last month	3	3						
GTS or ESCORT	-	6	6	1 = Escort	2 = GTS only	4 = Last on GTS	6 = No		
TYPE OF VESSEL	-	4	6	1 = VLCC	1 = Gas Carrier	3 = Bulk Carrier	2 = Yacht	2 = Tug	4 = Tug & Tow
SIZE OF VESSEL	meters	45	2						
CARGO MANEUVERABILITY	-	1	1	1 = Flexible	2 = Limited	3 = Restricted			
SHIP MANEUVERABILITY	No of propellers	1	1	1 = Bow + Aft	2 = 2 Aft propellers	3 = 1 Aft propeller			
TRAINED CREW	No of people	4	4	1 = All	2 = 1/2 of crew	3 = 1/3 of crew	4 = No		
COMMS COVERAGE	-	2	2	1 = Full satellite	2 = Partially	3 = No coverage			
CITADEL	-	3	4	1 = Yes	2 = Yes no comms	3 = No			
NON LETHAL WEAPONS	-	3	3	1 = Continuously	2 = On demand	3 = No			
VOYAGE SELECTION	-	4	4	1 = Sri Lanka	2 = Yemen	3 = GOA / Oman	4 = Bab El Mandeb		
CREW SAFETY	-	1	1	1 = No	2 = Yes				
TIME OF TRANSIT	No of nights	3	5	1 = 1 Dawn/Dusk	3 = 2 Dawn/Dusk	5 = 3 Dawn/Dusk	6 = 4 Dawn/Dusk+		
CREW EXPERIENCE	Times of high risk area transits	2	2	1 = 3-10 times	2 = 2 times	3 = 10+			
ARMED DOORS	-	4	6	1 = Yes All	2 = Machinery & Comms	3 = Main Deck	4 = No		
AIS -LRIT	-	3	3	1 = Standard On	2 = Mobile On (<30W)	3 = No			
CCTV	-	1	1	1 = Full Coverage	2 = Partial Coverage (50%)	3 = No			
LIGHTING - ALARMS	-	3	3	1 = Yes	2 = Partially (50%)	3 = No			
	TOTAL SUM		91						
	EXPECTED RISK LEVEL		EXTREMELY HIGH						

MV+VOYAGE RISK / WEATHER RISK / Φύλλο3

Table 45:Empirical Piracy model based on Subject Matter Expert reviews

Risk Model - Space Index

To start our analysis we need first to refer to PROMERC European funded program where University of the Aegean (including authors) is participating. This reference will give us the baseline for our analysis and will create a specific mindset for risk modeling and space indexing.

PROMERC is a consortium to provide enhanced non-military counter measures for merchant ships bringing together leading shipping companies, commercial, political, academic, and military entities along with leading research companies and agencies. Piracy has re-emerged as a global security threat.

There are many options available to shipping companies to mitigate the risk of piracy and to deter pirates. They include passive protection measures to discourage attacks and defensive measures to counter the pirates in the event of an attack. There has been a rapid growth in the use of private contracted armed security personnel to provide ship-board protection and some flag states permit the use of lethal force in order to protect their ships. There is also evidence that this militarization of the industry has been effective however there remains deep unease regarding the broader industrial, political, ethical, economic, social, legal and environmental implications which are poorly understood.

There are a bewildering number of options available to shipping companies to mitigate the risk of piracy and to deter pirates with scant information regarding their operational effectiveness or the cost benefits of their use, particularly when employed in combination as part of a holistic approach.

It is currently difficult for stakeholders to evaluate and compare the cost benefits and operational effectiveness of different counter measures.

Following the above and taking into account that space is a place where terrorists like pirates or illegal immigrants or generally people emerging from poor societies are not able to reach, we are researching the option of using very small satellites (like Lambdasat in the range of 1 kgr) in order to minimize the risk by providing critical information (in the form of text alert messages) to ships where sailing in distant or remote areas or even near shore. In this case we are trying to measure the risk of a ship by creating (initially) a linear model so as to estimate the most important parameters that compose it and secondly to add space capability using a Picosatellite like Lambdasat and minimize this risk by adding critical information to the equation and keep ship captains informed of any alert situation around his area.

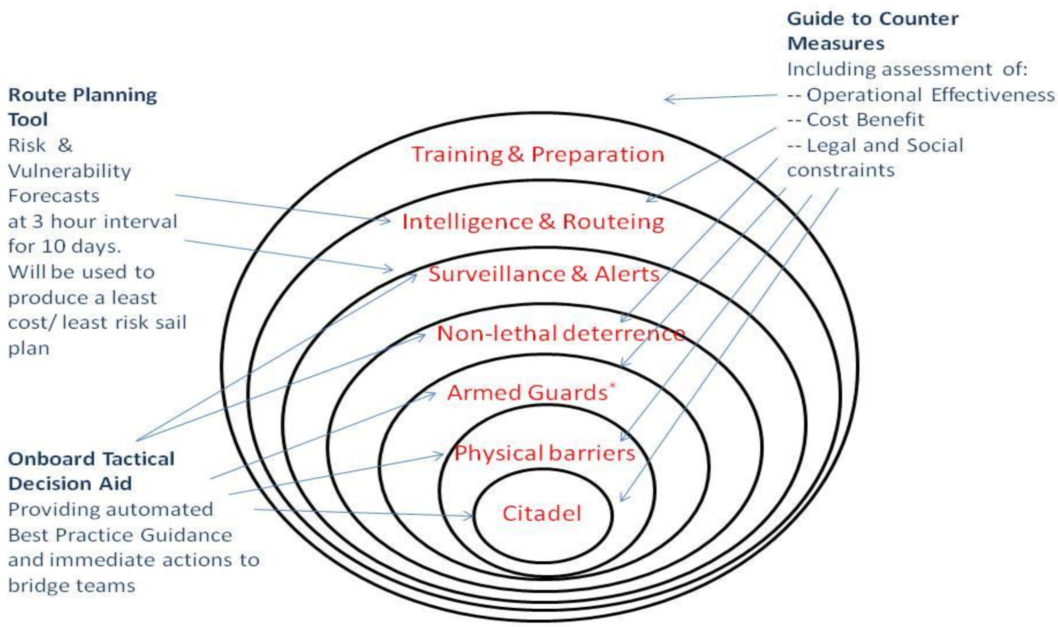


Figure 41: Maritime Piracy holistic approach

The risk model we have created is based on different approaches and with different factors. Time, visibility (in nautical miles), Speed (in Knots), Vessel Type, Wave Height (in meters), Freeboard and Piracy Type are some of the 22 different factors we have accumulated in order to create our piracy risk model. Starting our analysis we have created our model situation using the most important parameters of the above which are Time of the day, Freeboard and Speed of the vessel.

Based on available data collected from commercial sources on the internet (such as IMO, RECAAP and other credible maritime organizations) we have analyzed 130 piracy incidents regarding attacks, hijacks and approaches of suspicious pirate boats to marine vessels underway. These incidents has happened in 2012 and 2013. Our sole aim is to analyze available data and create a functional risk model where the three above mentioned factors will produce an equation with different rates and coefficients.

The methodology follows a linear regression modeling application as follows. Initially we have splitted the above mentioned incidents into groups based on time speed and freeboard. Then and in order to create our regression analysis table we have found the percentages of these parameters out of the general total sum of incidents happened. We are supposing that the first and more important factor is speed of merchant vessel, then from the remaining incidents Time is more critical (an incident is easier to happen in twilight than in day timeframe) and finally we accumulate to the remaining percentage Freeboard of vessel. In this categorization the below figure 6 groups and number of incidents allocated have been taken into consideration.

Time Groups			No of Incidents
1	0800-1700	Day	36
2	1700-2100 0500-0800	Twilight	9
3	2100-0500	Night	8

Speed Groups			No of Incidents
1	0 to 10	Observed Speed or Max	11
2	10 to 15		35
3	> 15		7

Freeboard Groups			No of Incidents
1	0 to 2	Depending on cargo status	5
2	2 to 4		45
3	>4		3

Table 46: Categorization of Piracy Incidents based on Time, Speed and Freeboard of attacked vessel.

To be more specific our cases are as follows:

1st Test Case: Merchant Vessel speed from 0-10 knots.

0-10 kts & 08-17 h & 0-2m
0-10 kts & 08-17 h & 2-4m
0-10 kts & 08-17 h & > 4m
0-10 kts & 17-21 & 05-08h & 0-2m
0-10 kts & 17-21 & 05-08h & 2-4m
0-10 kts & 17-21 & 05-08h & > 4m
0-10 kts & 21-05 h & 0-2 m
0-10 kts & 21-05 h & 2-4 m
0-10 kts & 21-05 h & >4 m

2nd Test Case: Merchant Vessel speed from 10-15 knots.

10-15 kts & 08-17 h & 0-2m
10-15 kts & 08-17 h & 2-4m
10-15 kts & 08-17 h & >4 m
10-15 kts & 17-21 & 05-08h & 0-2m
10-15 kts & 17-21 & 05-08h & 2-4 m
10-15 kts & 17-21 & 05-08h & >4 m
10-15 kts & 21-05 h & 0-2 m
10-15 kts & 21-05 h & 2-4 m
10-15 kts & 21-05 h & >4 m

3rd Test Case: Merchant Vessel speed is over 15 knots

>15 kts & 08-17 h & 0-2m
>15 kts & 08-17 h & 2-4m
>15 kts & 08-17 h & >4 m
>15 kts & 17-21 & 05-08h & 0-2m
>15 kts & 17-21 & 05-08h & 2-4 m
>15 kts & 17-21 & 05-08h & >4 m
>15 kts & 21-05 h & 0-2 m
>15 kts & 21-05 h & 2-4 m
>15 kts & 21-05 h & >4 m

Comparing all the above cases we create our Risk Percentage case which is the most important factor in order to use linear regression and find our model.

The equation used for the calculation of Risk percentage is as follows where a,b and c are coefficients calculated via our data:

Risk = f (Speed, Time, Freeboard)

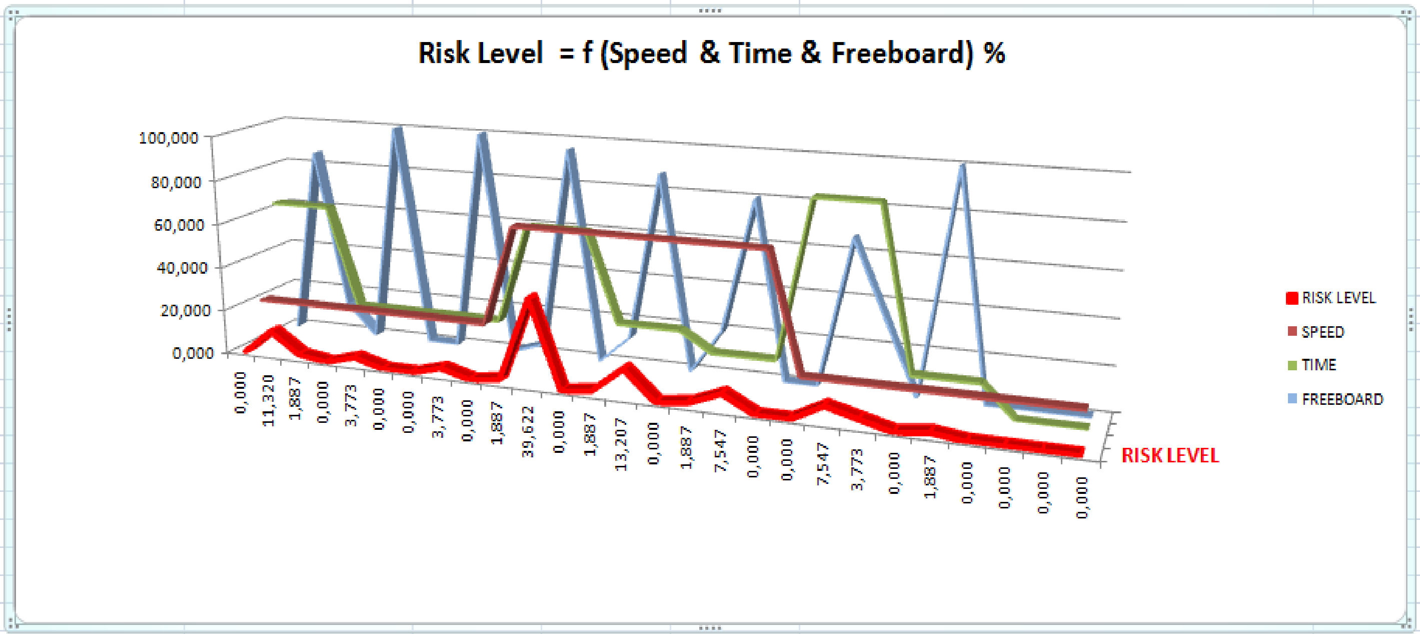
We are using initially as a first step linear regression since this is the first time that this research applies and thus a result stemming from this procedure will then lead us to maybe more complex applications.

Executing regression on historical data mentioning above the result provides the following coefficient equation:

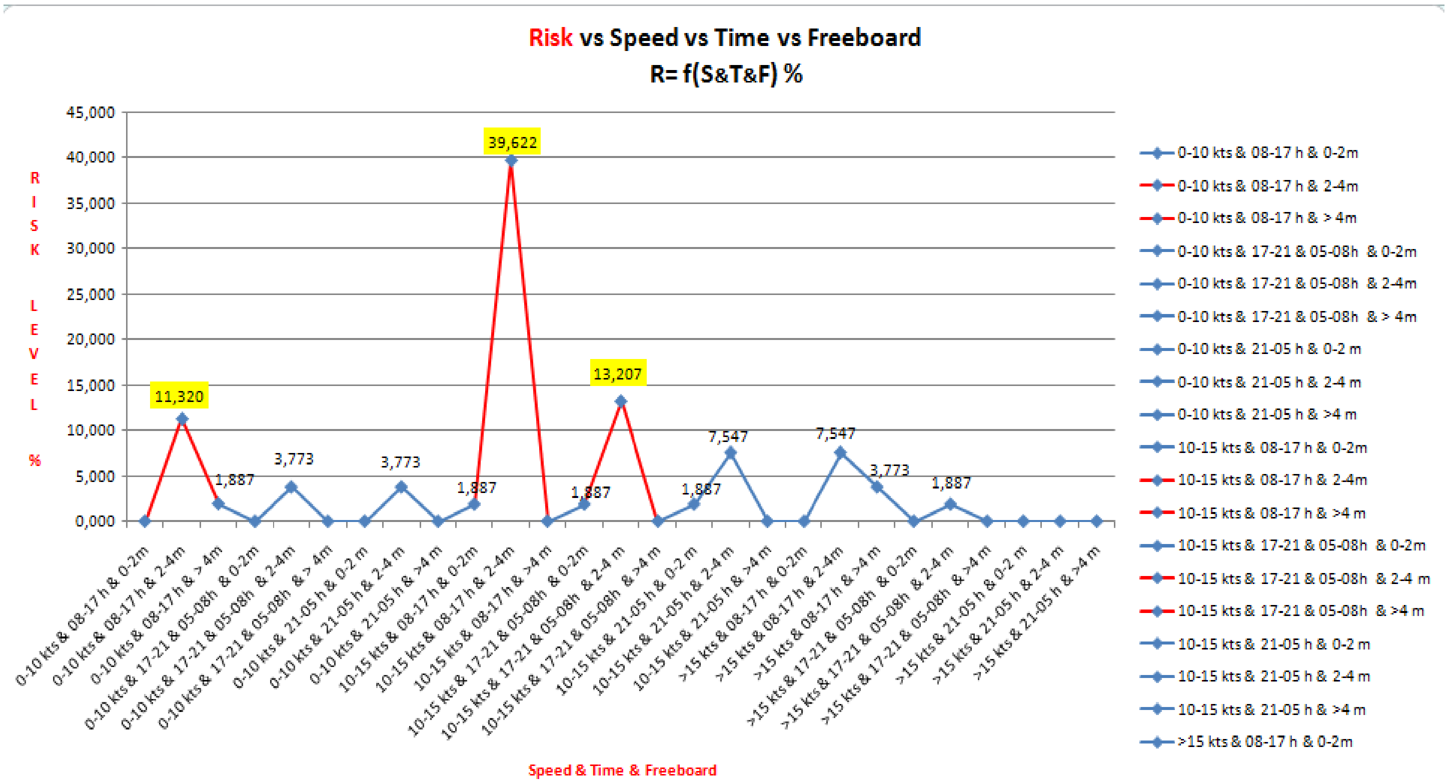
$$R = 4{,}96 - 0.0958 * S + 0.065 * T - 0{,}1114 * F$$

Applying different values of speed, time and freeboard to the above equation the Risk (probability of piracy event) is being calculated to near 43,096% if Speed is 5 knots, Time is in twilight and Freeboard is 1 m. This risk is similar with the risk observed in real time from security guards and captains on board ships. In another case and if Speed is 20 knots (a fast container vessel), time is day and freeboard is 30 meters then the risk is being calculated to the less number of zero possibility without even taking into account the daytime that the ship passes from the risk area.

The above equation though is being modulated positively or negatively as we stated above if we add a space information awareness factor (SIAF) that has been produced from our data analysis from Lambdasat or Funcube Picosatellite data received. Through the analysis of received data over a month period of time we conclude that we are able to transfer alert messages information via a Picosatellite with a percentage of 53 % on a day timeframe. This practically means that for a month timeframe the system is able to send successful alerted messages to ships at oceanic areas once every two days even though the satellite passes over it up to three times per day. Therefore if we have a vessel transiting in the Gulf of Aden during twilight with 5 knots and it has freeboard of 1m the ship has the capability of receiving messages once every two days (worst case scenario). If we add a Picosatellite in the communication scheme then the ship will have alerted message information once every two days.



Graph 30: Risk level % analysis of our 130 piracy incidents based on speed, time and freeboard.



Graph 31: Risk level % for different speed, time and freeboard parameters - linear regression analysis

Future Steps

In this place we need to insert another index which we call Information Awareness Index (IAI). This index needs to somehow count in our risk function with a coefficient “a” for example, in order to investigate further what is the quantitative conformation of Risk if via a picosatellite a merchant vessel has Information available once every one or two days. This is although outside of the scope of this research and is being left to the next researchers to create this quantifiable measurement. However and as part of a European Funded project PROMERC we have quantified through multidimensional analysis and rigorous research how much risk is being affected by trained or non-trained personnel that are participating in maritime piracy missions. The work is called “Maritime Piracy Competence Modeling” and has been published in TransNav Journal – The work is being explicitly registered in Appendix 7.

Picosatellites Cost Benefit Analysis

Finally and even though it is not the scope of this thesis, however we need to refer to cost benefit analysis of the use of Picosatellites since it is one of the main factors that nowadays drive the research. In this dissertation we are only mentioning some figures and facts giving only the baseline on what is the cost relation of a maritime mission related to a picosatellite.

Taking into account information collected from open internet as well as official satellite companies’ sources for pricing and policy with subscribers let’s consider the following case.

If we have available 1.000.000 € and we charge 1$ per minute (best rate) it means 1.000.000 min / 60 min per hour = 16666,66 hours of selling time / 24 hours per day = 694 days for returning the money back. (This is only for telephony - worst case scenario) or 450 subscribers to pay 200 € per month = 90.000 € * 12 months = 1.080.000 € per year (a ship-owner pays approximately 10.000 € per month for one ship for satellite communication services).

On table 47 we can easily see what a micro or picosatellite can provide to the costumers taking into account how many satellites we have on orbit concurrently and how many hours they can cover. As you can see (and this is only an indicative scale table) the services are numerous and can extent to as many users as the bandwidth allows.

A general rule is that a picosatellite can facilitate throughput up to 1.5Mbps. Finally in the last row of Table 47 pricing in approximate numbers is shown giving a rough indication of how much one or twelve Picosatellites can cost to be on orbit (all inclusive):

	Satellites					
Services	**1**	**2**	**4**	**8**	**16**	**24**
Coverage	0.5 h	1h	2,5 h	7 h	14 h	24/7
Video streaming				**X**	**X**	**X**
Voice				**X**	**X**	**X**
Telephone			**X**	**X**	**X**	**X**
Email exchange	**X**	**X**	**X**	**X**	**X**	**X**
Internet				**X**	**X**	**X**
Real Time Ship Tracking	**X**	**X**	**X**	**X**	**X**	**X**
Oriented Missions	**X**	**X**	**X**	**X**	**X**	**X**
Land Tracking	**X**	**X**	**X**	**X**	**X**	**X**
Photo streaming	**X**	**X**	**X**	**X**	**X**	**X**
Personal Satellite	**X**	**X**	**X**	**X**	**X**	**X**
Pricing (€)	100 K	200 K	400 K	800 K	1.6 M	2.4 M

Table 47: Services via number of Picosatellites that can be provided. Pricing in approximate numbers.

On the other hand Table 48 provides a generic / indicative representation of how a mini through femto satellite can alter its mass and cost as well as altitude and project lifetime in accordance with current technological trends and figures. Picosatellites (red colored row) can stay up on orbit for up to 2 years (with no propulsion scheme) and the cost is 160K $ per 1 kgr (this is the maximum cost - a mean cost as it has been referred previously is up to 100K $ all inclusive).

	Mass (kg)	**Altitude (km) Orb period**	**Project lifetime**	**Total Cost (M$)**	**Cost/Mass (k$/kg)**
Mini	**100 - 500**	**1000 – 5000 (2 – 3 hrs)**	**4 - 7 yrs**	**10-150**	**200**
Micro	**10 – 100**	**500 – 2000 (1.6 - 2 hrs)**	**2 - 5 yrs**	**1-30**	**400**
Nano	**1 - 10**	**300 – 800 (1.4 – 1.7 hrs)**	**2 - 3 yrs**	**0.1-10**	**800**
Pico	**0.1 – 1**	**200 - 400 (1.4 – 1.5 hrs)**	**1 - 2 yrs**	**0.05-2**	**160**
Femto	**< 100 g**	**200 – 400 (1.4 – 1.5 hrs)**	**1 yrs**	**< 0.05**	**320**

Table 48: A generic representation of satellites with respect to cost and mass.

Page intentionally left blank

CHAPTER 9

CONCLUSIONS - RECOMMENDATIONS

PROPOSALS – WAY AHEAD

Chapter 9: Conclusions - Recommendations - Proposals - Way Ahead

The above concrete analysis tried to provide to the researcher an alternative way of thinking and how picosatellites could affect the future maritime business. It is yet to be proved that solutions like pico-satellites will succeed in the years to come. Having in mind though the advent of microsatellites (space assets less than 100 kg) two decades ago, where it seemed unreal at that time, solutions like those tested in our thesis could place themselves in a way that would change absolutely the daily operational world.

Starting with our literature survey and having reviewed more than 100 small satellites, we defined a short but critical list of picosatellite operational characteristics (limitations and/or requirements). With these we understood thoroughly how maritime operations may be affected by the use of picosatellites. Therefore these very small satellites characteristics are:

- Provide fine resolution images from the area of operations
- Transfer real time information to merchant mariners
- Track in real or near real time vessels depending on the selection of orbital parameters and the area of operation.
- Communicate providing audio - voice and video to a fusion center ashore for the specified window
- Perform a two way communication implementing mesh networking techniques
- Cover a vast geographical sea area and provide partial or total situational awareness based on the number of satellites to be used.
- Provide lifetime coverage of up to 3 months without propulsion on board.
- Affected vastly from Doppler Effect taking into account that there speed is very high and dynamic Doppler compensation is much more difficult than in other types of orbits.

Another important fact that was being researched through this work is how micropropulsion systems are going to affect picosatellite maritime operations taking into account that lifetime capability is one of the most important factors if one wants to safely define what will be the operational status of the picosatellites in the years to come.

Therefore some of the most important findings are reported below (having reviewed more than 200 experimental and commercial applications):

- Power limitations decrease their lifetime on orbit (maximum up to 1 year).
- Electric propulsion on picosatellites is a solution but needs to be operationally proven from global research institutions. It provides lower thrust levels but comparing to chemical systems provide higher specific impulses. Therefore the picosatellite could execute a mission without carrying a vast amount of propellant. By that way it is able to build up a high final velocity but in longer periods of time. At the same time it can create more thrust for a longer period to produce a desired change in trajectory or velocity. In parallel, it has simpler electric power supplies compared to chemical and high performance, with simple feed systems and low inherent thrust to weight ratio.

Some of the derived unique technical requirements for a micropropulsion system are:

- Very low power consumption
- Simple or no propellant feeding mechanisms
- Minimal propulsion system mass
- Compact size
- Reduced life cycle cost, including reductions in procurement costs
- Mass reduction technologies
- Scalable technologies

To sum up until now the best acquired thrust level for a picosatellite electric propulsion system is 2.5 mN with only 1 watt and the best acquired thrust efficiency 12 % with only 3 watt power. Those are the available figures on market but space qualified solutions are not yet ready. We may need to wait 2 to 5 years in order to reach the acceptable operational level for electric micropropulsion systems on picosatellites.

Another factor that needs to be taken into serious account for a picosatellite mission is how it is being affected from space environment and how radiation and shielding is affecting it. Do not forget here that a picosatellite is usually being made from commercial of the shelve applications and thus space qualification procedures are at very low extent. Having analyzed the collected information some selected critical facts are listed as follows:

- A satellite orbiting in low earth orbits and close to the equator (300 km) is undergoing through a very low radiation environment.

- A satellite in low earth orbit with inclination of 45º has to overcome the effects of South Atlantic Anomaly. The incoming radiation is cumulative as it passes through the SAA region. That is to say the more the satellite passes through the SAA region the more is the effect of the radiation that is going to encounter.

- Heavier ions as He, C, N, O, Ne cannot affect satellites electronic systems but can have effect in charging of a satellite.

- Monatomic Oxygen is the only charged particle that can have severe effect on low earth orbiting satellites. In 200 km it has a density of 10^9 άτομα / cm^3 and in 800 km it is less than 10^5 άτομα / cm^3.

- Other charged particles that we have to take seriously into account and can affect our mission are energetic protons with energies more than 50 MeV in the inner radiation belt, if the satellite is flying a little higher or in polar orbits.

- A picosatellite can also be exposed to radiation from galactic cosmic rays when it is orbiting near the poles. It is not affected from galactic cosmic rays when is near the equator though.

- Future technologies recommend the usage of polymers in picosatellite missions or maybe other types of materials that could help safeguard microelectronics and avoid risks.

Having completed the above analysis regarding the collection of critical operational and environmental parameters on picosatellite missions we then moved to maritime oriented micro / nano and picosatellite missions. We reviewed more than 100 satellite missions and we found that 53 of them have similar characteristics with our Lambda picosatellite taking into account the technology used. But only 3 – 5 of them are realistically dealing with maritime operations. None of them though has ever dealt with the use of a picosatellite in maritime security operations support such as in piracy or any other type of maritime security operation. This fact gave us an indication of the prototype work that this thesis is trying to reveal. We all know AISsat series of satellites or maybe

M3MSat but none of the above satellites have use AIS signal in order to move encrypted text piracy messages to merchant mariners in the middle of the ocean. Our Lambdasat mission encompassed the below prototype characteristics as part of this thesis work and those are listed below:

- First ever 100% Greek space mission (design, construction, end users with scientific and plain Greek usage)
- First ever Greek cooperation with International Space Station.
- First ever Greek materialized cooperation with NASA with success.
- First space application for the Greek Shipping Industry (Leading by University of the Aegean)
- A low cost project driven effort but with high benefit with voluntary scientist participation (part of this Ph.D. dissertation performed here)
- First international Greek scientist's synergy with tangible and project driven application.
- Creation of a successful international cooperation model in Greece and abroad.
- First ever mission to successfully pass all systems testing, verification and integration procedure from NASA in order to join International Space Station Launch manifest.

Based on the above and having the belief and prove that our endeavors are in the prototype region we launched the Lambda picosatellite, created two Ground Stations in Greece and received data playing different scenarios with our but also with other micro and picosatellites on orbit in order to compare the results. From the data received and the scenarios played our results indicated the following important facts.

- Receiving data from 12 Jun until 12 Jul 2015 accumulated 65 single data lines even though the satellite passed on top of our Ground station almost 160 times Taking into account that all passes of the pico satellite were late at night (based on our location) and the weather was excellent during satellite pass we received 34 non corrupted messages which is a 52.3 percent of quality data received.
- When the elevation of the satellite was under 16.4 degrees then the communication was not effective.

- Doppler Effect was present but on the quality messages did not affect communication even though we did not use (on purpose) any error correction code.
- The duration of each satellite pass was almost 6 to 7 minutes – when quality messages received.
- When the elevation of the picosatellite was more than 30 degrees the error count was very low.
- The best possible communication scheme acquired for 10.1 minutes where the message was being received multiple times and in quality format.

Simulating also the use of picosatellite to maritime security scenarios and comparing that to the real picosatellite mission we concluded to the same results as follows:

- A ship will access the picosatellite in five days for a total of 165 minutes, which is proportional to 56 nautical miles, 11 passes of satellite and 2,33 % of the total daily time. If the ship's speed is less than 13 knots then the coverage time increases to 3,235% for the daily coverage time.
- With the use of 6 picosatellites on orbit the coverage daily time increases to 11% which is 160 minutes per day availability.

One can imagine though the operational advantage with the use of a cluster of picosatellites taking into account that one of them costs approximately 50.000 € (all inclusive) comparing to a traditional satellite that costs millions of euros and without having the redundancy / replacement ability.

Similar results acquired with modeling Tubesat picosatellites. Having six Tubesats in polar orbit would provide an operationally effective communication window, as big as four hours per day, depending on the configuration of the satellites. However, based on the described modeling results for four Picosatellites, we are going to have almost 2 and a half hours availability of communication which is enough time for applying mesh networking methods in operational use. The field officers need this capability in order to enhance their maritime mission success and safeguard their tasks performing work on board suspect vessels. The proposed picosatellite based networking model contributes directly to the emerging concept of Space Operations to Counter Maritime Terrorism.

Taking the above parameters from the use of picosatellites (real – Lambdasat and simulation - Tubesat) we then uncovered all the characteristics that a picosatellite has in supporting a maritime security operation. In parallel and analyzing through simple linear and logarithmic regression models the aggregated piracy data we concluded in creating a risk model that approximates merchant mariners' reality when transiting the oceans with pirates or suspect vessel luring the seas. This risk model can be effectively improved if we add the picosatellite index factor and quantify the use of space assets in maritime security operations. Right now the mariners receive (with no cost) once per day or two critical information relevant to their trip. Of course and if costly satellites services are in place then communication is effective everywhere. But with this work we need to create a framework where picosatellites at no cost deliver three times per day approximately important information anywhere, anytime in the world.

For this reason and having mentioned and analyzed all the above critical and concise information a future model needs to be investigated. In order to consider picosatellites working as "space orbital nodes" we need in the future to technically evaluate the use of mesh network applications on board a picosatellite and then try to understand what are the limitations we have if we decide to transfer mesh networking capabilities in space. It may not have only limitations but through this research feasible paths could appear that will open new roadmaps to future networking capabilities.

Another important fact that arose from this dissertation work is that by adding the space information awareness factor to the risk model we now do not know exactly how this affects the overall risk figures. In this dissertation we started this work by quantifying the merchant mariner's competence level of training when participating in a maritime piracy mission but similar research needs to be performed in order to accurately materialize the positive effect of picosatellites when merchant mariners receive critical information on time vice to not having today this capability.

Finally it is evident that more research must be done in creating a more rigorous risk regression model since we only created that as a part of this thesis and having the sole aim to use it as a primitive research tool for initially quantifying the figures. Maybe other types of models must be used and being compared in order for a statistical accurate model to be created. The model is also able with small alterations to be applied in other pillars of maritime security such as border security or illegal immigration.

Experiments performed and recorded during this thesis demonstrated with the more evident way, that picosatellites will ameliorate our businesses world in the very near future, if not they have already started to invade our daily routine. Future is not very far and the technology has proven numerous times that can provide solutions better that what we can imagine. It is only a matter of willingness, persistence and hard work that will lead us to another more cost effective future environment. Cost – benefit analysis of the pico-satellite system indicated above, with primitive though figures, that the equilibrium will be changed dramatically and that is why Google Corporation is already preparing the launch of a picosatellite constellation for executing business in the near future (2018). The operational needs though will seek demanding solutions, but as always historically proven technology will provide them. It remains though unclear if these solutions will affect geostrategically our world (small countries have now access to space), which to us seems a sure after effect and outcome taking into account that if cost diminishes with picosatellites and at the same time more and more operational needs can be satisfied, then our future world will be moving towards the application of space mesh networking solutions with the use of pico machines.

In a decade from now miniaturized satellites will take all the load of global applications and personal satellites will execute all of our daily routine. It is matter only of time to see this evolution in the modern era of engineering.

However we must never forget what Thucydides said 2000 years ago:

…whatever you do

“Mighty will apply his Own Right”

….even in space era.

Page intentionally left blank

APPENDICES

Appendices

Appendix 1: Orbitron Amateur Satellite Simulation Data

Data collection from Orbitron Amateur Satellite Simulation Software

Location : MALABO (3.9583° E, 2.6458° N)

Time zone : UTC +3:00

Search period : 2014-10-14 00:22:18 until 2014-11-01 00:22:18- 18 days

Conditions : Maximum sun elevation = -5 deg

Minimum sat elevation = 2 deg

Time	Satellite	Azm	Elv	Mag	Range	S.Azm	S.Elv
2014-10-14 06:18:05	FO-29	52.6	2.0	12.7	4114	97.9	-33.1
2014-10-14 06:25:37	FO-29	102.5	14.7	12.0	2990	97.9	-31.2
2014-10-14 06:33:00	FO-29	152.0	2.0	12.7	4055	97.8	-29.4
2014-10-14 08:00:23	FO-29	6.4	2.0	12.7	4070	97.8	-7.8
2014-10-14 08:10:17	FO-29	283.5	68.3	10.4	1407	97.9	-5.3
2014-10-14 08:20:09	FO-29	199.1	2.0	12.7	4045	98.0	-2.9
2014-10-14 21:26:44	FO-29	237.0	2.0	12.5	3119	262.1	-14.4
2014-10-14 21:29:10	FO-29	257.9	3.5	12.3	2957	262.1	-15.0
2014-10-14 21:31:38	FO-29	279.1	2.0	12.5	3136	262.1	-15.6
2014-10-15 07:06:08	FO-29	27.7	2.0	12.7	4095	98.1	-21.1
2014-10-15 07:15:47	FO-29	102.4	43.7	10.9	1760	98.0	-18.7
2014-10-15 07:25:13	FO-29	176.6	2.0	12.7	4019	98.1	-16.4
2014-10-16 06:13:58	FO-29	54.5	2.0	12.7	4125	98.9	-34.0
2014-10-16 06:21:15	FO-29	102.2	13.4	12.1	3077	98.8	-32.2
2014-10-16 06:28:20	FO-29	149.6	2.0	12.7	4031	98.7	-30.4
2014-10-16 07:55:58	FO-29	7.7	2.0	12.7	4092	98.6	-8.8
2014-10-16 08:05:57	FO-29	283.6	72.7	10.3	1373	98.6	-6.3
2014-10-16 08:15:45	FO-29	197.7	2.0	12.7	4012	98.7	-3.9
2014-10-16 21:21:35	FO-29	231.5	2.0	12.5	3118	261.3	-13.2
2014-10-16 21:24:40	FO-29	258.4	4.6	12.3	2860	261.3	-14.0
2014-10-16 21:27:47	FO-29	285.3	2.0	12.5	3159	261.3	-14.8
2014-10-17 07:01:50	FO-29	29.0	2.0	12.7	4112	98.9	-22.1
2014-10-17 07:11:27	FO-29	102.4	40.8	10.9	1824	98.8	-19.7
2014-10-17 07:20:43	FO-29	175.0	2.0	12.7	3991	98.8	-17.4
2014-10-18 06:09:53	FO-29	56.6	2.0	12.7	4131	99.8	-34.8
2014-10-18 06:16:53	FO-29	102.0	12.1	12.1	3163	99.7	-33.1
2014-10-18 06:23:38	FO-29	147.1	2.0	12.7	4007	99.6	-31.4

2014-10-18	07:51:35	FO-29	9.0	2.0	12.7	4105	99.3	-9.8
2014-10-18	08:01:37	FO-29	283.6	77.2	10.3	1343	99.3	-7.3
2014-10-18	08:11:21	FO-29	196.4	2.0	12.7	3984	99.4	-4.9
2014-10-18	21:16:32	FO-29	226.9	2.0	12.5	3122	260.6	-12.1
2014-10-18	21:20:09	FO-29	258.8	5.7	12.2	2765	260.6	-13.0
2014-10-18	21:23:50	FO-29	290.5	2.0	12.5	3191	260.6	-13.9
2014-10-19	06:57:34	FO-29	30.4	2.0	12.7	4119	99.7	-23.0
2014-10-19	07:07:05	FO-29	102.0	38.0	11.0	1890	99.6	-20.7
2014-10-19	07:16:12	FO-29	173.4	2.0	12.7	3962	99.6	-18.4
2014-10-20	06:05:51	FO-29	59.0	2.0	12.7	4129	100.8	-35.7
2014-10-20	06:12:30	FO-29	101.7	10.8	12.2	3249	100.6	-34.0
2014-10-20	06:18:54	FO-29	144.4	2.0	12.7	3983	100.5	-32.5
2014-10-20	07:47:13	FO-29	10.3	2.0	12.7	4114	100.0	-10.8
2014-10-20	07:57:17	FO-29	283.2	81.9	10.2	1319	100.0	-8.3
2014-10-20	08:06:55	FO-29	194.9	2.0	12.6	3947	100.1	-5.9
2014-10-20	21:11:34	FO-29	222.9	2.0	12.5	3126	259.8	-11.0
2014-10-20	21:15:38	FO-29	259.2	7.0	12.1	2671	259.8	-12.0
2014-10-20	21:19:48	FO-29	295.1	2.0	12.5	3226	259.8	-13.0
2014-10-21	06:53:19	FO-29	31.9	2.0	12.7	4123	100.5	-24.0
2014-10-21	07:02:44	FO-29	101.9	35.3	11.1	1957	100.4	-21.6
2014-10-21	07:11:39	FO-29	171.6	2.0	12.6	3927	100.4	-19.5
2014-10-22	06:01:52	FO-29	61.5	2.0	12.7	4120	101.7	-36.5
2014-10-22	06:08:06	FO-29	101.4	9.5	12.3	3334	101.6	-35.0
2014-10-22	06:14:07	FO-29	141.5	2.0	12.6	3957	101.4	-33.5
2014-10-22	07:42:51	FO-29	11.5	2.0	12.7	4124	100.7	-11.8
2014-10-22	07:52:57	FO-29	280.5	86.8	10.2	1299	100.7	-9.3
2014-10-22	08:02:28	FO-29	193.5	2.1	12.6	3910	100.8	-6.9
2014-10-22	21:06:39	FO-29	219.3	2.0	12.5	3132	259.1	-9.8
2014-10-22	21:11:07	FO-29	259.5	8.3	12.1	2579	259.1	-10.9
2014-10-22	21:15:44	FO-29	299.2	2.0	12.6	3269	259.1	-12.1
2014-10-23	06:49:04	FO-29	33.3	2.0	12.7	4129	101.3	-24.9
2014-10-23	06:58:22	FO-29	101.7	32.7	11.2	2025	101.2	-22.6
2014-10-23	07:07:05	FO-29	169.9	2.0	12.6	3891	101.1	-20.5
2014-10-24	05:57:55	FO-29	64.3	2.0	12.7	4108	102.7	-37.3
2014-10-24	06:03:43	FO-29	101.2	8.2	12.3	3418	102.5	-35.9
2014-10-24	06:09:16	FO-29	138.2	2.0	12.6	3929	102.4	-34.6
2014-10-24	07:38:31	FO-29	12.8	2.0	12.7	4124	101.4	-12.7
2014-10-24	07:48:36	FO-29	106.0	88.3	10.2	1286	101.4	-10.3
2014-10-24	07:58:01	FO-29	192.1	2.0	12.6	3877	101.5	-8.0
2014-10-24	21:01:46	FO-29	215.9	2.0	12.5	3142	258.4	-8.7
2014-10-24	21:06:35	FO-29	259.6	9.8	12.0	2488	258.4	-9.9

2014-10-24 21:11:38 FO-29 303.0 2.0 12.6 3315 258.4 -11.1

2014-10-25 06:44:51 FO-29 34.9 2.0 12.7 4124 102.1 -25.8
2014-10-25 06:53:59 FO-29 101.3 30.2 11.2 2095 102.0 -23.6
2014-10-25 07:02:30 FO-29 168.0 2.0 12.6 3856 101.9 -21.5

2014-10-26 05:54:03 FO-29 67.5 2.0 12.7 4086 103.7 -38.2
2014-10-26 05:59:19 FO-29 101.0 7.0 12.4 3502 103.5 -36.9
2014-10-26 06:04:22 FO-29 134.6 2.0 12.6 3904 103.4 -35.6
2014-10-26 07:34:11 FO-29 14.1 2.0 12.7 4124 102.1 -13.7
2014-10-26 07:44:14 FO-29 101.5 83.2 10.2 1278 102.1 -11.3
2014-10-26 07:53:32 FO-29 190.6 2.0 12.6 3837 102.1 -9.0
2014-10-26 20:56:55 FO-29 212.8 2.0 12.5 3154 257.6 -7.6
2014-10-26 21:02:04 FO-29 259.9 11.3 11.9 2399 257.7 -8.9
2014-10-26 21:07:31 FO-29 306.4 2.0 12.6 3367 257.7 -10.2

2014-10-27 06:40:39 FO-29 36.5 2.0 12.7 4116 102.9 -26.8
2014-10-27 06:49:36 FO-29 101.1 27.9 11.3 2166 102.8 -24.6
2014-10-27 06:57:53 FO-29 166.1 2.0 12.6 3816 102.7 -22.6

2014-10-28 05:50:16 FO-29 71.3 2.0 12.7 4057 104.7 -38.9
2014-10-28 05:54:54 FO-29 100.7 5.8 12.4 3586 104.5 -37.8
2014-10-28 05:59:22 FO-29 130.4 2.0 12.6 3878 104.3 -36.7
2014-10-28 07:29:52 FO-29 15.4 2.0 12.7 4119 102.8 -14.8
2014-10-28 07:39:53 FO-29 103.0 78.2 10.2 1277 102.8 -12.3
2014-10-28 07:49:01 FO-29 189.1 2.1 12.6 3790 102.8 -10.1
2014-10-28 20:52:05 FO-29 209.7 2.0 12.5 3172 256.9 -6.5
2014-10-28 20:57:33 FO-29 260.1 13.0 11.8 2311 257.0 -7.8
2014-10-28 21:03:22 FO-29 309.6 2.0 12.6 3416 257.0 -9.2

2014-10-29 06:36:28 FO-29 38.1 2.0 12.7 4103 103.8 -27.7
2014-10-29 06:45:13 FO-29 101.0 25.6 11.4 2238 103.6 -25.6
2014-10-29 06:53:15 FO-29 164.0 2.0 12.6 3778 103.5 -23.6

2014-10-30 05:46:36 FO-29 75.8 2.0 12.6 4020 105.7 -39.7
2014-10-30 05:50:29 FO-29 100.5 4.6 12.5 3670 105.5 -38.8
2014-10-30 05:54:15 FO-29 125.4 2.0 12.6 3856 105.4 -37.9
2014-10-30 07:25:34 FO-29 16.7 2.0 12.7 4109 103.5 -15.8
2014-10-30 07:35:30 FO-29 101.8 73.1 10.2 1283 103.5 -13.3
2014-10-30 07:44:30 FO-29 187.5 2.0 12.6 3749 103.5 -11.2
2014-10-30 20:47:17 FO-29 206.9 2.0 12.6 3189 256.3 -5.4
2014-10-30 20:53:01 FO-29 260.1 14.9 11.8 2225 256.3 -6.7
2014-10-30 20:59:13 FO-29 312.6 2.0 12.7 3472 256.3 -8.3

2014-10-31 06:32:19 FO-29 40.0 2.0 12.7 4080 104.6 -28.6
2014-10-31 06:40:48 FO-29 100.6 23.4 11.4 2311 104.4 -26.6
2014-10-31 06:48:36 FO-29 161.9 2.0 12.5 3741 104.3 -24.7

Appendix 2: Piracy text type message - LSAT decoding

FIELD	CODING	No of digits	COMMENT
Year	xxxx	4	2014 (example)
Month	xx	2	04(example)
Day	xx	2	04(example)
Hour	xx	2	12(example)
Minute	xx	2	22(example)
Latitude	xxxxxx	6	02 22 47(example)
North or South	x	1	1= North 2= South
Longtitude	xxxxxxx	7	003 12 27(example)
West or East	x	1	1=West 2= East
Piracy Event	x	1	1= Approach
			2= Hijack
			3= Attack
			4=Suspicious Activity
			5=Armed Robbery
			6=Miscellaneous
Source	x	1	1=IMO
			2=NSC
			3=IMB
			4=RECAAP
			5=EUNAVFOR
			6=ICC
			7=UKMTO
			8=MARITIMERISK.GR
			9=OTHER
Risk Level	x	1	0=Avoid Route
			1= Extremely High
			2= High
			3=Medium
			4=Low
			5=Very Low
			6=Clear - No Risk
			7= Risk from other terrorevents
			8=Illicit trafficking
			9=Narcoterrorism
Text	xxxxxx…..xxxxx	60	
	Total Sum of Digits	**90**	

Appendix 3: Ground Station Order - Cost Analysis

1. HF/VHF/UHF All Mode Transceiver (Cost: 1749 €)

KENWOOD TS-2000 - HF/VHF/UHF All Mode Transceiver

http://www.drele.com/catalogp/product_info.php?cPath=739_744&products_id=990

2. Power Supply (Cost: 140 €)

Model GZV-4000

http://www.drele.com/catalogp/product_info.php?cPath=741_748&products_id=289

3. Antenna (Cost: 300 €)

UHF 70cm (430 - 440MHz) Cross Yagi multiple (42 elements)

http://www.aesham.com/440-70cm/m2-antennas-436-cp42ug/

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

4. Phasing Harness – cross polarization (Cost 180 €)

http://www.aesham.com/antenna-parts/m2-antennas-ps-70cm/

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

5. Low loss coaxial cable

30 meters ECOFLEX 15 low loss coaxial cable (Cost 5 & 6: 100 €)

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

6. N type connectors

Four (4) for connecting antenna with transceiver to the ECOFLEX 15 cable

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

7. Rotor with Az – El (Cost: 749 €)

Azimuth-elevation rotator combination for satellite earth station for the antenna.

YAESU G5500

http://www.drele.com/catalogp/product_info.php?cPath=54&products_id=132

8. Wire for Rotor cabling (Cost 30 euro)

Cable with 6 wires (2 of them) 2x20 meters. (see attached G5500 Operating manual page 3)

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

9. Support mast for the antenna (Cost: 100 €)

Pipe and wires for the support of the antenna and the rotors.

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

10. Tracking satellite software (Cost: 50 €)

For automatic tracking of the satellite and auto movement of the antenna.

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

11. Rotor Software Interface (Cost: 150 €)

**we can also provide here from www.drelectronics.com (Mr Dimitris Argyropoulos)*

Total Price in Greece: 3548 €

Appendix 4: Detailed Microsatellite Propulsion Analysis

Propulsion Characteristics other than Electric

Moving forward, a reference to some critical comparisons among electric and other propulsive systems (chemical, nuclear, solar sails, MEMS and no propellant) that are available on the market and attract a lot of the interest among the designers, is needed. It is not our intent to analyze thoroughly all the above mentioned engines and ideas. They are only hereby referred for comparison purposes with the electric systems and most importantly in order to establish a common ground of understanding for limitations, advantages and disadvantages that we many need to encounter during our research.

Chemical

In a chemical thruster the propellant is burned and the hot gas is expelled from the thruster with the help of a nozzle. The exhaust velocity is closely linked to thermal heating and that is why it cannot reach very high magnitudes[17]. Some general characteristics of the chemical propulsion systems are as follows:

They are limited from nozzle temperatures (thermal heating) and exhaust velocities cannot reach high magnitudes, but only up to 10 km/sec[7]. If we want to escape a gravitational field, a thrust to weight ratio greater than one is needed.

The amount of energy is very limited and therefore the amount of propellant is an important issue during the mission designing process.

High mass flow rate permits high levels of thrust, even for low exhaust velocities.

They are very powerful for space vehicles to be able to quickly reach or escape Earth's orbit and gravitational field[17].

They are not a solution for future deep space missions, since they require a ΔV of 10 km/sec.

Chemical differ from Electric systems generally in the source used to energize and accelerate the gas. Electric propulsion uses electric energy to ionize the propellant and then impart kinetic energy to the resulting plasma.

They can provide too much thrust leading to control problems and cannot meet the minimum impulse bit requirements for attitude control[11]. In these cases electric propulsion is needed to take up and execute the mission finitely.

Finally, liquid chemical thrusters have the disadvantage of requiring a storage tank and having leakage concerns.

Cold Gas

These systems are simply comprised of an inert gas (nitrogen, argon, freon or hydrocarbon like propane) which is stored at high pressure and fed to a number of small thrusters. In the absence of combustion heat, the kinetic energy of the nozzle exhaust is solely determined by the driving pressure in the reservoir. It has the advantage of propellant storage, simplicity and compatibility with other facets of the spacecraft, such as the exhaust plume impingement on sensitive surfaces, solar cells etc. Thrust levels are small, typically in the order of mN. Applicable missions are high pointing accuracy and stability, jitter free viewing and other fine attitude requirement missions. The specific impulse is also small in the order of 50sec reflecting the reduced reservoir temperatures. They are not applicable for large ΔV missions but are important secondary propulsion systems if we want to reduce the system mass and the mission requirements are suitable for those to be applied[21].

Nuclear

This type of propulsion engine has been studied for many years although it has not totally pursued for flight applications, mainly due to political and environmental reasons. It reaches high figures of thrust in the order of hundreds of kN with specific impulses around 600-900 sec. It offers, as chemical rockets, high power but low propellant utilization with limited exhaust velocities. The power that they can accommodate is however limited compared to the Sun infinite capability of producing energy21. The types of nuclear propulsion are generally three: the fission reactor, the radioactive isotope decay source and the fussion reactor. In all these engines the heating of the gas is accomplished by energy derived from transformations within the nuclei of atoms. The power source is usually separated from the propellant. Nuclear fission reactor rockets allow shorter interplanetary trip transfer times, smaller vehicles and more flexibility. On the other hand isotope decay engines provide lower thrust, lower temperature and have not been maturely developed or flown. Finally, the fusion rocket engines are those who develop nuclear energy that can heat a working fluid. Concerns about an accident with the spreading of radioactive materials in the earth's environment and the high cost of development have prevented renewal of experimentations95, at least on the unclassified levels of scientific knowledge.

Chemical / Electric – Dual Mode

In order to try to combine the advantages of both chemical and electric propulsion a dual mode thruster is in development for micro-nano and picosatellites. It has strong potential for applications in space exploration, communication and scientific experiments. It combines a micro FEEP device with Isp of >1000sec and input powers <10 w along with a chemical thruster based on a plug annular micronozzle. This concept is suited for a number of missions with very limited power budgets, such as those to the outer planets, where a large amount of solar power is unavailable. Another benefit is the redundancy option and the extended lifetime of the thruster until all stored propellant is consumed.

MEMS

A propulsion system applicable to attitude dynamics and control is the MEMS (Micro Electro Mechanical System), which uses current pulses to ignite tiny cells of lead styphanate, to turn ignite the main propellant. It has the ability to provide milli to micro thrust pulses with as little power as milliwatts over a hundredth of a second. Arrays have been manufactured to contain over 256 squared elements using advanced semiconductor manufacturing technology.

The necessity for miniaturization of space systems has lead us to incorporate new ideas, like MEMS, in the propulsion environment, that can greatly reduce the cost of production and launch, increase flexibility and disperse risks of a mission. Micro cold gas MEMS systems have already been flown and proved that they are useful for a number of missions. However the low level of specific impulse acquired (60 - 300 sec) limits their usage today. Other disadvantages include the brittleness of silicon, wherever is used, the compatibility with traditional components and losses that occur when the size decreases and the increasing surface to volume ratio would result in heat and viscous losses for chemical propulsion and electron wall losses for electric propulsion. It is evident that all the above losses finally decrease the thruster performance and efficiency[11].

On the other hand they can be considered as an array of solid monopropellant microthrusters require low power to ignite each charge and contained in a single unit with low mass and low volume. They have no leakage issues, no moving parts and they provide redundancy from their array structure. Additionally to the above mentioned disadvantages, also include one shot use, spacecraft external surface area requirements, differing torque values depending on thruster distance from the center and the launch vehicle considerations for the energetic materials115.

No propellant

A new electric propulsion principle for spacecraft has lately been proposed by limited designers around the world. It uses microwave technology to achieve direct conversion of d.c. power to thrust without the need for propellant. It uses radiation pressure at microwave frequencies providing direct conversion from microwave energy to thrust without the need for propellant. Microwave energy is fed from a magnetron via a tuned feed to a closed, tapered waveguide, whose overall electrical length gives resonance at the operating frequency of magnetron. The experimental engine is still under examination / testing status from emdrive / SPR Ltd Corporation. The experimental thruster weights 15.5 kg, operates at 2540 MHz and is powered by a 850 W magnetron (still the power requirement is very high) providing thrust of 16.6mN. This system eliminates the use of propellant and together with the predicted thrust offer a major improvement in overall mission performance[207].

Another method that is considered propulsion without thrust, is the Antigravity technique which has been demonstrated theoretically up to now, but it requires a lot more experimental and testing procedures in order to be flight proven. However, it is considered as a non propellant system and that is why it is referred hereby[161].

The above mentioned systems are being listed as alternative propulsion concepts that are going to occupy a lot of research activities in the near future especially taking into account that the reduction of cost is the main driven in the future space mission and applications.

Solar Sails

Finally, a solar sail is a propulsion concept that makes use of a flat surface of very thin reflective material supported by lightweight deployable structures. There are several types of solar sails where acceleration is being accomplished under the pressure from the solar radiation (essentially a momentum transferred by reflected solar photons). Thus, the engine requires no extra propellant. They can essentially reduce total trip times and Earth launch mass for high Δv robotic missions in comparison to conventional chemical systems[122]. They also propose to tap the natural solar wind momentum flux for space propulsion with the help of long, thin, charged and centrifugally stretched tethers that deflect solar wind protor trajectories by electrostatic propulsion. Moreover, they can be thought as a natural ion thruster that does not have to carry propellant and that needs only modest onboard power to keep its tethers charged. Specific impulses are higher than those of chemical rocket by 100 – 1000 times[208].

Electrostatic

In this type of propulsion engines, ions are electrostatically accelerated[100,206] and no area changes are essential for direct gas acceleration. They rely on Coulomb forces to accelerate the propellant composed, whereas acceleration is achieved by interaction of electrostatic fields on non neutral or charged propellant particles such as atomic ions, droplets or colloids[95]. The steam of positively charged particles must be neutralized in order to avoid a charge build up opposite to that carried from the spacecraft in the beam, which would eventually lead to stalling of the thruster.

Electrostatic propulsion uses a high voltage electrostatic field to accelerate ions to large exhaust velocities. Many systems rely on gridded structures at the exhaust ports, for containing and producing high electric fields in order to accelerate the ions. Sometimes multiple grids are employed to divide the functions of propellant containment, ion acceleration and beam divergence control[4]. The basic types of electrostatic thrusters with their major characteristics are listed below:

Electron / Ion Bombardment

Positive ions from a monatomic gas are produced by bombarding the gas or vapor, such as xenon or mercury, with electrons emitted from a heated cathode. Ionization can be DC or RF and electrons are emitted from an axially mounted thermionic cathode, finally attracted from a concentric cylindrical anode. The electrons are thermionically excited and bombard neutral propellant atoms in the discharge chamber. At the same time, a weak externally applied magnetic field causes the electrons to spiral within the chamber and propellant ionization results from collisions between these electrons and the propellant vapor[206].This magnetic field serves finally the purpose of increasing the electron path length and residence time, allowing higher collision probability and propellant utilization efficiency[4].

Kaufman Ion

Similar to the function of ion engines, it features a strong diverging axial magnetic field that shields a cylindrical anode electrode located near the wall of the discharge chamber. In this case electron transport is limited by cross field diffusion concept[99]. The electrons are emitted from a hollow cathode and are accelerated on their way to the anode.

Contact Ion

Positive ions are produced by passing the propellant vapor, usually cesium, through a hot porous tungsten contact ionizer. Surface ionization is used and the work function of the wall metal must be higher than the ionization potential of the propellant in order to reach the desirable levels of performance. Acceleration is being acquired by the use of the applied electrostatic field[4].

Field Emission Electric Propulsion (FEEP)

Tiny droplets of propellant are charged either positively or negatively as passed through an intense electric field discharge. The droplets, typically created from propellants of liquid metals, are in the size of subnanometers[206]. This type of thruster has high efficiency, since no heat is lost in ionization due to the fact that the fluid is directly accelerated after ionization and extraction from the bulk material[4].

Colloid Ion

The combination of feed pressure, surface tension and electrostatic forces at the tip of a needle forms small positively charged multi-molecular droplets, which are subsequently accelerated in the electrostatic field among the needle and a negative biased extractor electrode surrounding the needle tip. The method used here is direct extraction of charged fluid droplets from a fluid surface. A Taylor cone is being created at the surface of the fluid, which is finally subject to strong electric field. The fluid forms a capillary jet at its apex that breaks up into a fine spray of positively charged droplets. These droplets are in the size of sub-microns. Colloid droplets have significantly larger masses and are able to produce high thrust densities[206]. Typical fluids used are glycerol or sodium iodine. The principal advantage of a colloid thruster over an ion one, is the production of larger thrust over a given power[103]. On the other hand, they are limited to the same mass to charge ratio and by the impressed voltages to small range of effective exhaust velocities.

Radiofrequency Ion Discharge (RIT)

They rely on ion creation by pumping a cavity with radio frequency radiation (MHz) usually in an insulated chamber. The ions are then extracted through the exhaust port by an accelerator grid similar to that in an electrostatic ion thruster. An external neutralizer is also used to avoid build up of opposite charge of the spacecraft[4].

Microwave Ion Discharge

Similar functioning with Radiofrequency Ion Discharge. They rely on ion creation by pumping a cavity with microwave frequency radiation (GHz) usually in an insulated chamber[4].

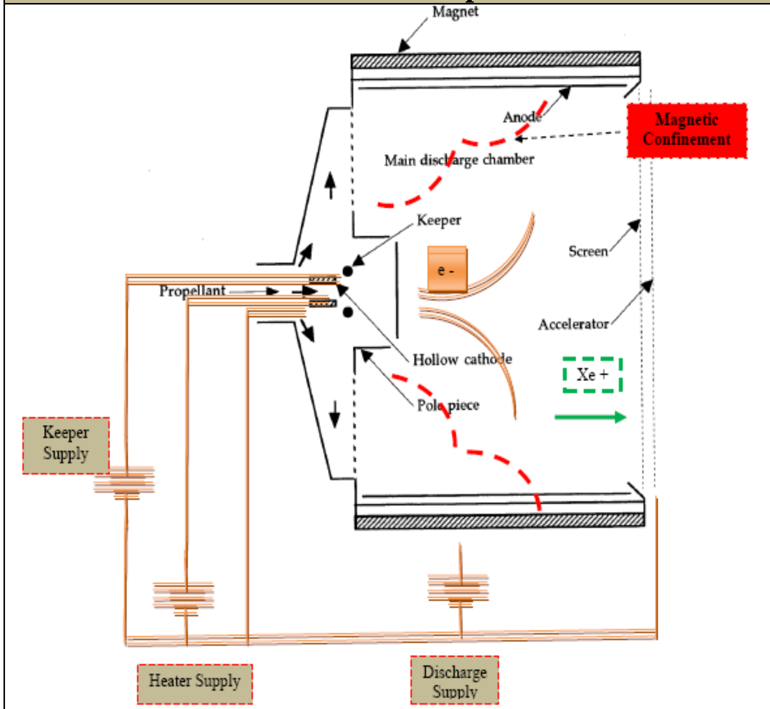
Plasma Separator Ion

Uses high density cesium vapor, which is pumped through an array of hollow cathodes having converging – diverging nozzles. Ions are created by discharge between the cathodes and annular anode ring at the end of the nozzles. After the ionization a conventional electrostatic acceleration system produces high exhaust velocities. No working model has been produced[4].

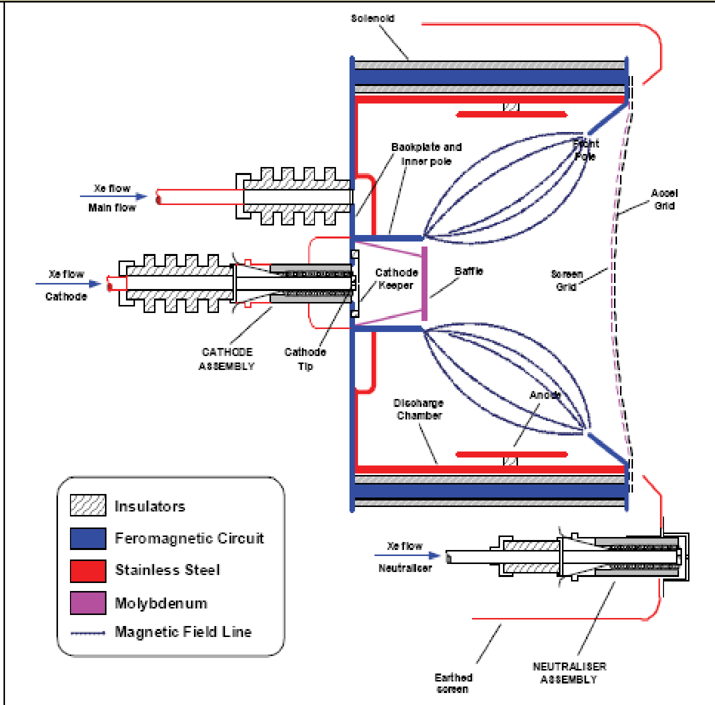
Radioisotopic Ion

Thrust is being produced by colloidal particles. A thin layer of fuel containing beta – decaying radioisotopes is spread over a large emitting surface with a net positive charge produced by the radioisotope fuel (typically Cesium 144). A large potential difference between surface and space is produced. Electrons emitted by the surface are collected by a shield and the potential difference finally provides acceleration. No working model has been produced[4].

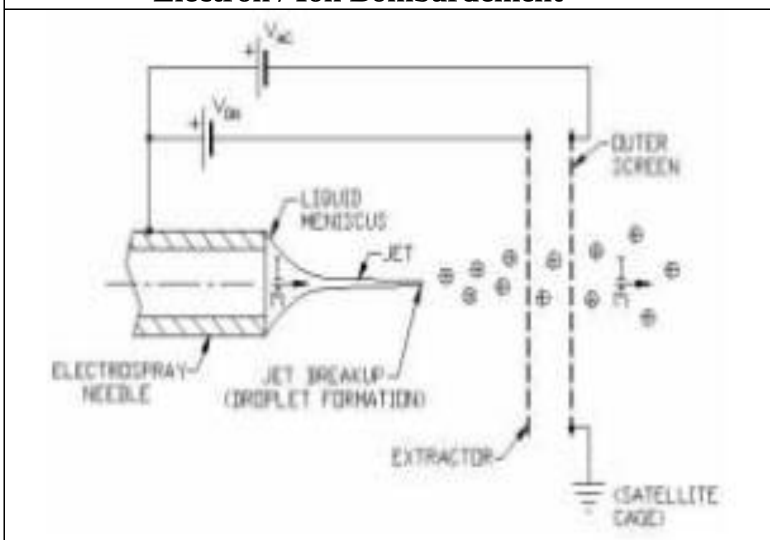
Basic representative schematics of various Electrostatic thrusters



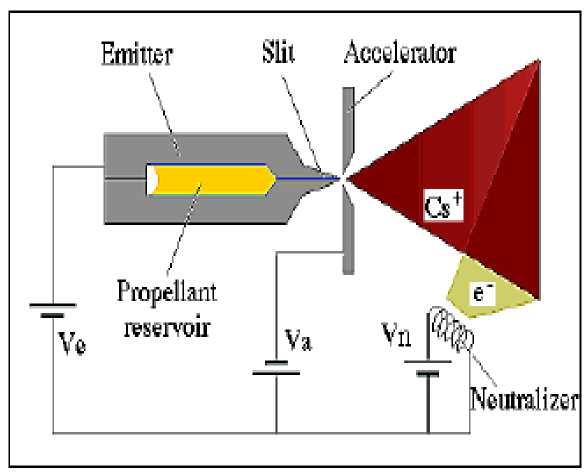
Electron / Ion Bombardement[99, 206]



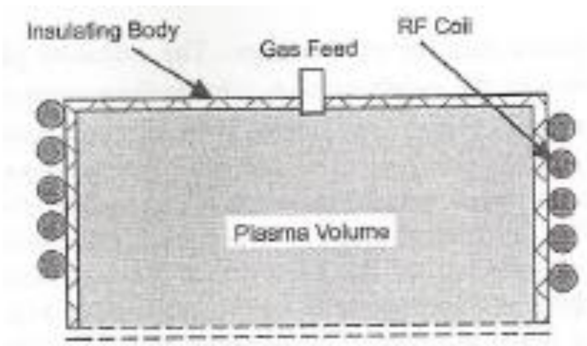
Kaufmann[99, 211]



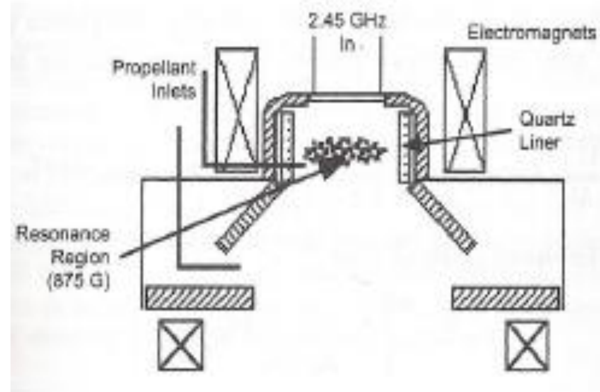
Colloid Ion[4]



FEEP[4]



Radiofrequency Ion discharge[95]



Microwave Ion discharge[95]

Electrothermal

In the second category of electric propulsion thrusters, which is called Electrothermal, propellant is heated electrically (via resistance element or arc[100]) and expanded thermodynamically (the gas is accelerated to supersonic speeds through a converging – diverging nozzle)[95]. During expansion enthalpy of the expellant is increased and converted into direct kinetic energy via the nozzle[206]. The principal advantage of electrothermal thrusters is simplicity, not only in the thrust chamber, but also in the propellant feeding system. The uncoupling of the working fluid from the energy input allows also a wide choice of propellants. Moreover on specific electrothermal thrusters, there is a capability of being pulsed, which makes them suitable for attitude control and possibly east-west stationkeeping. The major drawback though is that they are limited to operating temperatures depending on the chamber wall materials. The efficiency of the thruster is also limited by the energy, which must be deposited in non thermal modes in the propellant, such as molecular rotation, vibration and dissociation. Also, the electrothermal thrusters offer a limitation in the exhaust velocity related to each concept. Finally, we should pinpoint as an advantage the facts that electrothermal thrusters need very brief time for thruster preparation to operation and they can provide sufficient lifetime of operation, factors which definitely drive the mission's application selection processes[103]. The basic types of electrothermal thrusters are as follows:

Resistojets

Components with high electrical resistance dissipate power and in turn heat the propellant, largely by convection[95]. The propellant is passed through a tungsten heating element[206]. The most successful application has been based on superheating of catalytically decomposed hydrazine, which has the commonality with familiar fuel systems used in hydrazine monopropellant applications[98].

Arcjets

An arcjet has a cylindrical geometry and consists of an internal cone cathode, an anode forming the external channel and a propellant injection at the rear of the channel. When the thruster operates an arc is formed generating a very hot region on the symmetry axis where the temperature can reach large numbers and heat the propellant. The thermal energy of the propellant is then transformed into kinetic energy through a nozzle[106]. Generally in arcjets the current flows through the bulk of the propellant gas, which has been ionized in an electrical discharge[95]. This method eventually introduces more heat into the gas. Arcjets are like resistojets but the wall temperature limitation of the resistojet is overcome here depositing power internally in the form of an electric arc, typically between a concentric upstream rod cathode and a downstream anode that also serves as the supersonic nozzle[98]. Arcjets generally are engines with more specific impulse but lower efficiencies[204].

Arcjet DC

Use sub-kV arcs with high current between a cathode tip and a diverging conical anode nozzle walls with the propellant flowing through the inlet at the base of the cone around the cathode needle[122].

Arcjet AC

They are similar to dc arcjets but they have shorter lifetimes. Power condition requirements are similar to dc ones and because of the shorter lifetimes, very few space tests have been performed[4,122].

Arcjet Pulsed

These thrusters are similar to dc arcjets except instead of a steady current its pulses resulting from charge discharge of the input of capacitance. The discharge pulse occurs at the breakdown voltage of the gaseous propellant flowing between the anode and the cathode. Propellant flow though is continuous and not pulsed. It has very low specific impulse and few space tests have been performed[4, 122].

Electrothermal Hydrazine

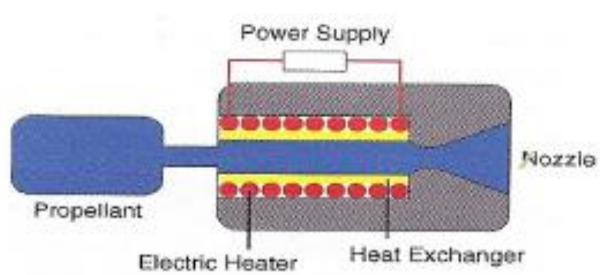
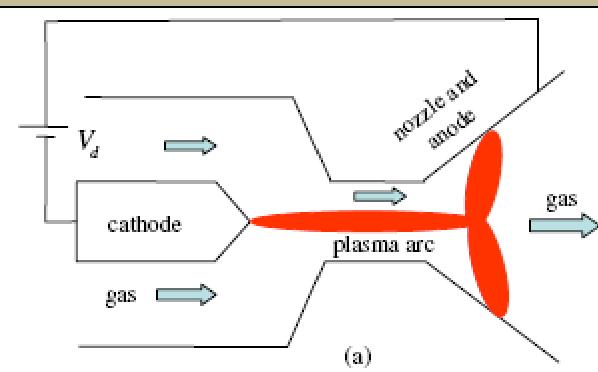
A hybrid of conventional electrothermal thruster using hydrazine and a monopropellant chemical hydrazine thruster is employed. In the first stage of the device conventional chemical decomposition of hydrazine is achieved to liberate the chemical energy. In the second stage the propellant is passed through a heating chamber where ohmic heating further raises the temperature and is then exhausted. A 30% increase in performance over conventional hydrazine chemical thrusters is achieved[4, 122].

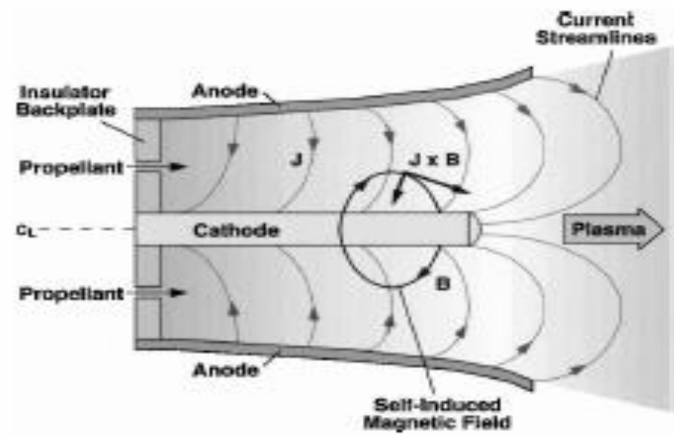
Microwave Electrothermal (MET)

Standing wave microwave radiation is fed from a waveguide into a plenum chamber. The microwave radiation accelerates electrons in high field regions which collide with injected neutral propellants. They can function in both steady state and pulsed modes. Since this is an electrodeless technique it has longer lifetimes than arc electrothermal thrusters[4, 103]. More detailed information is provided below where there is a dedicated independent section for microwave theory, design and implementation to space applications.

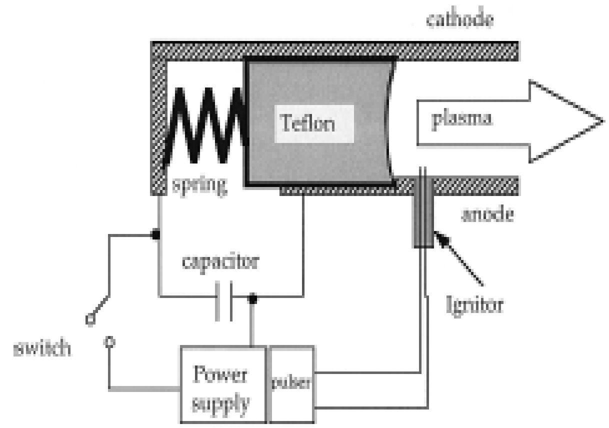
Pulsed Electrothermal

Eject pulsed plasma through a conventional converging – diverging supersonic nozzle which forms the anode of a propellant chamber. Plasma breakdown in the propellant is achieved by discharge of a capacitor across the inner electrode which heats the gas admitted to the cylindrical chamber.

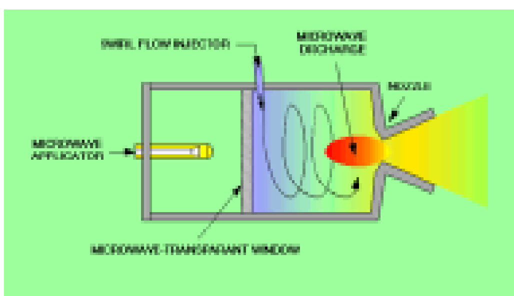
<table>
<tr><th colspan="2">Basic representative schematics of various Electrothermal thrusters</th></tr>
<tr><td>
</td>
<td>
</td></tr>
<tr><td>Resistojet[99, 98]</td><td>Arcjet[206]</td></tr>
</table>



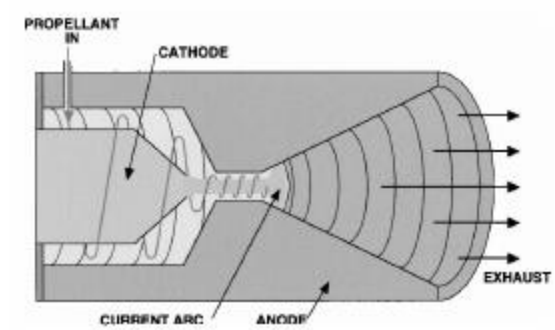
MPD[122]



PPT[206, 98]



MET[4]



DC Arcjet[4, 98]

Electromagnetic

In this type of electric thrusters, where the most sophisticated engines belong, acceleration is achieved by the interaction of electric and magnetic fields within plasma100. In an electromagnetic thruster there is a body of electrically conductive gas, a high current by means of an applied magnetic field and an acceleration of the propellant to a high velocity in the thrust vector direction with a significantly intense magnetic field[95]. Specifically, crossed electric and magnetic fields induce a Lorenz force in plasma and provide the desirable acceleration schemes[206]. In contrast to electrothermal thrusters, where the plasma discharge heats the propellant, electromagnetic thrusters use electromagnetic forces generated by a very high arc current discharge to accelerate the propellant plasma[106]. The accelerating force is proportional to the cross product of the electric current density and the magnetic field[204]. Some of the most significant types of the electromagnetic thrusters are hereby reported:

Magnetoplasmadynamic (MPD)

It is based on Faraday accelerator. A plasma conductor carries a current in the direction of an applied electric field but perpendicular to the magnetic field, with both of these vectors in turn normal to the direction of plasma acceleration[95]. There is an axisymmetric chamber typically with a cathode running at large currents. The potential difference between the electrodes ionizes the inflowing neutral gas. Once the plasma is ionized it is being accelerated by Joule heating and electrodynamic forces. The current carrying plasma interacts with a magnetic field result in a Lorenz acceleration which expels the plasma. They have the potential to provide high specific impulses at moderate thrust levels[103]. The MPD is characterized by a very high current and low voltage. The arc is sustained by thermionic emission of the hot cathode[106].

MPD Self Field

The cathode – anode configuration is charged with a dc power supply. The high temperature cathode produces most of the current through thermionic emission. An azimuthal magnetic field is generated by the current flowing along the cathode bar helping to initiate the JxB force on the plasma. In the self applied systems acceleration occurs as a result of the magnetic field produced by the high current flow along the cathode[4]. The self field MPD creates an azimuthal B field and a corresponding magnetic pressure by passing a strong radial currents between concentric electrodes similar to PPTs, but with difference in geometry. The thrust here is proportional to magnetic pressure which means that the efficiency of the thruster is low[98].

MPD Applied Field

The operation is similar to the MPD self field. Here though, the magnetic field is produces by an external solenoid source to enhance acceleration and plasma confinement. This is typically used for production of higher temperature plasmas[4].

MPD Steady State

Depending upon the architecture the MPD can be operated in steady state pulse mode for achieving pulse mode durations as short as a millisecond[4].

MPD Quasi Steady State

In this case a capacitive system discharges across the arc allowing for higher currents and higher magnetic fields for a given power level. Arc erosion here is more severe than in the pulsed arcjets[4].

MPD Arcjet

It evolved from the combination of electrothermal arcjet and the magnetoplasmadynamic thrusters. A neutral plasma is accelerated by means of both Joule heating and electrodynamic forces. This combination provides significant improvement to efficiency as the power requirements increases in the range of MW[206].

Pulsed Plasma – Self Induced (PPT)

It accelerates the plasma between two rail electrodes and fed by a capacitor which in turn charged by a power supply. The current flow through the plasma quickly discharges the capacitor and hence the mass flow rate must be pulsed according to the discharge schedule[95]. It can be considered as a variation of MPDs due to the fact that relies upon the interaction of an electric field with self induced magnetic field. A capacitor is used to initiate the pulse discharge in between two electrodes separated by a Teflon bar. The surface of this bar ablates because of the heating caused by the discharge. The magnetic filed acts to accelerate the ablative material[4]. It involves the use of an electrical discharge to drive a current through the working fluid. The interaction of this current with a properly configured magnetic field produces body forces which directly accelerate the propellant. The advantage of it is that produces kinetic energy directly without first depositing power into the thermal mode[103, 98]. Whenever the capacitor is triggered it produces the available thrust[204], which results in a great application benefit for a number of space missions.

Helicon Plasma

It is similar to PPTs but here the acceleration occurs through a helicon tube to produce an electromagnetic wave down the center of plasma chamber to maintain the high magnetic field strengths[4].

Pulsed Inductive Plasma (PIT)

Here a bank of high voltage capacitors is discharge into a flat induction coil strip surrounding a cylindrical chamber. Before the propellant can escape the chamber by diffusion the discharge pulse creates a high magnetic field within the chamber which both ionizes and accelerates the plasma away from the coil. Since the chamber is closed on one end the propellant plasma is confined and squeeze out of the exhaust end of the chamber[4]. One advantage is that it can operate with a variety of propellants such as hydrazine, ammonia, argon etc.

Electron Cyclotron Resonance

It is an electrodeless technique using microwave waveguide to deliver the energy for ionizing a gas. Circularly polarized transverse electric mode radiation is absorbed by the small population of free electrons constrained to move in cyclotronic paths within the plasma chamber in a magnetic field produced by an external surrounding solenoid. Collisions between neutral gas atoms and the circulating electrons ionize the gas. Divergence of the solenoid field towards the exhaust port accelerates the plasma to high velocity[4].

Variable Specific Impulse Plasma (VASIMR)

This technique relies on electrodeless cylindrical chamber in which ionization, plasma heating and conversion occur. In the forward portion of the chamber hydrogen is injected an ionized. The ions diffuse into the midsection of the chamber and are further heated by electron an ion cyclotron heating and whistler wave heating. Moving downstream the plasma enters the nozzle section where the shape and field strength and configuration converts the plasma's thermal energy into kinetic energy[4].

Hall Effect

An externally provided radial magnetic field is required. Within the volume enclosed by this field a continuous axial electric discharge is maintained in the low pressure. The interaction between the axial and the radial fields generates a Hall current, perpendicular to both the electric and magnetic fields and provides acceleration of the propellant. All Hall thrusters are gridless engines utilizing only body forces on charges in crossed electric and magnetic fields.

An anode is located at the rear of an annular channel whose walls are covered by dielectrics. The flux of primary electrons originates from a cathode located outside the channel that also serves to neutralize the ion beam. The propellant is released inside the thruster channel through the anode plane. The magnetic structure of a conventional Hall Effect thruster is constituted of a magnetic circuit with two pole pieces, cores and two magnetic screens, one internal coil and four external coils to achieve a maximum of radial magnetic field in the channel exit. Some prototypes exist with permanent magnets. The magnitude is large enough to trap electrons and low enough to avoid affecting the ion trajectories[106].

A Hall thruster operates by employing magnetic fields to deflect low mass electrons so that they are trapped under the influence of an ExB azimuthal field. The electrons finally are forced into an orbiting motion by the Hall effect current near the exit plane of the thruster[204].

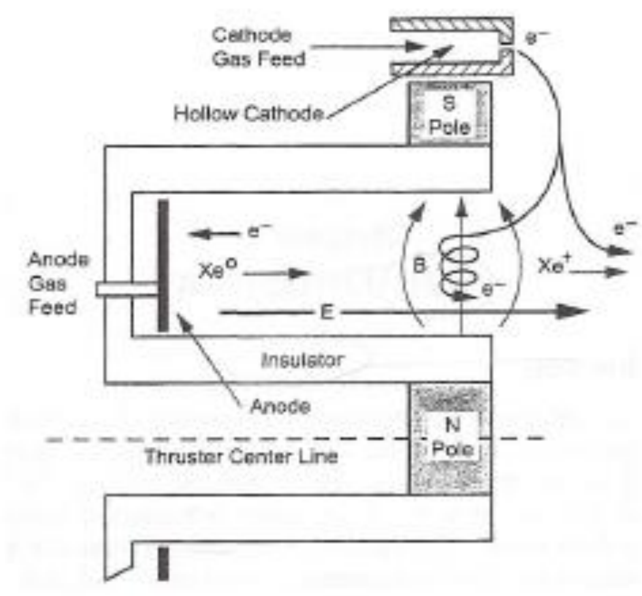
Hall Effect - SPT

When plasma densities are low enough and / or magnetic fields are high enough the Hall Effect electric field becomes quite significant. The Hall current that is being produced can be understood to represent the motion of the electron guiding center in a crossed electric and magnetic field arrangement where collisions must be relatively insignificant. It is called stationary plasma thruster (SPT) since the electron current swirls in place[95]. A dc electric field is established along the axis of the device with the anode located at the non exhaust end of the ionization and the cathode located externally or at the exhaust end. Electrons emitted from the cathode are pulled into chamber by applied electric field and have their circulation times increased through a force by E x B drift. As a result they are available to ionize the propellant injected from the non exhaust end of the chamber through collisions with larger times. The applied electrostratic field (Hall current) then accelerates the ions into the exhaust flow[4].

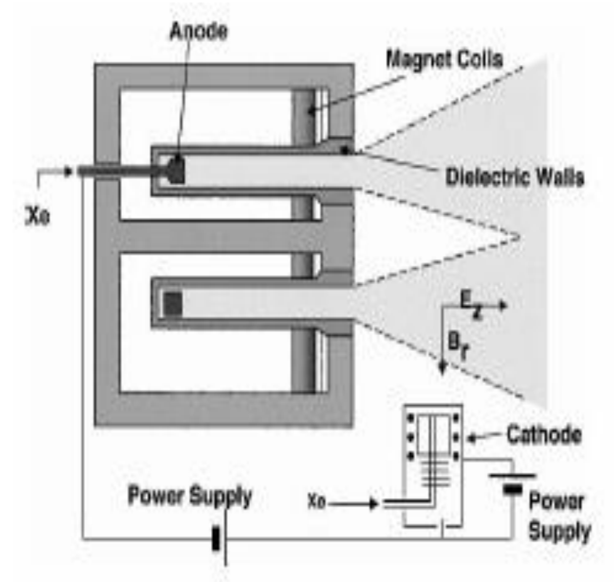
Hall Effect - TAL

A variation of the non conducting accelerator wall of SPT design is a smaller channel with metallic walls. This thruster is called thruster with anode layer (TAL) and has higher thrust density[95]. It is also called thruster with anode layer because the anodes are located downstream. The ion production region is located more externally than in SPT units. They are smaller and they have smaller erosion rates[4]. Here the walls are metallic and the channel is shorter and narrower.

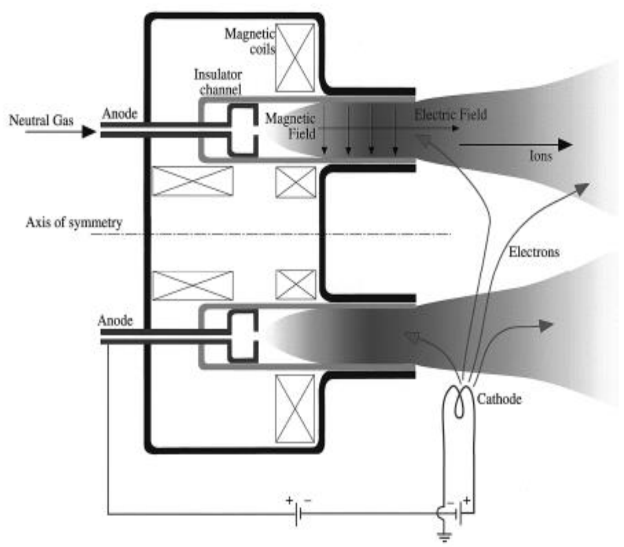
Basic representative schematics of various Electromagnetic thrusters



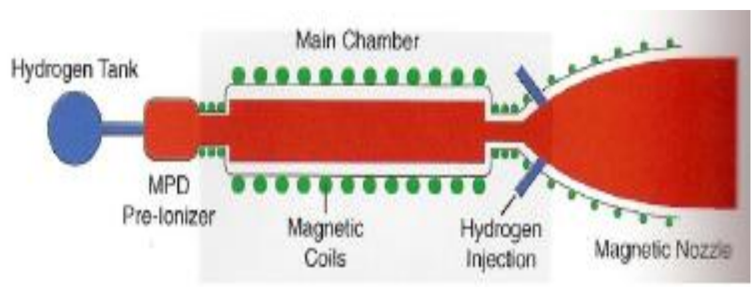
Hall[99]



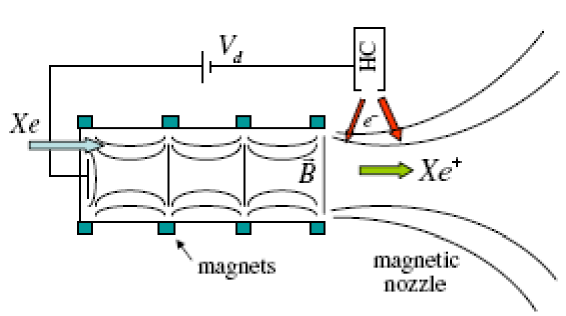
Hall SPT[122, 98]

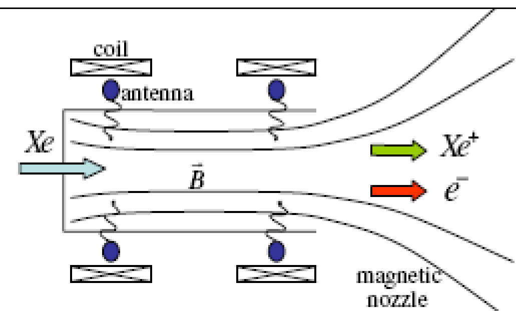


Hall[205]



VASIMR[4]





(f)

Hall with magnetic cusps[203]	Helicon[203]

Dual Stage Thrusters

NASA, ESA, JAXA and many other propulsion research organizations, have all used traditional electric propulsion for space applications and science missions. However, a trend to a dual stage hybrid engines is now under serious consideration in order to acquire combined engine performances and mix the advantages of the most well performed engines. Dual mode hybrid engines can provide mission flexibility with a single device providing either shorter transfer times or higher delivered mass without system complexities of multiple thruster systems. The dual mode hybrid engine concept is an attempt to combine the design attributes of the two different machines. Below there are four types of listed applications that are now undergoing experimentation and testing in order to be further investigated for future applications:

a. **Hall and Kaufman type Ion thruster** (Gray Research Ltd and NASA Glenn research Center - 2011). The system has several advantages. It should provide specific impulse at higher power levels, efficient packaging, an improved specific mass and it is a single thruster that should be broadly applicable to space missions[209].

b. **Combine Electrothermal and Electrostatic** acceleration in a **Microhollow Discharge plasma** thruster (University of Ulsan, South Korea - 2011). With this configuration the first stage located deeper from the exit is used to ionize the fuel gas and the second stage is used to accelerate it. Designers are trying to achieve both electrostatic and electrothermal acceleration which they are hoping to be more effective for future space micro applications[51].

c. **Microwave Ion Discharge and Hall** thruster (Kyushu University and JAXA - 2007). The thruster operates initially at high thrust but low specific impulse (Hall thruster) and later on high specific impulse but low thrust regime (microwave ion discharge). The first option is suitable for orbit raising, insertion and repositioning in which the main constraint is minimization of transfer duration and the second option is efficient for orbit correction, north-south stationkeeping in which low propellant is required[135].

d. **Double stage Hall** (Moscow institute of radio engineering and CNES France - 2005). The double stage hall is used to increase thruster efficiency by 70%. The first stage is used to ionize the substance and the second stage develops the sole acceleration mechanism. Specific impulses acquired reached the level of 3700sec. The purpose is to get a thruster with a very flexible operating point together with improved performances in terms of divergence and efficiency. The amount of power needed is at the range of kW[210].

Micro MET Detailed Comparative Analysis – Characteristics based on published papers

micro/ nano / pico Microwave Electrothermal Thruster Analysis											
	Institution →	**Kyoto University[22]**	**Kyoto University[21]**		**Kyoto University[20]**	**Kyoto University[18]**			**Kyoto University[17]**		
	Date →	**2011**	**2011**		**2009**	**2008**			**2007**		
	Paper Title →	**MW excited microplasma thruster with applied magnetic field**	**MW excited microplasma thruster with He and H_2**		**Numerical and experimental study of MW excited microplasma thruster and micronozzle flow**	**Microplasma thruster for ultra small satellites**			**Numerical Analysis and experiments of a Microwave Excited Microplasma Thruster**		
No	MW Characteristics										
1.	Magnetic Field	2.4 kG	N/A		N/A	N/A			N/A		
2.	Microplasma	azimuthally symmetric microwave excited	azimuthally symmetric microwave Surface wave excited source		azimuthally symmetric microwave Surface wave excited source	azimuthally symmetric microwave excited Surface wave excited source			Transverse gas entrance microwave surface wave excited source		
3.	Microplasma Source	Cylindrical	Rod antenna on axis with dielectric envelope		Rod antenna on axis with dielectric envelope						
4.	Microplasma source material	Quartz and Ultra Torr around the chamber	Quartz tube and envelope		Quartz tube and envelope	Quartz tube and envelope			Quartz and Ultra Torr around the chamber		
5.	Micro nozzle shape	Conical	Conical		Conical	Conical					
6.	Micro nozzle	De Laval - CD	De Laval - CD		De Laval - CD	De Laval - CD					
7.	Micro nozzle material		Quartz			Quartz metal grounded					
8.	Micro nozzle length	1.0 mm	1 mm		1 mm						
9.	Micro nozzle inlet diameter	0.6 mm	0.6 mm			0.6 mm					
10.	Micro nozzle Throat	0.2 mm	0.2 mm		0.2 mm	0.2 mm					
11.	Micro nozzle Exit Diameter	0,8 mm	0.8 mm			0.8 mm					
12.	Micro nozzle half angle										
13.	Chamber Pressure	10 kPa	0.5 – 12 kPa		31 kPa	50 kPa			10kPa	20kPa	50kPa
14.	Chamber / Wall Temperature		500 K		890 K	500 K			500 K		
15.	Heavy Particle Temperature					1000 K					
16.	Chamber Length	10.6 mm	10.5 mm		10 mm	10 mm			4.48 – 12.48mm		
17.	Chamber Inner Diameter	2.0 mm	1.5 mm		1.5 mm	1.5 mm			1.5 mm		
18.	Chamber Outer Diameter	6.0 mm	3.0 mm		3.0 mm	3.0 mm			3.0 mm		
19.	Dielectric material	Quartz	Quartz		Quartz	quartz	mullite	zirconia	quartz		
20.	Dielectric Envelope Length around MW antenna				9.5 mm	10 mm			10 mm		
21.	Dielectric Envelope Inner Diameter				0.5 mm	2.0 mm			0.75 mm radius		
22.	Dielectric Envelope Outer Diameter				1.0 mm	1.0 mm					
23.	Propellant Gas	Argon	He	H_2	Argon + 5% N_2 and H_2	Argon + 5% N_2 and H_2					
24.	Propellant mass	High	Low	Low							
25.	Diffusivity	Low	High	High							
26.	Thermal Conductivity	Low	High	High							
27.	Surface to Volume Ratio	Large									
28.	Thrust performance	Improved by	No magnets		No magnets						

	with magnets	2.8 – 12.3%				
29.	Power Input	3W and 6W	6 W (> 10W available power in microsat)	6 W (> 10W available power in microsat)	1 – 10 W	
30.	Mass flow rate (mg/s)					
31.	Gas flow rates (sccm)	> 20 sccm	2-70 sccm	50 sccm + 5% N_2 and H_2	66 sccm	
32.	Flow velocity		2 times ↑ than in Ar			
33.	Electrodes	N/A	N/A	N/A	N/A	
34.	Neutralizer	N/A	N/A	N/A	N/A	
35.	MW frequency	4 GHz	4 GHz	4 GHz	2 GHz 4 GHz	4 GHz 10 GHz
36.	MW Antenna Length		8.5 mm			
37.	MW Antenna Diameter		0.5 mm			
38.	Signal Generator	Agilent E8257C		Agilent E8257C		
39.	Coaxial Cable	Semirigid	Semirigid	Semirigid RG-405/U	Semirigid 10mm long	Semirigid RG-405/U
40.	Plasma Ignition	Tesla Coil				
41.	Plasma Temperature				700 – 1200 K	
42.	Magnet Placement	Top and Bottom of Quartz Chamber	Antenna is placed inside the plasma and non magnetic confinement is needed	Antenna is placed inside the plasma and non magnetic confinement is needed	Antenna is placed inside the plasma and non magnetic confinement is needed	Antenna is placed inside the plasma and non magnetic confinement is needed
43.	Ring Magnet Magnetic Field	Ne-Fe-B of 11.4 kG				
44.	Magnet Outer Diameter	13.0 mm				
45.	Magnet Inner Diameter	7.0 mm				
46.	Magnet Length	10 mm				
47.	Thrust Measurement method in cold gas	Target	Target	Target	Target	N/A
48.	Thrust Measurement method in plasma discharging	Pendulum	Pendulum	Pendulum	Pendulum	N/A
49.	General Findings	Investigate the shape of the magnetic field in order to confine energetic electrons sufficiently	High Diffusivity and thermal conductivity of light mass propellants do not lead to deterioration in performance	The thrust performance found to increase with the discharge on and with increasing microwave power	As power increases Thrust increases, as power increases Isp increases and as power increases thruster efficiency decreases.	With frequency 4.0 GHz plasma is little affected by the shape of the plasma source & In 10 GHz microwaves higher electron density and heavy particle temperature were achieved with shorter plasma chamber. So in this MW range and shorter chamber can improve thrust performance.

	Institution →	**Kyoto University[16]**	**Kyoto University[19]**	**Kyoto University[14]**	**Kyoto University[15]**	**Kyoto University[13]**
	Date →	**2007**	**2008**	**2006**	**2006**	**2004**
	Paper Title →	**A miniature electrothermal thruster using microwave –**	**Microwave Excited microplasma thruster: a numerical and experimental**	**A miniature electrothermal thruster using microwave**	**Performance testing of a miniature electrothermal**	**Development and Modeling of a microwave excited**

		excited microplasmas: Thrust measurement and its comparison with numerical analysis	study of the plasma generation and micronozzle flow	excited plasmas: a numerical design consideration	thruster using microwave excited microplasmas	microplasma thruster
No	MW Characteristics					
1.	Magnetic Field	N/A	N/A	N/A	N/A	N/A
2.	Microplasma	Transverse gas entrance microwave Surface wave excited source	microwave surface wave excited source	Azimuthally symmetric microwave surface wave excited source	Azimuthally symmetric microwave surface wave excited source	Azimuthally symmetric microwave surface wave excited source
3.	Microplasma Source	Cylindrical dielectric tube	Cylindrical dielectric tube	Cylindrical dielectric tube	Cylindrical dielectric tube	Cylindrical dielectric tube
4.	Microplasma source material	quartz	Quartz	Quartz	Straight quartz tube 10 mm	Fused silica or ceramics
5.	Micro nozzle shape	Conical	Conical	Conical	Conical	Conical
6.	Micro nozzle	De Laval C-D	De Laval C-D	De Laval C-D	De Laval C-D	De Laval C-D
7.	Micro nozzle material					
8.	Micro nozzle length	1mm 1mm 1.4mm	1 mm	1-2 mm		
9.	Micro nozzle inlet diameter	0.6 mm	0.6 mm	0.6 mm	0.6 mm	0.6 mm
10.	Micro nozzle Throat	0.2mm 0.12mm 0.2 mm	0.2 mm	0.2 mm	0.2 mm	0.2 mm
11.	Micro nozzle Exit Diameter	0.8 mm	0.8 mm	0.8 mm	0.8 mm	0.8 mm
12.	Micro nozzle half angle			10˚ 20˚ 30˚	20˚ 30˚	10˚ 20˚ 30˚
13.	Chamber Pressure	10-100 kPa	10-50 kPa		4-20 kPa	6 kPa
14.	Chamber / Wall Temperature		500 K			
15.	Heavy Particle Temperature			7400 K		
16.	Chamber Length	10 mm	10.5 mm			40 cm
17.	Chamber Inner Diameter	1.5 mm	1.5 mm			
18.	Chamber Outer Diameter	3 mm	3 mm			
19.	Dielectric material	Quartz tube	Quartz tube	Quartz tube	Quartz tube	
20.	Dielectric Envelope Length around MW antenna	10 mm	9.5 mm	10 mm	10 mm	
21.	Dielectric Envelope Inner Diameter	0.5 mm	0.5 mm	2 mm	2 mm	
22.	Dielectric Envelope Outer Diameter	1 mm	1 mm			
23.	Propellant Gas	Ar	Ar + 5% N_2 and H_2	Ar (high enthalpy)	Argon and N_2	Ar
24.	Propellant mass					
25.	Diffusivity					
26.	Thermal Conductivity					
27.	Surface to Volume Ratio					
28.	Thrust performance with magnets	N/A	N/A	N/A		
29.	Power Input	3 W 6 W	6 W	10 W	5 - 9 W	10 W
30.	Mass flow rate (mg/s)					
31.	Gas flow rates (sccm)	60 sccm	33 sccm		10-50 sccm	280 sccm
32.	Flow velocity					
33.	Electrodes	N/A				
34.	Neutralizer	N/A				

35.	MW frequency	4 GHz	4 GHz	1-25 GHz	4 GHz	4 GHz
36.	MW Antenna Length		8.5 mm			
37.	MW Antenna Diameter		0.5 mm			
38.	Signal Generator	Agilent 8648D			Agilent 8648D	
39.	Coaxial Cable	Semirigid Rg-405/U	Semirigid Rg-405/U		Semirigid Rg-405/U	
40.	Plasma Ignition					
41.	Plasma Temperature					
42.	Magnet Placement	N/A	N/A	N/A	N/A	N/A
43.	Ring Magnet Magnetic Field	N/A	N/A	N/A	N/A	N/A
44.	Magnet Outer Diameter	N/A	N/A	N/A	N/A	N/A
45.	Magnet Inner Diameter	N/A	N/A	N/A	N/A	N/A
46.	Magnet Length	N/A	N/A	N/A	N/A	N/A
47.	Thrust Measurement method in cold gas	Target	Target	Target		
48.	Thrust Measurement method in plasma discharging	Pendulum	Pendulum	Target		
49.	General Findings	Thrust efficiency decreases with increase of the microwave power Thrust performance among three micronozzles is insignificant changing only throat diameters	Applicable for attitude control and stationkeeping (as all others) for microspacecrafts <10kg	Surface waves tends to be established in the microplasma source at high frequencies and permitivities & Microwave power absorbed in plasmas increases with increasing frequency and permittivity.	Thrust and Isp were improved by discharging plasma and increased with microwave input power & The thrust increased with increasing gas flow rate whereas Isp had minimum values at around 20-30sccm and then increased at 10sccm in plasma discharging operation	Microwave power absorbed in plasmas increases with increasing frequency

	Institution →	**Xian Polytechnique University[35]**	**Xian Polytechnique University[152]**	**Korea Ulsan University[162]**	**Penn State University[8]**	**Penn State University[118]**	**Penn State University[154]**	**Penn State University[181]**	**Princeton University[69]**
	Date	**2008**	**2011**	**2011**	**2007**	**2010**	**2011**	**2011**	**2004**
	Paper Title	**Development and research of a coaxial microwave plasma thruster**	**Optimization of GEO using electric propulsion based on genetic algorithm**	**Exhaust Plume characteristics of microhollow cathode discharge plasma thruster**	**Design and Initial testing of a miniature microwave electrothermal thruster**	**Evaluation and Optimization of an 8 GHz MET**	**Modeling and direct thrust measurements of an 8GHz MET**	**The design and development of a 30GHz MET**	**A 300W microwave Electrothermal thruster**
No	MW Characteristics								
1.	Magnetic Field	0.5 T						30 T	
2.	Microplasma								
3.	Microplasma Source				microwave antenna		circular waveguide cavity	microwave antenna	
4.	Microplasma source	Magnetron or Solid							

	material	State with Arsenide							
5.	Micro nozzle shape				De Laval C-D	Different sizes and shapes of nozzles D1, D2 etc			
6.	Micro nozzle								
7.	Micro nozzle material								
8.	Micro nozzle length								0.0189
9.	Micro nozzle inlet diameter							0.0150 cm	
10.	Micro nozzle Throat								
11.	Micro nozzle Exit Diameter							0.221 cm	
12.	Micro nozzle half angle								
13.	Chamber Pressure								
14.	Chamber / Wall Temperature								
15.	Heavy Particle Temperature								
16.	Chamber Length	1.5 and 3 m		1-3 cm				Cavity: 0.40857cm radius & 1.4299cm height	20 cm
17.	Chamber Inner Diameter								
18.	Chamber Outer Diameter								
19.	Dielectric material								
20.	Dielectric Envelope Length around MW antenna								
21.	Dielectric Envelope Inner Diameter								
22.	Dielectric Envelope Outer Diameter								
23.	Propellant Gas	He			He				N_2O, He
24.	Propellant mass								
25.	Diffusivity								
26.	Thermal Conductivity								
27.	Surface to Volume Ratio								
28.	Thrust performance		0.025 mN						
29.	Power Input (w)	70	120	0.52 – 1.62	20	100-250		10	150
30.	Mass flow rate (mg/s)	4.09 -6.14	4.4		2.15				
31.	Gas flow rates (sccm)			80					
32.	Flow velocity								
33.	Electrodes								
34.	Neutralizer							No	No
35.	MW frequency				7.5GHz	7.9-8.4GHz	8GHz	30GHz	7.5GHz
36.	MW Antenna Length							0.5mm 1mm	
37.	MW Antenna Diameter								
38.	Signal Generator				microwave antenna				
39.	Coaxial Cable								
40.	Plasma Ignition								
41.	Plasma Temperature				298-360K				
42.	Magnet Placement								
43.	Ring Magnet Magnetic Field								
44.	Magnet Outer Diameter								

45.	Magnet Inner Diameter								
46.	Magnet Length								
47.	Thrust Measurement method in cold gas								
48.	Thrust Measurement method in plasma discharging								
49.	General Results	The average gas temperature is increased with increasing microwave power & When the microwave power is increased the electron density increases gradually	MET can be used for drag compensation, solar pressure cancelation of low earth orbit spacecraft, formation flying, precise positioning of small satellite, repositioning of GEO and main propulsion for interplanetary missions	**Double stage** with the use of electrothermal and electrostatic acceleration. **MET + Hall** Thrusters Very low power requirements	Thickness of the dielectric caused lack of significant heating to the plasma & Increased mass flow rate increase of thrust	Increase in flow rate and pressure forces the plasma closer to the nozzle entrance which decreases losses. Maximum thermal efficiency is not a function of input power Utilizing a shorter antenna improved performance Increase nozzle diameter increases the efficiency	simulation of plasma physics with COMSOL – coupling of electromagnetic effects with thermodynamic effects	The resonant frequency is exactly 29.939Ghz and the power coupling increased by reducing the antenna length	

Analytical Literature Review Based on Papers for micro METs

Kyoto University

Publications

a. Development and Modeling of a microwave excited microplasma thruster, Yoshinori Takao and Kouinchi Ono, Kyoto University, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauderdale, Florida

<u>Analysis - Characteristics</u>

(1) Microplasma thruster with surface wave excited source, electron heating occurs in a thin (a few mm deep or less) skin depth layer.

(2) Cylindrical dielectric tube made of fused silica glass or ceramics. Length of 10mm and diameter of 2mm.

(3) Coaxial cable, semirigid

(4) Oscillator Agilent Technologies 8648D

(5) f=4GHz

(6) Quartz tube cover. Length 10mm and diameter 1.5mm. It is used to protect electrodes from erosion by plasmas

(7) Chamber 40cm in diameter and 40cm in height.

(8) Power input 10W

(9) Power absorption tends to increase with increasing microwave frequency

(10) Nozzle inlet, throat and exit diameter are 0.6, 0.2 and 0.8 mm.

(11) Conical Nozzle half angles selected to be 10, 20 and 30 degrees

(12) Pressure: 6kPa

(13) Mass flow rate 280sccm

(14) Propellant Gas: Argon

(15) Microwave power absorbed in plasmas increases with increasing frequency

(16) Thrust of 4.3mN and Isp=320s at a power of 3.1W

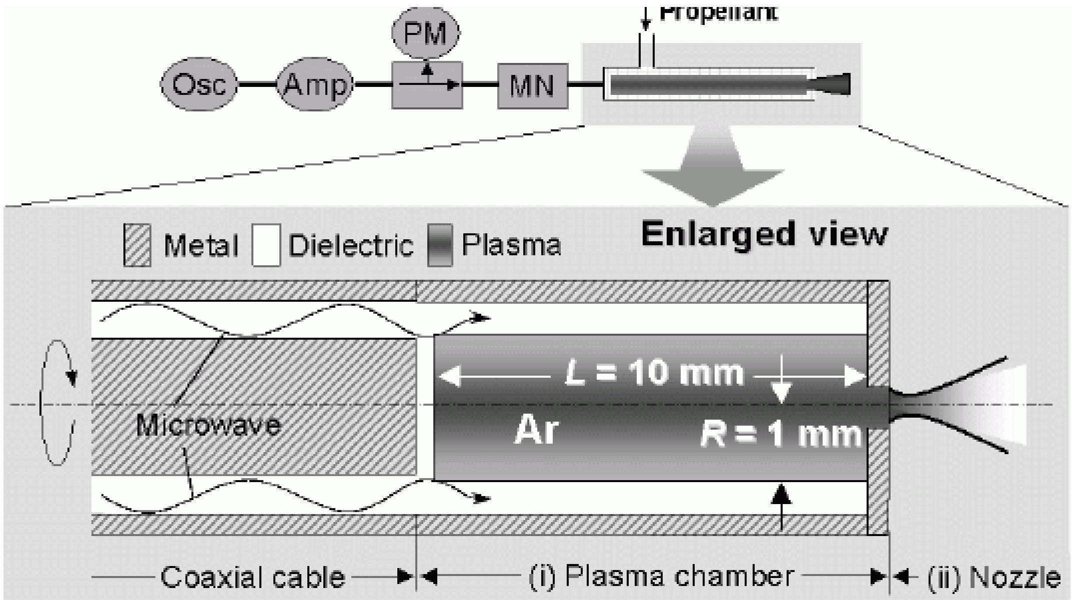


Figure 1. A schematic diagram of the microwave-excited microplasma thruster.

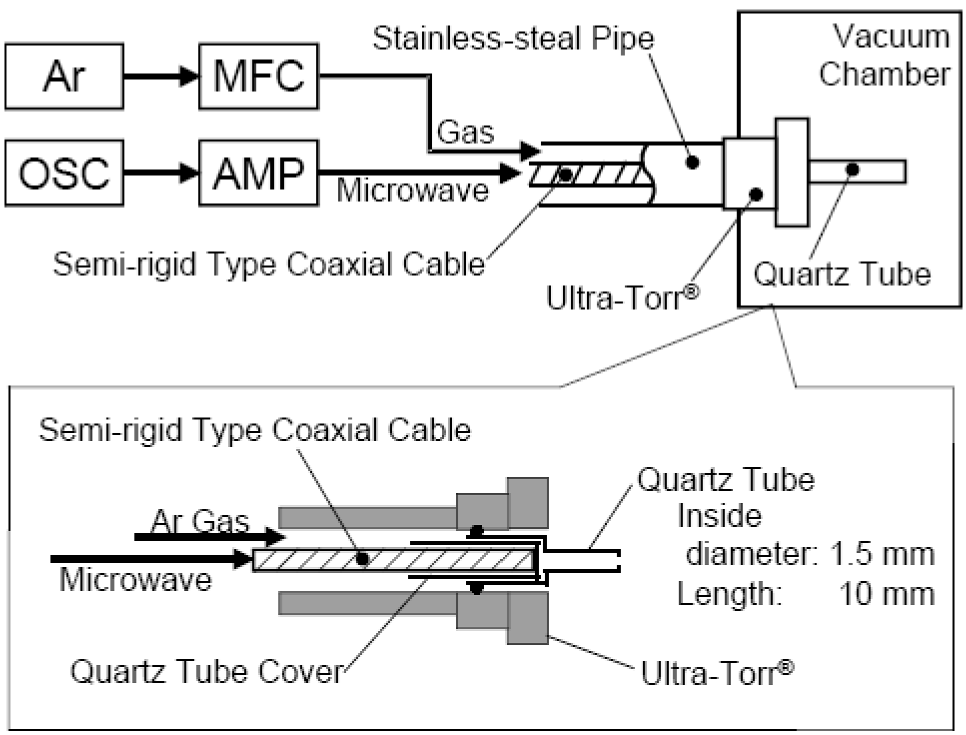


Figure 3. A schematic of the experimental setup (top) and the profile of the plasma source in the vacuum chamber (bottom).

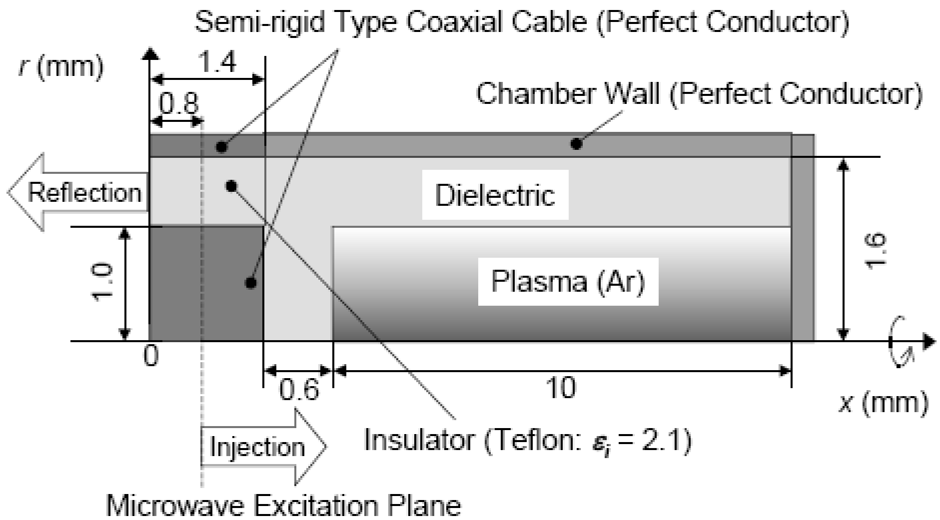


Figure 4. A schematic of a simulation area of the microplasma source.

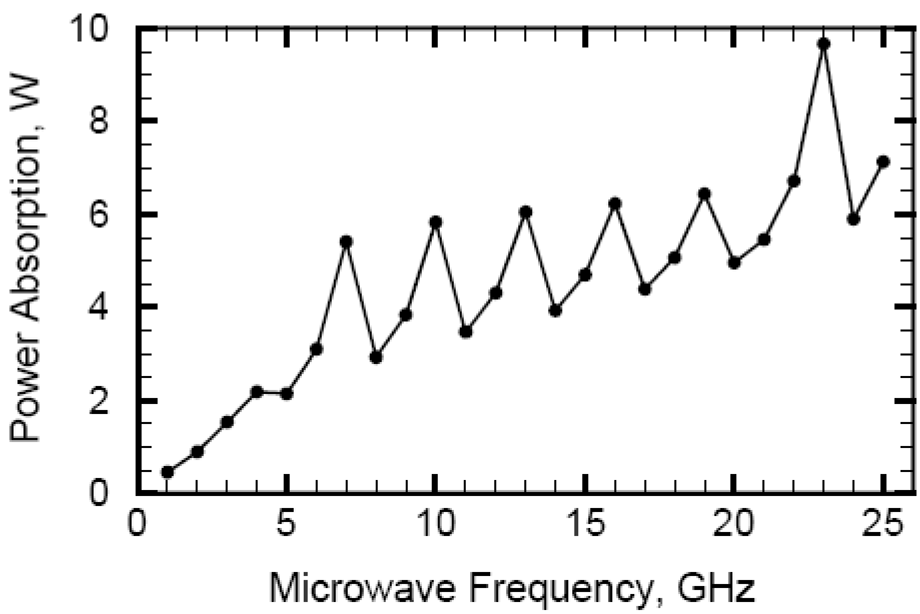


Figure 5. Dependence of the power absorption on the microwave frequency at ε_d = 20.

b. Development of a Microwave Excited microplasma thruster, Yoshinori Takao and Kouinchi Ono, Kyoto University, 29th Electric Propulsion Conference, Princeton, IEPC 2005-056

Analysis - Characteristics

(1) Miniature Electrothermal Thruster

(2) f=4Ghz

(3) Power 5 W

(4) Mass flow 1.5mg/sec

(5) Propellant Argon
(6) Thrust efficiency 12%
(7) Dielectric tube 10mm length and 1.5 inner diameter
(8) Conical micronozzle
(9) Thrust 2.0 mN
(10) Isp 136sec

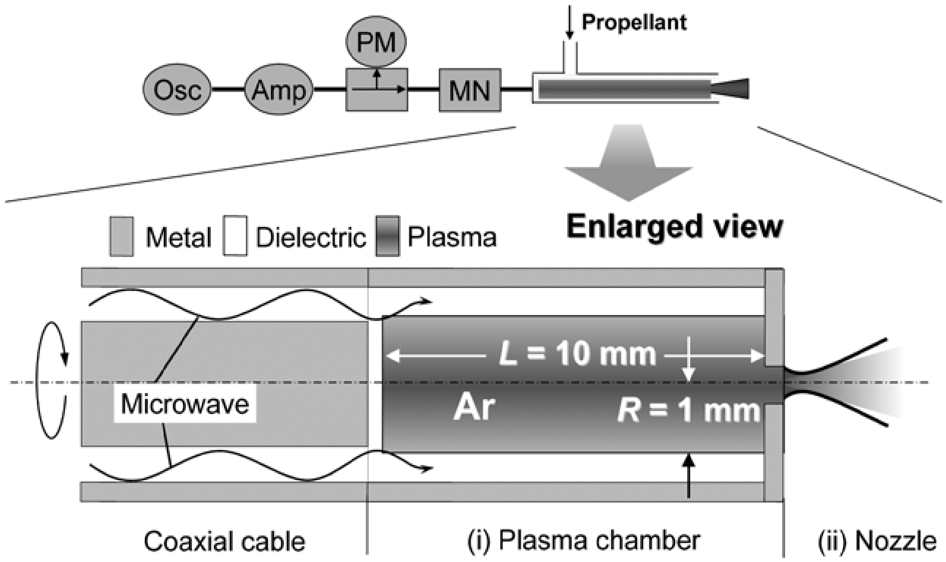
c. A miniature electrothermal thruster using microwave excited plasmas: a numerical design consideration, Yoshinori Takao, Kouinchi Ono, Institute of Physics publishing, Plasma sources science technology 15 (2006) 211-277, March 2006, Kyoto University, Department of Aeronautics and Astronautics.

Analysis - Characteristics

(1) Microplasma thruster with surface wave excited source, electron heating occurs in a thin (a few mm deep or less) skin depth layer.
(2) Azimuthally symmetric microwave excited plasma
(3) Low cost performance of great advantage for microspacecrafts in fleet missions.
(4) Use of high enthalpy plasma gases
(5) Cylindrical dielectric chamber covered with grounded metal. Inner diameter of 2mm and length of 10mm
(6) Surface waves propagation of plasma (advantageous – power absorption in a thin skin layer depth along the interfaces – generate overdense plasmas in a very small space without magnetic field confinement)
(7) Micronozzle is conical 1-2 mm length, De Laval C-D, throat=0.2mm diameter.
(8) Three different experiments with 10,20 and 30 degrees half angle conical nozzles, investigate the angle dependence. The inlet, throat and exit diameters are 0.6mm, 0.2mm and 0.8mm.
(9) Coaxial cable
(10) Working gas is Argon
(11) Pressure 100kPa
(12) Power input 10 W
(13) Absorbed power increased with increased frequency from 0 to 25GHz
(14) At 23Ghz the plasma absorbs most of the microwave input power
(15) Local peaks of the absorbed power occur when the quarterwave length is multiplied by some odd numbers is between chamber length and the plasma length
(16) Heavy particle temperature 7400K
(17) Mass flow rate 2.0mg/sec
(18) Surface waves tends to be established in the microplasma source at high frequencies and permitivities.
(19) Microwave power absorbed in plasmas increases with increasing frequency and permittivity.

(20) Nozzles tend to be very lossy. It was found that it is better to short the nozzle length by increasing the half cone angle than to provide as much power as possible to suppress the effects of viscous loss and thus to enhance the thrust.

(21) Thrust from 2.5-3.5mN, Isp=130-180sec



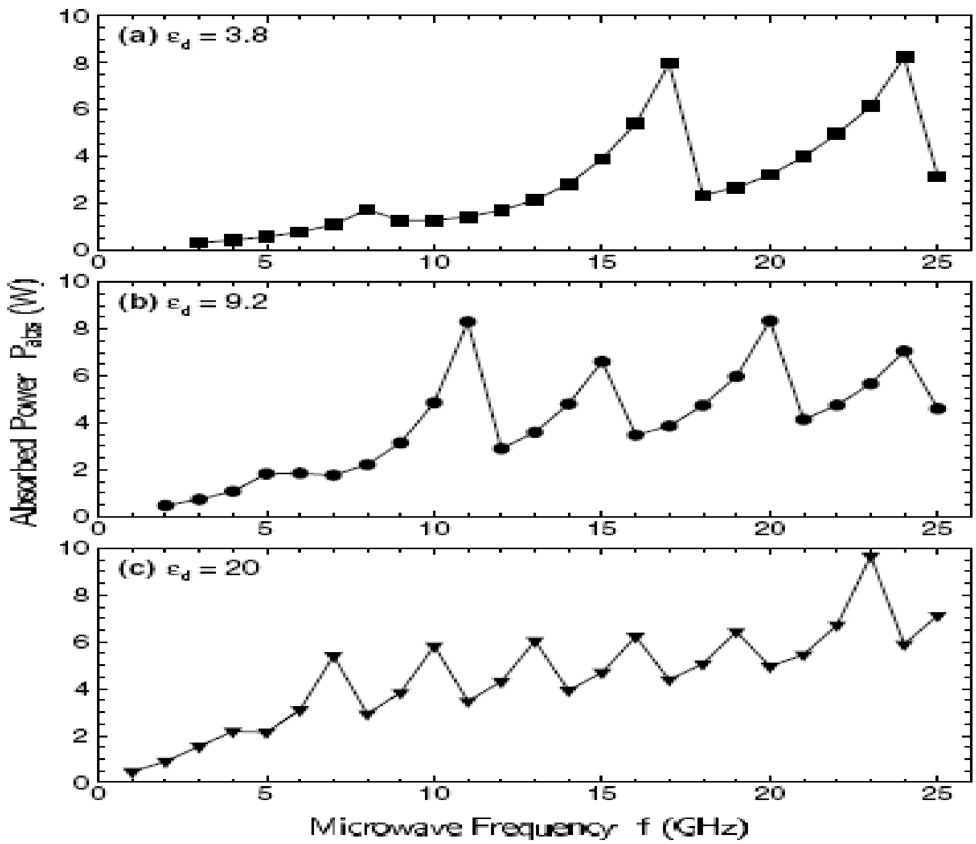


Figure 6. Absorbed power P_{abs} in the microplasma as a function of microwave frequency f for different relative permittivities ε_d = (*a*) 3.8, (*b*) 9.2, and (*c*) 20 of dielectrics, calculated at pressure $p = 1.0 \times 10^5$ Pa with a microwave input power $P_{in} = 10$ W. Note that the power which is not absorbed in the plasma is reflected and leaves the simulation area or the microplasma source.

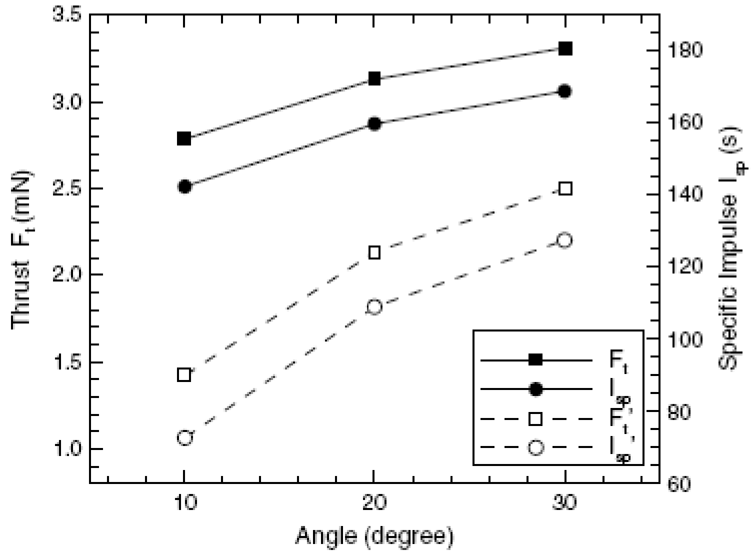


Figure 17. Thrust F_t, F_t' and specific impulse I_{sp}, I_{sp}' as a function of the half-cone angle of the micronozzle shown in figure 3, calculated at an absorbed power $P_{abs} = 5.0$ W in the microplasma source with a mass flow rate $\dot{m} = 2.0\,\mathrm{mg\,s^{-1}}$ under radiative wall conditions of the micronozzle.

d. Performance testing of a miniature electrothermal thruster using microwave excited microplasmas, Yoshinori Takao and Kouinchi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 9-12 July 2006, Sacramento, California (AIAA 2006-4492)

Analysis - Characteristics

(1) Microplasma thruster with surface wave excited source, electron heating occurs in a thin (a few mm deep or less) skin depth layer (simple structures, long time operation).

(2) Dielectric tube length 10mm and 2mm diameter

(3) Microwaves are injected to plasma through coaxial cable, semirigid, RG-405/U

(4) F=4GHz

(5) Oscillator Agilent 8648D

(6) Propellant gases Argon and N_2

(7) Microplasma source of straight quartz tube 10mm length and 3mm inner diameter

(8) Ultra Torr vacuum fitting

(9) Micronozzle 20 and 30 degrees half cone angles, conical, 0.6,0.2 and 0.8 inlet, throat and exit diameters.

(10) Thrust measurement method explanation to evaluate efficiency

(11) Power input of 5W and increased to 9 W

(12) Mass flow rate 10-50 sccm

(13) Pressure 4-20kPa

(14) The thrust and Isp were improved by discharging plasma and with microwave input power.

(15) The thrust increased with increasing gas flow rate whereas Isp had minimum values at around 20-30sccm and then increased at 10sccm in plasma discharging operation.

(16) Thrust efficiency at 5W was larger than in 9W.

(17) Thrust 1.1mN, Isp 73s, and trust efficiency 4.2% with Ar at flow rates 50 sccm and input power 9W.

(18) No difference between the adiabatic and isothermal wall conditions in cold gas operation

(19) Generally thrust performance improved by discharging the plasma

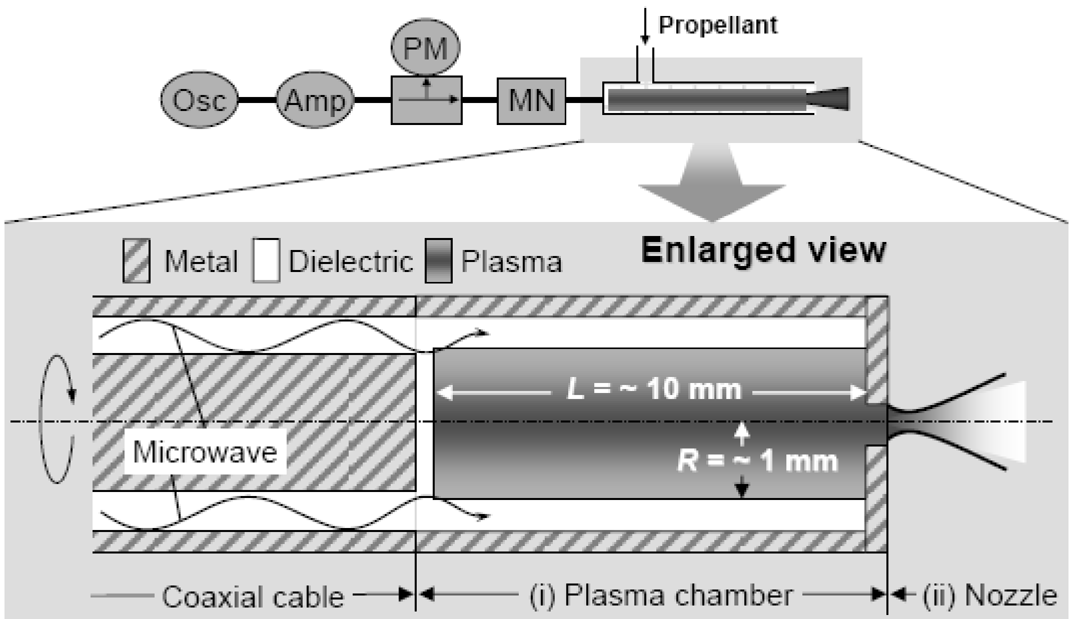
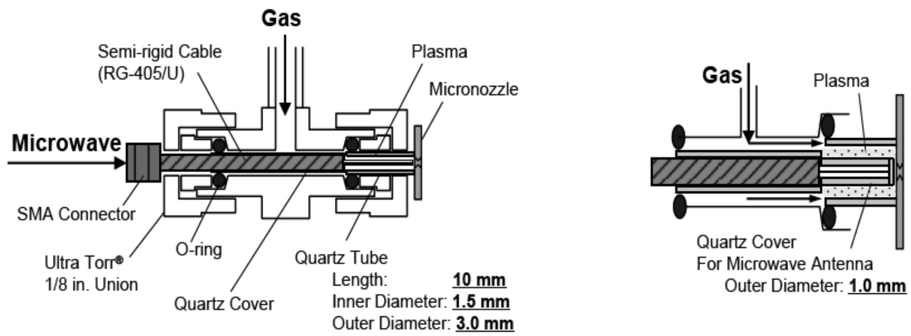
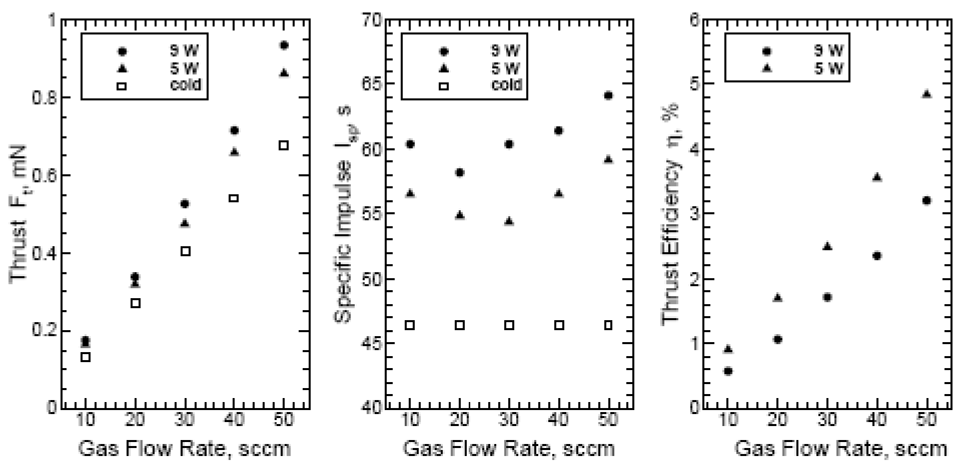


Figure 1. Schematic of a microplasma thruster using microwave-excited plasmas, consisting of (i) an azimuthally symmetric microplasma source and (ii) a converging-diverging (Laval) micronozzle.



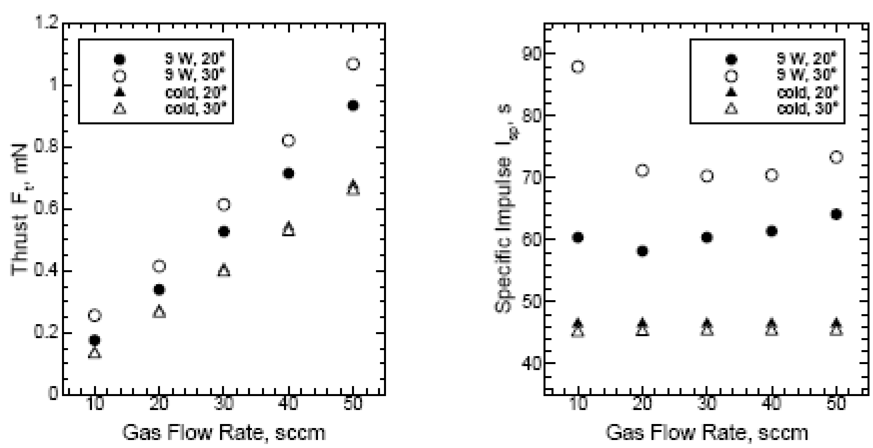
(a) Cross-sectional view of a microplasma thruster. (b) Radially enlarged view.

Figure 3. (a) Cross-sectional view of a microplasma thruster presently developed and (b) its radially enlarged view describing feed mechanism of working gases.



(a) Thrust. (b) Specific impulse. (c) Thrust efficiency.

Figure 7. Thrust performance as a function of Ar gas flow rate for different 4-GHz microwave input powers of 9, 5 W, and cold-gas operation without plasma discharges. Here, the 20°-half-cone-angle nozzle was employed.



(a) Thrust. (b) Specific impulse.

Figure 8. Half-cone-angle dependence of the thrust performance for different Ar gas flow rates, measured at a microwave power of 9 W and cold-gas operation without plasma discharges.

e. A miniature electrothermal thruster using microwave – excited microplasmas: Thrust measurement and its comparison with numerical analysis, Journal of Applied Physics 101, 123307, June 2007, Yoshimori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Japan.

Analysis - Characteristics

(1) Microplasma thruster with surface wave excited source, electron heating occurs in a thin (a few mm deep or less) skin depth layer.

(2) Surface wave plasmas are those where electron oscillations exist at the interface between two materials. The dielectric changes sign across the interface.

(3) Cylindrical dielectric tube for plasma source

(4) Semirigid Coaxial cable, rod antenna covered with quartz tube

(5) Propellant gas: Ar

(6) Pressure of propellant: 10 – 100 kPa

(7) This MW electrothermal thruster has an Electromagnetic Resonance Cavity (ECR) which is more practical for microspacecrafts less than 10kg.

(8) Microplasma source of quartz tube, 10 mm length, 1.5 mm inner diameter, 3 mm outer diameter.

(9) Coaxial cable Rg-405/U protruding 10mm beyond the insulator.

(10) Microwave antenna inserted into the plasma area of quartz tube length of 10 mm, 0.5 mm inner diameter and 1 mm outer diameter.

(11) Plasma source and antenna are inserted into a stainless steel Ultra Torr vacuum

(12) Microwave Frequency of 4 GHz

(13) Agilent 8648D oscillator

(14) Power of 10 w

(15) Critical electron density on which electrons can propagate is $9.5 \times 10^{17} m^{-3}$ for a microwave frequency of 4 GHz and dielectric constant of 3.8. Electron density is being measured with a Langmuir probe.

(16) Three different micronozzles with the same inlet and exit diameters but different throat diameter. Throat Diameter=0.2 mm and Nozzle length=1 mm, Throat Diameter=0.12 mm and Nozzle length=1 mm, Throat Diameter=0.12mm and Nozzle length=1.4 mm. Inlet diameter=0.6mm and Outlet Diameter=0.8 mm

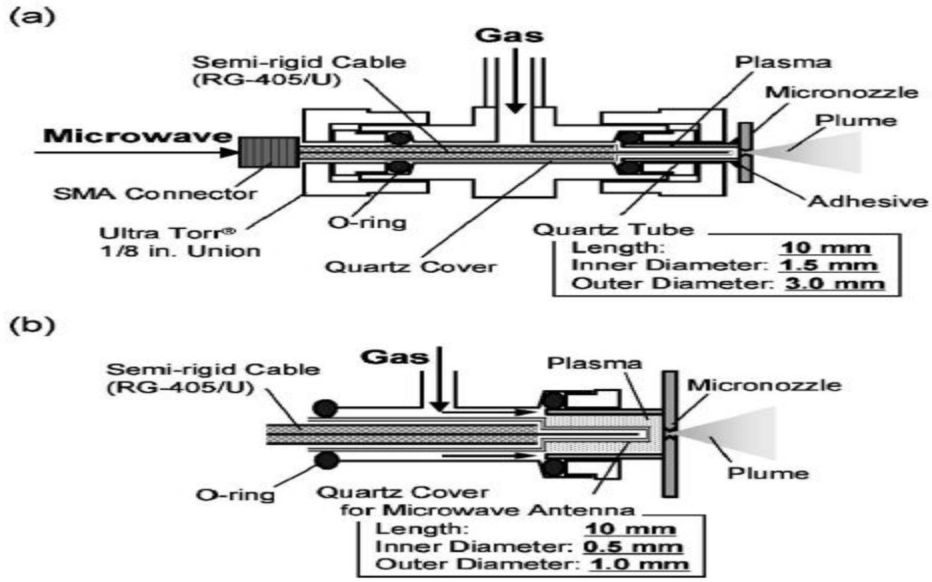
(17) Pendulum type measurement for thrust in discharge plasma ops.

(18) For gas flow rate of 60 sccm, thrust is 1.2mN at power 3W and specific impulse of 66sec with thrust efficiency at 12%

(19) Thrust is 1.4mN for power of 6W, Isp=79sec and thrust efficiency at 8.7%

(20) Thrust efficiency decreases with increase of the microwave power.

(21) Thrust performance among three micronozzles is insignificant



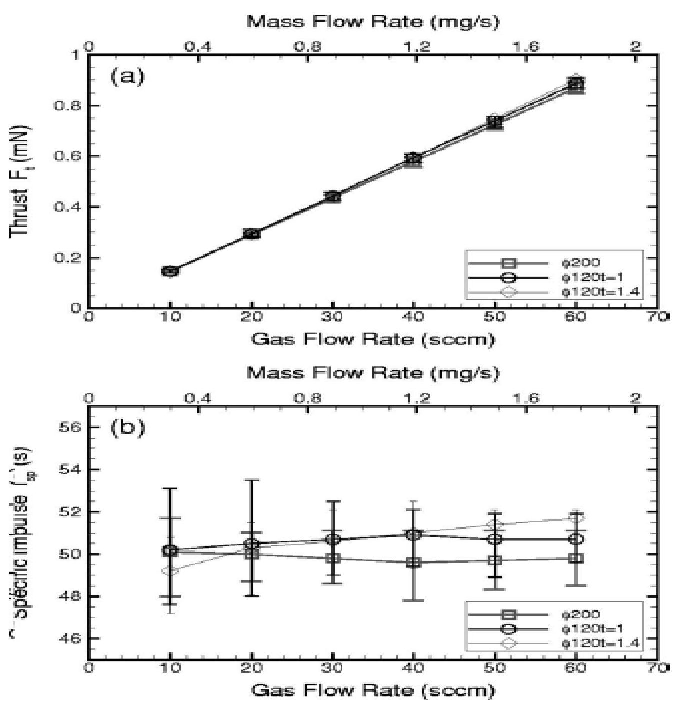


FIG. 5. (a) Thrust and (b) specific impulse in cold-gas operation, measured as a function of gas flow rate for three types of micronozzles: $\phi 200$, $\phi 120t=1$, and $\phi 120t=1.4$.

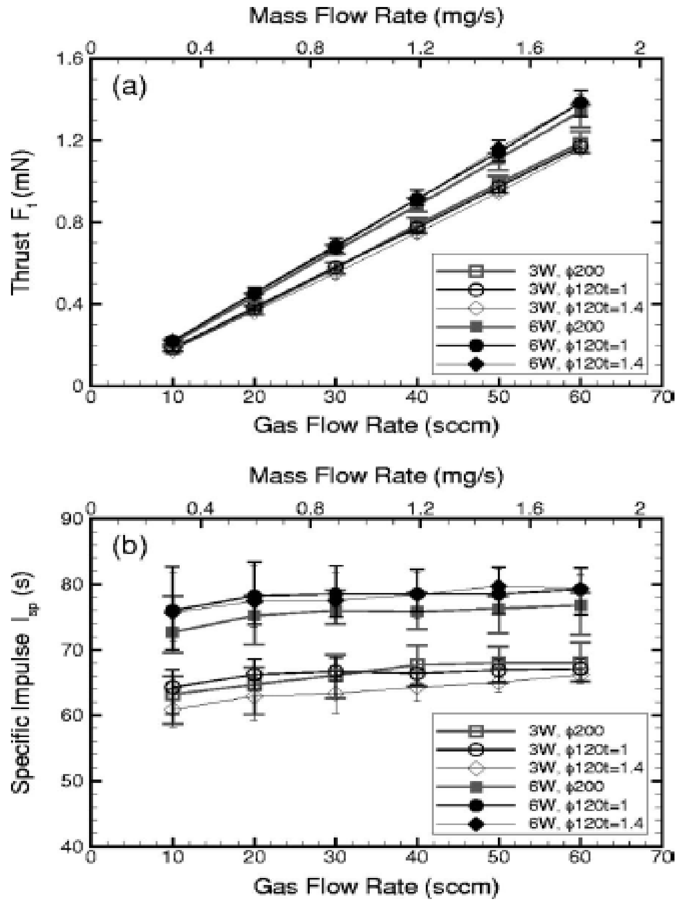


FIG. 7. (a) Thrust and (b) specific impulse in plasma-discharging operation, measured as a function of gas flow rate for three types of micronozzles: $\phi 200$, $\phi 120 t=1$, and $\phi 120 t=1.4$. Here, the microwave powers are 3 W (open symbols) and 6 W (closed symbols).

f. Numerical Analysis and Experiments of a Microwave Excited Microplasma Thruster, IEPC-2007-029, 30th International Electric Propulsion Conference, Florence, Italy, 17-20 September 2007, Takeshi Takahashi, Yoshinori Takao, Koji Eringuchi and Kouinchi Ono, Graduate School of Engineering, Kyoto University, Japan.

Analysis - Characteristics

(1) Microplasma thruster with surface wave excited source

(2) Electron heating occurs in a thin skin-depth layer along the plasma dielectric interfaces that is, the power absorption in plasmas becomes maximum at interfaces.

(3) Microplasma source of a dielectric chamber of 0.75 mm radius and 10 mm length and a metal around the chamber

(4) Coaxial cable propagation

(5) Surface wave excited plasma (SWP)

(6) MW frequency 4 GHz and 10 GHz

(7) Gas pressure 20 kPa

(8) Chamber wall temperature: 500 K

(9) Chamber length:10.48 mm, Quartz Dielectric

(10) Heavy Particle temperature reached 1050 K

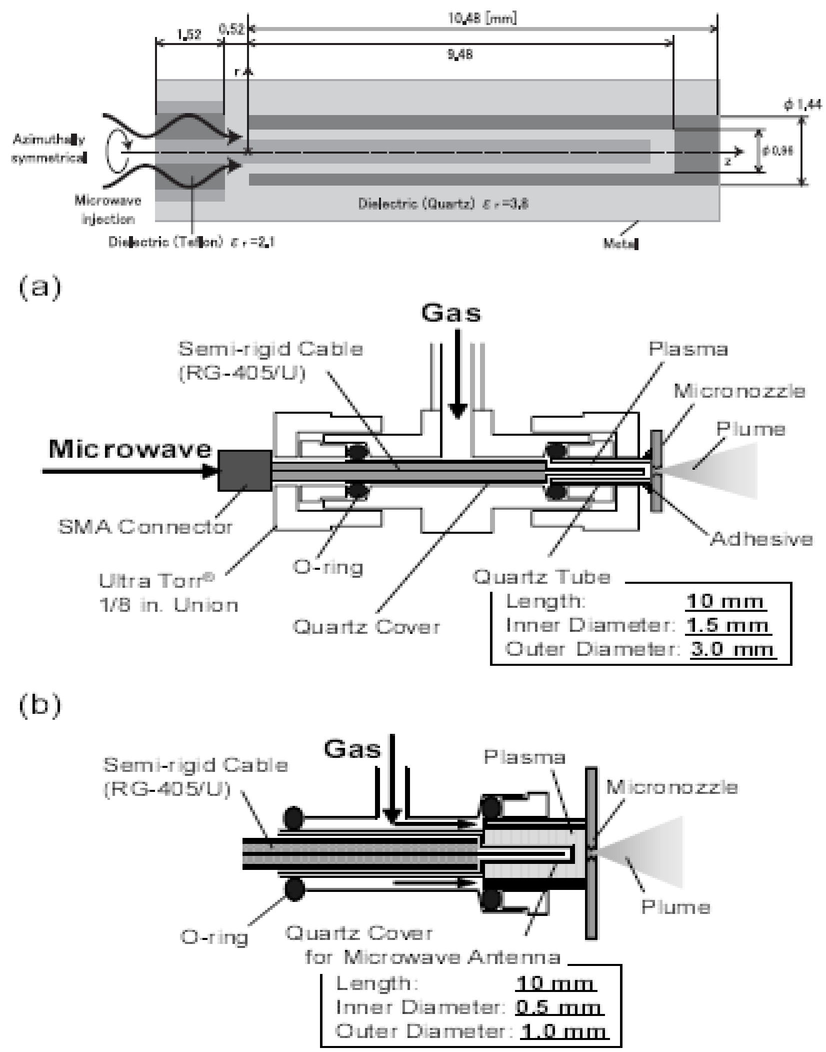
(11) Changed chamber length: 4.48 – 12.48mm

(12) Pressure 10,20,50 kPa

(13) Electron Density and heavy particle temperature increased with power. Under high pressure the electron density was 20% lower than because more frequent collisions occurred.

(14) When used 4.0 GHz the electron density and heavy particle temperature had little dependence on the plasma length. Advantage of MW 4.0 GHz frequency that plasma characteristics are little affected by the shape of the plasma source.

(15) In 10 GHz microwaves higher electron density and heavy particle temperature were achieved with shorter (4.48 and 5.48) plasma chamber. So in this MW range and shorter chamber can improve thrust performance.



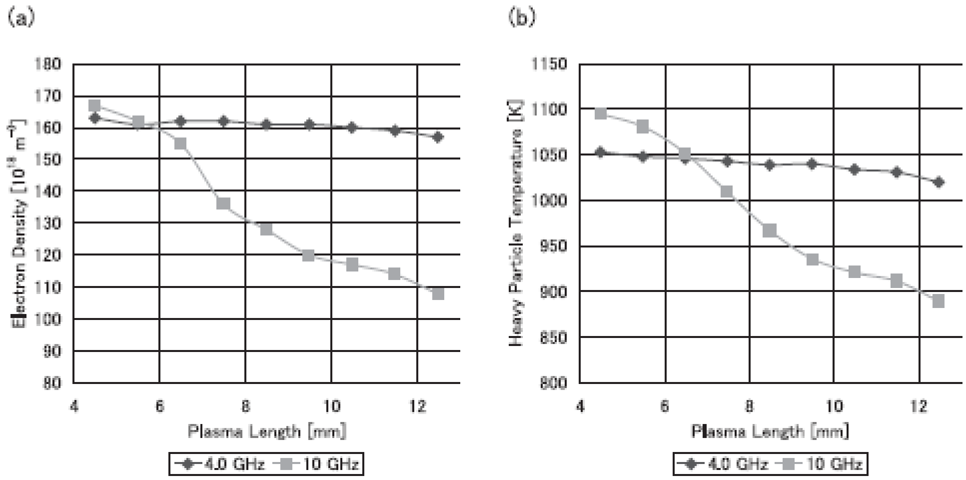


Figure 7. (a) Electron density and (b) heavy particle temperature as a function of length of plasma source.

g. Microplasma thruster for ultra small satellites: Plasma chemical and aerodynamical aspects, Yoshinori Takao, Takeshi Takahashi, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan, Pure Applied Chemistry, Vol. 80, No. 9, pp. 2013-2023, 2008.

Analysis - Characteristics

(1) Thrust for microspacecrafts <10kg in the mN range for stationkeeping and for attitude control in the μN range

(2) Azimuthally symmetric microwave excited microplasma

(3) Dielectric chamber of 2mm inner diameter, length:10 mm, metal grounded

(4) Metal rod antenna axis

(5) Converging Diverging De Laval micronozzle of length 1mm and throat 0.2mm

(6) The biggest advantage of electrothermal thrusters is that they do not require electrodes, neutralizers and magnets so they are simple structurally.

(7) Gas: Argon with 5% of N_2 and H_2 for plasma diagnostics

(8) Pinput=1-10 W changing

(9) Wall Temperature = 500k

(10) MW Frequency=2 and 4 GHz

(11) Heavy particle temperature=1000K

(12) Mass flow rate of 2 mg/sec or 66sccm assuming no slip conditions on the nozzle wall (velocity of particles on the wall is zero).

(13) Microplasma source of quartz tube 10 mm length, 1.5 mm inner diameter and 3 mm outer diameter.

(14) Coaxial cable 10mm long protruding into the plasma 10mm

(15) Dielectric envelope 10mm length, 0.5 mm inner diameter, 1mm outer diameter.

(16) Dielectrics used where quarz, mullite and zirconia for different investigation with ε=3.8,6,12-25 changing of the envelope characteristics

(17) Micronozzle of inlet diameter 0.6mm, throat diameter 0.2 mm and exit diameter 0.8 mm.

(18) Plasma temperature range 700-1200 K

(19) Thrust measurement with pendulum type stand for cold gas ops and thrust type stand for plasma discharging ops.

(20) Thrust=1.4mN

(21) Isp=80sec

(22) Thrust efficiency: 8.7%

(23) Argon gas flow rate 60 sccm or 1.8mg/sec

(24) Results: As power increases Thrust increases, as power increases Isp increases and as power increases thruster efficiency decreases.

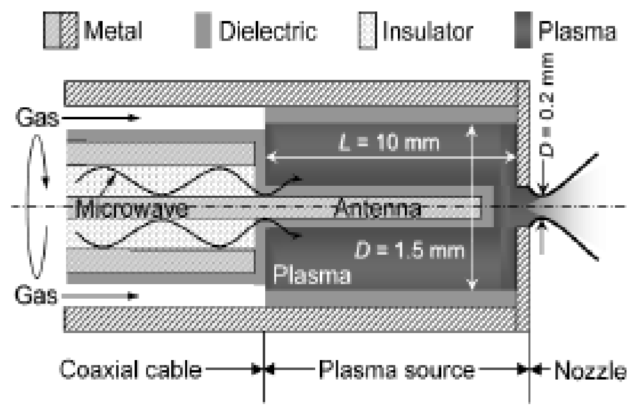


Fig. 1 Schematic of the microplasma thruster using azimuthally symmetric microwave-excited microplasmas.

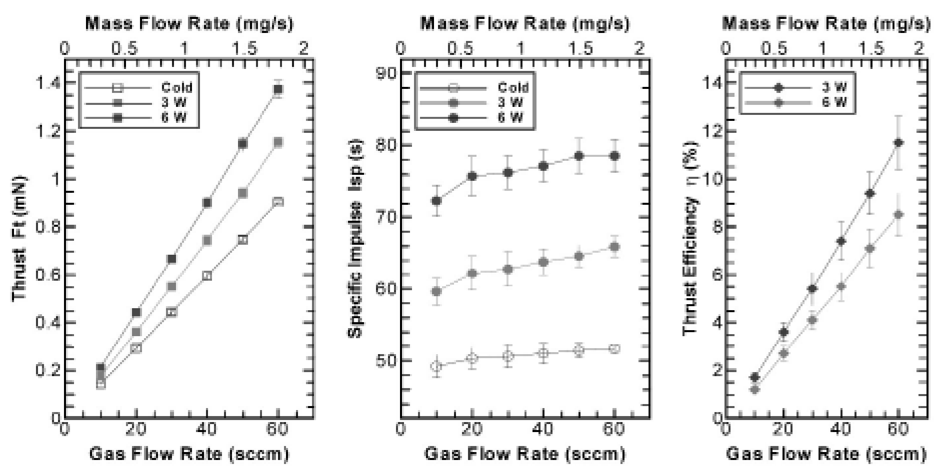


Fig. 8 Thrust performance (thrust F_t, specific impulse I_{sp}, and thrust efficiency η_t) measured as a function of Ar gas flow rate for different microwave input powers P_{in}. Here, P_{in} = 0 W corresponds to the cold-gas operation without plasma discharges. The experimental conditions were the same as in Figs. 5 and 6.

h. Microwave Excited microplasma thruster: a numerical and experimental study of the plasma generation and micronozzle flow, Takeshi Takahashi, Yoshinori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate school of Engineering, Kyoto University, Journal of Physics D: Applied Physics 41 (2008) 194004 (6pp)

Analysis - Characteristics

(1) Thrust for microspacecrafts <10kg in the mN range for stationkeeping and for attitude control in the μN range

(2) Dielectric Chamber inner diameter:2mm, length:10mm, Quartz material

(3) Rod antenna on axis, dielectric envelope

(4) Micronozzle De Laval C-D, 1mm in length, throat diameter 0.2mm

(5) Power <10 W, which is the available power for microspacecrafts

(6) Surface waves to excite the plasma

(7) Pinput=6W

(8) f=4GHz

(9) Propellant gas=Argon

(10) Mass flow rate = 1 mg/sec (33 sccm)

(11) Chamber wall temperature 500K

(12) Plasma max temperature 900K

(13) Microplasma source Chamber of 10.5mm length, inner diameter 1.5mm and outer diameter of 3mm.

(14) Coaxial cable semirigid protruding 10mm inside the plasma area

(15) Antenna 8.5mm length and 0.5mm diameter

(16) Dielectric envelope of quartz covering the antenna was 9.5mm length, 0.5mm inner diameter and 1mm outer diameter

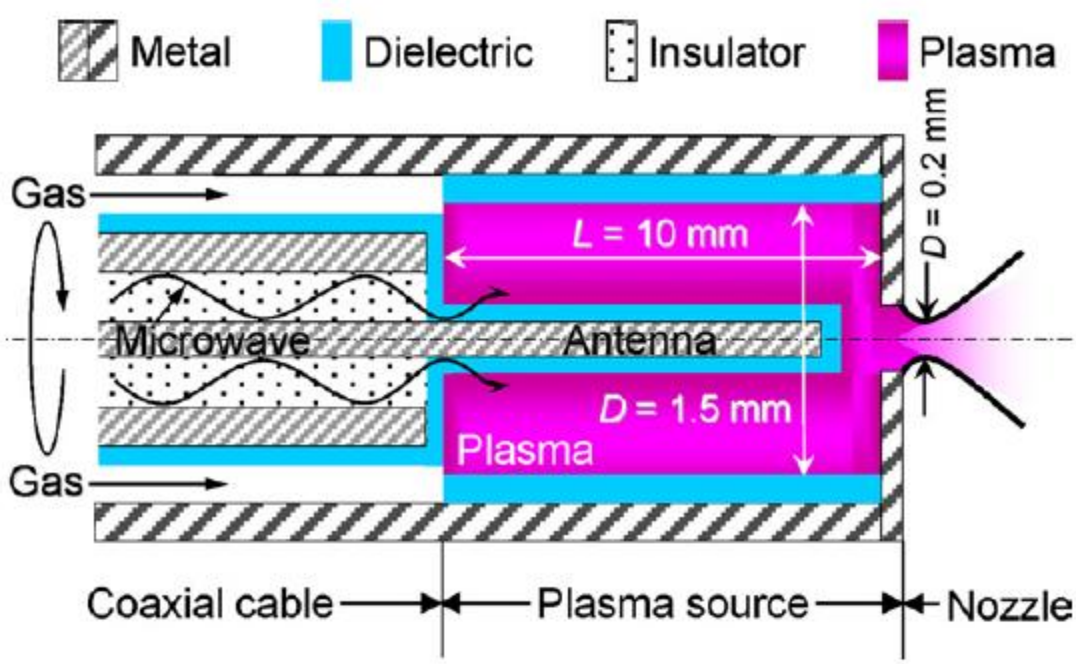
(17) Plasma diagnostics with insertion of <5% H_2 and N_2.

(18) Micronozzle of inlet=0.6mm,throat=0.2mm and exit diameter=0.8mm

(19) Thrust measurement with pendulum and target type

(20) Thrust of 1.4mN and Isp=80s with thrust efficiency of 8.7% at a power of 6W and flow rate of 60sccm

(21) Microplasma source region pressure 10-50kPa



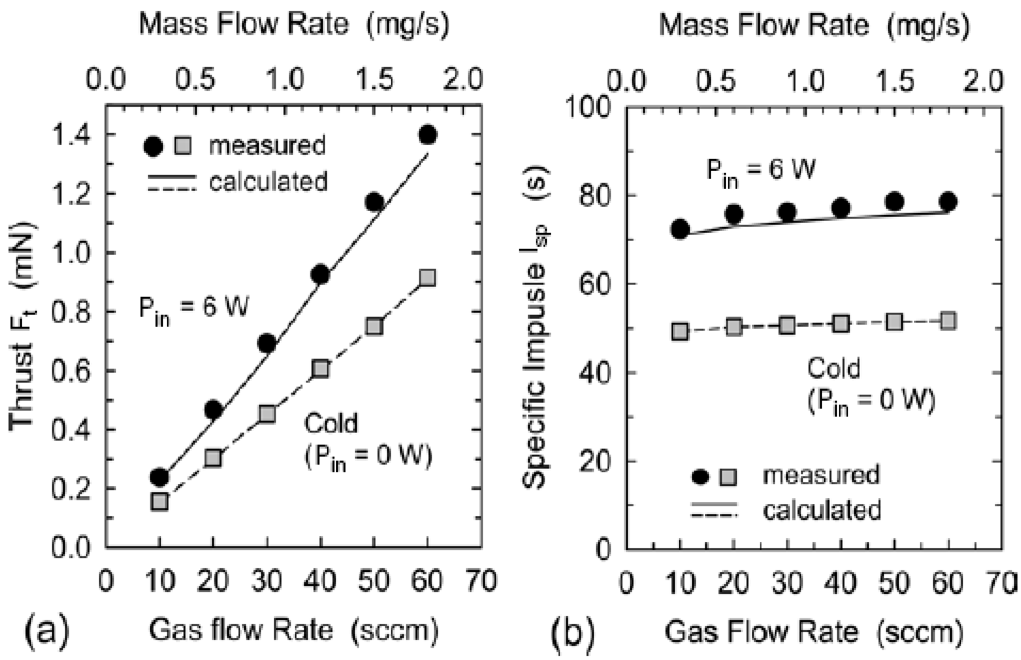


Figure 6. Thrust performance of (*a*) thrust F_t and (*b*) specific impulse I_{sp}, measured and simulated as a function of Ar gas flow rate for microwave input powers of $P_{in} = 0$ and 6 W, where $P_{in} = 0$ W corresponds to the cold-gas operation without plasma discharges. The experimental conditions were the same as in figures 4 and 5.

i. Numerical and experimental study of microwave-excited microplasma and micronozzle flow for a microplasma thruster Takahashi, Takeshi (Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan); Takao, Yoshnori; Eriguchi, Koji; Ono, Kouichi Source: Physics of Plasmas, v 16, n 8, 2009

Analysis - Characteristics

(1) Thrust for microspacecrafts <10kg in the mN range for stationkeeping and for attitude control in the µN range

(2) Uses azimuthally symmetric microwave excited microplasmas

(3) Microplasma source of dielectric chamber of 1.5mm inner diameter and 10mm long, covered with metal grounded, metal rod antenna on axis with dielectric envelope.

(4) Micronozzle is a De Laval nozzle, 1mm in length, throat of 0.2mm

(5) Power input: <10 W

(6) No magnetic confinement.

(7) Generation of plasma from MW penetration into the plasma. This configuration is used when no magnetic confinement in place

(8) No electrode, no Neutralizer, no magnets

(9) Gas: Argon

(10) Plasma macroscopically quasineutral or the electron density equals the ions

(11) Chamber with quartz and envelope

(12) Mass flow rate of 1.5mg/sec or 50sccm being supplied by N_2 and H_2 by 5%

(13) Microwave frequency: 4GHz

(14) Signal Generator for MW: Agilent 8648D

(15) Microplasma source, of quartz tube length:10dmSm, inner diameter 1.5mm, outer diameter 3.0mm.

(16) Coaxial cable: semirigid RG-405/U, protruding 10 mm beyond the insulator.

(17) Dielectric envelope around the microwave antenna. Length:9.5mm, Inner diameter: 0.5mm, outer diameter:1.0 mm.

(18) MW Antenna Length: 8.5mm, Diameter:0.5 mm

(19) Micronozzle of 1mm quartz thickness plate, Inlet:0.6mm, Throat:0.2mm, Exit diameter:0.8mm

(20) Observation through a small 1mm hole inside the chamber housing at the end of the antenna or dielectric envelope

(21) Initial Pressure:31kPa

(22) Temperature 890 K, Temperature increased by increasing power input and decreased with increasing flow rate or with decreasing initial pressure in the plasma source.

(23) Pendulum type method for cold gas and target type stand for thrust measurement in plasma discharge operation

(24) Thrust: 1.4mN, Isp=80s, Thrust efficiency: 8.7%,Pin:6W, Flow rate: 60sccm or 1.8mg/s

(25) Generally the thrust performance found to be F:0.2-1.4mN, Isp=50-80sec and thrust efficiency:2-12%

(26) The thrust performance found to increase with the discharge on and with increasing microwave power.

(27) Future research with lighter gases of He and H_2

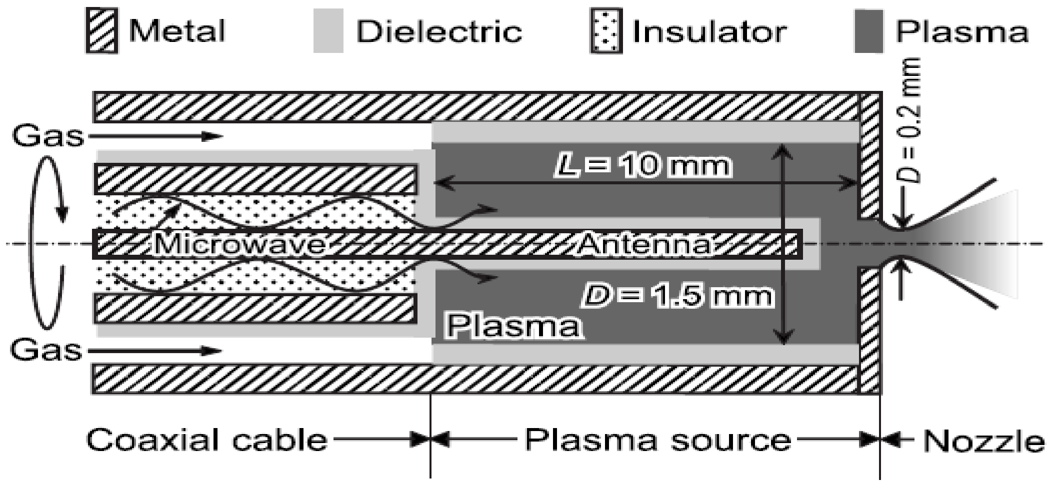


FIG. 1. Schematic of the microplasma thruster using azimuthally symmetric microwave-excited microplasmas, consisting of a microplasma source with a rod antenna on axis and a converging-diverging (Laval) micronozzle.

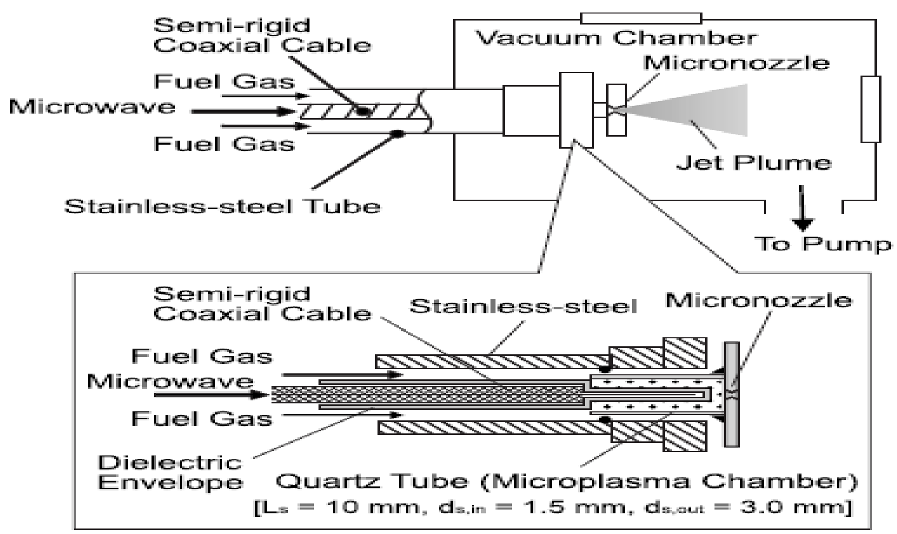


FIG. 9. Experimental setup, together with an enlarged view of the microwave- excited microplasma source having a configuration and size similar to those shown in Figs. 4, 5, and 7. Here, the dielectric envelope was also made of quartz. Optical emission spectroscopy was employed in the side-view direction, through a small hole of the stainless-steel housing around the end of the antenna or dielectric envelope, just upstream of the micronozzle inlet (Ref. 28).

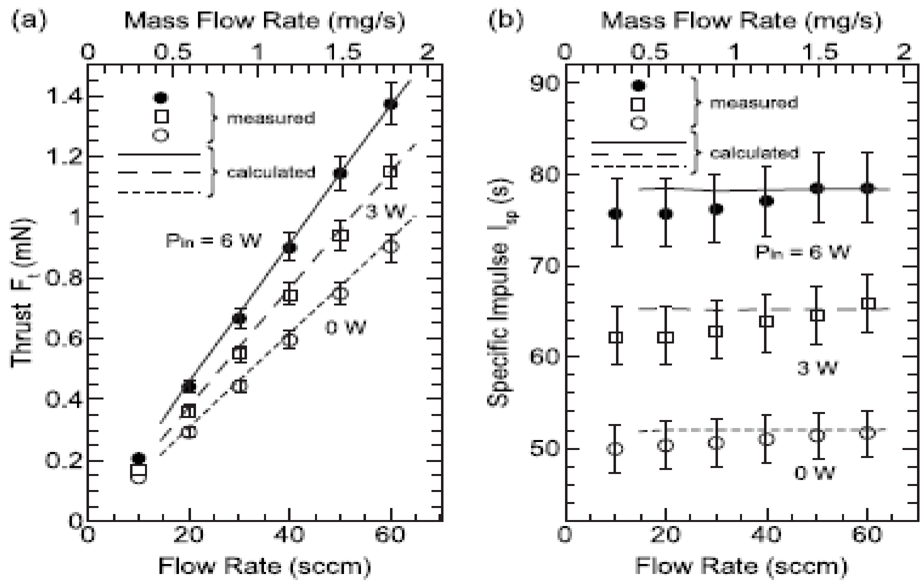


FIG. 14. Thrust performance [(a) thrust F_t and (b) specific impulse I_{sp}] measured as a function of Ar gas flow rate for different microwave powers P_{in} under the same conditions as in Fig. 13 (f=4 GHz, $\epsilon_d \approx 3.8$). Here, P_{in}=0 W corresponds to the cold-gas operation without plasma discharge. Also shown in the figure are the curves of F_t and I_{sp} calculated from the numerical analysis as in Figs. 6 and 8.

j. Microwave – excited microplasma thruster with helium and hydrogen propellants, Takao Takahashi, Yoshinori Takao, Yugo Ichida, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan, Physics of Plasmas 18, 063505, June 2011.

Analysis - Characteristics

(1) Propellant Gases: He and H_2, High specific impulse due to low masses of Helium and Hydrogen but high diffusivity and thermal conductivity that may lead to significant thermal energy losses.

(2) Converging-Diverging micronozzle

(3) Power: >10W , taking into account the power source of solar cells in a microsatellite.

(4) Rod antenna on axis covered with dielectric envelope

(5) Plasma is generated by microwaves penetration into the plasma and the electron heating occurs in a thin skin depth layer. Advantage in a non magnetic confinement configuration.

(6) Numerical analysis for the spatial distribution of electron density n_e, Electron temperature T_e, heavy particle temperature T_h, absorbed power density Q_{abs}, pressure p, axial flow velocity u, He gas or ground state density n_g and He^* metastable state density n_*.

(7) Input power: 6W, Microwave frequency: 4 Ghz, mass flow rate 50sccm, quartz chamber and envelope.

(8) From numerical analysis electron n_e and electron metastable n_* densities are two orders lower in He plasma than in Argon plasma.

(9) Flow velocity u in the nozzle is more than two times larger in He than in Argon owing to higher sonic speed of He.

(10) Microplasma source made of quartz tube.

(11) L=10.5 mm, Inner diameter=1.5mm, Outer diameter=3.0mm

(12) Microwave antenna L=8.5mm, diameter=0.5mm

(13) Nozzle 1mm thick quartz plate, inlet diameter=0.6mm, Throat diameter=0.2mm and Exit diameter=0.8mm.

(14) Gas flow rates at 2-70 sccm

(15) Source pressure at 0.5-12kPa and Chamber Temperature at 500K

(16) For He = Thurst 0.51mN, I_{SP}=250s, thrust efficiency n=10.1% at Pin=6W and mass flow rate 70sccm (0.21mg/sec)

(17) For H_2= I_{sp} was 1.5 times bigger than in helium owing to bigger mass. Thrust remained the same with helium.

(18) I_{sp} with He and hydrogen (light mass propellants) higher than in Argon while thrust was higher in Ar.

(19) In microplasma thrusters the high diffusivity and thermal conductivity of light mass propellants do not lead to a deterioration in performance.

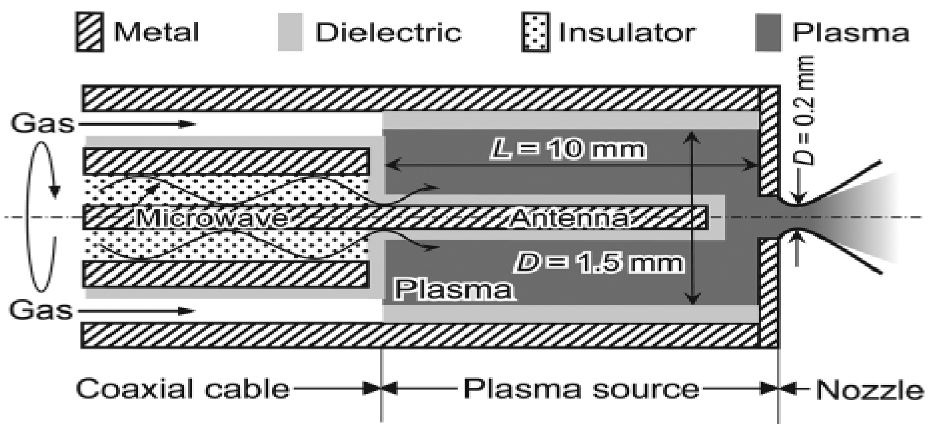


FIG. 1. Schematic of the microplasma thruster using azimuthally symmetric microwave-excited microplasmas, consisting of a microplasma source with a rod antenna on axis and a converging-diverging (Laval) micronozzle. Here, the microplasma source is ~ 1.5 mm in diameter and ~ 10 mm long, and the micronozzle is ~ 1 mm in length, having a throat ~ 0.2 mm in diameter.

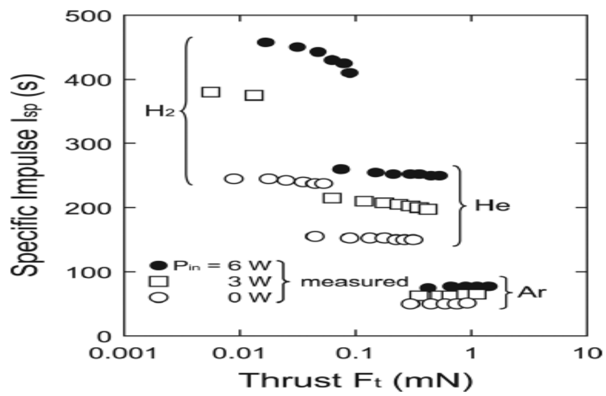


FIG. 13. Thrust F_t versus specific impulse I_{sp} measured for different microwave powers P_{in} and gas flow rates with three different propellant gas. The data for He and H_2 were taken from the preceding Figs. 11 and 12, respectively, and the data for Ar were from Fig. 14 of our previous paper.[34]

k. Microwave – excited microplasma thruster with applied magnetic field, IEPC 2011-262, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11-15, September 2011, Tetsuo Kawanabe, Takeshi Takahashi, Yoshinori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan

Analysis - Characteristics

(1) Applied Magnetic Field: 2.4 kG

(2) Cylindrical microplasma source

(3) Conical micronozzle

(4) Propellant gas: Argon

(5) Large surface to volume ration in the chamber so increased diffusion loss and for that reason apply strong axial magnetic field. Diffusion loss is a serious problem. The larger the surface to volume ratio the bigger is the diffusion loss.

(6) Strong axial magnetic field to reduce diffusion loss.

(7) Comparison among magnetic field and without magnetic field experiments showed improved thrust performance by 2.8 – 12.3%

(8) Power input: 3W and 6W

(9) Mass flow rate: >20 sccm

(10) No electrodes

(11) 4 Ghz microwaves used for this study

(12) Chamber pressure: 10 kPa

(13) Converging – Diverging De Laval nozzle

(14) Microplasma source made of quartz and Ultra Torr around the chamber. Cupper line to avoid leakage of microwaves, eliminate the electric potential between metal and quartz.

(15) Chamber Inner Diameter: 2.0 mm

(16) Chamber Outer Diameter: 6.0 mm

(17) Chamber Length: 10.6 mm

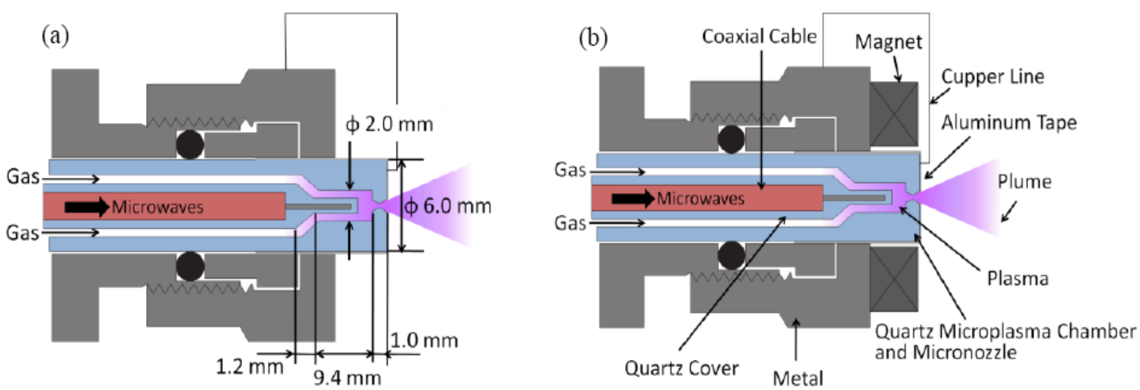
(18) Signal Generator: Agilent E8257C

(19) Tesla coil for ignition of plasma

(20) Micronozzle diameter changed among 0.6,0,2 and 0,8 mm.

(21) Micronozzle length is 1.0mm
(22) Placement of magnet at the top and bottom of the quartz chamber.
(23) Ring magnet made of Ne-Fe-B with residual magnetic field of 11.4 kG.
(24) Outer diameter of the magnet: 13.0 mm
(25) Inner diameter of the magnet: 7.0 mm
(26) Length of the magnet: 10.0 mm
(27) Pendulum thrust measurement method in cold gas operation
(28) Target method in plasma – discharging operation
(29) 3W: thrust increase by 1.8-5.6%
(30) 6W: thrust increase by 2.8-12.3%
(31) 3W:
With magnet: Thrust: 1.08mN, Isp:62sec, Thrust efficiency:10%
Without magnet: Thrust: 1.03mN, Isp:59sec, Thrust efficiency:9.2%
(32) 6W:
With magnet: Thrust: 1.23mN, Isp:70sec, Thrust efficiency:6.8%
Without magnet: Thrust: 1.11mN, Isp:64sec, Thrust efficiency:5.6%
(33) Future Research: Further investigate the shape of the magnetic field and strength in order to confine energetic electrons sufficiently.

II. Experimental Setup



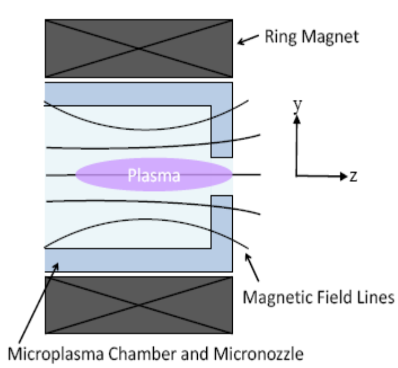


Figure 2. Schematic view of axial diverging field created by an axially magnetized ring magnet.

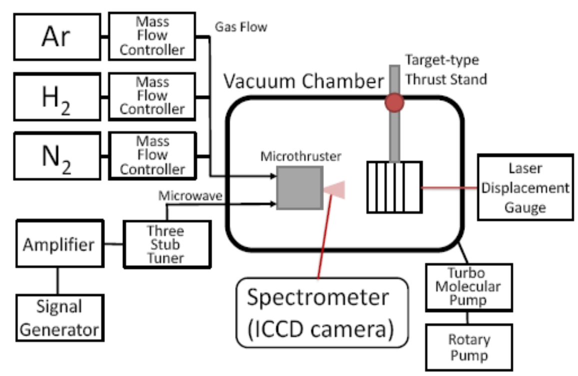


Figure 3. Experimental setup.

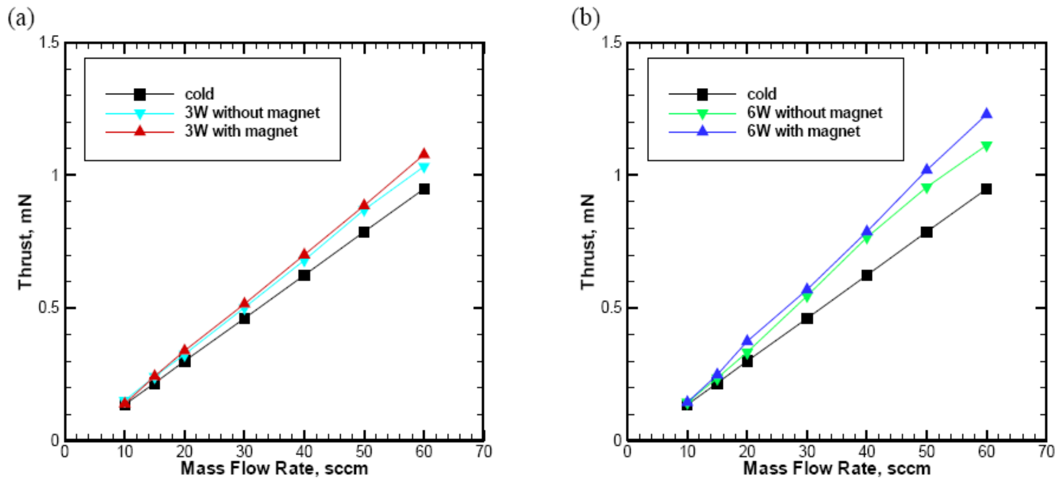


Figure 8. Thrust measured as a function of gas flow rate in cold-gas and plasma-discharging operation with and without the magnet at the microwave power of (a) 3 W and (b) 6 W.

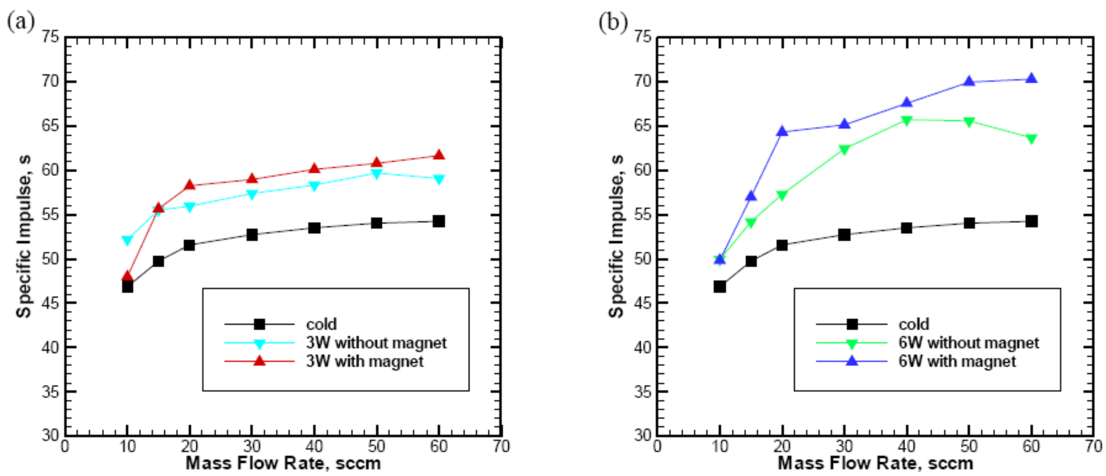


Figure 9. Specific impulse as a function of gas flow rate in cold-gas and plasma-discharging operation with and without the magnet at the microwave power of (a) 3 W and (b) 6 W.

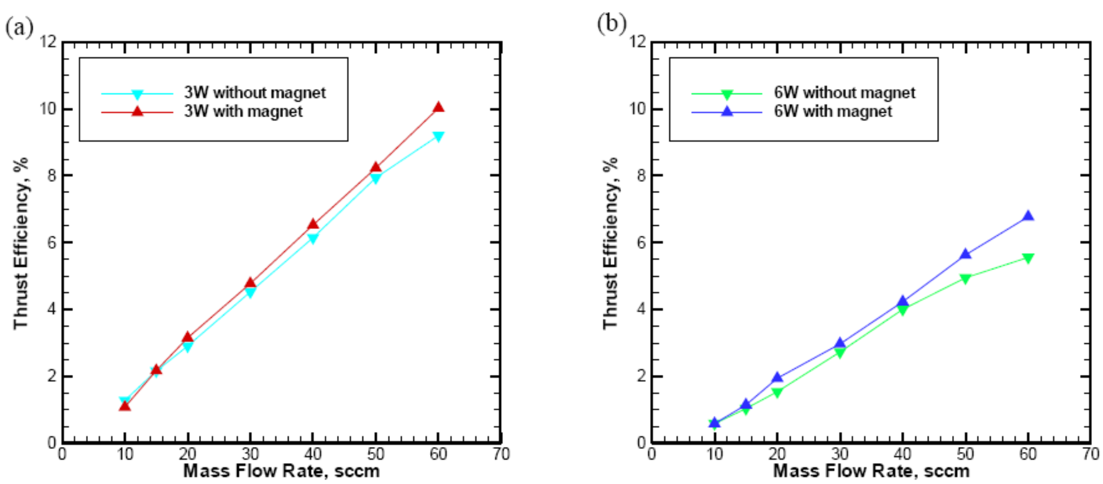


Figure 10. Thrust efficiency as a function of gas flow rate in cold-gas and plasma-discharging operation with and without the magnet at the microwave power of (a) 3 W and (b) 6 W.

<RECORD 3>
Plasma diagnostics and thrust performance analysis of a microwave-excited microplasma thruster Takao, Yoshinori (Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan); Ono, Kouichi; Takahashi, Kazuo; Eriguchi, Koji Source: Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, v 45, n 10 B, p 8235-8240, October 21, 2006

Database: Compendex
<RECORD 4>
Numerical simulation of microwave-excited microplasma thruster with helium propellant Takahashi, Takeshi (Kyoto University, Japan); Takao, Y.; Eriguchi, K.; Ono, K. Source: 61st International Astronautical Congress 2010, IAC 2010, v 8, p 6204-6206, 2010, 61st International Astronautical Congress 2010, IAC 2010

Database: Compendex

Research

Active research σε microplasma microwave thrusters, Program Lead is the Associate Professor Yoshinori Takao. There is no available info on University's site. There are available 8 published papers.
http://www.aa.t.kyoto-u.ac.jp/en/information/labo/propulsion (University Lab)

Michigan State University

Publications

a. Transport Properties of plasmas in microwave electrothermal thrusters, Scott Stanley Haraburda, DTIC, Master's Thesis, Michigan State University, 1990

Analysis - Characteristics

(1) Background theory of properties of plasmas in microwave eletrothermal thursters

b. Demonstration of a new electrothermal concept, S. Whitehair, J. Asmussen, 8 May 1984, Applied Physics 44, 1014(1984)

Analysis - Characteristics

(1) Input power 200-600W
(2) f=2.45GHz
(3) Thruster efficiencies at 30-60%
(4) Thrust of 0.24Nt and Isp= 600-800sec
(5) Microwave discharge electrothermal coaxially fed
(6) Pressure >100Torr
(7) Mass flow rates at 2000-6000 sccm

c. Microwave Thruster development, William Herald, Aerojet Systems and Michigan State University, AIAA 87-2123

Analysis - Characteristics

(1) Power: 500W
(2) Tests with helium similar with nitrogen
(3) Differences among microwave electrothermal thrusters
(4) With discharge chamber length equal to cavity length absorption efficiency was 95 to 99%
(5) Isp at 310sec
(6) Chamber temperature at 4100 and 1600 K
(7) Alumina is not a suitable material to use near discharge zone because it becomes a susceptor at relatively low temperatures

d. Microwave electrothermal thruster performance in Helium Gas, S. Whitehair et al, Michigan State University, Journal of Propulsion Vol3, No 2.

Analysis - Characteristics

(1) Pressure 40-1100T
(2) mass flow of 150x10-6kg/sec or $8x10^6$kg/sec
(3) Power 200-1200W
(4) f=2.45GHz
(5) Efficiency of 10-50%

e. Experimental Performance of a microwave electrothermal thruster with high temperature nozzle materials, S. Whitehair etal, Michigan State University, Department of Electrical Engineering, AIAA -87-1016.

Analysis - Characteristics

(1) Boron Nitride and metal nozzles for the experiments
(2) Efficiencies were mediocre
(3) Use of boron nitride in high temperature microwave plasmas is successful without melting and erosion problems
(4) The metal nozzle had excellent results in nitrogen at very low flow rates

f. Review of research and development on the Microwave Electrothermal Thruster, Martin Hawley et al, Journal of Propulsion, Vol 5, No 6, Nov – Dec 1989, Michigan State University.

Analysis - Characteristics

(1) Comparison table of competitive electrothermal propulsion systems

g. Magnetically enhanced inductive source for electric propulsion applications, J.E. Foster et al, University of Michigan, AIAA 2007-5294

Analysis - Characteristics

(1) RF magnetically induced plasma
(2) Power hundrends of W to KW, 500W for this experiment
(3) 13.56MHz
(4) Very heavy application outside of our research

h. Weatherford, B. and Foster, J., "Initial Performance of an ECR Waveguide Plasma Cathode with Permanent Magnets," Proceedings of the 31st AIAA International Electric Propulsion Conference, Ann Arbor, MI, Sept. 20 - 24,2009, Paper No. IEPC-2009-211

i. Development of a microwave cusp accelerator driven by electron cyclotron resonance, University of Michigan, John E. Foster et al, AIAA-2010-6518

Analysis - Characteristics

(1) Theory of Microwave device design
(2) For 2.45GHz the resonant magnetic field is 875G
(3) Resonance design requires careful consideration of the geometry and magnetic field application
(4) Use of Sm-Co magnets
(5) Propellant gas Argon
(6) No use of physical acceleration grid
(7) Creation of a well performed ECR

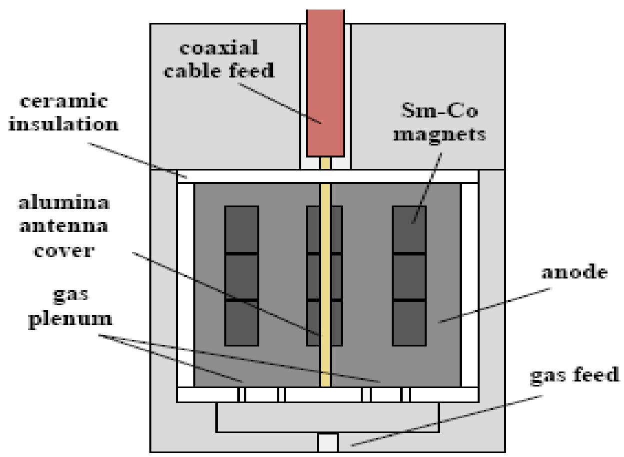


Figure 3. Microwave Device (Top View). *Device shown without slot extraction cover. Ceramic walls and floor isolate the anode from the outer device body.*

j. Weatherford, B., Foster, J., and Kamhawi, H., "Improved Performance of the ECR Waveguide Plasma Cathode with Permanent Magnets," Proceedings of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit,Nashville, TN, July 25-28, 2010, Paper No.AIAA-2010-6519

Research

Professor John E. Foster, Microwave ECR Plasma and Cathode, Nuclear Engineering Department University of Michigan
http://www-ners.engin.umich.edu/lab/pstlab/propulsion/mpc.html

Northwestern University, Xian, China

Publications

a. Development and research of a coaxial microwave plasma thruster, Juan Yang, Yingqiao Xu, Jinlan Tangm Genwang Mao, Tielian Yang, Xiaoquen Tan, College of Astronautics, People's Republic of China, American Institute of Physics, 79, 083503, 2008

Analysis - Characteristics

(1) Microwave plasma thruster is an electrodeless engine

(2) Composed of microplasma source. resonant cavity and a propellant supply

(3) Microwave frequency is the one occupies most of the efficiency of the engine

(4) The plasma must be formed near the entrance of the nozzle in order for the efficiency to be high

(5) The goal of the experiments in the thruster cavity is to find the best discharge gap

(6) Magnetic field strength is 0.5T

(7) Heavy and bulky magnetron source (200W)

(8) 100W solid state microwave source

(9) Performance with magnetron. P=210W, Weight=16kg and efficiency is 50%

(10) Performance with solid state with arsenide, P=110W, Weight=2.5kg and efficiency is 34.6%

(11) Vacuum chamber of 1.2m and 3m length

(12) Pressure of 10Pa

(13) Thrust was ranging from 20 to 120mN.

(14) Power of 70W, Thurst of 15mN, and Isp of 340sec

(15) When we apply magnetic field the electron density is being augmented by 2.1-3.5 times compared to the nonfield case

(16) Mass flow rate at 4.09 -6.14 mg/sec

(17) The average gas temperature is increased with increasing microwave power

(18) When the microwave power is increased the electron density increases gradually

(19) The effect of applied magnetic field increases the peak temperature in the discharge region by 24%

Research

Professor Juan Yang, Microwave Thrust without propellant.

http://emdrive.com/

http://www.nwpu.edu.cn/en/2.html

Pennsylvania State University

Publications

a. Microwave Electrothermal Thruster Using Waveguide Heated Plasmas, AIAA-90-2562, Michael Micci, 1990

Analysis - Characteristics

(1) Use of a bluff body of dielectric material (boron nitride) into the flow in order to stabilize the plasma

(2) If the dimensions are properly chosen then the flow speed is increased for plasma. Behind the bluff body there is a recirculation zone.

(3) The microwave power is generated by a 3000W magnetron

(4) Waveguide inside a quartz tube of 20mm diameter and 120cm length

(5) Coupling efficiencies obtained for up to 90% being a strong function of mass flow rate through the engine while gas pressure had little effect. Coupling efficiencies dropped however with increasing input power.

(6) Operation of a waveguide applicator at high power levels ensure high mass flow rates, so higher thrust levels and therefore shorter mission trip times.

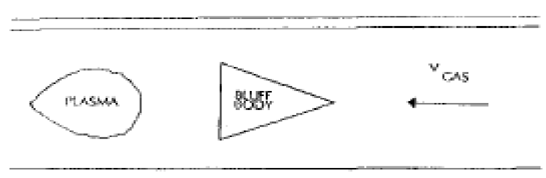


Fig. 2: Stabilization of the plasma by means of a blunt body

b. Microwave Waveguide Helium Plasmas for Electrothermal Propulsion, Journal of Propulsion and Power, Vol 8, No 5, Sept – Oct 1992, Michael Micci.

Analysis - Characteristics

(1) Absorption of microwave energy by a gas within a waveguide.

(2) Advantages of MW thruster engines in comparison to other propulsion systems

(3) Microwave absorption concepts are resonant cavity, coaxial applicator and waveguide applicator

(4) Resonant cavity: a plasma is sustained in the maximum field regions and tuning the system is being done by adjusting the cavity length. For Helium the overall resonant cavity efficiencies are up to 45%, while specific impulses are 600sec

(5) For nitrogen thruster efficiencies are up to 35% and Isp200sec with mass flow rates at 150mg/sec

(6) The coaxial applicator is the oldest concept. The plasma here is formed at the tip of a movable center conductor allowing flexible positioning.

(7) Input power of 650W, using nitrogen with mass flow rates of 62mg/sec gives efficiency of 24% with Isp 250sec.

(8) Waveguide absorption chamber: Here the advantage is that we have the highest experimentally measured microwave plasma temperatures, so higher specific impulses and temperatures around 11000K for power of 4.5kW.

(9) Coupling efficiencies increase with mass flow. This is due to skin effect.

(10) With waveguide absorption techniques temperatures are 2000K higher than the resonant cavity.

(11) The use of a bluff body stabilization is successful towards the utilization of a waveguide configuration.

(12) Microwave thrusters based on the waveguide configuration offer the potential of delivering higher specific impulses than other MW designs.

c. Investigation of free floating Resonant Cavity Microwave plasmas for propulsion, Journal of Propulsion, Vol 8, No 1, Jan-Feb, 1992, Michael Micci.

Analysis - Characteristics

(1) Use of a microwave resonant cavity

(2) Propellant gases of high pressurized Helium and Nitrogen.

(3) Cylindrical resonant cavity shape

(4) Input power at 500-1500W

(5) f=2.45GHz

(6) Thruster efficiencies for Helium at 20% and for Nitrogen 26%

(7) Coupling efficiencies have overcome 79% by keeping discharge away from solid surfaces

d. Performance Testing Exhaust Plume characterization of the Microwave Arcjet Thruster, AIAA 94-3127, Michael Micci, 1994.

Analysis - Characteristics

(1) Microwave Arcjet Thruster with power inputs of 250-6000W

(2) Microwave Arcjet produces a free floating ac plasma discharge where the location of the discharge is located at the maximum power density.

(3) Simple Arcjet thrusters have problems with arc formation, arc stability and erosion of the cathode tip. In microwave arcjets we do not have these issues

(4) The power supply is a magnetron based microwave generator.

(5) f=2.45GHz

(6) Propellant gases is Nitrogen diatomic and Helium monatomic

(7) Microwave arcjet can operate at a single power level and thus not require power processing

(8) Free floating plasmas are called because they are being formed and located in regions of maximum electric field density within the interior of the cavity

(9) Diameter of the cavity is 10.16cm and the theoretical resonant length is 15.87cm.

(10) Diameter of the nozzle throat is 0.1cm and the conical nozzle has a 30 degree half angle converging and a 15 degree half angle diverging.

e. Current status of Microwave arcjet thruster, AIAA 95-3065, Michael Micci, 1995.

Analysis - Characteristics

(1) Use of a microwave resonant cavity with free floating plasma discharge

(2) It does not require specific electric isolation techniques
(3) The design structure is mentioned in the above paper
(4) Power at around 500W

f. Numerical Investigation of Bluff-Body Stabilized microwave plasmas, Journal of Propulsion and power, Vol 11, No 2, March – April 1995, C.L.Merkle, S. Venkateswaran.

Analysis - Characteristics
(1) Bluff body stabilized microwave plasma
(2) Isp of 600sec with power at around 500W
(3) Application of Navier Stokes and Maxwell equations (good examples)
(4) Plasma temperature at 12000K
(5) Thrust at around 0.6N with 0.12g/sec mass flow rates
(6) Curves of Isp and Thrust with respect to mass flow rates

g. Final Report, Plasma stabilization in low power C band microwave arcjets, Michael Micci, DTIC, 31 Oct 1999

Analysis - Characteristics
(1) Use of a microwave resonant cavity
(2) f=7.5GHz and 2.45GHz
(3) Cavity dimensions of 1.3’’ and 2.0’’long
(4) Propellant gases of helium, nitrogen and ammonia
(5) Temperatures are 1800K for He, 2100 for nitrogen and 1250K for ammonia
(6) Input power levels at 100W
(7) The best propellants for this system are low molecular weight systems, monatomic gases
(8) Thrust with Helium around 5mN, Isp=58sec and mass flow at 2-4.43mg/sec
(9) Thrust with Nitrogen around 6mN, Isp=31sec and mass flow at 21mg/sec
(10) The 7.5GHz thruster will be lighter and convective heat losses from the plasma to the cavity
(11) The shorter cavity length is therefore likely to yield a higher thrust to weight ratio

h. Low power microwave arcjet testing: Plasma and Plume diagnostics and Performance Evaluation, Michael Micci etal, AIAA 99-2717, 1999

Analysis - Characteristics
(1) Use of a microwave resonant cavity
(2) Same results like in the above paper

i. University Propulsion programs at Penn State, AIAA 2004-3322, Robert Santoro, 2004

Analysis - Characteristics
(1) Electric propulsion leader Michael Micci and S. Bilen

j. Numerical Electromagnetic modeling of a low power microwave electrothermal thruster, AIAA 2005-3699, Michael Micci, 2005

Analysis - Characteristics

(1) Free floating arc plasma discharge
(2) Microwave cavity absorption chamber
(3) The plasma is being formed directly upstream of the nozzle
(4) Nozzle erosion concerns needs to be taken into account
(5) The microwave arcjet thruster has the advantage of operation in single power level
(6) It has been shown that plasma discharge near the inlet of the nozzle produces the most efficient transfer of thermal energy to the propellant gas.
(7) f=7.5GHz
(8) Power input 70W

k. Microwave electrothermal thruster chamber temperature measurements and performance calculations, Journal of Propulsion and Power, Vol 22, No 1, January-February 2006, Michael Micci, 2006

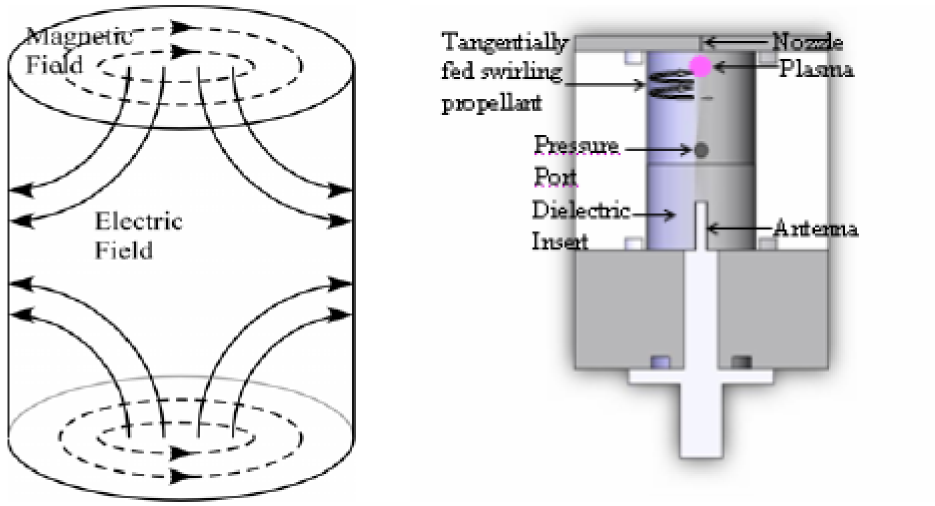
Analysis - Characteristics

(1) Study for Oxygen and Nitrogen characteristics as propellant gases.
(2) Temperature of Oxygen 2000K and for Nitrogen 5500K
(3) Power inputs at kW ranges
(4) f=2.45GHz

l. Design and Initial testing of a miniature microwave electrothermal thruster, AIAA 2007-5293, Michael Micci, 2007

Analysis - Characteristics

(1) Low power microwave arcjet electrothermal thruster
(2) f=14.5GHz
(3) Circular cavity with free floating plasma discharge
(4) Calculation of the resonant frequency
(5) Power at 20W
(6) Thrust 0.2-4.5mN
(7) Mass flow rate 2.15mg/sec
(8) Isp 169-197sec
(9) Chamber temperature 298-360K which is very low
(10) Thickness of the dielectric caused lack of significant heating to the plasma
(11) Increased mass flow rate increase of thrust



(a) (b)

Figure 1. (a) Field configuration for the TM^{z}_{011} mode. (b) Diagram of the 14.5-GHz MET.

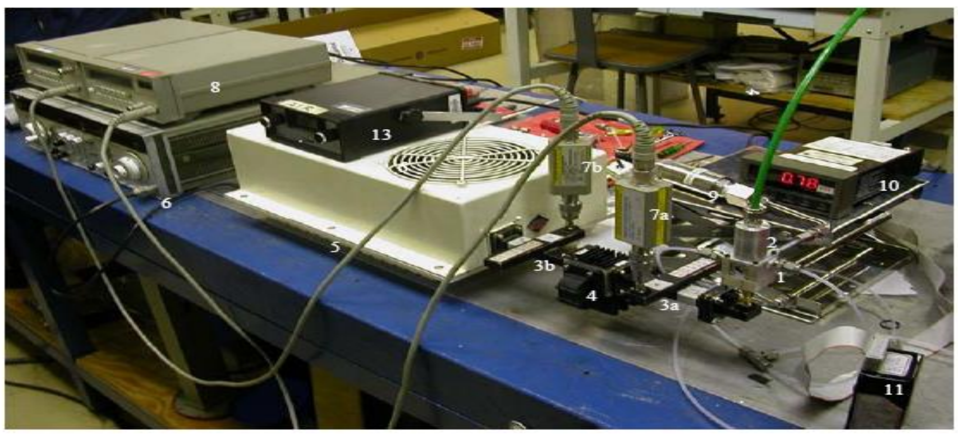


Figure 3. Experimental setup used for the 14.5-GHz MET testing (helium propellant supply tank and vacuum pump not shown).

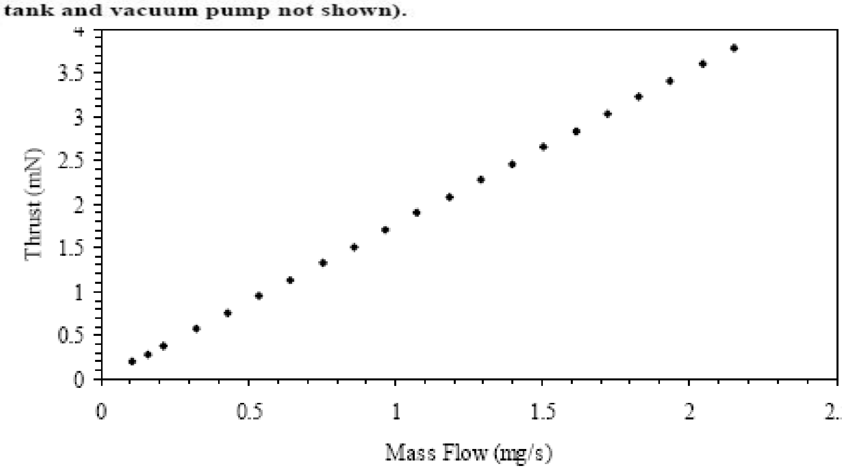


Figure 6. Cold flow ideal thrust versus experimental mass flow rate. Propellant is helium.

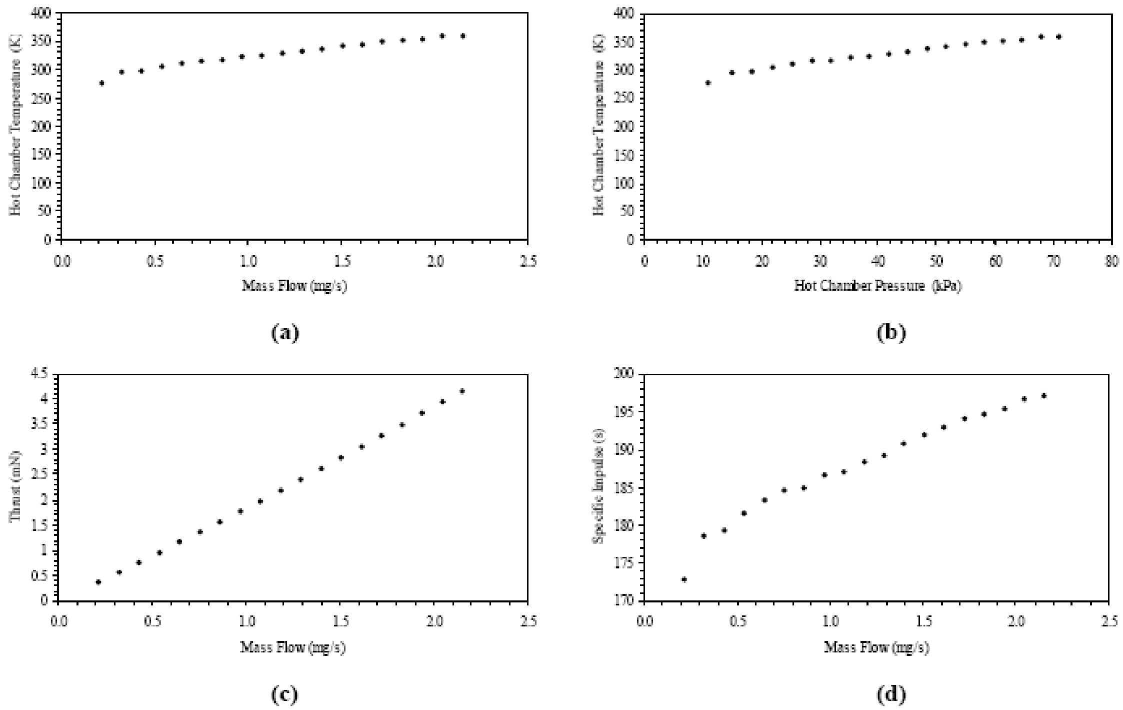


Figure 10. (a) Hot fire chamber temperature versus mass flow rate; (b) Hot fire chamber temperature versus hot fire chamber pressure; (c) Hot fire calculated thrust versus mass flow rate; (d) Hot fire calculated specific impulse versus mass flow rate. Propellant is helium.

m. “Evaluation and Optimization of an 8 GHz Microwave Electrothermal Thruster”, Daniel Clemens, Michael Micci et al, Penn State Universtity, 46^{th} AIAA/ASME/SAE/ASEE Joint Propulsion & Conference Exhibit, 25-28 July 2010, Nashville, TN

<u>Analysis - Characteristics</u>

(1) Low power microwave arcjet electrothermal thruster

(2) f=8GHz

(3) Comsol finite element analysis

(4) No electrodes in the flow path result in lower thermal losses and less life limiting erosion.

(5) Power 100-350 W regime from a TWTA

(6) Isp from 321-434sec

(7) Efficiency from 95%

(8) Lightweight MET of approximately 500grams was created

(9) Used ammonia and hydrazine

n. Design and Testing of a High Power 14.5 Ghz Miniature Microwave Electrothermal Thruster, Michael Micci, IEPC-2011-165

o. Performance and Evaluation of High Power 14.5 Ghz Miniature Microwave Electrothermal Thruster, Master’s Thesis Rohid Adussumilli, 2011.

p. Design of a microwave frequency Ion Thruster, Michael Micci, IEPC-2011-164

q. Cubesat Microwave Electrothermal Thruster (CµMET), Michael Micci, Electrodynamic Applications Company, IEPC-2011-162

Research

Professor M. Micci, active research in electric propulsion. Last papers presented in IEPC 2011.
http://www.aero.psu.edu/Research/SpacePropulsion.html

Ulsan University, South Korea

Publications

a. "Exhaust Plume characteristics of microhollow cathode discharge plasma thruster", Jichul Shin and Pham Dinh Tuyen, 7 June 2011, IEEE transactions on plasma science Vol 39, No 11, November 2011.

Analysis - Characteristics

(1) Microwave excited miniature plasma source for a thrust level of 2.5 and 3.5 mN and a specific impulse of 130-180sec with an input power 1-5 W it can exist but here they apply Electrothermal and electrostatic acceleration schemes.

(2) Electrothermal acceleration concept include a micro ion engine with a diameter of 1-3 cm and a micro Hall thruster.

(3) Microhollow cathode discharge configuration as an ion source for a very small scale plasma thruster. This is the first stage where the gas is ionized and the second stage located near the exit is used for the acceleration of the ions produced in the first stage. By this we can achieve both Electrothermal and electrostatic acceleration . (mixed operation mode)

Research

http://aerolab.ulsan.ac.kr/Research.htm

Aerospace Corporation

Publications

a. The physics and Chemistry of Radio Frequency and Microwave Thrusters, S. Janson, M.W. Crofton, R. P. Welle, J.E. Polland, R.B. Cohen, Aerospace Corporation Los Angeles, California, AIAA 1990.

Analysis - Characteristics

(1) Expansion through C-D nozzle. Heating method, non thermal ionization, dissociation, excitation, vibrational, rotational state of propellant/molecules/atoms/ions. Rapid relaxation to thermal conditions is the key to high thrust efficiency.

(2) Isp relation to mean molecular weight of the exhaust gas, stagnation temperature and the ratio of specific heats k of the exhaust gas

(3) Frozen flow losses analysis

b. The impact of advanced diagnostics techniques on Electrothermal Thruster design, AIAA 92-3242, S.W. Janson, Aerospace Corporation, Los Angeles, California, AIAA/SAE/ASME/ASEE 28TH Joint Propulsion Conference and Exhibit, July 6-8 1992, Nashville, Tennessee.

Analysis - Characteristics

(1) 1kW class laboratory arcjet operational thruster (way too much power)

(2) Equations regarding mass of propellant function to years on orbit

(3) The ideal thruster performance for an electrothermal thruster is when all input power is converted into stagnation enthalpy (enthalpy at a stagnation point) which is subsequently converted to direct kinetic energy in the plume by an adiabatic expansion to infinite Mach number with final temperature of 0 degrees K. (example of hydrogen dissociation and calculation of Isp)

Thruster	I_{sp}	Efficiency	Eff./I_{sp}($\times 10^{-3}$)	Power Level
Hydrazine Resistojet	~300 s	~95 %	3.2 s^{-1}	0.4 - 0.8 kW
Hydrazine Arcjet	~500 s	~34 %	0.68 s^{-1}	0.3 - 1.8 kW
Ammonia Arcjet	~800 s	~34 %	0.43 s^{-1}	10 - 30 kW
Hydrogen Resistojet	~850 s	~85 %	1.0 s^{-1}	3 - 30 kW
Hydrogen Arcjet	~1200 s	~40 %	.33 s^{-1}	3 - 30 kW
Xenon Stationary Plasma	~1600 s	~55 %	.34 s^{-1}	0.4 - 1.4 kW
Xenon Ion Engine	~3000 s	~65 %	.22 s^{-1}	0.3 - 5 kW

c. Microwave Electrothermal Thruster Performance, Journal of Propulsion and Power, Vol. 23, No 1, January-February 2007, Kevin Diamant, Byron Zeigler and Ronald Cohen, Aerospace Corporation, Los Angeles California.

Analysis - Characteristics

(1) 1kW and 5kW microwave electrothermal thruster (way too much power)

(2) Produces thrust 100-250Mn

(3) Isp of 428sec

(4) 1.2m length of chamber

(5) Microwave f=2.45GHz

(6) Propellant gases: Water, He, N_2 and N_2O

Research

No active research on microwave thrusters

http://www.aero.org/

Princeton University

Publications

a. Numerical Simulation of Microwave – Sustained Supersonic Plasmas for Application to Space Propulsion/ AIAA-01-0962/ V.P. Chiravalle, R.B. Miles and E.Y. Choueiri, Mechanical and Aerospace Engineering Department, Princeton University, 39th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January 2001, Reno, Nevada.

Analysis - Characteristics

(1) Adding energy to an expanding supersonic flow using microwave sustained plasma.

(2) Microwave sustained argon plasma at 2.45GHz

(3) Power 2.2KW (negative to application of microspacecrafts

b. A non equilibrium Numerical Study of a Microwave Electrothermal Thruster / AIAA 2003-3663, V.P. Chiravalle, R.B. Miles and E.Y. Choueiri, Mechanical and Aerospace Engineering Department, Princeton University, 38th AIAA Joint Propulsion Conference, July 7-10 2002, Indianapolis

Analysis - Characteristics

(1) Simulate the flow in a standard microwave thruster

(2) Maxwell equations and Navier Stokes analysis

(3) Fluid conservation equations, applications and analysis

c. Laser – Induced Fluorescence Measurements of a two stage Microwave Electrothermal Thruster Plume, AIAA 2003-4294, V. Chiravalle, S. Zaidi, E. Choueiri, R. Miles, 34th AIAA Plasmadynamics and Lasers Conference, 23-26 June 2003, Orlando, Florida.

Analysis - Characteristics

(1) Prototype two stage microwave electrothermal thruster with a novel supersonic energy addition stage

(2) Water vapor as a propellant

(3) Maximum temperature that can be sustained by the thruster walls is 2000K.

(4) Higher flow rates 600mg/sec

(5) Specific impulse of 400s

(6) Power of 1kW

d. A passive propellant feeding mechanism for micropropulsion using capillarity / AIAA 2002-3949, E.Y. Choueiri, Mechanical and Aerospace Engineering Department, Princeton University, 38th AIAA Joint Propulsion Conference, July 7-10 2002, Indianapolis

Analysis - Characteristics

(1) Use of capillarity to passive control the propellant flow in microthrusters.

(2) 1D Fluid model analysis with passive fluid flow

e. A 300W Microwave Thruster Design and Performance Testing, AIAA 2004-4122, Daniel Sullivan, John Kline, S. Zaidi, R. Miles, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauderdale, Florida.

Analysis - Characteristics

(1) 300 W microwave electrothermal thruster

(2) f=7.5GHz through magnetron

(3) Efficiency of 50%, so only 150 W available to heat the propellant gas

(4) Propellant gases of He and Nitrous oxide

(5) Microwave thruster length = 20cm

(6) Microwave power to maintain plasma discharge

(7) Mass flow rate of 0.025mg/sec

(8) Calculations of Isp, Thurst and all other characteristics of a thruster for given propellant gases.

(9) Thrust stand used for measurements

(10) Microwave electrothermal thruster which has the magnetron coupled directly to the thruster in a more compact design.

Research

Robert Miles – Applied Physics Laboratory, Research: Weakly Ionized Plasmas και MHD. Το τελευταίο paper δημοσιεύτηκε το 2004 ενώ από τότε μέχρι σήμερα δεν έχει active research για microwave thrusters.
http://www.princeton.edu/mae/people/faculty/miles/homepage/applied_physics/

Alabama University – Propulsion Research Center

Publications

a. Rayleigh Doppler Velocimetry Measurements of a Microwave Thruster, AIAA 99-3717, M. Culley, J. Jones, C. Hawk, Propulsion Research Center, University of Alabama, 30th Plasmadynamics and Lasers Conference, 28 June – 1 July 1999, Norfolk.

Analysis - Characteristics

(1) Measurement of velocity and temperature in the plumes of a microwave plasma thruster.

(2) Use of Rayleigh scattering method.

(3) A non equilibrium plasma generated in a microwave resonant cavity that drives an MHD accelerator.

b. Experimental study of a crossed field MHD Accelerator Coupling with Microwave Plasma, AIAA 2001-3495, Zhongmin Li, Clark Hawk, Propulsion Research Center University of Alabama, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 7-11 July 2001, Salt Lake City, Utah.

Analysis - Characteristics

(1) Investigation of MHD accelerator coupled with microwave thrusters for space applications.

(2) The proposed propulsion system include a microwave thruster, a crossfield MHD plasma accelerator and a coaxial applied MPD thruster. The microwave thruster is used to produce non equilibrium plasma for the plasma accelerators and also preliminary accelerate the plasma flow.

(3) Microwave f=2.45GHz

(4) Microwave power of 3KW (negative for micro applications)

(5) Propellant gases of Argon, He, Nitrogen, Carbon dioxide and steam.

(6) Nozzle throat diameter 3.81mm

(7) Mass flow rate of 160mg/sec

(8) Gas Temperature of 600-750K

(9) Pressure of 1 Torr

(10) The idea of coupling microwave thrusters with other engines may yield to better thrust and efficiency performance overall.

Research

Plasma Modeling, Dr. Cassibry, last publication in 2001
http://prc.uah.edu/Propulsion_Research_Center/Core_Competencies.html
http://www.mae.uah.edu/faculty/cassibry.shtml

Texas A&M University

Publication

a. Efficient power supply for the Microwave Electrothermal Thruster, M.Ehsani and J. Mahdavi, Texas A&M University, I. Pitel Magna Power Electronics, J. E. Brandenberg, Research Support Instruments Inc and F.E. Little, Texas A&M University, IEEE AES Systems Magazine, May 1998

Analysis - Characteristics

(11) Resonant switch mode power supply for the MET.

(12) Magnetron tube of 2.45 GHz

(13) Power of multi kW.

(14) Zero voltage switching which guarantees high frequency of operation at high efficiency

(15) Efficiency of the power supply at around 90%

Research

No active research on microwave thrusters

Russia, Fakel enterprises

Publications

a. State of the works on Electric Thrusters in the USSR, Bober A.S., Kivi V.P. and Koroteev A.S., IEPC 91-003, FAKEL

Analysis - Characteristics

(1) Electrothermal and Electrostatic thrusters in a detail manner.

b. Development and application of Electric propulsion thrusters in Russia, A. Bober and N. Maslennikov, FAKEL enterprises, Kaliningrad, Russia, IEPC 93-001.

Analysis - Characteristics

(1) Design of an electrothermal thruster using ammonia

(2) Weight: 2gr

(3) Isp=230sec

(4) Lifetime of 50hrs

(5) Thruster with a porous heater

(6) Thrust of 0.05-0.3 N
(7) Isp up to 280sec
(8) Power consumption of 0.1 to 0.45Kw – 450W

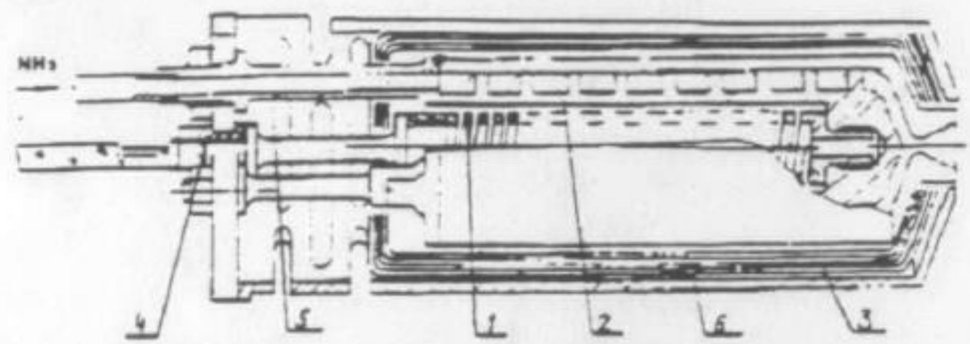


Figure 8. Conceptual Design of Electrothermal Thruster
1 heater, 2 heat exchanger, 3 thermal insulation, 4 insulator, 5 current supply, 6 body

Research

No active research on microwave thrusters

NASA Lewis Research Center

Publications

a. Experimental Demonstration of the effects of an Electric Thruster Plasma Plume on Microwave Propagation, K.M. Lambert, A.J.Zamman and F.M. Curran, NASA Lewis Research Center, 1991.

<u>Analysis - Characteristics</u>

(1) The impact of electric thruster plume on microwave propagation is of key parameter and of great concern.

(2) Arcjets have a lightly ionized plume and they have a little effect on satellites communication

(3) Cylindrical vacuum chamber 20m long and 5m in diameter.

(4) Examine the effects of transmission through different ion densities of the plume

(5) Frequency range was 6.5 to 18GHz and data was acquired every 8 MHz.

(6) Calculated the amplitude and phase difference of the signal with the plume on.

(7) Frequency phase lead increases as the thrust power increases.

b. The NASA Lewis research center electric propulsion program, D. Buyers, AIAA 91-3443

Analysis - Characteristics

(1) Mercury Ion thrusters
(2) MHD reference
(3) PIT reference
(4) Brief Comparison among solar propulsion systems and Nuclear ones.

c. An overview of NASA Electric Propulsion Program, Francis Curran, L. Bennet, Marcus Watkins, NASA Lewis Research Center and JPL,1991

Analysis - Characteristics

(1) Hydrazine Arcjets analysis (0.1-1kW)
(2) High Power Arcjets (25-30 kW)
(3) Resistojets
(4) Microwave Electrothermal Thruster analysis
(5) 30 kW at 915 MHz
(6) Magnet field of 5.75T
(7) By adding energy in the supersonic region where the stagnation temperature limit is higher it should be possible to increase thruster performance. Evaluate the energy density in the supersonic heating region, the microwave attenuation of the supersonic flow, the kinetics of thermal energy transfer from electrons to heavy species and boundary layer effects
(8) Electrostatic systems general characteristics
(9) Electromagnetic systems general characteristics
(10) Electron number density versus position in the arcjet plume

d. Microwave Electrothermal Propulsion for Space, John Power, IEEE Transactions on microwave theory and techniques, Vol 40, No 6, June 1992

Analysis - Characteristics

(1) Plasma created in a resonant cavity
(2) Analysis of the microwave electrothermal thruster concept (Very fundamental and useful to understand all the functionality inside the MW thruster)
(3) Three types of applicators: resonant cavity, coaxial and waveguide applicator
(4) In order to have a resonant cavity three requirements must be met. First a single mode must be selectively excited in order to concentrate all microwave incident power absorption in a single volume element. Second this energy absorption volume must be located on the axis of the cavity in order to separate plasma from cavity walls. Third the cavity must be provided with tuning mechanisms permitting exact frequency and impedance matching. TM011 and TM012 allow the above requirements to take place.
(5) Results for 15-27kW.

Databases searched

1. AIAA

2. IEEE
3. BOSUN (NPS)
4. COMPENDEX
5. Journal of Applied Physics
6. Journal of Propulsion and Power
7. SPIE
8. Web of Knowledge
9. DTIC (US MILITARY)
10. Engineering Village
11. American Institute of Physics
12. IEPC – International Electric Propulsion Conference
13. ERPS- Electric Rocket Propulsion Society
14. Open Sources
15. JPL Database

Other Electric Propulsion Sites:

1. Univeristy of Wisconsin – Electric Propulsion Theory
http://fti.neep.wisc.edu/~jfs/neep533.lect31.99/plasmaProp.html
2. Electric Rocket Propulsion Society
http://fti.neep.wisc.edu/~jfs/neep533.lect31.99/plasmaProp.html
3. Electric Propulsion Sites
http://erps.spacegrant.org/index.php?page=sites
4. University of Stuttgart (power range of KW)
http://www.irs.uni-stuttgart.de/forschung/elektrische_raumfahrtantriebe/index.en.html
5. NASA JPL – Electric Propulsion Laboratory
http://ep.jpl.nasa.gov/
6. University of Giessen (only ion and RF ion thrusters)
http://www.uni-giessen.de/cms/fbz/fb07/fachgebiete/physik/einrichtungen/ipi/home/homepage/research-profile/rit-en/view?set_language=en
7. Wright Patterson Air Force Base (propulsion directorate)
http://www.wpafb.af.mil/afrl/rz/
8. Michigan University PERL Research Project
http://www.umich.edu/~peplweb/projects/NanoFET.html
9. SNECMA satellite propulsion systems
http://www.snecma.com/-satellite-propulsion-.html
10. University of Toronto Electric Propulsion Lab

http://www.utias.utoronto.ca/Research/Engineering_Physics/pmi/pmi-proj.htm
11. Astrium
http://cs.astrium.eads.net/sp/spacecraft-propulsion/ion-propulsion/index.html
12. Alabama University Research Lab
http://prc.uah.edu/Propulsion_Research_Center/Core_Competencies.html
http://www.mae.uah.edu/faculty/cassibry.shtml
13. JAXA
http://www.isas.ac.jp/e/about/professor/index.shtml
14. JPL
http://ep.jpl.nasa.gov/
15. Hokkaido Institute of Technology
http://www.hit.ac.jp/eng/faculties/e_div_mecha.html
16. Aerojet
http://www.aero.org/
17. Kyushu University, Japan
http://www.isc.kyushu-u.ac.jp/g30/programs-e_aerospace.html

Papers for Dual Mode / Stage Thrusters

1. Hirokazu Tahara, “An overview of Electric Propulsion activities in Japan”, Graduate School of Engineering and Science, Osaka University, 2003.

2. Riame, “Investigation of physical processes in SPT MAG”, IEPC 2005-146, Moscow RIAME, 2005.

3. “Overview in Electric Propulsion in France”, IEPC 2005-162, 2005.

4. H. Kuwano, “Development and Thrust Performance of a Microwave Discharge Hall Thruster”, IEPC-2007-085, Kyushu University, 2005.

5. J. Dankanich, “Mission Performance of the Dual Mode Hybrid Engine”, AIAA 2011-5664, Gray Research Inc., 2011.

6. Jichul Shin and Pham Dinh Tuyen, “Exhaust Plume Characteristics of Microhollow Cathode Discharge Plasma Thruster”, Ulsan University Korea, IEEE transactions on plasma science, Vol. 39, No. 11, November 2011

Books – Papers reviewed

1. Stuhlinger Ion propulsion for space flight, 1964 (book)
2. Space Propulsion Analysis and Design Chapter 9 P. Turchi Electric Rocket propulsion systems.(book)

3. Wirz, R., Sullivan, R., Przybylowski, J., and Silva, M., "Hollow Cathode and Low-Thrust Extraction Grid Analysis for a Miniature Ion Thruster," International Journal of Plasma Science and Engineering 2008, 1-12 (2008).

4. Ziemer, J. K., Randolph, T. M., Franklin, G. W., Hruby, V., Spence, D. et al., "Delivery of Colloid Micro-Newton Thrusters for the Space Technology 7 Mission," AIAA Paper 2008-4826, July 2008.

Book chapter

5. “Mueller, J., “Thruster Options for Microspacecraft: A Review and Evaluation of State-of-the-Art and Emerging Technologies”, *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 3. (book)

6. “Mueller, J., Chakraborty, I., Bame, D., and Tang, W., “The Vaporizing Liquid Micro-Thruster Concept: Preliminary Results of Initial Feasibility Studies”, *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 8. (book)

7. “Plasma diagnostics and thrust performance analysis of a microwave-excited microplasma thruster Takao, Yoshinori (Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan); Ono, Kouichi; Takahashi, Kazuo; Eriguchi, Koji Source: Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, v 45, n 10 B, p 8235-8240, October 21, 2006

8. “Numerical simulation of microwave-excited microplasma thruster with helium propellant Takahashi, Takeshi (Kyoto University, Japan); Takao, Y.; Eriguchi, K.; Ono, K. Source: 61st International Astronautical Congress 2010, IAC 2010, v 8, p 6204-6206, 2010, 61st International Astronautical Congress 2010, IAC 2010

9. “Development and research of a coaxial microwave plasma thruster”, Juan Yang, Yingqiao Xu, Jinlan Tangm Genwang Mao, Tielian Yang, Xiaoquen Tan, College of Astronautics, People’s Republic of China, American Institute of Physics 79, 083503, 2008.

10. “Thruster options for microspacecraft: a review and evaluation of existing hardware and emerging technologies”, Juergen Mueller, Jet Propulsion Lab, CalTech, AIAA 97-3058

11. “Review of RF Plasma thruster Development”, IEPC 2007-309, Ivana Hrdud, G. Elijah Kemp, Allen Yan, Jacob Gedrimas, Purdue University, Department of Aeronautics and Astronautics

12. “Electric Propulsion. Which one for my spacecraft?”, Ian J.E. Jordan, Whiting School of Engineering, Space Systems Course I, December 6, 2000.

13. “The physics and chemistry of RF and Microwave thrusters”, S.W. Janson et al, Aerospace Corporation, 1990.

14. “Performance Testing and Exhaust Plume Characterization of a Microwave Arcjet Thruster”, Michael Micci, Penn State, AIAA-94-3127, 30th Joint Propulsion Conference, June 1994

15. “Final Report, Plasma stabilization in low power C band microwave arcjets, Michael Micci, Penn State University, DTIC, 31 Oct 1999

16. “Design and Initial testing of a miniature microwave electrothermal thruster, Penn State, AIAA 2007-5293, Michael Micci, 2007

17. “Applications for PPTs and the development of small PPTs for microspacecraft”, AIAA 2000-3434, W.A. Hoskins et al, Primex Space Systems, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 16-19 July, Huntsville, Alabama

18. “Compact Vacuum Arc microthruster for small satellite systems”, N.Qi J. Schein et all, Berkeley University, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8-11 July 2001, Utah

19. “Design and Fabrication of a MEMS based millinewton level hydrazine thruster”, University of Cheng Kung, Taiwan,Tony Yuan et al, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2-5 August, Denver, Colorado

20. “Performance modeling of a coaxial radio frequency gas discharge microthruster”, William Stein et al, Purdue University, Journal of Propulsion and Power, Vol 24, No 5, September – October 2008

21. “Development and Modeling of a microwave excited microplasma thruster, Yoshinori Takao and Kouinchi Ono, Kyoto University, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauderdale, Florida

22. “A miniature electrothermal thruster using microwave excited plasmas: a numerical design consideration, Yoshinori Takao, Kouinchi Ono, Institute of Physics publishing, Plasma sources science technology 15 (2006) 211-277, March 2006, Kyoto University, Department of Aeronautics and Astronautics.

23. “Performance testing of a miniature electrothermal thruster using microwave excited microplasmas, Yoshinori Takao and Kouinchi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 9-12 July 2006, Sacramento, California (AIAA 2006-4492)

24. **“**A miniature electrothermal thruster using microwave – excited microplasmas: Thrust measurement and its comparison with numerical analysis, Journal of Applied Physics 101, 123307, June 2007, Yoshimori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Japan.

25. “Numerical Analysis and Experiments of a Microwave Excited Microplasma Thruster, IEPC-2007-029, 30th International Electric Propulsion Conference, Florence, Italy, 17-20 September 2007, Takeshi Takahashi, Yoshinori Takao, Koji Eringuchi and Kouinchi Ono, Graduate School of Engineering, Kyoto University, Japan.

26. “Microplasma thruster for ultra small satellites: Plasma chemical and aerodynamical aspects, Yoshinori Takao, Takeshi Takahashi, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan, Pure Applied Chemistry, Vol. 80, No. 9, pp. 2013-2023, 2008.

27. **“**Microwave Excited microplasma thruster: a numerical and experimental study of the plasma generation and micronozzle flow”, Takeshi Takahashi, Yoshinori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate school of Engineering, Kyoto University, Journal of Physics D: Applied Physics 41 (2008) 194004 (6pp)

28. “Numerical and experimental study of microwave-excited microplasma and micronozzle flow for a microplasma thruster Takahashi, Takeshi (Department of

Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan); Takao, Yoshnori; Eriguchi, Koji; Ono, Kouichi Source: Physics of Plasmas, v 16, n 8, 2009

29. "Microwave – excited microplasma thruster with helium and hydrogen propellants", Takao Takahashi, Yoshinori Takao, Yugo Ichida, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan, Physics of Plasmas 18, 063505, June 2011.

30. "Microwave – excited microplasma thruster with applied magnetic field", IEPC 2011-262, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11-15, September 2011, Tetsuo Kawanabe, Takeshi Takahashi, Yoshinori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan

31. "Plasma diagnostics and thrust performance analysis of a microwave-excited microplasma thruster Takao, Yoshinori (Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan); Ono, Kouichi; Takahashi, Kazuo; Eriguchi, Koji Source: Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, v 45, n 10 B, p 8235-8240, October 21, 2006

32. "Numerical simulation of microwave-excited microplasma thruster with helium propellant Takahashi, Takeshi (Kyoto University, Japan); Takao, Y.; Eriguchi, K.; Ono, K. Source: 61st International Astronautical Congress 2010, IAC 2010, v 8, p 6204-6206, 2010, 61st International Astronautical Congress 2010, IAC 2010

33. "Transport Properties of plasmas in microwave electrothermal thrusters, Scott Stanley Haraburda, DTIC, Master's Thesis, Michigan State University, 1990

34. "Demonstration of a new electrothermal concept, S. Whitehair, J. Asmussen, 8 May 1984, Applied Physics 44, 1014(1984)

35. "Microwave Thruster development, William Herald, Aerojet Systems and Michigan State University, AIAA 87-2123

36. "Microwave electrothermal thruster performance in Helium Gas, S. Whitehair et al, Michigan State University, Journal of Propulsion Vol.3, No. 2.

37. “Experimental Performance of a microwave electrothermal thruster with high temperature nozzle materials, S. Whitehair etal, Michigan State University, Department of Electrical Engineering, AIAA -87-1016.

38. “Review of research and development on the Microwave Electrothermal Thruster, Martin Hawley et al, Journal of Propulsion, Vol 5, No 6, Nov – Dec 1989, Michigan State University.

39. “Magnetically enhanced inductive source for electric propulsion applications, J.E. Foster et al, University of Michigan, AIAA 2007-5294

40. “Weatherford, B. and Foster, J., "Initial Performance of an ECR Waveguide Plasma Cathode with Permanent Magnets," Proceedings of the 31st AIAA International Electric Propulsion Conference, Ann Arbor, MI, Sept. 20 - 24,2009, Paper No. IEPC-2009-211

41. “Development of a microwave cusp accelerator driven by electron cyclotron resonance, University of Michigan, John E. Foster et al, AIAA-2010-6518

42. “Weatherford, B., Foster, J., and Kamhawi, H., "Improved Performance of the ECR Waveguide Plasma Cathode with Permanent Magnets," Proceedings of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit,Nashville, TN, July 25-28, 2010, Paper No.AIAA-2010-6519

43. “Development and research of a coaxial microwave plasma thruster, Juan Yang, Yingqiao Xu, Jinlan Tangm Genwang Mao, Tielian Yang, Xiaoquen Tan, College of Astronautics, People’s Republic of China, American Institute of Physics, 79, 083503, 2008

44. “Microwave Electrothermal Thruster Using Waveguide Heated Plasmas, AIAA-90-2562, Michael Micci, 1990

45. “Microwave Waveguide Helium Plasmas for Electrothermal Propulsion, Journal of Propulsion and Power, Vol 8, No 5, Sept – Oct 1992, Michael Micci.

46. “Investigation of free floating Resonant Cavity Microwave plasmas for propulsion, Journal of Propulsion, Vol 8, No 1, Jan-Feb, 1992, Michael Micci.

47. “Performance Testing Exhaust Plume characterization of the Microwave Arcjet Thruster, AIAA 94-3127, Michael Micci, 1994.

48. “Current status of Microwave arcjet thruster, AIAA 95-3065, Michael Micci, 1995.

49. “Numerical Investigation of Bluff-Body Stabilized microwave plasmas, Journal of Propulsion and power, Vol 11, No 2, March – April 1995, C.L.Merkle, S. Venkateswaran.

50. “Final Report, Plasma stabilization in low power C band microwave arcjets, Michael Micci, Penn State, DTIC, 31 Oct 1999

51. “Low power microwave arcjet testing: Plasma and Plume diagnostics and Performance Evaluation, Michael Micci etal, AIAA 99-2717, 1999

52. “University Propulsion programs at Penn State, AIAA 2004-3322, Robert Santoro, 2004

53. “Numerical Electromagnetic modeling of a low power microwave electrothermal thruster, AIAA 2005-3699, Michael Micci, 2005

54. **“**Microwave electrothermal thruster chamber temperature measurements and performance calculations”, Journal of Propulsion and Power, Vol 22, No 1, January-February 2006, Michael Micci, 2006

55. “Design and Initial testing of a miniature microwave electrothermal thruster, AIAA 2007-5293, Michael Micci, 2007

56. “Design and Testing of a High Power 14.5 Ghz Miniature Microwave Electrothermal Thruster, Michael Micci, IEPC-2011-165

57. “Performance and Evaluation of High Power 14.5 Ghz Miniature Microwave Electrothermal Thruster, Master’s Thesis Rohid Adussumilli, 2011.

58. “Cubesat Microwave Electrothermal Thruster (CμMET), Michael Micci, Electrodynamic Applications Company, IEPC-2011-162

59. “Exhaust Plume characteristics of microhollow cathode discharge plasma thruster”, Jichul Shin and Pham Dinh Tuyen, 7 June 2011, IEEE transactions on plasma science Vol 39, No 11, November 2011.

60. “Effects of a magnetic field configuration on thrust performance in a miniature microwave discharge ion thruster, Naoji Yamamoto, Department of Advanced Energy Engineering Science, Kyushu University, Japan, Journal of applied physics 102, 123304, 2007

61. “Internal Plasma Structure Measurement in a Miniature Microwave Discharge Ion Thruster, IEPC 2007-101, 30th International Electric Propulsion Conference, Florence,

Italy, Shinya Kondo, Takayuki Chikaoka etal, Department of Advanced Energy Engineering Science, Kyushu University, Japan

62. “Development of two fluid magnetohydrodynamics model for non equilibrium anisotropic plasma flows, K. Miura, C. Groth, University of Toronto, Institute for Aerospace Studies, AIAA2007-4373

63. “The physics and Chemistry of Radio Frequency and Microwave Thrusters, S. Janson, M.W. Crofton, R. P. Welle, J.E. Polland, R.B. Cohen, Aerospace Corporation Los Angeles, California, AIAA 1990.

64. “The impact of advanced diagnostics techniques on Electrothermal Thruster design, AIAA 92-3242, S.W. Janson, Aerospace Corporation, Los Angeles, California, AIAA/SAE/ASME/ASEE 28TH Joint Propulsion Conference and Exhibit, July 6-8 1992, Nashville, Tennessee.

65. “Microwave Electrothermal Thruster Performance, Journal of Propulsion and Power, Vol. 23, No 1, January-February 2007, Kevin Diamant, Byron Zeigler and Ronald Cohen, Aerospace Corporation, Los Angeles California.

66. “Plasma Diagnostics and numerical modeling of a microwave ion engine, AIAA 98-3341, I. Funaki et al Institute of Space and Astronautical Science Sagamihara, S. Satori, Hokkaido Institute of Technology, Japan

67. “Endurance Test of Microwave Engine, W. Kim et al, Astro Research Corporation Kanagawa, S. Satori, Hokkaido Institute of Technology, R. Nam, Korea Advanced Institute of Science and Technology, Journal of Propulsion and power, Vol 22, No 5, Sept-Oct 2006

68. “Design and fabrication of a Micro Ion engine”, Juergen Mueller et al, AIAA 2000-3264, JPL, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 16-19 July 2000, Huntsville, Alabama.

69. “Ion propulsion development activities at the NASA Glenn research center, Michael Patterson et al, NASA Glenn, AIAA 2003-4709

70. “JPL Micro Thruster propulsion activities”, Juergen Mueller et al, JPL, AIAA 2002-5714, Nanotech 2002,12 September Houston, Texas

71. “Discharge characterization of a 40cm microwave ECR Ion Source and Neutralizer, John Foster and Michael Patterson, AIAA 2003-5012

72. “Operation of a microwave Electron Cyclotron Resonance Cathode, Hani Kamhawi, John Foster and Michael Patterson, AIAA 2004-3819

73. “Numerical Simulation of Microwave – Sustained Supersonic Plasmas for Application to Space Propulsion/ AIAA-01-0962/ V.P. Chiravalle, R.B. Miles and E.Y. Choueiri, Mechanical and Aerospace Engineering Department, Princeton University, 39th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January 2001, Reno, Nevada.

74. “A non equilibrium Numerical Study of a Microwave Electrothermal Thruster / AIAA 2002-3663, V.P. Chiravalle, R.B. Miles and E.Y. Choueiri, Mechanical and Aerospace Engineering Department, Princeton University, 38th AIAA Joint Propulsion Conference, July 7-10 2002, Indianapolis

75. “Laser – Induced Fluorescence Measurements of a two stage Microwave Electrothermal Thruster Plume, AIAA 2003-4294, V. Chiravalle, S. Zaidi, E. Choueiri, R. Miles, 34th AIAA Plasmadynamics and Lasers Conference, 23-26 June 2003, Orlando, Florida.

76. “A passive propellant feeding mechanism for micropropulsion using capillarity / AIAA 2002-3949, E.Y. Choueiri, Mechanical and Aerospace Engineering Department, Princeton University, 38th AIAA Joint Propulsion Conference, July 7-10 2002, Indianapolis

77. “A 300W Microwave Thruster Design and Performance Testing, AIAA 2004-4122, Daniel Sullivan, John Kline, S. Zaidi, R. Miles, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauderdale, Florida.

78. “Microwave Plasma Contractor”, Hitoshi Kuninaka, JAXA, Kanagawa, IEPC-1993-040.

79. “Verification tests of carbon-carbon composite grids for microwave discharge ion thruster, I. Funaki et al, Journal of Propulsion and Power, Vol 18, No 1, January-Feb 2002, Institute of Space and Astronautical Science, Kanagawa, Japan, JAXA

80. “Rayleigh Doppler Velocimetry Measurements of a Microwave Thruster, AIAA 99-3717, M. Culley, J. Jones, C. Hawk, Propulsion Research Center, University of Alabama, 30th Plasmadynamics and Lasers Conference, 28 June – 1 July 1999, Norfolk.

81. “Experimental study of a crossed field MHD Accelerator Coupling with Microwave Plasma, AIAA 2001-3495, Zhongmin Li, Clark Hawk, Propulsion Research

Center University of Alabama, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 7-11 July 2001, Salt Lake City, Utah.

82. “The Air Force Electric Propulsion Program, D. Perkins, AIAA 94-2734

83. “The Air Force Electric Propulsion Program, R. Spores, AIAA 95-2378

84. “The USAF Electric Propulsion Program, Ronald Spores, AIAA 97-

85. “The USAF Electric Propulsion Program, Ronald Spores, AIAA 99-2162

86. “Efficient power supply for the Microwave Electrothermal Thruster, M.Ehsani and J. Mahdavi, Texas A&M University, I. Pitel Magna Power Electronics, J. E. Brandenberg, Research Support Instruments Inc and F.E. Little, Texas A&M University, IEEE AES Systems Magazine, May 1998

87. “Thruster options for microspacecraft: a review and evaluation of existing hardware and emerging technologies, Juergen Mueller, Jet Propulsion Lab, CalTech, AIAA 97-3058

88. “Development and application of Electric propulsion thrusters in Russia, A. Bober and N. Maslennikov, FAKEL enterprises, Kaliningrad, Russia, IEPC 93-001.

89. “Experimental Demonstration of the effects of an Electric Thruster Plasma Plume on Microwave Propagation, K.M. Lambert, A.J.Zamman and F.M. Curran, NASA Lewis Research Center, 1991

90. “The NASA Lewis research center electric propulsion program, D. Buyers, AIAA 91-3443

91. “An overview of NASA Electric Propulsion Program, Francis Curran, L. Bennet, Marcus Watkins, NASA Lewis Research Center and JPL,1991

92. “Microwave Electrothermal Propulsion for Space, John Power, IEEE Transactions on microwave theory and techniques, Vol 40, No 6, June 1992

93. “Microwave Thruster Development, William Herald, Aerojet Systems and Michigan State University & Aerojet TechSystems Company, AIAA 87-2123

94. “ASTRIUM Research: http://cs.astrium.eads.net/sp/spacecraft-propulsion/ion-propulsion/index.html

95. “Univeristy of Wisconsin – Electric Propulsion Theory: http://fti.neep.wisc.edu/~jfs/neep533.lect31.99/plasmaProp.html

96. “Electric Rocket Propulsion Society: http://fti.neep.wisc.edu/~jfs/neep533.lect31.99/plasmaProp.html

97. “Electric Propulsion Sites: http://erps.spacegrant.org/index.php?page=sites

98. University of Stuttgart (power range of KW): http://www.irs.uni-stuttgart.de/forschung/elektrische_raumfahrtantriebe/index.en.html

99. NASA JPL – Electric Propulsion Laboratory: http://ep.jpl.nasa.gov/

100. University of Giessen (only ion and RF ion thrusters): http://www.uni-giessen.de/cms/fbz/fb07/fachgebiete/physik/einrichtungen/ipi/home/homepage/research-profile/rit-en/view?set_language=en

101. Wright Patterson Air Force Base (propulsion directorate): http://www.wpafb.af.mil/afrl/rz/

102. Michigan University PERL Research Project: http://www.umich.edu/~peplweb/projects/NanoFET.html

103. “Rocket Propulsion Elements” 7th Edition, George Sutton and Oscar Biblarz, John Wiley & Sons Publications, 2001, Chapter 19, Electric Propulsion, page 662, Table 19-1

104. “Rocket Propulsion Elements” 7th Edition, George Sutton and Oscar Biblarz, John Wiley & Sons Publications, 2001, Chapter 2,page 40,Table 2-1

105. “Rocket Propulsion Elements” 7th Edition, George Sutton and Oscar Biblarz, John Wiley & Sons Publications, 2001, Chapter 19, page 698, Table 19-7

106. M. Martinez-Sanchez and J. E. Pollard, “Spacecraft Electric Propulsion – An Overview”, Journal of Propulsion and Power, Vol. 14, No.5, September-October 1998, pp. 688-699, AIAA5331-401

107. “Fundamentals of Electric Propulsion. Ion and Hall Thrusters”, Dan M. Goebel and Ira Katz, JPL Space Science and Technology Series, John Wiley & Sons Publications, 2008, Chapter 1, Table 1-1, page. 5.

108. “Space Mission Analysis and Design – SMAD”, Wiley J. Larson and James R. Wertz, Third Edition, 2005, Chapter 17, Table 17-4 & 17-9, p. 692 & 703

109. “Electric Propulsion Activity in Russia”, Vladimir Kim, Gari Popov, RIAME MAI (Moscow Aviation Institute) and Boris Arkhipov, Fakel

110. “Asteroid Rendezvous of Hayabusa Explorer using Microwave Discharge Ion engines”, Hitoshi Kuninaka et al, JAXA, 29TH IEPC, 31 October- 4 November 2005, IEPC 2005-10

111. “ State of the works on Electric Thrusters in the USSR”, Bober A.S., Kivi V.P. and Koroteev A.S., IEPC 91-003, FAKEL

112. "Plasma Production Process in an ECR Ion thruster", Tamaya Funaki et al, JAXA, 33rd AIAA Plasma Dynamics and Lasers /14th International MHD Conference May 20-23, 2002, Maui, AIAA-2002-2196

113. "Survey of Electric Propulsion", Kenn E. Clark, Princeton University, Journal of Spacecraft, November 1975

114. "Electric Propulsion: Comparison between different concepts", L. Garrigues and P. Coche, Universite de Toulouse, Plasma Physics Control and Fusion 53(2011) 124011(11pp)

115. "Spacecraft Electric Propulsion – An overview", M.Martinez- Sanchez, MIT and J.E. Pollard, Aerospace Corporation, Journal of Propulsion and Power, Vol.14, No. 5, September-October 1998.

116. "Kato, M. Takayama S: Road map of small satellites in JAXA, 56TH International Astronautics Congress Paper, IAC-05.B5.6.B.01, Fukuoka, Oct 2005

117. "Micropropulsion System Selection for Precision Formation Flying Satellites", Jeffrey Reichbach, Raymond Sedwick and Manuel Martinez-Sanchez, 37TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 8-11, 2011 Salt Lake city, AIAA 2001-3646.

118. "Qualification status of the FEEP-150 Electric Micropropulsion Subsystem", L. Biagioni et al, Alta Company, M. Andrenucci, Department of Aerospace Engineering, University of Pisa, 41ST AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 10-13 July 2005, Tuscon, Arizona, AIAA 2005-4261.

119. "Micropropulsion for Nanosatellites", SNSBs hearing, November 11, 2011, Tor-Arne Gronland, www.sscspace.com/nanospace

120. "Development of Propulsion means for microsatellites", C. Scharlemann and M. Tajmar, Austrian Research Centers GmbH –ARC, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 8-11 July 2007, Cincinnati, Ohio, AIAA 2007-5184.

121. "Micropropulsion Using a Laser Ablation Jet", C. Phillips, Photonic Associates, Santa Fe, New Mexico, Journal of Propulsion and Power, Vol 20, No 6, November – December 2004

122. www.tno.nl/gasgenerators, Ir M. Sanders, TNO, Plug and Play micropropulsion

123. "Solid Propellant Microthruster Design for Nanosatellite Applications", Kartheeplan Sathiyanantha, Regina Lee, Hugh Chesser, York University of Toronto, Journal of Propulsion and Power, Vol 27, No 6, November – December 2011.

124. "Overview of US Academic Programs in Electric Propulsion", Nikos Gatsonis, Worchester University and Manuel Martinez-Sanchez, MIT, 36TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 16-19 July 2000, Huntsville, Alabama, AIAA 2000-3148

125. "Monopropellant Micro propulsion system for Cubesat", Chris Bibby, Stellar-exploration company & California Polytechnique University

126. "Evaluation and Optimization of an 8 GHz Microwave Electrothermal Thruster", Daniel Clemens, Michael Micci et al, Penn State, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 25-28 July, Nashville, TN, AIAA 2010-6520

127. "Development and Chamber Testing of a Miniature Radio Frequency Ion Thruster for Microspacecraft", Michael Micci, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauderdale, Florida, AIAA 2004-4124

128. "The design, development and in flight operation of a water resistojet micropropulsion system", D. Gibbon, Dr. Coxhill, Surrey Satellite Technology Ltd, University of Surrey, Nicolini, ESA, ESTEC, 40TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauredale, Florida, AIAA 2004-3750

129. "Performance Modelling of a Coaxial Radio Frequency Gas discharge microthruster", William B. Stein, Alina A. Alexeenko and Ivana Hrbud, Purdue University, Journal of Propulsion and Power, Vol.24, No.5, September – October 2008.

130. "Advanced Space Propulsion for the 21ST Century", Robert H. Frisbee, JPL, Journal of Propulsion and Power, Vol19, No6, November-December 2003.

131. "Cubesat Development in Education and Industry", Robert Twiggs, Director Space Systems Lab, Stanford, Space 2006, 19-21 September 2006, San Jose, California, AIAA 2006-7296

132. "An overview of Electric Propulsion activities in Japan", Hirokazu Tahara, Graduate School of Engineering and Science, Osaka University.

133. "Electric Propulsion in Germany: Current Program and Perspectives", IEPC 2005-130, Hans Meusemann, German Aerospace Center et.al.

134. “Introduction to the European Activities in Electric Propulsion”, G. Saccoccia, Head of Propulsion and Aerothermodynamics Division, ESA, ESTEC, Netherlands, IEPC 03-341.

135. “Development and qualification of a Neutralizer Device for the FEEP Micropropulsion on Microscope and Lisa pathfinder”, M. Capacci et.al., IEPC 2007-154

136. “The Brazilian Electric Propulsion Program”, Gilberto M. Sandonato et.al., Rodrigo I. Marques et al University of Southampton, IEPC 2007-147

137. “Fundamental Study of Laser Micropropulsion using powdered propellant”, S. Yokoyama etal, Tokai University and JAXA, IEPC 2007-230

138. “RAM Electric Propulsion for Low Earth Orbit Operation: an ESA Study”, D.Di Cara and J. Gonzalez del Amo et al, IEPC 2007-162.

139. “Microwave Discharge Ion Thruster using Argon as Propellant”, Makoto Miyoshi, Naoji Yamamoto etal, Kyushu University, IEPC 2007-205

140. “Development of Next Generation APPT at RIAME”, Garry Popov etal, RIAME, Moscow, IEPC 2007-134

141. “Development of low power Hall Thruster with lifetime up to 3000 hours”, Mikhail Belikov et al, IEPC 2007-129, Keldysh Research Center Moscow

142. “Micro Pulsed Plasma Thruster Development”, S. J. Pottinger etal, Austrian Research Centers GmbH- ARC, IEPC 2007-125

143. “Development and Thrust Performance of a Microwave Discharge Hall Thruster”, IEPC-2007-085, Kyushu University, Hirohisa Kuwano.

144. “Micro Newton RIT Power Control Unit Development”, Matthias Gollor etal, Astrium, Giessen University, IEPC 2007-19

145. “Ion thruster Development at L-3 ETI for Small Satellite Applications”, William G. Tighe etal, L-3 Communications and JPL, IEPC 2007-024

146. “Vacuum Testing of the Miniature Radio Frequencey Ion Thruster”, Valerie Mistoko, Michael Micci, Penn State University, IEPC 2005-265

147. “Investigation of Various Microwave Electron Cyclotron Resonance Cathode Configurations”, Hani Kamhawi and John Foster, NASA Glenn, IEPC 2005-283

148. “Ambitious Challenges of Japanese Electric Propulsion”, Hitoshi Kuninaka, JAXA, IEPC 2005-323

149. "Coaxial Micro Cathode Arc Thruster (CA-μCAT) Performance Characterization", Taisen Zhuang, Michael Keidar etal, The George Washington University, AIAA 2011-5884, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 31 July – 03 August 2011, San Diego, California.

150. "Cubesat Lunar Mission Using a miniature Ion thruster", Ryan Conversano and Richard Wirz, University of California, AIAA 2011-6083, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 31 July – 03 August 2011, San Diego, California.

151. "Performance Characterization of a μCAT Arc Thruster", Taisen Zhuang, Michael Keidar etal, The George Washington University, AIAA 2011-5884, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 31 July – 03 August 2011, San Diego, California.

152. "Miniature Cyclotron Resonance Thurster", Kevin Diamant and William Cox etal, Aerospace Corporation, AIAA 2011-5882, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 31 July – 03 August 2011, San Diego, California.

153. "In FEEP cluster for LISA pathfinder", N. Buldrini, M. Tajmar, IEPC 2005-224

154. "Endurance Test of 150μN FEEP Microthrusters", M. Andrenucci and M. Saviozzi, IEPC 2005-183

155. "APPT Propulsion system for small satellites", Nikolay Antropov and Gary Popov, RIAME, Moscow, IEPC 2005-111

156. "Development of a Microwave Excited microplasma thruster", Yoshinori Takao etal, Kyoto University, Japan, IEPC 2005-056

157. "Research and Development on Coaxial PPT for small satellites", Masayuki Mukai etal, Tokyo Metropolitan University, IEPC 2007-243

158. "Status of the Indium FEEP Micropropulsion Subsystem development for LISA pathfinder", M. Tajmar, Austrian Research Centers GmbH-ARC, IEPC 2007-122

159. "Performance of a Low Power Cylindrical Hall Thruster", Kurt Polzin etal, NASA Marshall Center and Princeton University, IEPC 2005-011

160. "Optimization of GEO using electric propulsion based on genetic algorithm", Han Xianwei etal, Xian Polytechnic University, China

161. "Microspike based Chemical/Electric Thruster Concept for Versatile Nanosat Propulsion", Anthony Cofer etal, Purdue University, AIAA 2011-5921, 47TH

AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 31 July – 03 August 2011, San Diego, California.

162. “Modeling and Direct Thrust Measurements of a 8 GHz Microwave Electrothermal Thruster”, Jeffrey Hopkins and Michael Micci, Penn State, AIAA 2011-5885, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 31 July – 03 August 2011, San Diego, California.

163. “Ignition Test of Bi-propellant propulsion system based on green propellants for microsatellites”, Nobuyoshi Suzuki etal, Tokyo Metropolitan University, AIAA 2011-5771, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 31 July – 03 August 2011, San Diego, California.

164. “Vaccuum Arc Thruster for Cubesat Propulsion”, Jochen Schein etal, University of Illinois, IEPC 2003

165. “Development of a Microwave Engine”, S W Kim etal, Hokkaido Institute of Technology, IEPC 2005

166. “Micropropulsion using a Laser Ablation Jet”, C. Philips etal, Photonics Associates, Journal of Propulsion and Power Vol 20, No 6, November-December 2004.

167. “Performance of the miniature and low power microwave discharge ion engine µ1”, Hiroyuki Koizumi and Hitoshi Kuninaka, JAXA, AIAA 2010-6617

168. “Comparisons in Performance of Electromagnet and Permanent Magnet Cylindrical Hall Effect Thrusters”, Kurtz Polzin, Princeton Plasma Physics Laboratory, AIAA 2010-6695

169. “A new concept and design aspects of an antigravity propulsion mechanism based on inertial forces”, Christopher Provatidis and Vasileios Tsirigkakis, National Technical University of Athens, AIAA 2010-6684

170. “Exhaust Plume Characteristics of Microhollow Cathode Discharge Plasma Thruster”, Jichul Shin and Pham Dinh Tuyen, IEEE transactions on plasma science, Vol. 39, No. 11, November 2011

171. “Ion velocity evaluation with channel width, magnetic topology and propellant in a 200W Hall Thruster”, G. Bourgeois etal, ICARE-CNRS, IEPC 2011-123

172. “Design Development and evaluation of an 8µPPT propulsion module for a 3U Cubesat application”, Peter Shaw, Vaios Lappas etal, Surrey University, IEPC 2011-115

173. “Thrust Measurements of a small scale helicon Double layer Thruster”, T. Harle etal, University of Surrey & Australian National University, IEPC 2011-103

174. “The Quad Confinement Thruster – Preliminary Performance Characterization and Thrust Vector Control”, Aaron Knoll, Vaios Lappas etal, University of Surrey, IEPC 2011-099

175. “Helicon Double Layer Thruster Performance Enhancement via manipulation of Magnetic Topology”, S.J. Pottinger, Vaios Lappas etal, University of Surrey & The Australian National University, IEPC 2011-097

176. “Two Dimensional Particle in Cell Simulation of a Micro RF Ion Thruster” Yoshinori Takao etal, University of Kyoto, IEPC 2011-076

177. “Research and Development of Very Low Power Cylindrical Hall thruster for Nano satellites”, Tomoyuki Ikeda etal, Osaka Institute of Technology and Osaka University, IEPC 2011-039

178. “A thermal pulsed plasma thruster for Microsatellite propulsion”, Matthias Lau etal, University of Stuttgart, IEPC 2011-140

179. “RIT Micro Propulsion system for Lisa Pathfinder”, D.DI Cara etal, ESA, Astrium & Giessen University, IEPC 2011-325

180. “Experimental Investigation on CW Laser Microthruster”, Hitoshi Yonamine etal, Tokai university & JAXA, IEPC 2011-320

181. “Performance Evaluation of a Miniature Ion Thruster μ1 with a Unipolar and Bipolar Operation”, Hiroyuki Koizumi etal, Tokyo University & JAXA, IEPC 2011-297

182. “Study on ionization characteristics of low power hall thruster with variable cross-section channel”, Zhongxi Ning etal, Harbin Institute of Technology, China, IEPC 2011-286

183. “A very low power Arcjet (VELARC) for small satellite missions”, Birk Wollenhaupt etal, University of Stuttgart, IEPC 2011-257

184. “Thruster Development Set up for Helicon Plasma Hydrazine Combined micro Research Project”, D. Pavarin etal, University of Padova & ENEA, Frascati & Dedalos,Thesalloniki & ONERA, France, IEPC 2011-241

185. “Design and Testing of a Micro Pulsed Plasma Thruster for Cubesat Application”, F.Guarducci etal, Southampton University, IEPC 2011-239

186. “The comparison of results and tests of low power hall thrusters: SPT and TAL”, Titov Loyan etal, Ukraine National University, IEPC 2011-199

187. “Propulsion for Nanosatellites”, M. Tajmar etal, University of Applied Science, Austria, IEPC 2011-171

188. “Design of a miniature microwave frequency Ion Thruster”, Daniel Lubey, Michael Micci etal, Penn State University, IEPC 2011-164

189. “The design and development of a 30GHz microwave electrothermal thruster”, Erica Capalungan, Michael Micci etal, Penn State University, IEPC 2011-162

190. “Hollow Cathode Thruster Design and Development for small satellites”, D. Lamprou, Vaios Lappas etal, University of Surrey & SSTL & EADS Astrium, IEPC 2011-151

191. “Development of a Microthruster module for Nanosatellite applications”, Mingo Perez etal, University of Southampton & Mars Space Ltd, IEPC 2011-144

192. “Analysis of Micro Vacuum Arc Thrusters for Earth Orbiting and Lunar Missions”, Therese Suaris etal, George Washington University & NASA Goddard Space Center, IEPC 2011-031

193. “ESA Electric Propulsion Activities”, J. Gonzalez, ESA, IEPC 2011-329

194. “Rocket Propulsion Elements” 7th Edition, G.Sutton and O.Biblarz, John Wiley & Sons Publications, 2001, Chapter 19, Electric Propulsion, p. 665 (HTAN TO ENA APO THN PALIA ARITHMISI)

195. “Fundamentals of Electric Propulsion. Ion and Hall thrusters”, Dan Goebel and Ira Katz, John Wiley and sons, JPL Space Science and Technology Series, p.27

196. www.daviddarling.info/encyclopedia/E/electricprop.html

197. “Powering Cube satellites”, MIT news, 2010, (article) www.web.mit.edu/newsoffice/2010/cubesat-01115.html

198. “Aerojet and NEC to develop Ion propulsion systems for satellites”, Staff Writers, August 05, 2009, (article) www.space-travel.com/reports/Aerojet_And_NEC_to_Develop_Ion_Propulsion.html

199. “Successful flight demonstration of Plasma Thruster under Microgravity” , Space Daily, February 27, 2011, (article) www.bibliotecapleyades.net/ciencia/secret_projects/project305.html

200. "New Mini Microwave Thruster for satellites is most powerful in its Class", Penn State, Michael Micci, 1999, October 18, (article) www.sciencedaily.com/releases/1999/10/991018080035.html

201. "Improved Microwave Electrothermal Thruster Systems for Satellites and Space Flights", Maria Callier, Wright Patterson Air Force Base, December 2008, (article) www.wpafb.af.mil/news/story.asp?storyID=123129612

202. "Electric Propulsion Theory" January 19, 2004, www.fluid.ippt.gov.pl/sbarral/basics.html

203. "Electric Ion Propulsion and beyond – A talk with NASA's Glenn Research Center engineer Michael Patterson", 2011, (article) www.electricalfun.com/ElectronCafe/NASA_ion_engine.aspx

204. "Visible Plume from a low power ECR Waveguide plasma cathode for electric propulsion systems", Brandon R. Weatherford, John E. Foster and Hani Kamhawi, IEEE transactions on plasma science Vol39, No 11, November 2011.

205. "Design and fabrication of a Micro Ion engine", Juergen Mueller et al, AIAA 2000-3264, JPL, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 16-19 July 2000, Huntsville, Alabama.

206. "Applications for PPTs and the development of small PPTs for microspacecraft", AIAA 2000-3434, W.A. Hoskins et al, Primex Space Systems, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 16-19 July, Huntsville, Alabama

207. "JPL Micro Thruster propulsion activities", Juergen Mueller et al, JPL, AIAA 2002-5714, Nanotech 2002,12 September Houston, Texas

208. "Pulsed Plasma Thrusters for Micropropulsion", Daniel Simon and Bruce Land, John Hopkins University Applied Physics Laboratory, AIAA 2003-5170, 39TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23 July 2003,Huntsville, Alabama

209. "Performance modeling of a coaxial radio frequency gas discharge microthruster", William Stein et al, Purdue University, Journal of Propulsion and Power, Vol 24, No 5, September – October 2008

210. "Electric Propulsion: Comparison between different concepts", L. Carriques and P. Coche, Universite de Toulouse, Plasma Physics and Control Fusion 53 (2011) 124011 (11pp).

211. "Plasmas for space propulsion", Eduardo Ahedo, University of Madrid, Plasma Physics and Controlled Fusion 53(2011) 124037 (18pp)

212. "Low thrust propulsion technologies, Mission Design and Application', John Dankanich, Gray Research Inc. USA, Chapter 12 on Book Aerospace Technologies Advancements by Dr Thawar T. Arif, ISBN 978-953-7619-96-1, pp 492, January 2010.

213. "Electric Propulsion", Robert G. Jahn and Edgar Y. Choueiri, Princeton University, Encyclopedia of Physical Science and Technology, Third Edition, Volume 5.

214. "Propulsion Systems", J. Barries Moss and John W. Stark, Shool of Enginering Cranfield University and Queen Mary University of London, Spacecraft Systems Engineering (Third Edition), Edited by P. W. Fortescue and J. W. Stark, 2003, John Wiley and Sons Ltd. (Book Chapter 6)

215. "A theory of microwave propulsion for spacecraft", Roger Shawyer, SPR Ltd, www.emdrive.com

216. "Electric Solar Wind sail propulsion system development", Pekka Janhaunen etal, University of Helsink, IEPC 2011-058

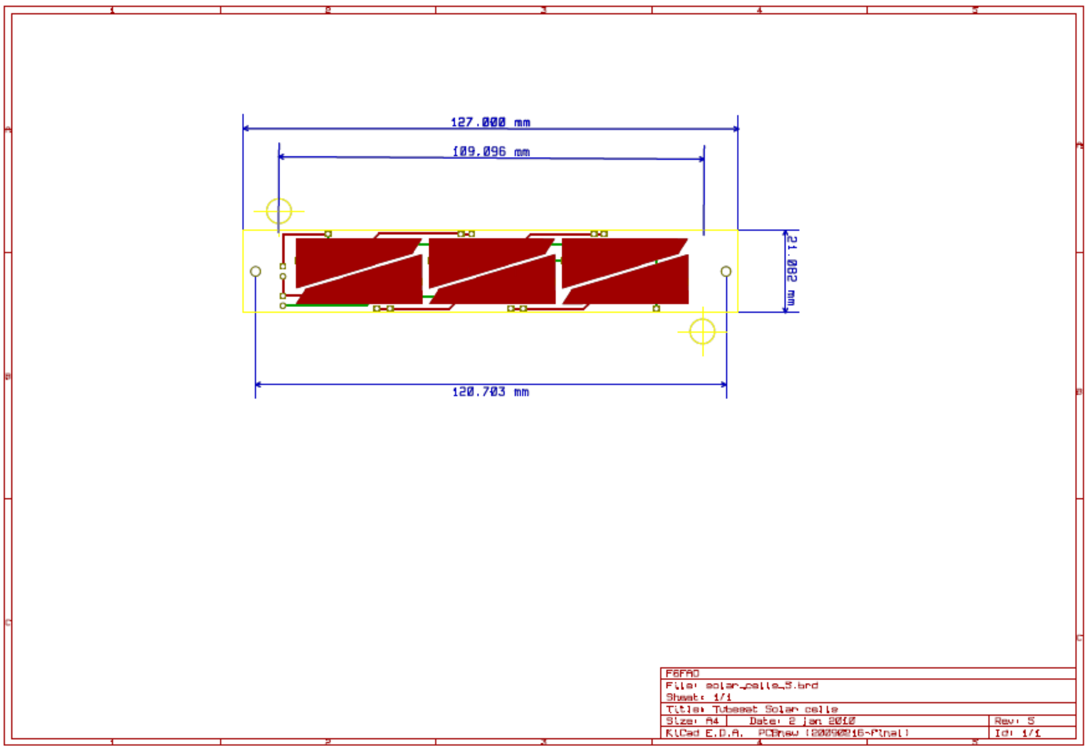
217. "Mission Performance of the Dual Mode Hybrid Engine", John Dankanich and Michael Petterson, NASA Glenn Research Center, AIAA 2011-5664

218. "Investigation of physical processes in SPT MAG", A. I. Burgova etal, Moscow Institute of Radioengineering, Electronics and Automatics, Moscow, Russia, IEPC 2005-146

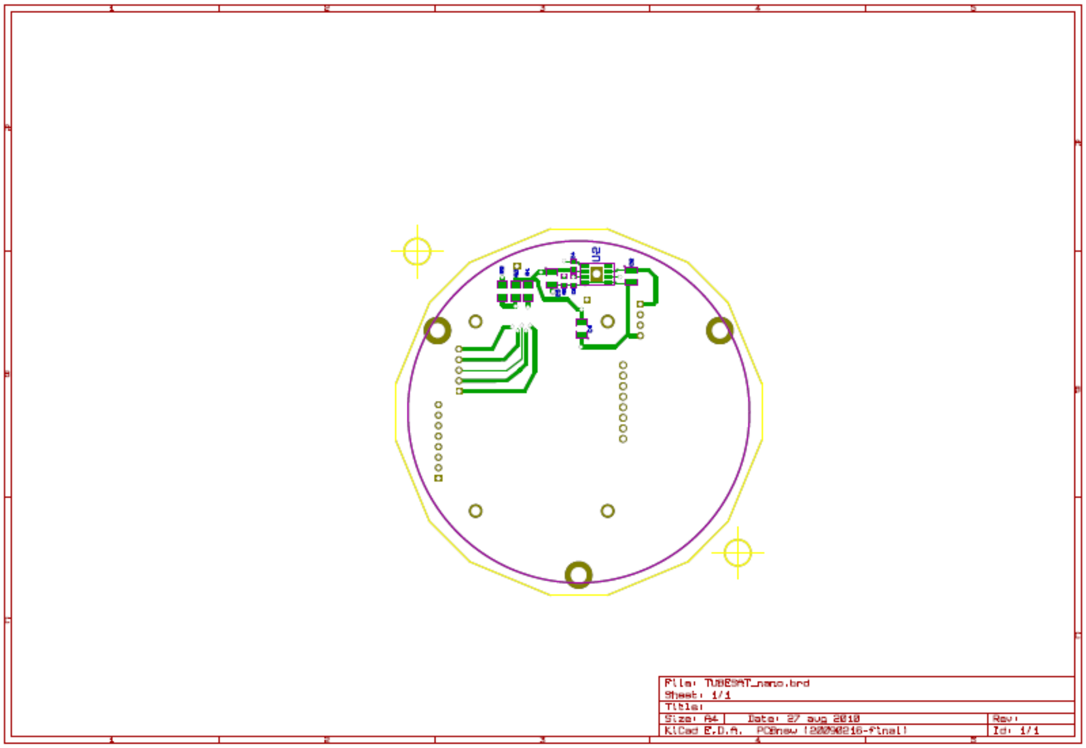
219. "Solar Electric Propulsion Subsystem. Architecture for an all electric spacecraft", Dr. Michele Coletti etal, University of Southampton, Chapter 6, Advances in Spacecraft Technologies.

Appendix 5: Tubesat Electrical - OBC Schematics

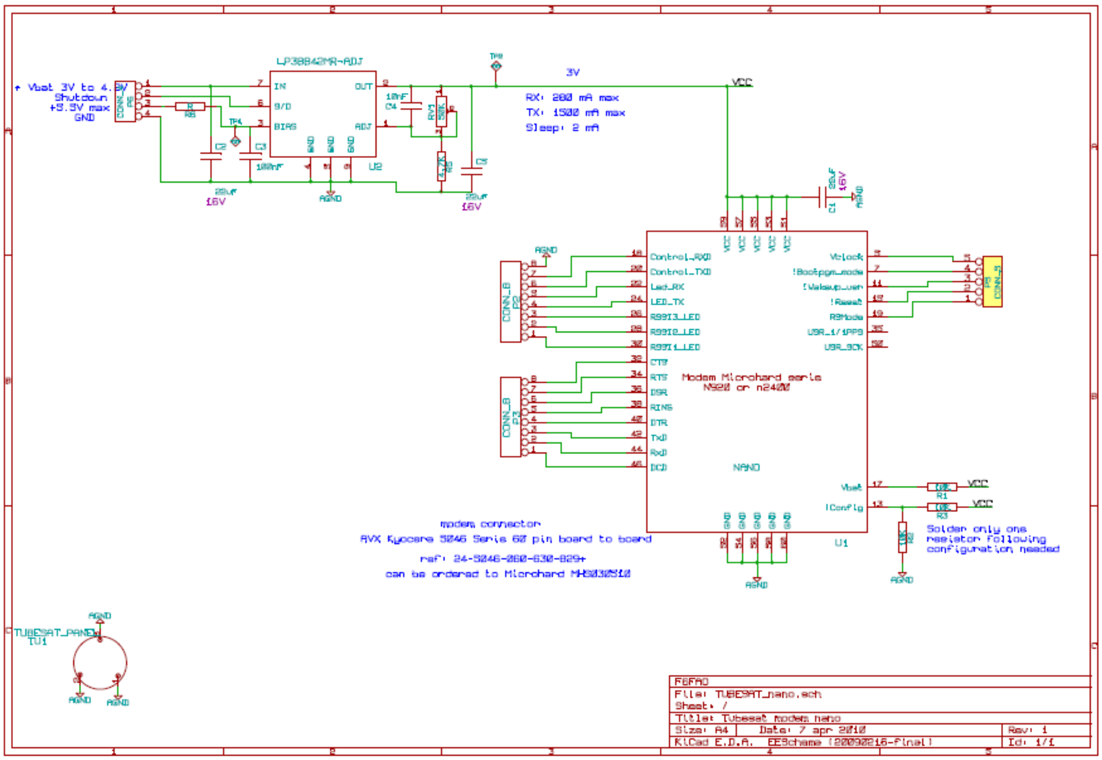
Below one can see Tubesat Electrical, Power, Thermal and On Board Computer Schematics. The original schematics had to be adequately altered from Naval Postgraduate School Team - CENETIX Lab (**Principal Investigator: Dr Alex Bordetsky and Chief Engineer: Mr Eugene Bourakov)** in order to finally manage to make the satellite communicate with the ground station.



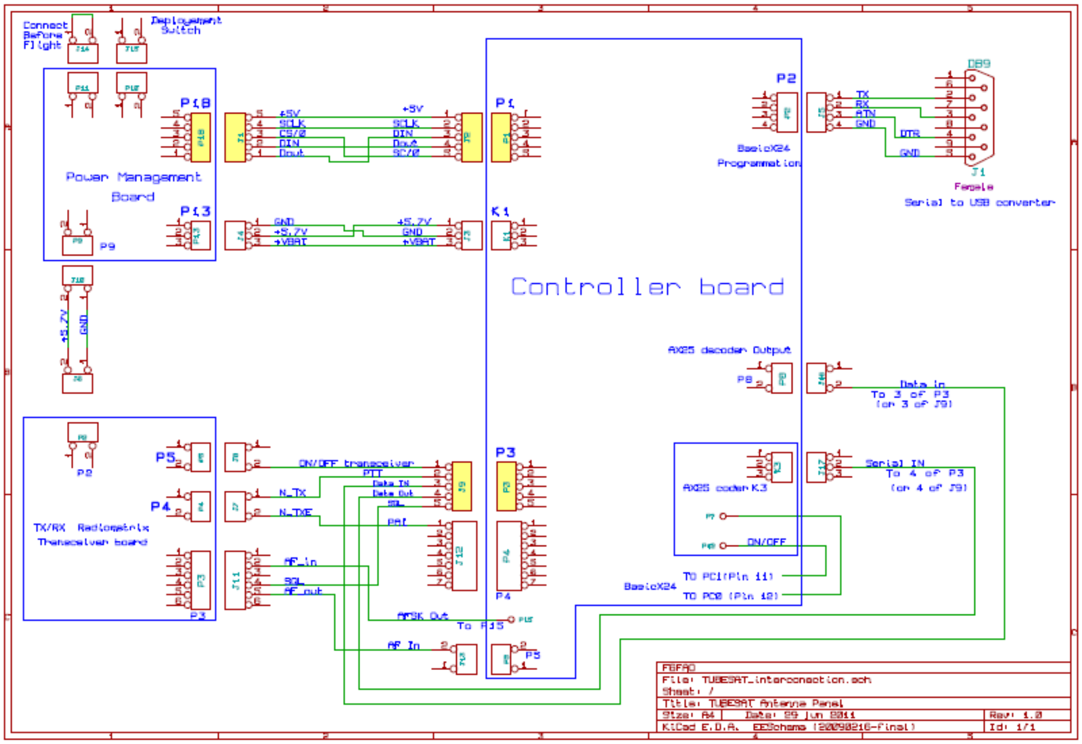
Tubesat Solar Panels Configuration



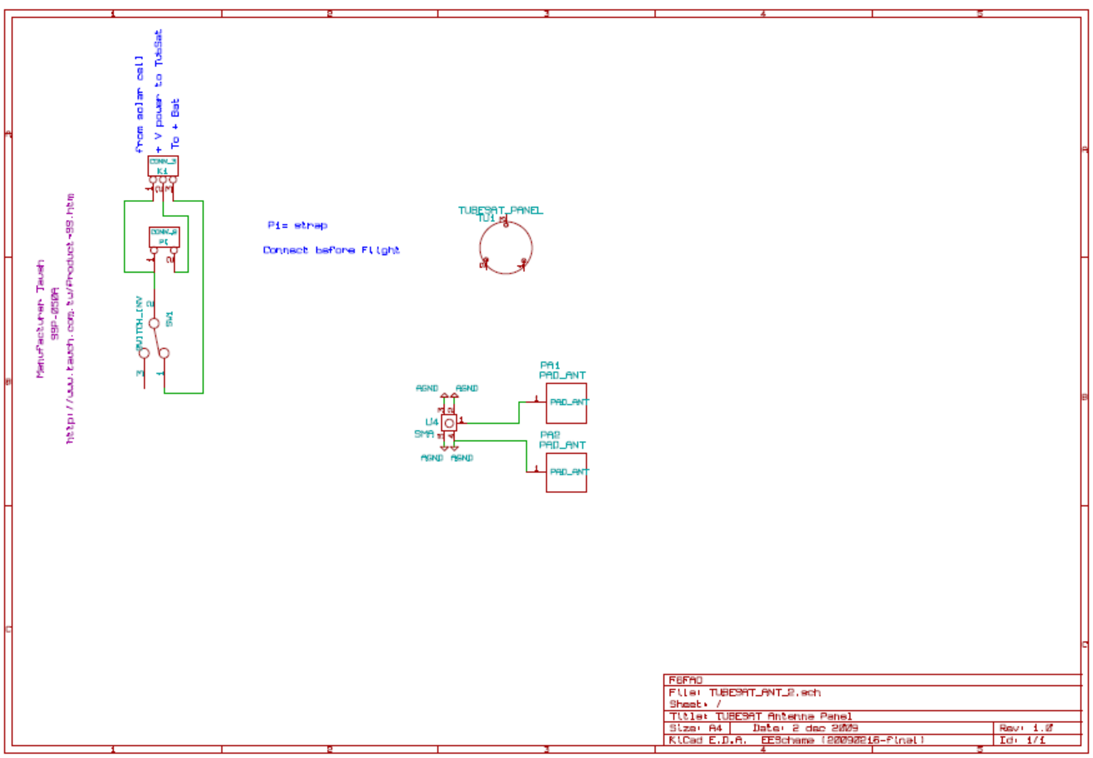
Radio Microhard Receiver Soldering



Radio Microhard Transceiver Connectivity



BasicX-24 On Board Computer Connectivity Schematic



Antenna Panel Connectivity Schematics

Appendix 6: L-sat signals decoder scheme (in Greek)

Σε κάθε αποστολή δεδομένων του Λ-Sat μέσω Beacon Stensat (437.462 MHz) θα προηγείται το στάνταρ μήνυμα:

KK6DFZ/TELEM>CQ>UI,?,F0: LAMBDASAT.COM_HELLAS:

Τα data που λαμβάνονται έχουν την εξής μορφή:

1. House Keeping Data

HKD

P1,V879,T255,ST10011111,D101011,IRD100,GR81,HKD73,MSG22,IR28,M1,MSGL0, R3,W218,RSSI5

HKD: Διακριτικό ότι πρόκειται για house keeping data

P1: Το main computer λειτουργεί με τον Pic 1 [1-3]

V879: Τάση μπαταρίας (Voltage [730-920])

Π.χ. V730 → 6.70 Volts

V740 → 6.80 Volts

V760 → 7.00 Volts

V790 → 7.20 Volts

V800 → 7.29 Volts

V830 → 7.57 Volts

V835 → 7.62 Volts

V875 → 8.00 Volts

V920 → 8.40 Volts

T255: Τελευταία μέτρηση θερμοκρασίας (Temperature) από την πλακέτα γραφενείου [0-255]

temp= (T*0.0192 - 1.375)/0.0225

οπου temp: η θερμοκρασία σε βαθμούς κελσίου

T: η μέτρηση που έστειλε ο Λ

ST10011111: Κατάσταση (STatus) συσκευών AIS,Iridium,Graphene,Stensat του Λ. Τα 4 MSB (αριστερά) δηλώνουν ποιες συσκευές είναι ενεργοποιημένες από το κέντρο ελέγχου και τα 4 LSB (δεξιά) δηλώνουν ποιες συσκευές είναι ενεργοποιημένες από το mode του Λ.

Π.χ. 1ο bit (1): AIS Receiver ενεργοποιημένος από το κέντρο ελέγχου

2ο bit (0): Iridium modem απενεργοποιημένο από το κέντρο ελέγχου

3ο bit (0): Graphene experiment απενεργοποιημένο από το κέντρο ελέγχου

4ο bit (1): UHF transmitter ενεργοποιημένο από το κέντρο ελέγχου

5ο bit (1): AIS Receiver ενεργοποιημένο από το mode

6ο bit (1): Iridium modem ενεργοποιημένο από το mode

7ο bit (1): Graphene experiment ενεργοποιημένο από το mode

8ο bit (1): UHF transmitter ενεργοποιημένο από το mode

Για να λειτουργήσει κάποια συσκευή, θα πρέπει και τα δυο bits που αντιστοιχούν σε αυτήν να είναι 1

D101011: Δηλώνει την παρούσα κατάσταση των συσκευών (Devices)

Π.χ. 1ο bit (1): AIS Receiver ενεργοποιημένο

2ο bit (0): Iridium modem απενεργοποιημένο

3ο bit (1): UHF Receiver ενεργοποιημένο

4ο bit (0): Graphene experiment απενεργοποιημένο

5ο bit (1): UHF transmitter ενεργοποιημένο

6ο bit (1): Φόρτιση μπαταρίας ενεργοποιημένη

IRD100 : Δηλώνει ποια data θα στέλνονται με το Iridium (IRidium Data)

Π.χ. 1ο bit (1): AIS Data στέλνονται με το Iridium

2ο bit (0): Graphene Data δε στέλνονται με το Iridium

3ο bit (0): HKD Data δε στέλνονται με το Iridium

GR81,HKD73,MSG22,IR28 : Αντίστροφοι μετρητές μέχρι να ενεργοποιηθούν οι λειτουργίες GRaphene/HKD/MeSsaGe/IRidium

Π.χ. GR81: Σε 81 κύκλους προγράμματος θα ενεργοποιηθεί το Graphene Experiment [0-10.800]

HKD73: Σε 73 κύκλους προγράμματος θα ενεργοποιηθεί η καταγραφή HKD [0-45]

MSG22: Σε 22 κύκλους προγράμματος θα ενεργοποιηθεί η αποστολή μηνύματος πειρατείας μέσω UHF[0-90]

IR28: Σε 28 κύκλους προγράμματος το Iridium modem θα αναζητήσει εισερχόμενο μήνυμα από το κέντρο ελέγχου [0-2.700]

M1 : O Λ-Sat λειτουργεί σε Mode 1 [1-2]

1: Nominal Mode

2: Safe Mode

MSGL0,R3 : Ένδειξη ύπαρξης φορτωμένου μηνύματος πειρατείας προς εκπομπή (MeSsaGe Loaded [1-0]) και του αριθμού των επαναλήψεων (Repeats [1-99])

MSGL0: Δεν υπάρχει φορτωμένο μήνυμα πειρατείας προς εκπομπή

R3: H αποστολή μηνύματος πειρατείας , όταν φορτωθεί, θα γίνει 3 φορές

W218: Μετρητής επιτήρησης κεντρικού υπολογιστή (Watchdog [0-255])

RSSI5 : Τελευταία γνωστή ένταση σήματος Iridium (Received Signal Strength Indication [0-5])

2. Graphene Experiment Data (graphene)

T104 G4=118,119,118,118,126,117,130,119,116,120,127,113,119,118,110, 118,122,119,119,117,118,116,116,108,109,110,122,135,123,115,122,115,109,116,120,107,123,123,117,117,121,118,125,116,118,114,116,114,122,117,116,118,116,129,122,119, 122,115,127,119,118,120,117,119

T104: Θερμοκρασία κατά τη διάρκεια μέτρησης του πειράματος Γραφενείου [0-255]

G4: Μέτρηση του τρανζίστορ γραφενείου No4 [1-6]

118,119,… :Τιμές μέτρησης τρανζίστορ γραφενείου [0-255]

3. AIS Message Transmittion (σήμα από εμπορικά πλοία)

!AIVDM,1,1,,A,15MvK1PP0EG?IM2Ea4Ar?Ow:08Ep,0*7B

!AIVDM: Χαρακτηριστικό μηνύματος AIS

1,1,,A, : AIS Data (αποκωδικοποίηση στο www.lambdasat.com & www.marinetraffic.com)

4. Piracy Message Transmission (σήμα προς εμπορικά πλοία)

FIELD	CODING	No of digits	COMMENT
Year	xxxx	4	2014 (example)
Month	xx	2	04(example)

Day	xx	2	04(example)
Hour	xx	2	12(example)
Minute	xx	2	22(example)
Latitude	xxxxxx	6	02 22 47(example)
North or South	x	1	1= North 2= South
Longtitude	xxxxxxx	7	003 12 27(example)
West or East	x	1	1=West 2= East
Piracy Event	x	1	1= Approach
			2= Hijack
			3= Attack
			4=Suspicious Activity
			5=Armed Robbery
			6=Miscellaneous
Source	x	1	1=IMO
			2=NSC
			3=IMB
			4=RECAAP
			5=EUNAVFOR
			6=ICC
			7=UKMTO
			8=MARITIMERISK.GR
			9=OTHER
Risk Level	x	1	0=Avoid Route
			1= Extremely High
			2= High
			3=Medium
			4=Low
			5=Very Low
			6=Clear - No Risk
			7= Risk from other terrorevents
			8=Illicit trafficking
			9=Narcoterrorism
Text	xxxxxx…..xxxxx	60	
	Total Sum of Digits	**90**	

Appendix 7: Counter Piracy Competencies - Interlinked Networks

Apart from the fact that quantification methods are being applied to counter piracy operations it is of utmost importance for the shipping companies, the maritime security providers / companies as well all those that they deliver maritime security products to have an insight on how much an individual is competent on dealing with counter piracy / high risk situations. We all know and in fact there are initiatives globally that tent to measure the psychological factors that affect an operation but most importantly they are trying to quantify under a simple metric system the percentage of competence in order to pre-evaluate a ship's passage from a high risk area. It is a well-known fact now for years that trained personnel can act professionally and successfully in marginal situations like a counter piracy one that can happen on an ad hoc basis in the middle of the ocean.

The work that is being quoted below is a part of a general European Union project (the so-called PROMERC - Protection of Merchant Vessels at Sea) where after an interview to selected Subject Matters Experts we defined a function and at the same time we measured different situations and individuals on how much trained should be in order to participate in a merchant ship's voyage that may interfere with pirates when transiting through a high risk area.

We would like to thank the partners in the project for their valuable thoughts during the execution of the analysis and research during teleconferences and personal discussions and for performing the review. We also appreciate and acknowledge the kind support of the NATO Maritime Interdiction Operational Training Center (NMIOTC) for its valuable contribution and experience and last but not least all of stakeholders participated at the PROMERC workshop in NMIOTC, Crete, Souda Bay from 23-25 Sept 2014.

Executive summary

Competencies is a study that tries to identifies first and then set the relevant associated factors in order for the maritime professionals to perform above a specific status / level during the protection of merchant vessels in counter piracy operations. Following the below mentioned analysis and essentially the steps and following the order of training for countering piracy maritime professionals will need to have specific competencies in order to be able to accomplish their mission which is eventually the protection of their merchant vessel through transiting of a high risk area.

Without a minimum required training status the mission is precarious and the level of risk is being elevated to an absolute maximum. Further more training lessen the cost associated with counter piracy operations taking into account that trained people minimize the use of costly counter measures.

This work will evaluate the measure of effectiveness that training has to the evaluation of available options and give an effectiveness index in order to materialize and quantify the reality.

Aim

The objective of this work is to define the training competence / status of the people that are going to use the counter measures in order to effectively counter maritime piracy when necessary. If a merchant mariner / seafarer is not trained effectively and efficiently on how to react in a counter piracy operation (e.g. use the available and suitable counter measures, have the available psychological situation in order to react positively and also generally to follow the procedures then the mission is deemed to fail or in a real situation this person instead of helping the defense of a merchant vessel in a holistic approach, he/she deteriorate the situation of his fellow seafarers instead of supporting them.

By this study we should evaluate / give the available tools to evaluate the measure of effectiveness that training has to the use of options during the counter piracy operation.

Scope

It is not under the scope of this feasibility study to spent critical time in order to investigate and finally create methods that would not be used in the future operational environment. Innovative results would be produced taking into account stakeholder's workshop and operational experiences collected from counter piracy professionals. Therefore, the sole scope is to use available means that will simulate counter piracy training reality and support professionals in the selection process of their personnel elsewhere needed. Of course the results we are going to produce / provide at the end of this research will be a prototype and consequently will create hopefully a new roadmap in the training selection / evaluation process for counter piracy operations or at least support them as much as possible in this direction.

Methodology

In this work we firstly performed a literature survey in order to evaluate all (to the extent of our resources and knowledge) the available training materials / roadmaps / guides and competencies methods that robust / rigorous organizations like IMO or government courses, like Australia, Greece or UK (traditional navy nations) are using for training their fellow mariners.

Then a use of a questionnaire during the NMIOTC Workshop in Crete, Souda Bay was disseminated to stakeholders for completion in order for them to evaluate the most critical factors during the training process taking into account their operational and/or training experiences on the field.

As a last step a multidisciplinary analysis was performed in order for us to measure the available effectiveness levels and produce quantifiable indexes that will help create safe results. Under the above context we should also mention that tables in the form of check of list have been created in order for a seafarer to be evaluated by his/her superiors before participate as a crew member of a merchant vessel to a counter piracy operation.

Literature search

Having searched thoroughly the available literature (as per selective references literature at the end of this study) we first identified that all international maritime organizations are using similar techniques and methods where superiors are quantifying the level of competence either using indexes of training effectiveness either through other more sophisticated methods. On the other side maritime oriented universities or generally universities that perform research on the above field are creating models through complex factor systems and try to evaluate training status and approximate reality as more as possible. All the below referenced documents and more created the mindset / mind lock so as to create a starting point for this study which has a more operational than traditional academic focus.

Workshop

A workshop was held to benefit from stakeholders and partners knowledge, professional experience and expertise (see Appendix I). Include photographs, agenda and instructions as Appendices.

Final discussions and Conclusions

After literature and stakeholders surveys, Partners in the EU project PROMERC contributed with their final remarks and comments that were included / embedded / modified positively the whole operational research effort.

Quantitative Analysis

ProMerc is a study that tries to analyze all Piracy Counter Measures during different realistic scenarios and provide to the European Community valid results for the best available use of them during a real operation, so as this study to eventually support merchant mariners during transiting a high risk area. Therefore, in this training competence study is of utmost importance to have in the back of our minds that the competence that we are planning to acquire for should be such as for a person to perform effectively in the below mentioned scenarios. Additionally the individual evaluation should fulfill all the different requirements that he/she needs to acquire in order to undergo efficiently a situation similar to the below mentioned realistic piracy scenarios. We must mention here that these scenarios is a consolidated research study from ProMerc participants and have been decided as such in previous tasks and deliverables and through rigorous analysis / workshops and research.

Primary Scenario Candidates (International waters)

- Large vessel with high freeboard at high speed during day in international waters.
- Large vessel with low freeboard at slow speed at dawn or dusk in int'l waters.
- Small vessel with low freeboard at low speed during day in international waters.
- Small vessel with low freeboard drifting at night in international waters

Secondary Scenario Variants (Territorial Waters)

- Large vessel with low freeboard at slow speed at dawn or dusk in territorial waters)
- Small vessel with low freeboard steaming at low speed during day in territorial waters.
- Small vessel with low freeboard drifting at night in territorial waters
- Small vessel with low freeboard at anchor at night in harbor area

Coming to the competencies baseline requirements it is essential to understand that in appointing a maritime professional in a Counter Piracy measures environment, consideration should be given to the overall competency to undertake the mission role (in accordance with the associated work position - for example if he/she is an officer or belongs to the lower crew members) and their physical capability to perform these duties.

The Baseline Scenario we are going to use in order to design the minimum acceptance competence for a maritime professional during a counter piracy operation / mission (with the use of counter measures available on board a vessel) is inevitably the worst case scenario since if someone is successful on completing the task during the worst operational situation he / she should be also effective in any other operational situation that may arise. It is very important to mention here that this material refers only to the operational level professionals and not to maintenance, support or management levels. For those, other criteria should be applied and it is not under the scope of this study. The competencies referred here are only applicable to seafarers that operate counter piracy measures during counter piracy missions / passages from high risk areas.

In our case the baseline scenario (as mentioned above and proposed from the University of the Aegean to the Consortium) and having interviewed maritime security professionals from various operational environments (Gulf of Aden, West Africa, Malacca Strait etc) is to have a Large vessel (low maneuverability capability) with low freeboard (full of cargo - cargo costs a lot so it is an allured prey for aspiring pirates) and moving in international or territorial waters at dawn or dusk (in this specific timeframes of the day the illumination is very low and therefore pirates can act more freely without being noticed (especially when transiting with high speeds).

Under this scope we will try to evaluate the measure of effectiveness (MOE) that training competence has to the evaluation of the available options.

In order to fulfill the above critical task a detailed design and outline of minimum training and qualifications requirements must be performed. This is referenced below as follows:

The Person:

- must hold at least a <u>Certificate</u> in Security from a class Organization that is in force (not allowed to hold a certificate from its own shipping company or any other private non certified organization).
- must have undergone <u>theoretical</u> training of at least 2 days with exams
- must have undergone <u>simulated</u> training scenarios of at least 2 days with exams

- must have undergone practical training of at least 2 days of using available CMs that will be provided
- must have undergone a total training period of at least 5 days (including theory, simulation and practice)
- mush have a working experience on board vessels having transited a high risk area of at least 3 consecutive days during one single passage

All these above training requirements are mentioned explicitly in the below Table 1 and in conjunction with Knowledge (K), Understanding (U) and Processing (P) factors that an individual must acquire.

In order to perform the quantitative analysis the mathematical approach selected was the Multi-Criterial Decision Analysis tool / weightings, as the most appropriate taking into account all accumulated operational experience collected. The most important reason to that was the fact that in this analysis, stakeholder's opinions were included based on their different criteria. Each SME ranked its preferences in accordance to training levels and competence and supported the process in a sense that their operational experience was accumulated in the mathematical function, so as to create a more realistic quantifiable training competence index. At the same time NMIOTC (NATO Maritime Interdiction Operational Training Center) the sole sound organization for training in NATO provide their invaluable feedback and with SMEs opinions made the survey state of the art and unique. Below in Table 1 an analysis of the different criteria is referred.

Level of Competence (C)	Knowledge (K)	Understanding (U)	Processing (P)
The Person must:			
Theoretical Training (TT)			
hold at least a Certificate in Security from a class Organization that is in force (not allowed to hold a certificate from its own shipping company or any other private non certified organization).	√	-	-
have undergone theoretical training of at least 2 days with exams	√	-	-
Simulated Training (ST)			
have undergone simulated training scenarios of at least 2 days with exams	√	√	
Practical Training (PT)			
have undergone practical training of at least 2 days of using available CMs that will be provided	√	√	-
Working Experience (WE)			
have undergone a total training period of at least 5 days (including theory, simulation and practice)	-	-	√
have a working experience on board vessels having transited a high risk area of at least 3 consecutive days during one single passage	-	-	√
Real World Evaluation (RWE)			
Maintain and Supervise the implementation of CMs in conjunction with SSP	-	-	√
Assess Security Risk Threat and Vulnerability	-		√
Undertake regular inspections to ensure appropriate security measures are implemented and maintained	-	-	√
Ensure CM systems are operational tested and calibrated	-	-	√
Encourage Security awareness and training	-	-	√
Recognition of Security Threats	-	-	√
Ensure proper usage of security equipment - CM	-	-	√

Table 1: Level of Competence Subcategories for a Maritime Professional divided in Knowledge, Understanding and Processing Fields

Quantitative Analysis Method

$$C = K \quad x \quad U \quad x \quad P \qquad (1)$$

$$= (TT + ST + PT) \times (ST + PT) \times (WE + RWE) \qquad (2)$$

Competence is being defined here as the multiplication function of Knowledge (K), Understanding (U) and Processing (P) (function (1)). Whereas K, U and P respectively in accordance with table 1 is further being analyzed in Theoretical Training (TT), Simulated Training (ST) and Practical Training (PT) for Knowledge, Simulated and Practical Training for Understanding and Working Experience (WE) and Real World Evaluation (RWE) for the Processing part of the function.

Further to this analysis and taking now into consideration the Table 2 SMEs questionnaire we are more dividing the above mentioning factors from function (2) into important subcategories where weight factoring is going to take place taking into account all available thematic areas that a trainee should perform in order to finally acquire the minimum desirable training competence. These weight factors are going to be different of course for Officers and the crew members of a merchant vessel since their duties and responsibilities on board a vessel is way different on these levels of hierarchy.

NMIOTC workshop SMEs will reply to the Table 2 questionnaire and by collecting all of their ideas / operational knowledge and experiences regarding the training level that a maritime professional should have will then move to the analysis part and define Competence Level (C) index which is the requested data for this analysis.

Weightings using Multi Criteria Decision Analysis will then be put to the following function (3) and by using an excel spreadsheet Competence Level results will define the future roadmap regarding competence training levels.

Therefore, the final competence level will be calculated from the below function as follows:

$$C = \prod_{i=1}^{n} w_i A_i \qquad (3)$$

where,

C = Competence Level

w_i= criteria weight

A = Criterion Average across SMEs

n = number of total criteria

In this study each criterion (Theoretical, Practical, Simulated training etc) is considered to be of the same importance, except if SMEs comment on that with a different approach.

If this happens then Table 3 will fill this gap in our analysis and we will then evaluate the total competence with the respect of the following additional function (4) before we use function (3).

$$w_i = I_c \ x \ w_c \qquad (4)$$

where,

w_c= specific subcriteria weight

I_c= Relative Importance of the training level in accordance to the other training levels

As an aftermath anyone who wants to testify his/her own maritime professional should use the above mentioned Competence index as a rule of thumb in order to select individuals and have the safety that this individual will be able to perform on a worst case scenario (counter piracy situation) as mentioned in detail above.

C	K	U	P
T T (0-10)	C=K		
ST (0-10)	C=K*U		
PT (0-10)	C=K*U		
WE (0-10)			C=P

WRE (0-10)		C=P

Table 2: *Level of Competence Subcategories in accordance with Knowledge, Understanding and Processing*

$$C = K \quad x \quad U \quad x \quad P$$

$$= (TT + ST + PT) \times (ST + PT) \times (WE + RWE)$$

(i) for 50% then weight is 5 out of 10 so C=(5+5+5)*(5+5)*(5+5)=1500 units of competence (approximately for crew and back office personnel)

(ii) for 70% then weight is 5 out of 10 so C=(7+7+7)*(7+7)*(7+7)=4116 units of competence (for officers)

(iii) for 100% - maximum possible value will be 10 out of 10, so C=(10+10+10)*(10+10)*(10+10)=12000 units of competence which means that we have a professional / excellent and full competent expert in counter piracy operations. In this case as we see the ability is becoming 4 times stronger than in the second case and 11 times bigger that in the first case. So competency increases drastically from first to second (approximately 3 times) and 6 times approximately for the maximum possible case. Thus by training a person on how to handle a counter piracy operation we increase drastically the possibilities to perform the mission successfully.

Questionnaire Analysis

The desirable objective aim of the training process of a maritime security professional should be in general terms the following:

- Acquire the capability to assess global piracy risk / threat.
- Use all available tools to design an operational passage from a high risk area by implementing risk mitigation techniques in order to complete the mission / voyage successfully.
- Increase ability of measuring piracy operational risk so as to act proactively.
- Enhance knowledge in risk management procedures to react effectively to counter piracy situations when on board a merchant vessel.

For performing the above mentioning general tasks Knowledge, Understanding and Processing should be evaluated in the different subcategories as listed in the below tables 2 and 3 (different weighting may appear for each of the above functions):

TO BE FILLED DURING NMIOTC WORKSHOP FROM SMEs - STAKEHOLDERS			
Current Job Status: *(eg. Captain or Analyst in Counter Piracy)* ***Experience with Counter Piracy:*** *(Please state your experience briefly)*			
Please fill out the right hand column of weight factor with a scale of 0 to 10 responding to question:* *(0 is less important - not necessary & 10 is of utmost importance - unsafe to perform a piracy operation without it)* **Please discriminate weight factors among Officers and Crew* ***How important is iaw your opinion for a maritime professional / Seafarer to have acquired the following levels of training competence in order to perform his/her job (passage through a piracy high risk area) successfully.*			
Competence Levels	**Thematic Areas**	**Weight Factor (0-10)**	
		Officers	**Crew**
Theoretical Training	**Global Maritime Piracy Overview**	-	-
	Piracy in Gulf of Aden through Gulf of Oman and Somali Basin		
	Piracy in Gulf of Guinea and elsewhere (e.g. STROG)		
	Pirates Modus Operandi, Psychology and Business model		
	Piracy in Gulf of Aden through Gulf of Oman and Somali Basin		
	Piracy Risk Assessment Theory	-	-
	Piracy Risk Assessment Theory and Methodology (techniques)		
	Matrix Risk Calculation, General Risk Assessment, SWOT Analysis etc		
	Merchant vessel risk calculation (examples)		
	Daily Piracy Intelligence Synthesis	-	-
	Information gathering		
	Intelligence collection and analysis to support daily Risk Assessment and Management procedures		
	Piracy Risk Management	-	-
	Risk Management methodology through check off lists and Standard Operating		

	procedures (Pre passage planning and on board MVs)		
	Lessons Learned, Safety precautions and BMP 4 implementation		
Simulated Training	**Case Studies Analysis**	-	-
	Piracy Incidents Analysis (region specified)		
	Why some M/Vs hijacked and some managed to evade - case base reasoning (analysis of real data)		
	Case Study Exercises	-	-
	Assess the pirate risk on high risk route / voyage.		
	Low and High risk MV examples. Differences and risk management techniques.		
Practical Training	**Final Assessment**	-	-
	Questions and Answers exercise on a real scenario		
	Syndicate Table Top Exercise with injects for a design of a high risk MV passage - Performance		
Working Experience	At least one passage from the high risk area		
Real World Evaluation	At least 5 days of training during a passage of a high risk area		
Other	***Please specify any other comments***		
	(10 thematic areas * 20 units per area) **Max Training Competence**	**200 units**	

Table 3: Survey Questionnaire for Workshop Participants regarding the Importance of different levels of Training Competence for a Maritime Professional

**Please rate how important is the below competence level of training for a maritime security professional with respect to perform a counter piracy operation mission successfully when onboard a merchant vessel as a crew transiting high risk area.*

0 = Not important

10 = Very important

Training Level	Weight Factor (0-10)	
	Officers	Crew
Theoretical Training		
Simulated Training		
Practical Training		
Working Experience		
Real World Evaluation		
Other (please specify)		

Table 4: *Rating of different training level of a maritime professional and how this enhances in total the overall competence level of an individual in order to perform a counter piracy mission successfully.*

Questionnaires surveyed throughout Stakeholders and Partners Experience and Knowledge

In this section all collected Questionnaires from workshop participants will be listed as a cumulative analysis table (ref below) and analyzed accordingly. There were 14 stakeholders - partners that participated in this research that were coming from different cultural environments. 8 of them were coming from the Operational environment whereas 6 were academic oriented. Therefore the analysis was balanced among experts from operational and academic world giving the desired reality to the below extracted results. Questionnaires are available upon request.

Questionnaires Analysis - Results

During the analysis all answers received from questionnaires plus all received comments (oral or written) from the NMIOTC stakeholders workshop have been accumulated to the below results. The analysis has been divided into different steps as follows:

Firstly all SMEs inputs were tabulated into excel spreadsheets as the one below. As we can see there are three different tables associated with the three main categories that we analyze in our research. These are the Officers on board the merchant vessels, the crews and finally (as was being commented from SMEs during the workshop) the back office people that need to be educated well in order to support real counter piracy operations. On the horizontal axis we have all the inputs from 14 SMEs whereas on the vertical axis we have the levels of training / competence that a person must acquire. There are also three columns at the end, the Total Sum points, the average (points with respect to 10) and final the % percent for each associated training level. The numbers that are listed in EXCEL cells under each SME is the weight factor associated per SME stemming from the respective questionnaire.

Competencies Questionnaires surveyed throughout Stakeholders and Partners Experience and Knowledge

In this section all collected Questionnaires from workshop participants will be listed as a cumulative analysis table (ref below) and analyzed accordingly. There were 14 stakeholders - partners that participated in this research that were coming from different cultural environments. 8 of them were coming from the Operational environment whereas 6 were academic oriented. Therefore the analysis was balanced among experts from operational and academic world giving the desired reality to the below extracted results. Questionnaires are available upon request.

Competencies Questionnaires Analysis - Results

During the analysis all answers received from questionnaires plus all received comments (oral or written) from the NMIOTC stakeholders workshop have been accumulated to the below results. The analysis has been divided into different steps as follows:

Firstly all SMEs inputs were tabulated into excel spreadsheets as the one below. As we can see there are three different tables associated with the three main categories that we analyze in our research. These are the Officers on board the merchant vessels, the crews and finally (as was being commented from SMEs during the workshop) the back office people that need to be educated well in order to support real counter piracy operations. On the horizontal axis we have all the inputs from 14 SMEs whereas on the vertical axis we have the levels of training / competence that a person must acquire. There are also three columns at the end, the Total Sum points, the average (points with respect to 10) and final the % percent for each associated training level. The numbers that are listed in EXCEL cells under each SME is the weight factor associated per SME stemming from the respective questionnaire.

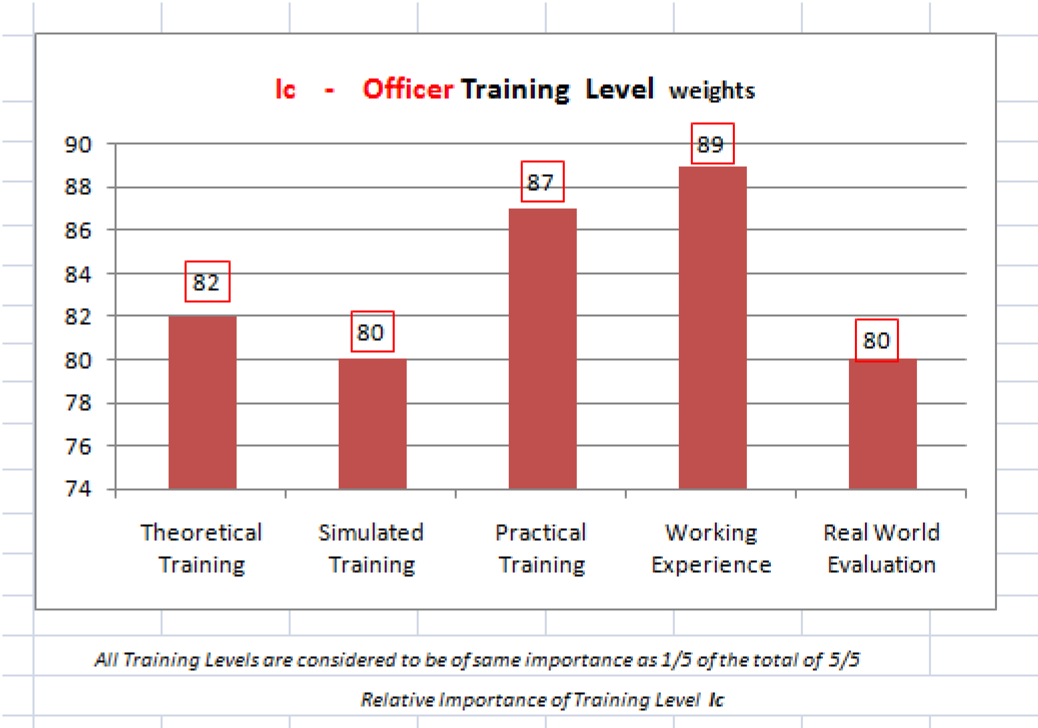
Training Level	Officers (weight Factors per SME)																
	SME 1	SME 2	SME3	SME 4	SME 5	SME 6	SME 7	SME 8	SME 9	SME 10	SME 11	SME 12	SME 13	SME 14	Total Sum	Average per Training Level (lc)	Total Average per Training Level (lc) %
POSITION	CPT	NMIOTC	ACADEMIC	ACADEMIC	CSO	ACADEMIC	SCIENTIST	ACADEMIC	ANALYST	ANALYST SW	NMIOTC	NAVY CPT	NMIOTC	NMIOTC			
OPERATIONAL / ACADEMIC	OPER	OPER	ACADEMIC	ACADEMIC	OPER	ACADEMIC	ACADEMIC	ACADEMIC	OPER	ACADEMIC	OPER	OPER	OPER	OPER			
Theoretical Training	9	8	9	10	5	9	6	9	8	9	10	8	8	8	116	8	82
Simulated Training	9	8	7	8	5	9	6	9	8	8	8	9	9	9	112	8	80
Practical Training	10	10	10	10	5	9	8	10	6	9	8	9	9	9	122	8	87
Working Experience	9	10	10	10	4	9	9	10	9	10	10	9	8	8	125	8	89
Real World Evaluation	9	9	10	10	2	9	8	9	9	10	3	9	8	8	113	8	80
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Training Level	Crew (weight Factors per SME)																
	SME 1	SME 2	SME3	SME 4	SME 5	SME 6	SME 7	SME 8	SME 9	SME 10	SME 11	SME 12	SME 13	SME 14	Total Sum	Average per Training Level (lc)	Total Average per Training Level (lc) %
POSITION	CPT	NMIOTC	ACADEMIC	ACADEMIC	CSO	ACADEMIC	SCIENTIST	ACADEMIC	ANALYST	ANALYST SW	NMIOTC	NAVY CPT	NMIOTC	NMIOTC			
OPERATIONAL / ACADEMIC	OPER	OPER	ACADEMIC	ACADEMIC	OPER	ACADEMIC	ACADEMIC	ACADEMIC	OPER	ACADEMIC	OPER	OPER	OPER	OPER			
Theoretical Training	7	8	5	3	1	8	6	8	6	6	8	6	5	5	82	5	58
Simulated Training	7	8	5	6	3	9	7	8	7	8	5	6	9	9	97	6	69
Practical Training	9	9	5	7	10	9	9	10	7	9	5	7	9	9	114	8	81
Working Experience	9	8	5	7	7	9	9	9	9	9	8	6	8	8	111	7	79
Real World Evaluation	9	8	5	10	2	9	7	9	9	10	2	6	8	8	102	7	72
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Training Level	Back Officer (weight Factors per SME)																
	SME 1	SME 2	SME3	SME 4	SME 5	SME 6	SME 7	SME 8	SME 9	SME 10	SME 11	SME 12	SME 13	SME 14	Total Sum	Average per Training Level (lc)	Total Average per Training Level (lc) %
POSITION	CPT	NMIOTC	ACADEMIC	ACADEMIC	CSO	ACADEMIC	SCIENTIST	ACADEMIC	ANALYST	ANALYST SW	NMIOTC	NAVY CPT	NMIOTC	NMIOTC			
OPERATIONAL / ACADEMIC	OPER	OPER	ACADEMIC	ACADEMIC	OPER	ACADEMIC	ACADEMIC	ACADEMIC	OPER	ACADEMIC	OPER	OPER	OPER	OPER			
Theoretical Training	10	8	6	10	4	9	8	8	8	7	10	10	6	6	110	7	78
Simulated Training	9	8	6	9	4	9	8	8	8	8	8	9	8	8	110	7	78
Practical Training	8	9	7	10	7	8	9	10	6	9	8	9	7	7	114	8	81
Working Experience	9	9	7	10	5	8	10	9	8	9	10	10	7	7	118	8	84
Real World Evaluation	9	8	7	10	2	8	9	9	8	10	1	10	7	7	105	7,5	75
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

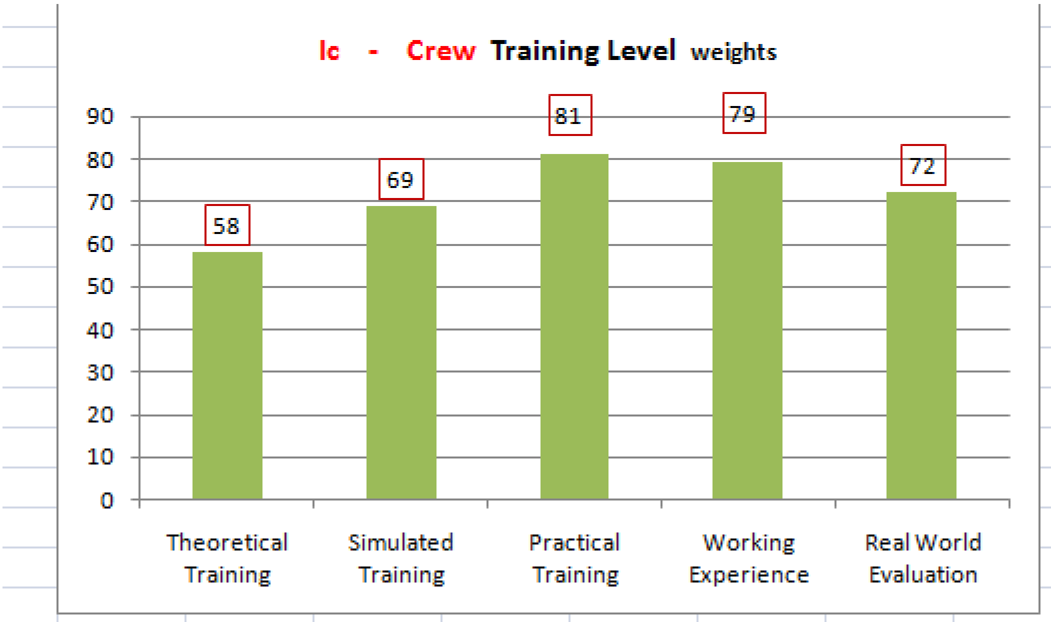
***Table 5:** Tabulated results from SMEs for Officers, Crews and Back Office people.*

Taking into account the above tabulated results we proceeded to analysis and graphs that were being created in association with each of the above tables.



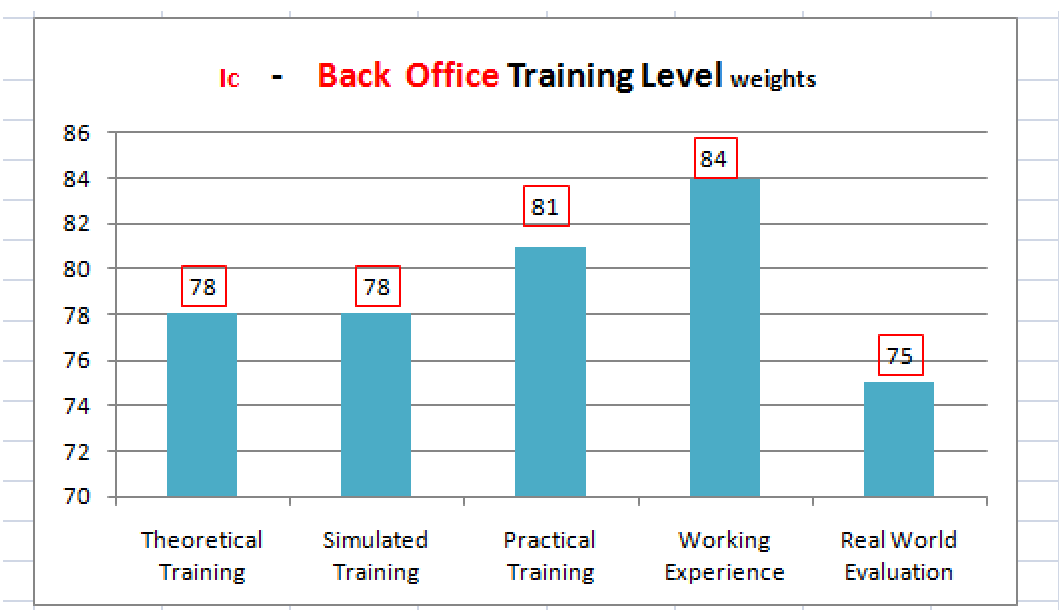
Graph 1: *Officer Training Level percentages - Ic*

On the above graph 1 one can distinguish the different levels for Officers training during the different training levels. The index depicted here is the Ic factor (function 4 above). For example SMEs decided that working experience training and practical training are the most important aspects for Officers training with a collected average of 89 and 87 % respectively. Additionally it is important to mention from the above graph that Officers training is important enough to collect more than 80% overall in any different level. This is not the case in the crew and back office personnel training as we can see in the next graphs.



Graph 2: *Crew Training Level percentages - Ic*

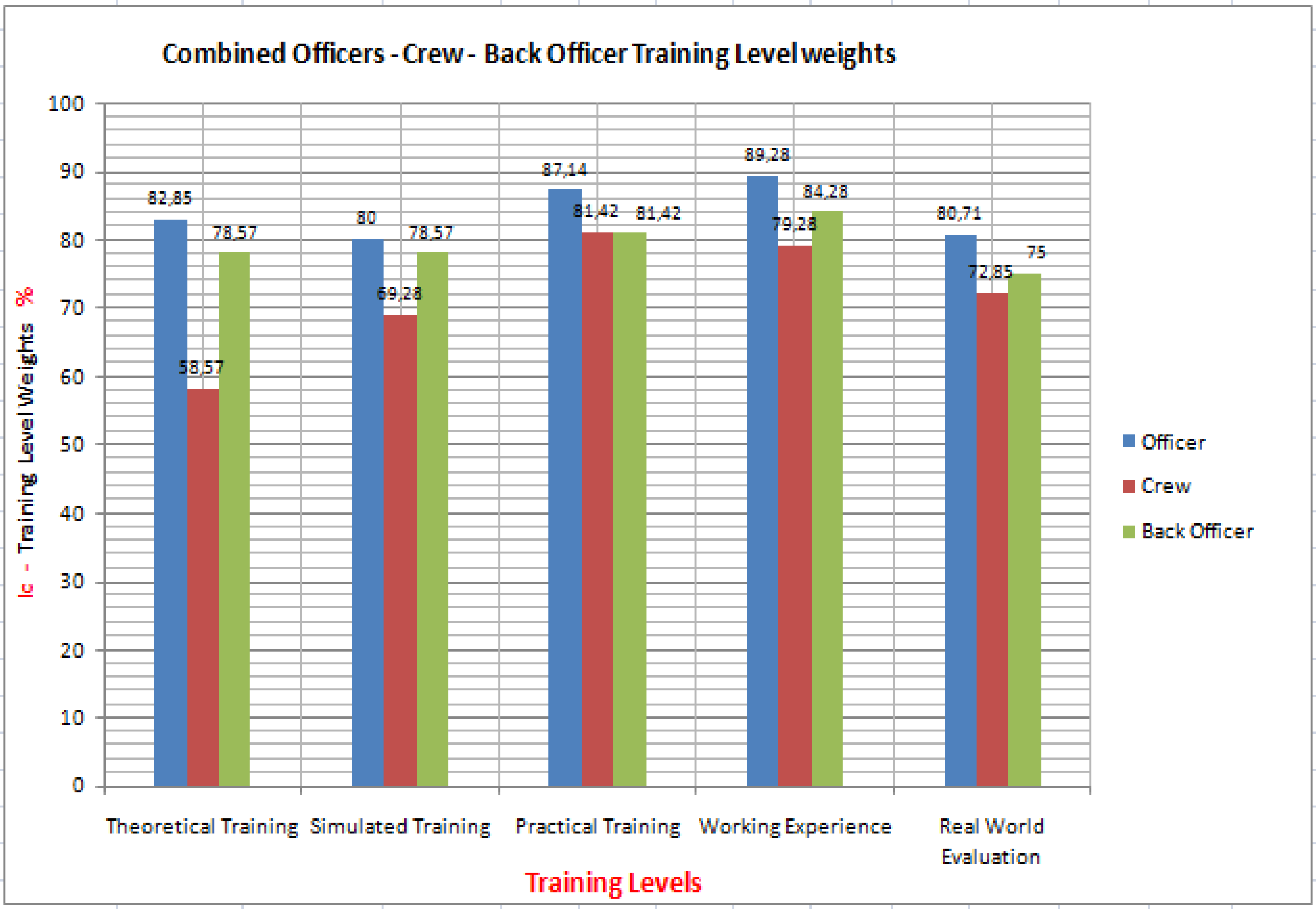
For the crew - graph 2 - the case is not the same. Here SMEs decided that training is not so important as in Officers and Back Office personnel level with averages to almost reach 80%. But it is apparent that practical training and working experience are also the most important aspects of the training environment with theoretical training here to reach only 58% which practically means that crew can receive 30% less theoretical training that the Officers and the operation could still be successful.



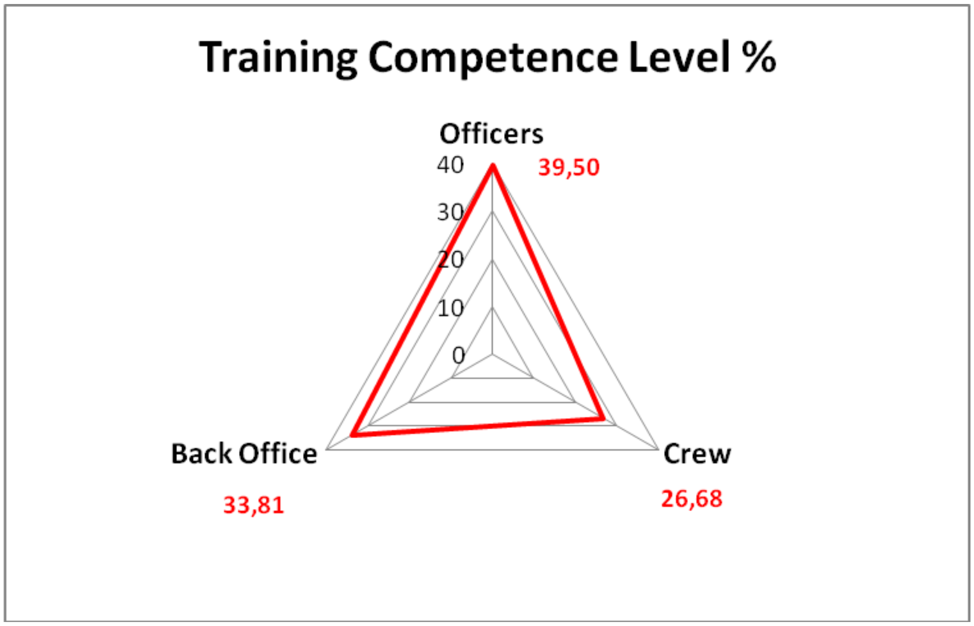
Graph 3: *Back Office Training Level percentages - Ic*

Finally Back Office training / competence is almost at the same levels as for the Officers (graph 3). This is alone is a very important result since we understand that it is more significant for a company / organization that deals with counter piracy operations to train its Officers on board the merchant vessels and its Back Office personnel in order to effectively support the operation. The crew can still perform adequately even if receives 30-50% training less than the others. This practically means decrease of the training costs for the company which is a driving factor in nowadays world.

The above graphs can be combined into a single representation and by that way a cumulative result can be shown on a more effective way as follows.



Graph 4: *Combined Officers - Crew - Back Office training Level weights*



Graph 5: *Overall Competence Training Level (%) Officers - Crew - Back Office*

In the above graphs 4 and 5 we depict in % how much training Officers, Back Office personnel and Crew could receive. For example If we have to train a number of personnel participating in a real counter piracy operation we should train 39.5% of our Officers, 33,81% from our Back office personnel and only 26,68 % of our Crew. This result depict that if we select not to train our crew at all the mission will still be accomplished with well trained personnel from our Officers on board the vessel and of our support officers at the Back office ashore.

Competence Training Index

The desired result from this analysis is of course, as we stated above, to find out an index where we will have an indication on how competent is an individual before participating on a high risk counter piracy mission (ship's voyage etc). By using SMEs inputs for we tried to split a counter piracy mission / operation into different thematic areas and to ask subject matter experts what is their opinion. Is it needed for a specific individual belonging to one of the three distinct above categories (Officers, Crew and Back Office personnel) to have knowledge on the available information and how much of it is needed in knowledge depth and time. The results were indeed very interesting taking into account that all interviewed SMEs are leaders in the counter piracy world environment either from an academic perspective either from an operational / commercial view. Having tabulated all the results we have acquired the below Table 6 where the last columns are the computational tools in order to find out our desired results. It is not the scope to underline in depth all the methodology and mathematics here but we have followed in general the above mentioned (in the above paragraphs) methodology based on weighting criteria.

Competence Level	Training Subcategories	SME 1	SME 2	SME3	SME 4	SME 5	SME 6	SME 7	SME 8	SME 9	SME 10	SME 11	SME 12	SME 13	SME 14	Criterion Average Across SMEs Ai	Competence Level	Competence Level %	Competence Level max	Competence Level out of 18 Subcategories %
	Crew Weight Factors - Wi																			
	JOB	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		Ai*Ic*Wc			
	JOB CATEGORY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
Theoretical Training	**Global Maritime Piracy Overview**	-	-	-	-	-	-	-	-	-	-	-	-	-	-				Ai*Ic*Wc	
	Piracy in Gulf of Aden through Gulf of Oman and Somali Basin	7	6	2	5	0	7	5	8	6	6	8	7	3	3	5	29930	15,27040816	10*140*10*14=196.000	5,303559215
	Piracy in Gulf of Guinea and elsewhere (e.g. STROG)	7	6	2	5	0	7	5	8	6	6	8	7	3	3	5	29930	15,27040816		5,303559215
	Pirates Modus Operandi, Psychology and Business model	5	6	2	7	1	6	3	5	6	6	8	7	3	3	4	22304	11,37959184		3,952241387
	Piracy Risk Assessment Theory	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-
	Piracy Risk Assessment Theory and Methodology (techniques)	6	6	2	2	0	5	1	6	6	9	3	6	5	6	4,5	23247	11,86071429		4,119339828
	Matrix Risk Calculation, General Risk Assessment, SWOT Analysis etc	6	5	2	2	0	5	0	6	6	9	0	6	5	5	4	18696	9,53877551		3,312908222
	Merchant vessel risk calculation (examples)	5	5	2	0	2	5	3	6	5	9	3	6	5	5	4	20008	10,20816327		3,545393009
	Daily Piracy Intelligence Synthesis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-
	Information gathering	5	6	2	3	0	6	10	6	8	6	3	5	3	3	4	21648	11,04489796		3,835998994
	Intelligence collection and analysis to support daily Risk Assessment and Management procedures	5	5	2	3	0	6	1	5	7	9	3	5	3	3	4	18696	9,53877551		3,312908222
	Piracy Risk Management	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-
	Risk Management methodology through check off lists and Standard Operating procedures (Pre passage planning and on board MVs)	5	5	2	1	0	7	3	6	7	10	8	6	5	5	5	28700	14,64285714		5,085604726
	Lessons Learned, Safety precautions and BMP 4 implementation	8	5	2	8	10	8	4	6	8	6	8	7	5	6	6,5	48503	24,74642857		8,594671987
Simulated Training	**Case Studies Analysis**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-
	Piracy Incidents Analysis (region specified)	6	5	2	1	3	8	1	6	6	9	3	6	0	5	4	23668	12,0755102		4,193940511
	Why some M/Vs hijacked and some managed to evade - case base reasoning (analysis of real data)	8	4	2	7	3	9	0	8	6	6	3	6	0	7	4	26772	13,65918367		4,743965496
	Case Study Exercises	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-		-
	Assess the pirate risk on high risk route / voyage.	0	4	2	1	3	8	6	6	7	7	3	7	5	6	4	25220	12,86734694		4,468953003
	Low and High risk MV examples. Differences and risk management	0	4	2	5	2	7	6	6	7	7	3	6	5	6	4	25608	13,06530612		4,537706126
Practical Training	**Final Assessment**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-		-
	Questions and Answers exercise on a real scenario	8	6	7	4	4	9	1	10	6	8	1	8	5	6	5	47310	24,1377551		8,383273854
	Syndicate Table Top Exercise with injects for a design of a high risk MV passage - Performance	9	5	5	3	4	9	3	8	5	8	1	8	5	5	5	31980	16,31632653		5,666816695
Working Experience	At least one passage from the high risk area	9	6	9	4	1	9	5	10	7	10	6	10	9	9	7	80808	41,22857143		14,31907828
Real World Evaluation	At least 5 days of training during a passage of a high risk area	9	9	0	1	0	9	6	10	8	10	1	0	9	9	5	41310	21,07653061		7,320081228
Other	Please specify any other comments	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		-
	Total Competence Units Sum per SME	108	98	49	62	33	130	63	126	117	141	73	113	78	95	-				
	Total Competence Units Sum per SME %	54	49	24,5	31	16,5	65	31,5	63	58,5	70,5	36,5	56,5	39	47,5	45	564338			100
	Average Competence Level from all SMEs	45	91																	
	Max Training Competence Units	200																		

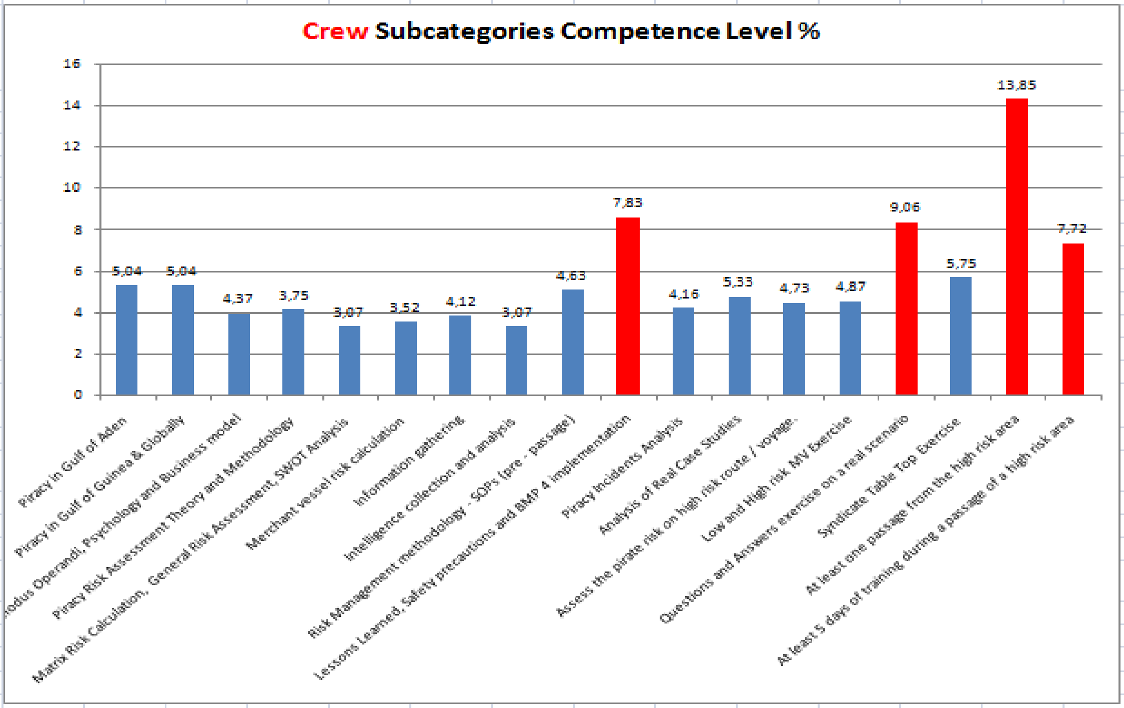
__Table 6:__ SMEs Tabulated results for Crew importance (weighting) on Counter Piracy Training Thematic areas.

On below graph 6 we have quantify the need for an individual belonging on the crew to have knowledge on specific thematic areas relevant to counter piracy. As one can see areas like Lessons Learned, BMP implementation procedures, QA sessions relevant to real case study scenarios and at least one real voyage passage from the area of operations is acquiring the most attention of the SMEs. In other words the most important thing is for a crew member of a vessel to have a onetime experience from the area and to have studied previous lessons learned and BMP implementation methods. All other theoretical areas are considered to be under an average level of knowledge. In this graph if one can add all the thematic areas the total percent is 100%. So for a person to be capable from a crew one need only to have acquired knowledge from the red column thematic areas plus some other selective areas in order to reach the 26.68% that the research computed on the above paragraphs graph. Having these metrics we can now infer on how competent is a crew member of a vessel for performing and contributing to a counter piracy mission effectively.

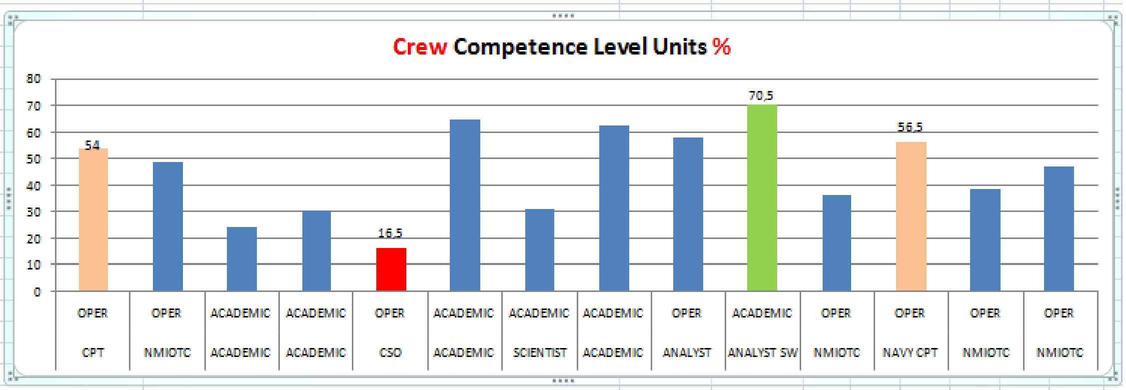
To be more specific and give a real example let's consider that we have an individual and we want to measure its effectiveness prior to board a vessel and participate in a counter piracy mission. In the below graph we see all the thematic areas that a person should know theoretically in order to have a training competence 100%. The red columns, as we mentioned also above, are those that the SMEs pinpointed as the most important thematic fields and gave the fact that without the knowledge of these thematic areas one should not participate in a counter piracy mission. These areas are:

- Lessons Learned - Safety precautions and BMP implementation
- Exercise in a real scenario
- One passage from the counter piracy area
- Five days of training during a passage of a high risk area

The above fields have in the total competence of a trainee 7,83 - 9,06 - 13,85 - 7,72 percent respectively with the most important to be the "At least one passage from the high risk area". All the above thematic areas have a total sub-percentage of 38,46% of the total training competence that one must have. One member of the crew though to be considered as counter piracy competent must collect a total of 45,56% and that directly means that except the red column training thematic areas must at least take two other thematic areas (from the blue columns with the associated percents) in order to meet the least requirement of 45,56% and be considered competent, in accordance with SMEs opinion.

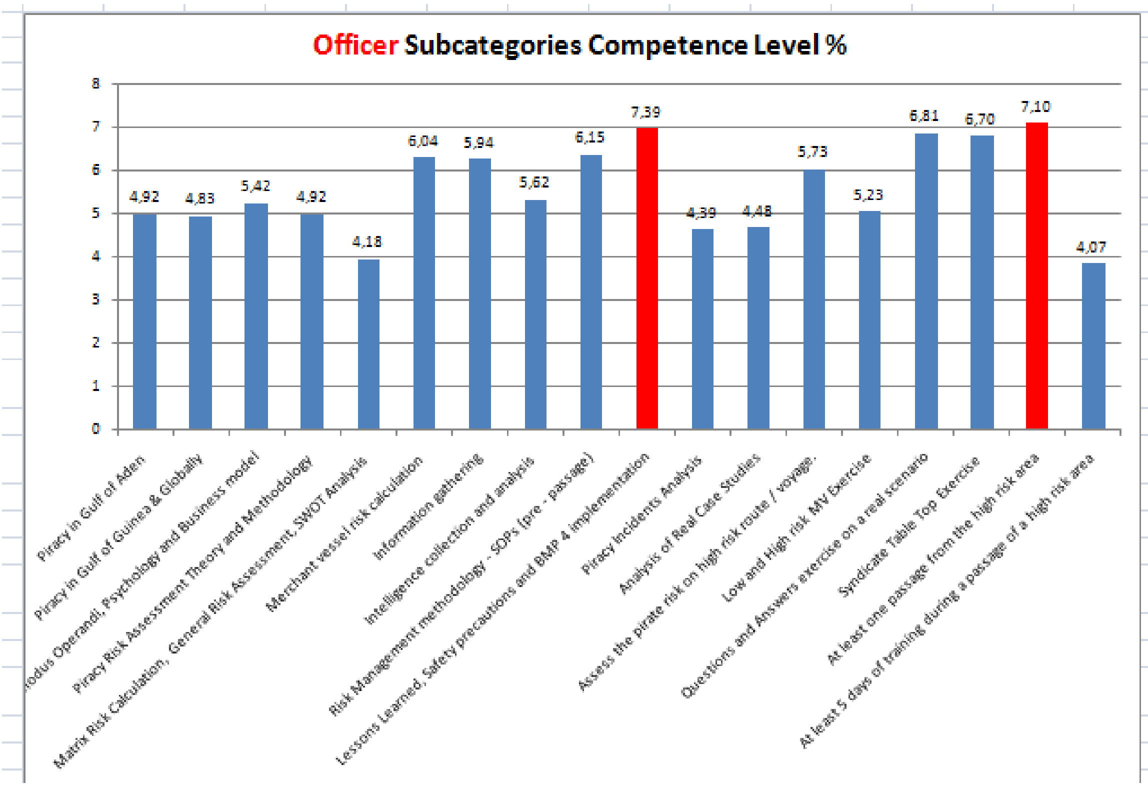


Graph 6: *Crew Subcategories Competence Level (%) in accordance with training thematic field*



Graph 7: *Crew Competence Level Units % based on SMEs opinions*

On the above graph 7 we tried, following the interview on the SMEs, to tabulate the results relevant to how many competence level units % SMEs proposed during the research. We clearly see that Operational users (Captains on merchant vessels coming from companies that are dealing with the counter piracy missions) give the maximum percentages on the training of their crews as well as academic (NMIOTC) personnel who give a percentage of 70,5% necessity for the crews to be trained. If we go though to operational users ashore (red column) we see that there is no direct necessity for the crew to be trained for a counter piracy mission (only a 16,5% is given) taking into account that all the operational work is being performed from the Officers on board the vessel and the back office support ashore. This in fact is a reality in the counter piracy operational world and this fact appears here in the SME research we performed.

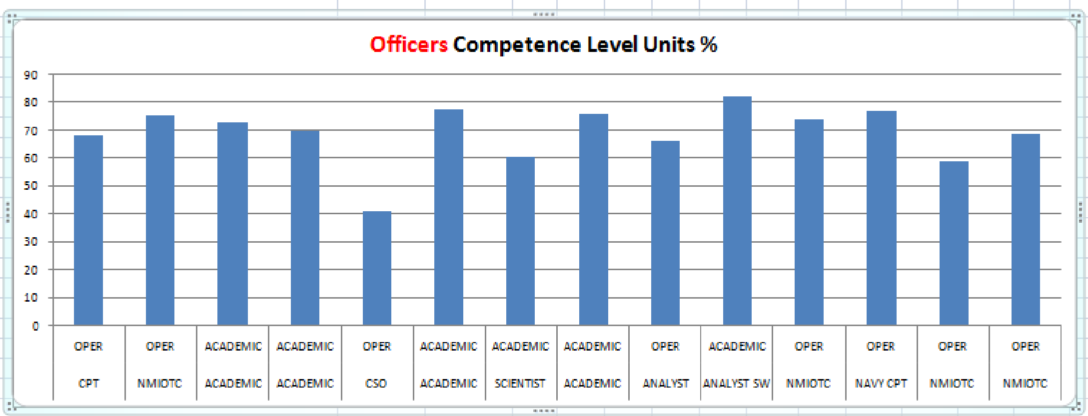


Graph 8: *Crew Subcategories Competence Level (%) in accordance with training thematic field*

Following the same logic as the above analysis for crew members the research gave important results for the Officers indicating that the most important thematic areas for an officer (red column training fields on graph 8) are again Lessons Learned - Safety precautions and BMP implementation (importance of 7,39%) as well as at least one passage from the high risk area (importance of 7,1%). All the other thematic areas though are also important and near to 6% of the training competence having only a 1% statistical distance from the red column thematic areas. This directly means that for an officer all theoretical / simulation and practical training is important for his competence taking into account that he is the decision maker during the real operation.

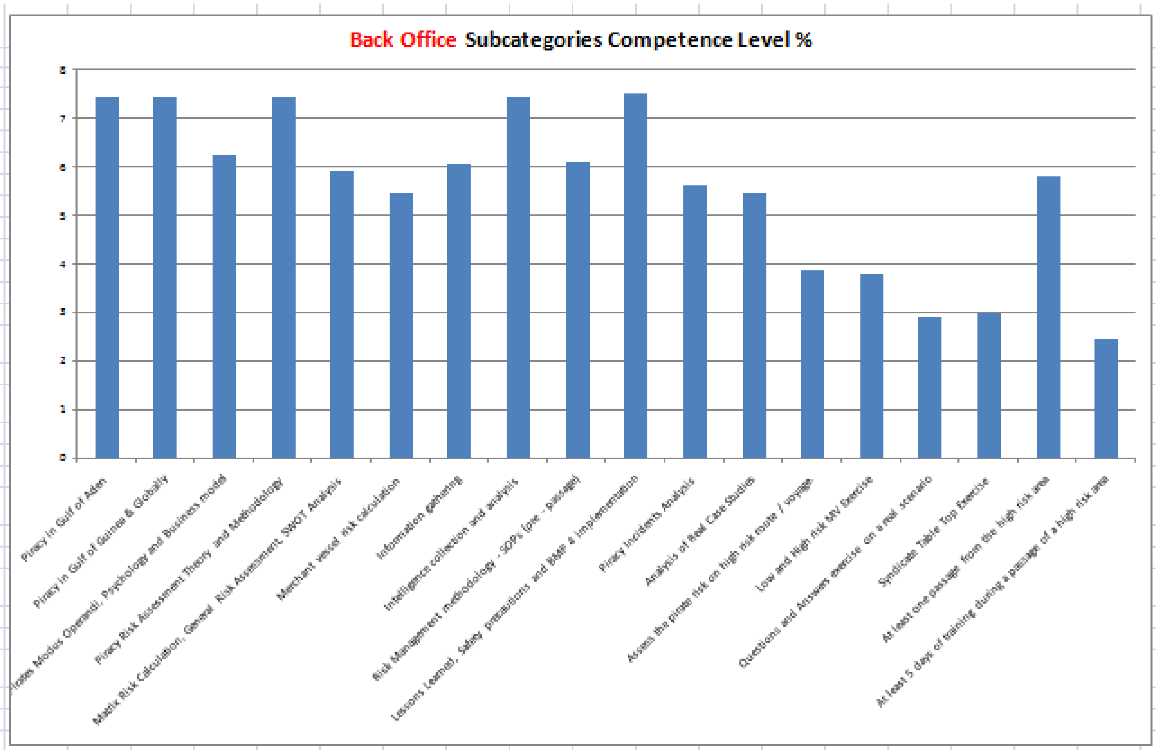
Combining that result with the overall competence level (graph 12) that for an officer should be 69,28% we understand that an individual of this category should be trained in a lot of thematic areas in order (accumulating all the percentages) to have a total of training competence level of 69,28%. This of course give the obvious result that an officer should be trained in most of the above determined thematic areas in order to understand the whole background of the mission and be able to take the correct decision when the situation arise.

Respectively with the crew analysis we performed above on the SMEs opinion here the results are a little bit different as we see in graph 9. Most of the SMEs believe that Officers competence should be very high with that percent to reach more than 70% in most of the cases, whereas the operational users (navy captains and shipping companies SMEs) give the least percentage of all but still is 40% of competence level. Comparing with 16% that they gave to crews competence we understand that also for their world is very important to have trained and competent officers to act accordingly and take logic and safe decisions when asked to act so.



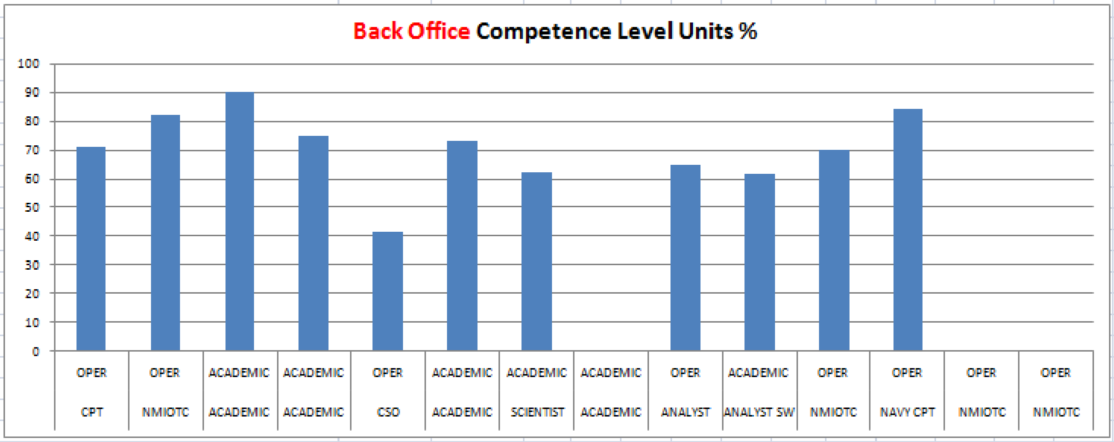
Graph 9: *Officers Competence Level Units % based on SMEs opinions*

Finally, the research ends with Back Office personnel, those who stand behind the scenes on a shipping company and their daily work is to support the merchant vessel in any possible way. Here the results are a bit different. As we all understand and know most of these people are civilians that in most cases may not have been on board a merchant vessel ever in their lives. However are scientific personnel who act in support of a merchant vessel mission and they have consolidated knowledge in many areas that an onboard crew member does not. These people have a lack of knowledge of basic things regarding high risk areas / missions and the real operational world. For this main reason and as we clearly see in the below graph 10 they must be acquainted with basic knowledge of what is piracy, piracy in regions of the world, lessons learned, intelligence from high risk areas and at least they must participate in one passage from a high risk area.



Graph 10: *Back Office Subcategories Competence Level (%) based on training thematic fields*

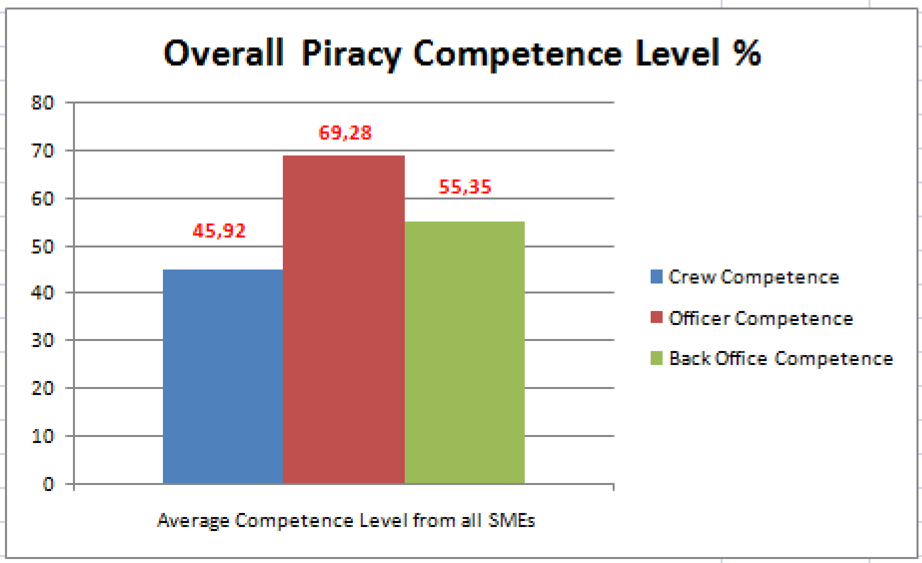
Similarly, graph 11 depicts back office competence level units (%) based on SMEs opinions as we explained above with again Operational users (captains and shipping companies) to express their importance on the necessity for those people to acquire the basic knowledge on a high risk - counter piracy mission. Academic users here cannot express their opinions since a back office personnel is only relevant to shipping companies and merchant vessel acquainted personnel.



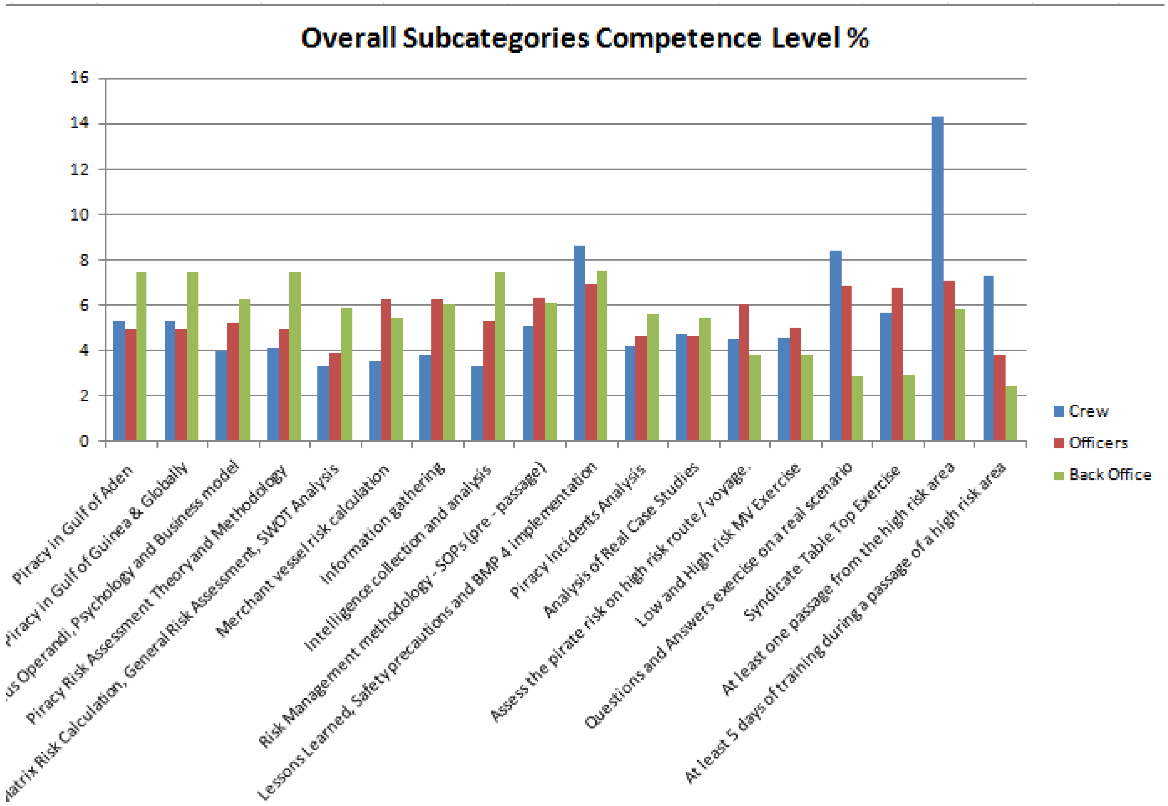
Graph 11: *Back Office Competence Level Units % based on SMEs opinions*

Graph 12 is the digest - epitome of all the above performed research analysis since it directly show to us competence level percentage comparison for Officers, Crew and Back office personnel. From this graph SMEs defined that Officers should acquire no less than percentage of 69,28 % when being trained in counter piracy thematic areas whereas this percentage is 55,35 for Back Office personnel and 45,92 for the crew of the vessel.

Therefore it is more important and necessary to train Officers and Back Office personnel and be safe that your mission will be successful when dealing with counter piracy. On graph 13 all these different subcategories of training thematic areas we analyzed above and that give the overall competence have been depicted on a comparison graph for Officers, Back Office personnel and crews and one can infer the importance in any different sub - training thematic field that his/her personnel must acquire.

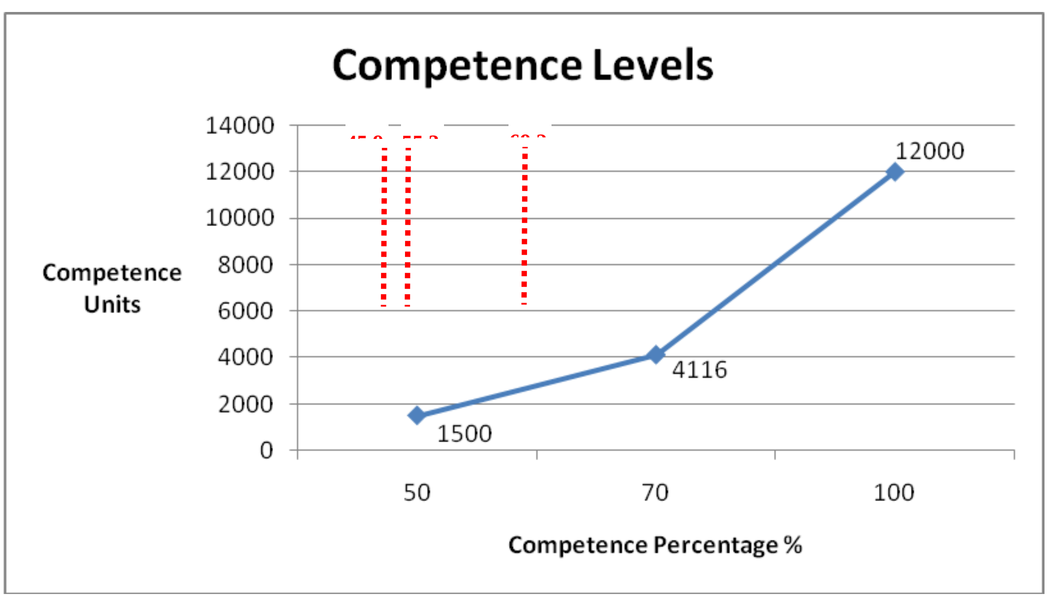


Graph 12: *Overall Piracy Training Competence Level (%)*



Graph 13: *Overall Subcategories Competence Level (%) for Officers, Back Office personnel and Crews.*

Having completed the research analysis from the received SMEs opinions we know return to our theoretical calculation of the training competence level of an individual as explained in para. 3.2 of this study (quantitative competencies analysis). We tried to find a way of resembling the real training environment - competence level with the use of a simple mathematical model since it is the first time that this approach is performed for a counter piracy operation. Based on the model that we used Competence (C) is a function given by the multiplication of Knowledge, Understanding and Processing. Therefore and in order for an individual to complete a specific percentage in the above mentioned thematic areas (as we have shown in the above analysis with graphs) we have assigned, based on the weights that the SMEs provided, metric units and calculated through functions 1 to 5 the competence level units in order to give a specific quantifiable metric for an individual competence level. These metrics (in thousand competence level units) have been calculated and produced graph 14 which is the quantification epitome of our research. On the graph we have depicted an example with competence level units for three different individuals (Crew, Back Officer and Officer) where they must specific units in order to be able to be considered competent for a counter piracy mission. The crew member has accumulated 1500 units which is a little more from the 45,92% that the research gave us as a limitation percentage. The Back officer respectively has 4116 units a lot more than the 55,35 % that he should acquire in order to be considered competent and finally the Officer has acquired 12000 units which is way more than 69,28% that he should have in order to be considered confident.



Graph 14: *Competence Level Units (Quantification approach) for a Crew, Back Office and Officer (example case)*

To move one step further we should note that 1500 units for a crew member is respective to have participated in 5 of the most important thematic areas and get a 50% total training competence. 4116 units is for a Back Officer to have acquired 7 of the most important courses - thematic areas and 12000 is for an officer to have acquired 10 of the most important thematic areas. With this simple quantification process we now have a metric on how a person is competent enough to participate in a counter piracy mission / operation / trip / voyage or not.

Conclusions

Having performed the above analysis we deduce the following important conclusions that are useful for the design and execution of a counter piracy mission / operation when a merchant vessel is to go through / transit high risk area:

- Officers are the individuals that must be trained the most when we have to participate in a piracy operation.
- Back Office personnel is the next team that a shipping company focus on its training efforts since those people need to support effectively and in most cases to understand thoroughly the situation in the ocean since they are the decision makers ashore.
- Crew needs to be competent on a relevant percentage of around 50% of the thematic areas.
- SMEs believe that training is important not only in Officers and Crew members of the vessel but also for Back Office personnel where in most cases they are not individuals coming from the shipping world but from science oriented environments.
- Quantification of training competence has been performed and we now have a metric system on measuring the level of competence of a person dealing with a piracy - high risk area situations.
- Multi Criteria Decision Analysis and weightings from SMEs interview give us similar results and a safe method of measuring the competence of an individual.
- The above method gives results based on worst case scenario which is the passage of the vessel with low freeboard, with low visibility and low speed from a high risk area.

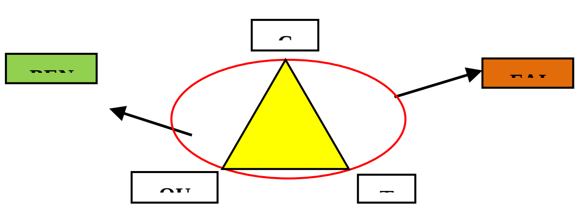
Finally and to sum up this research and analysis study it is worth to mention that a quantification method in place gave logical and important results for those that deal with counter piracy missions daily. It is also important that the above methodology can be performed in any high risk mission taking into account that training thematic areas will be defined from the user first in order for the methodology to quantify a person's competence level to participate in a high risk - maritime security mission such as counter weapons of mass destruction, counter narcotics, counter illicit trafficking, maritime theft etc.

Recommendations

The next step is to inform through this study Benefits Realization Task 3.6 where it will be created a roadmap for end users and other key stakeholders which will sequence the steps required in order to deliver maximum benefit from the use of the counter-measure manual, Counter Measures Decision and Voyage Planning Tool as part of a holistic approach including training, planning and procedures. SAMI organization is leader in this work through the end of the project (Month 19).

Benefits Realization

Schematic below indicates how benefits realization tasking is seen based on one and single perspective in our world today. Definitions for benefits realization vary across academia and commercial oriented organizations but the end result is that a common word rules out the whole concept and idea behind it. Benefits realization is the positive outcome of change that occurs based on cost, quality and time as the below graph simply indicates. The below mentioned three dimensional diagonal parameters are a daily phenomenon in our business lives but when the three come together it is generally difficult to quantify them as a function of one to the other and at that point project managers or businessmen have to decide which peak of the triangle has to be enhanced. However the time where the three peaks of the triangle maintain their equilateral principles then we directly know that a balance occur and at that specific moment the result is efficient and effective towards all directions.



In this procedure under the word benefit for an organization is correct to reckon in all actions, behaviors, products, services or any other action that provide utility to the organization as well as to all those bearers stemming from these actions. To be more specific and having already mentioned the word benefit we need to further analyze this concept by explaining in depth what is a benefit and at the end that a quantification procedure is a measurable improvement resulting from an outcome perceived as an advantage by one or more stakeholders. In this procedure though we must not forget the disadvantages that may occur or the negative outcomes that are usually called disbenefits. In these disbenefits another important word arise - the word risk - in which negative consequences of specific activities influence our organizational cohesion and finally drive us to an unsuccessful or failure event.

PROMERC follows the above mentioned procedure and under this simple but very critical notion for today's maritime security businesses taking into account three basic principles:

a. Improved customer services

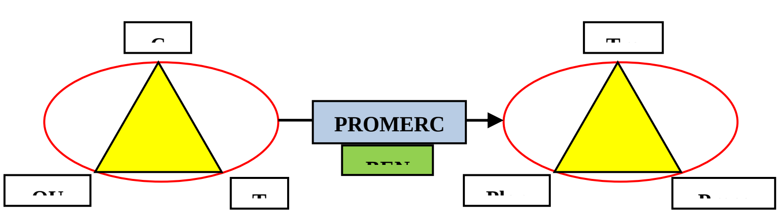
b. Reduced Cost and

c. Increased Productivity

Regarding improved customer services and having analyzed all different parameters that exist in counter piracy world today we collected a set of countermeasures that at the end when inserted into software was an excellent added value taking into account that served as decision making parameters to those utilizing the counter piracy decision making tool and the manual. With this approach customer (in this case the maritime or maritime security companies) can now design and calculate their actions in accordance with specific measured factors that are not theoretical but real and measurable. Having followed this procedure the consortium managed to create a reduced cost decision making procedure or at least and as the results shown the customer can alone calculate costs and decides on how to minimize risk during the trip. Finally, productivity has been increased dramatically because we now utilize one person to only import parameters in the software tool and create decisions that in other cases were very difficult and time consuming to occur. Practically the approach followed by PROMERC is now a world leading tool that will enhance all three parameters of benefits realization procedure, time, cost and quality. To the best of consortium's knowledge failure events have not been reported taking into account that the decision aiding tool promote service only to positive directions.

Benefits stemming from PROMERC are tangible (cost savings, time calculation for a trip etc) and at the same time intangible effects have been minimized to absolute zero. This means that if one uses the decision support tools that consortium created then only measurable and positive effects arise for their decision process. There are no theoretical or conceptual decisions that someone would not know on how to incorporate to its design daily procedure, especially when we are talking for companies that have operational departments which deal with counter piracy operations in order to safeguard and minimize risk for their vessels. Not to mention that there are already reports and results from assorted organizations and subject matter experts that used PROMERC tools that have already realized that these tools support capability creation and delivery functionality by ensuring success to their operational divisions.

PROMERC managed through analysis and collection of reporting to alter the above mentioned fundamental concept of benefits realization into an approach where cost, quality and time parameters are being implemented to counter piracy concept and enhance positively training, planning and procedures so as the final result to be a success and not failure for the specific mission. Below graph shows in a simple but aggregated format links among the above mentioned notions.



One specific area / example that PROMERC incorporated the benefits realization procedure is the in depth analysis concerning Training Competencies for all personnel affiliated with counter piracy operations. In this analysis (journal papers was presented to TRANSNAV 2015) members of the consortium created metrics for personnel trying to visualize what is the most applicable knowledge level that one must acquire in order to participate in a counter piracy mission or in the decision making chain (back office personnel, mariners or management). The metrics that have been created based on SMEs interviews serve as perfect benefits realization example on how a company must decide for the engagement of its personnel to a counter piracy mission minimizing the assertive risk to acceptable low levels. This example is shown and analyzed explicitly on the following pages.

Risk in Interlinked Networks

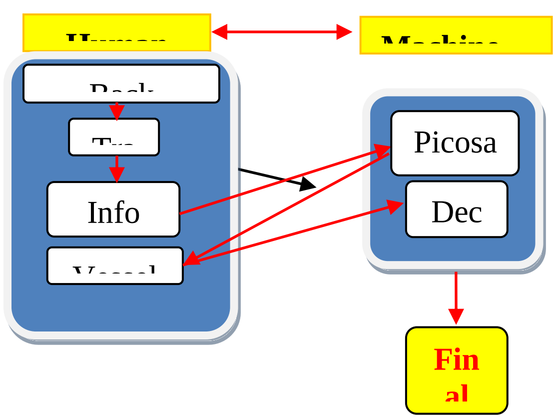
Having said and explained thoroughly the above analysis there is one more area that is worth mentioning and analyzed in a qualitative manner. The quantitative analysis of this specific topic is a matter of a follow on postdoctoral research that is not part of this work. However concept analysis and theoretical foundation of the work is going to be set up here.

In order to support the full hierarchy levels of a counter piracy or generally counter terror operation we need to finally through the Picosatellite send the information to the vessel afloat. This is a procedure that has been already done, through design and experimentation and is in depth analyzed in the previous chapters through the use of Picosatellite Lambdasat, the Funcube and the Tubesat. The question though that arises now is how much effectiveness (in a quantitative manner) has the acquisition of alert data from the mariners when they are in the middle of the ocean. For example let’s suppose that a vessel is away from any shore, in the middle of an ocean and only a small Picosatellite can send accurate alert/emergency data that terror or pirate events have happened in a distance from it towards its route (e.g. 150 miles in front of his route and towards to it). When the master mariner or officer of watch receives this information finally he knows that there is an incident in front of his vessel. This critical piece of information directly alters the courses of action for the next hours as such altering the course, imposing more defensive countermeasures or conducting other actions that will finally safeguard the trip, the vessel and the cargo and avoid being trapped into a counter piracy unhappy event. It is inevitable and self logical that if the alert data reaches the ship in the middle of nowhere and this is happening three times at least per day then Risk is being minimized. The question arises here is how much is the risk minimizes - a quantifiable metric is needed to be measured in an effective way. This amount of data strengthens in a way the psychological factor of each person and that affects positively the whole mission result as well as is the manner to drive the solutions in the correct path. Of course here one can argue that the major parameter that may alter the decision making procedure from a positive to a negative impact is the time interval between the minute the mariner received the data until the minute that is going to reach the incident area. If this time is ample enough for crew personnel to take calm decisions then the data have positive effect otherwise the data, in accordance with each personality may even have more negative effect from those that one may had if an incident was happening without any further notice. That is why though the competencies analysis above took place in order to minimize this type of risk and guide effectively human resources managers to disqualify crew, back office personnel or maintenance staff to be engaged with counter piracy operations without any prior training and knowledge on the field. That is why the above described situation is called Risk in an Interlinked network and it has parameters that may be quantified in a future research effort.

However a qualitative research is needed to be performed in a conceptual level so as to understand how risks can be managed in interlinked networks so as a minimum acceptable level of risk is being maintained. In these networks humans and machines are being interacted in a dynamic way such as machine reasoning is interrelated with human performance creating an environment of vulnerabilities and insecurities. There must be a developed ontology where knowledge, training and machine behavior may interact in a way that risk assessment management procedures will lead to a successful result for the execution of an operation or mission.

Regularly the complexity and criticality of existing human and machine parameters creates a super vulnerable environment to tackle with. Nonetheless a well defined risk management methodology ensure sufficiently that humans and machines create interlink networks that overcome risks and provide effective and efficient results for the mission.

To start with the recording of the procedure we must set the operational environment first. A ship is sailing in the middle of an ocean, with only a few windows of ability to communicate with ashore stations through Picosatellites that arriving in the area of operation for only three to four times per day. The Picosatellite similar to Lambdasat or Tubesat can send information to the master of the vessel indicating an area of risk, an incident of risk and any other critical information that can be conveyed in a 7 minute timeframe each time the satellite cross over above the area where the ship is sailing. By the time that the vessel receives the information decision making procedure starts on how the vessel will react to the received info by conducting actions so as to minimize the terror risk during its trip. Therefore the various stakeholders in this case are: The crew of the vessel, the back office personnel who sends the information, the manner (different syntax has different psychological impact) in which the information is being processed and released to the people on board the vessel and the Picosatellite measure of performance (two, three or four times of passes on each day make a huge difference on the amount of data released to the ship and alter positively the decision making approaches). This approach appears in the following schema.



In this representation it is obvious that human and machine made parameters is needed to be synchronized in a matter where a final Human decision is being made so as to minimize the risk and produce the successful result which in this case is to deliver the ship (crew and cargo) safely in the next port of call. In our research above we have quantify Back Office personnel capability and competence, training competence of crew, back office and maintenance personnel as well as Picosatellite capability. Info Syntax Modus parameter has not been quantified and is out of the scope of this research. However, in order to measure effectively the interlink risk factor we also need to calculate connection among info syntax modus (psychological factor) how affects the whole risk minimization procedure. When this is performed then a Final Human Decision metric can be produced knowing exactly how a Picosatellite presence is minimizing the risk when flying over a vessel sailing without any other information in the middle of a vast oceanic area. This procedure is an intelligent real time reasoning risk management tool and it has to use aggregation or detection complex event processing techniques in order to reach a safe and logical result.

References - Competencies selected bibliography:

1. STCW 2010/03 Aug 2010, Manila Amendment
2. Non Lethal Weapons Effectiveness Assessment Development and Verification Study, Final Report of Task Group SAS-060, CMRE Technical Report, October 2009
3. Technology Achievements in Maritime Educational Procedures: Behavioral Assessment Framework, Vasilakis Panagiotis, Prof. Nikitas Nikitakos, University of the Aegean, Dept. Shipping Trade and Transport.
4. Malone 1990. "Theories of learning: A historical approach" . Bel-mont, CA: Wadsworth.
5. Jeffrey D. Doyle, and Eric M. Webber,and Ravi S. Sidhu,2007 "A universal global rating scale for the evaluation of technical skills in the operating room." The American Journal of Surgery : 551–555.
6. IMO, 2000 "Sub-Committee on Standards of Training and Watchkeeping. Validation of model training courses." Vol. 32nd session. London.

7. Marzano and Robert J. 1989"A Theory-Based Meta-Analysis of Instructions, USA Colorado: Mid-continent Regional Educational Laboratory.

8. IMO STCW/ISCG 2/5/3, Training of Personnel operating in ice - covered waters, Norway, 27 July 2009

9. STW 43/3/3, IMO Subcommittee on standards of training and watchkeeping, 43rd session, Agenda item 3, Validation of model training courses for Ship Security Officers, 4 August 2011

10. STW 43/3/2, IMO Subcommittee on standards of training and watchkeeping, Model courses – Security awareness training for seafarers with designated security duties and Security awareness training for all seafarers, 25 July 2011

11. STW 37/10/1, IMO Subcommittee on standards of training and watchkeeping, Development of Competencies for Ratings, 18 October 2005

12. IMO Model Course for Maritime English Professionals

13. Competencies for Maritime Security Guards (Baseline Requirements), Australian Government

14. Maritime Transport Education and Competence, Development in a Maritime EU, FP7, Press Transport Consortium, Cybion Srl et.al, Maritime Development Center Europe, www.press4transport.eu

15. SEC-2013.2.4-2-Protection for Merchant Ships, EU FP7 Funded project

16. An Intelligent Fault Monitoring and Risk Management Tool for Complex Critical Infrastructures: The SERSCIS Approach in Air Traffic Surface Control, Dr. Kostopoulos, G. Leventakis, V. Tsoulkas, N. Nikitakos, Journal of UKsim

Appendix 8: Additional References Reviewed

The below references have been thoroughly studied and reviewed prior to research start in order for the author to fully understand the framework of dissertation. They are compiled of maritime security, space in maritime interdiction operations as well as general references that reviewed in order to set up a complete and robust idea / view of the research limitatations and/or requirements.

1. A. Bordetsky and D. Netzer, “Testbed for tactical networking and collaboration”, International C2 Journal, 3(4), 2010

2. A. Bordetsky and A. Dougan, “Networking and Collaboration on Maritime-sourced Nuclear Threats”, Online Proceedings of Sixth Security Workshop, Washington, D.C., 2008

3. A. Bordetsky, G. Mantzouris, “Picosatellites in Maritime Interdiction Operations”, 15th ICCRTS Conference, Santa Monica, LA, CA, 22-24 June 2010, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA525245

4. www.interobital.com

5. Satellite Analysis Toolkit, www.stk.com

6. Jerry Jon Seller, “Understanding Space, An introduction to Astronautics”, Second Edition, Mc Graw Hill, 2004

7. Wiley J. Larson and James R. Wertz, “Space Mission Analysis and Design”, Third Edition, Space Technology Library, 2005

8. http://www.nasa.gov/mission_pages/station/research/experiments/PSSC.html#applications

9. http://caneus.org/2006/pilotproject3/index.html

10. http://www.dlr.de/iaa.symp/Portaldata/49/Resources/dokumente/archiv5/1401_Kayal.pdf

11. http://www.amsat.org/amsat-new/satellites/satInfo.php?satID=83&retURL=satellites/futures.php

12. Phillip Anderson, “Development of a Cubesat Pico Satellite”, Undergraduate Researcher Mechanical and Aerospace Engineering and Jan Sojka, Faculty Mentor, Department of Physics UTAH University

13. Jonas Sølvhøj, “Onboard Computer for Picosatellite”, Technical University of Denmark, Oersted, 2002

14. Marco Schmidt, “Pico satellite activities of the University of Wuerzburg”, Dipl - Inform, www.informatik.uni-wuerzburg.de

15. http://indianspacestation.com/student-initiative/102-studsat.html and http://www.teamstudsat.com/about.html

16. Nanosatellite Tracking Ships: Responsive, Seven-Month Nanosatellite Construction for a Rapid On-Orbit Automatic Identification System Experiment, Freddy M. Pranajaya and Robert E. Zee, Space Flight Laboratory, University of Toronto, Institute for Aerospace Studies, 7th Responsive Space Conference April 27–30, 2009 Los Angeles.

17. http://www.utias-sfl.net/nanosatellites/AISSat-1/

18. Optimal Microsatellite Cluster Design for Space-Based Tracking Missions, J. Daniel Griffiths and Leena Singhy, The Charles Stark Draper Laboratory, Cambridge, Massachusetts Institute of Technology, Cambridge,

19. http://www.nasa.gov/mission_pages/tacsat-2/main/ <accessed on 06/1/2013>

20. P. Rothwell, C. Lynam, The plasmapause, the plasmasheet and energetic trapped electrons in the earth's magnetosphere, Planet Space Science, 1969, Vol. 17, pp. 447-454, Pergamon Press.

21. www.maritimerisk.gr

22. http://www.interorbital.com/TubeSat_1.htm

23. Bordetsky, G. Mantzouris, Picosatellites in Maritime Interdiction Operations, 15th ICCRTS, Santa Monica, LA, CA, 22-24 June 2010, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA525245

24. Military Micorsatellites: Matching requirements and technology, Matt Bille (AIAA Senior Member), AIAA-2000-5186 space 2000 conference and exposition, Long Beach, CA.

25. Low Cost Microsatellites: Innovative approaches to breaking the cost paradigm, Ruth L Moser and Michael J. Stallard, AIAA-2000-5195.

26. Radar satellites and maritime domain awareness, J.K.E. Tunalay, London Research and development Corporation, Ottawa, Ontario.

27. http://www.utias-sfl.net/nanosatellites/CanX6/

28. Optimal Microsatellite Cluster Design for Space-Based Tracking Missions, J. Daniel Griffiths and Leena Singhy, The Charles Stark Draper Laboratory, Cambridge, Massachusetts Institute of Technology, Cambridge,

29. http://www.nasa.gov/mission_pages/tacsat-2/main/

30. The Analysis of Network Centric Maritime Interdiction Operations (MIO) Using Queuing Theory, Mark G. Hazen, TTCP MAR Action Group 1, Presented to 8th ICCRTS, June 2003, Defense Research and Development Canada.

31. Responsive Space for the Canadian Forces (AIAA-RS-5-2007-3004) Captain Donald Bédard & Major Aaron Spaans AIAA 5th Responsive Space Conference 2007 Los Angeles, CA.

32. Bjorn T. Narheim, Oystein Olsen, Oystein Helleren, Richard Olsen, Alexander M Beattie, Robert E. Zee, "A Norwegian Satellite for Space-based Observations of AIS in the High North," Proceedings of the 22nd Annual AIAA/USU Conference on Small Satellites, Logan, UT, USA, Aug. 11-14, 2008.

33. Torkild Eriksen, Gudrun Høye, Bjørn Narheim, Bente Jensløkken Meland, "Maritime traffic monitoring using a space-based AIS receiver," Acta Astronautica, Vol. 58, Issue 10, May 2006, pp. 537-549.

34. Satellite AIS from USCG, Article in Digital Ship Magazine, April 2007, pg 27.

35. From big GEO's to Small Satellites: A step forward in User Friendly Satellite Services, Fulvio Ananasso, AIAA 94-1056-CP

36. Commercial Applications for Microsatellites, AIAA-2001-4743, AIAA Space 2001 Conference and Exposition, Albuquerque, NM, 28-31 August 2001.

37. Advanced small satellite bus concepts, AIAA-94-1171, Robert W. Davis, Chantilly, Virginia, USA.

38. Why Small Sats?, James D. Rendleman, Colonel, USAF (ret.), JD, LLM, Colorado Springs, AIAA-2009-6416, Space 2009 Conference and Exposition, 14-17 September 2009, Pasadena, California.

39. Low Cost Microsatellites: Innovative approaches to breaking the cost paradigm, Ruth L Moser and Michael J. Stallard, AIAA-2000-5195.

40. http://www.cnw.ca/ (M3MSat)

41. Radar satellites and maritime domain awareness, J.K.E. Tunalay, London Research and development Corporation, Ottawa, Ontario.

42. Maritime Galileo Application, SEA GATE test environment, Rostock Port, Germany.

43. New Possible roles of small satellites in maritime surveillance, Terje Wahl, Gudrun K. Hoye, Norwegian Defense Research Establishment (FFI), Kjeller, Norway.

44. http://www.nasa.gov/mission_pages/station/research/experiments/PSSC.html#applications

45. "MIO Experimentation at NMIOTC: Networking and Collaboration on small craft maritime sourced nuclear radiological threat detection and interdiction", Professor A.

Bordetsky and Georgios Mantzouris, Ph.D. Candidate, NMIOTC MIO Journal 2nd Issue, November 2010 http://www.hellenicnavy.gr/hosted/nmiotc/files/NMIOTCJournal2.pdf

46. "Modelling of Picosatellite Network Applications to Maritime Interdiction Operations", Dr Alex Bordetsky and Georgios Mantzouris, Ph.D. Candidate, 16th International Command and Control Research and Technology Symposium – ICCRTS, Quebec, Canada, 21-23 June 2011 http://www.dodccrp.org/events/16th_iccrts_2011/papers/163.pdf

47. "MIO Satellite Interdiction Operations", Lt Georgios Mantzouris, Hellenic Navy Proceedings, Nov 2010 (in Greek), (3rd Award for best naval research study from Chief of the Navy)

48. "SPACE MIO: Modelling of Picosatellite Network Applications to Maritime Interdiction Operations", Dr. Alex Bordetsky, Principal Investigator for MIO Experimentation, NPS, & Lt Georgios Mantzouris, Ph.D. Candidate , NMIOTC MIO Journal 3rd Issue, June 2011 http://www.hellenicnavy.gr/hosted/nmiotc/files/NMIOTCJournal3.pdf

49. "Modeling of Pico Satellite Network Applications to Maritime Interdiction Operations", Dr. Alex Bordetsky and Georgios Mantzouris, Ph.d Candidate, 2nd International Conference on Space Technology, 15-17 Sept 2011, Athens http://ieeexplore.ieee.org/search/freesearchresult.jsp?newsearch=true&queryText=mantzouris&x=30&y=11

50. "Joint NPS – Lawrence Livermore National Lab Experimentation", Dr. Alex Bordetsky and Georgios Mantzouris, Ph.D. Candidate, NMIOTC MIO Journal 4th Issue, November 2011, http://www.hellenicnavy.gr/hosted/nmiotc/files/NMIOTCJournal4.pdf

51. "Picosatellites in support of Maritime Safety Awareness while transiting high risk areas. A preliminary analysis and design", Professor Nikitas Nikitakos, University of the Aegean Sea, LtCdr Georgios Mantzouris, Ph.D. Candidate, Journal on Southeastern European Security Strategy and Transatlantic Leadership, Vol. II, November 2011, http://www.strategyinternational.org/magazine/#/50

52. "Picosatellites in MIO tracking WMD materials", Georgios Mantzouris, NMIOTC MIO Journal Inaugural Issue, Feb 2010. http://www.hellenicnavy.gr/hosted/nmiotc/files/NMIOTCJournal1.pdf

53. "Micro and Pico Satellites in Maritime Interdiction Operations" Dr. Alex Bordetsky and Georgios Mantzouris, Ph.D. Candidate, 15th International Command & Control Research & Technology Symposium, 22-24 June 2010, Santa Monica, CA, http://www.dodccrp.org/events/15th_iccrts_2010/papers/179.pdf

54. Master Thesis: "Thermo mechanical Analysis of Ground Based Directed Energy Weapons on Satellites and Intercontinental Ballistic Missiles", Lt Georgios Mantzouris, NPS Sep 2006, http://edocs.nps.edu/npspubs/scholarly/theses/2006/Sep/06Sep_Mantzouris.pdf

55. Mantzouris G., Professor Kolar R., "Simulation of Thermo-mechanical Behavior of a Ballistic Missile Model", MSC Virtual Product Development Conference 2006, July 17-19, Huntington Beach, California http://www.mscsoftware.com/events/vpd2006/na/presentations/tech_papers/73.pdf

56. Mantzouris G., Professor Kolar R., "Simulation of Thermo-mechanical Analysis of Ground Based Directed Energy Weapons on a Satellite Model", 5th Directed Energy Test and Evaluation Conference 2006, Aug 1-3, Albuquerque, New Mexico. Submitted for publication in The Journal of Directed Energy, http://www.deps.org/store/merchandise/TOCs/DETE06TOC.html

57. "Modelling Human performance in MIO", Dr. Trevor Dobbins, Georgios Mantzouris, NATO RTO-MP-HFM-202, October 2010, NATO RTO Conference, Brussels.

58. "Hellas Sat and its applications to Hellenic Navy", LtJG Georgios Mantzouris, (in Greek), Classified Research study, Assistant Head Officer's Operational School, Sep 2001.

59. "Greece and International Organizations. A comparison analysis with duties and advantages", Lt Georgios Mantzouris, Junior War College Thesis (in Greek), Classified Research Study, Feb 2008.

60. "Microsatellites in maritime interdiction operations" , Lt Georgios Mantzouris, Hellenic Navy Proceedings, Oct 2008 (in Greek)

61. "Interdiction of small low earth orbiting satellites from on board military crafts", Lt Georgios Mantzouris, Hellenic Navy Proceedings, Sep 2009 (in Greek), (1st Award for best naval research study from Chief of the Navy)

62. "NMIOTC: The Hellenic and NATO training facility for Maritime Interdiction Operations", Lt Georgios Mantzouris, July 2010 (in Greek)

63. “Understanding, Assessing and Responding to Terrorism. Protecting Critical Infrastructure and Personnel”, Brian T. Bennett, Wiley Interscience 2007

64. https://www.google.com/earth/ - Google Earth map / route representation

65. http://www.interorbital.com/interorbital_03302014_014.htm (Tubesat Launch Manifest)

66. http://www.pe0sat.vgnet.nl/satellite/amateur-radio-satellites/fo-29/

67. G.I. Pugacheva, A.A. Gusev, U. Jayanthi, I.M. Martin, W.N. Spjeldvik, Antiparticles and light Element isotope ions in the Earth’s magnetosphere, Jounal of Atmospheric and Solar Terrestrial Physics, 64, 2002, 625-631, Elsevier.

68. P. Rothwell, C. Lynam, The plasmapause, the plasmasheet and energetic trapped electrons in the earth’s magnetosphere, Planet Space Science, 1969, Vol. 17, pp. 447-454, Pergamon Press.

69. Sebastien Bourdarie and Daniel Boscher, “Earth Radiation Belts”, ONERA/ DESP, BP 4025, 2. Av. E. Belin, 31055 Toulous Cedex 04, France

70. Juan G. Roedeger, “The International Magnetospheric Study”, Acta Astronautica, Vol.1, pp1-14, Pergamon Press 1974

71. Jean Claude Boudenot, Radiation Space Environment, Thales Research and Technology, RD 128, 91767 Palaiseau Cedex, France.

72. Sebastien Bourdarie and Michael Xapsos, The Near Earth Space Radiation Environment, IEEE Transactions on Nuclear Science, Vol. 55, No 4, August 2008.

73. Richard B. Setlow, The US National Research Council’s View of the Radiation Hazards in Space, Mutation Research 430 (1999), 169-175, Elsevier.

74. G. Pugacheva, A.A. Gusev, U.B. Jahanthi, N.G. Schuch, W.N. Spejeldvik, K.T. Choque, Trapped Antiprotons produced by cosmic rays in the Earth’s Magnetosphere, Advances in Space Research, 34, 2004, 1433-1437, Elsevier.

75. D.N. Baker, S.G. Kanekal, Solar Cycle changes, geomagnetic variations and energetic particle properties in the inner magnetosphere, Journal of Atmospheric and Solar Terrestrial Physics 70, 2008, 195-206, Elsevier.

76. Takeshi Sesada, Satoshi Ichikawa, Toshiki Kanai, In flight Measurements of space radiation effects on commercial DRAM, IEEE, 2004.

77. E.E. Antonova, N. Yu. Ganushkina, V.F. Bashikov, “Quiet time distribution of plasma pressure in the inner earth’s magnetosphere, Advances of Space Research, Vol. 25, No 12, pp. 2361-2364, 2000, Moscow, Russia, Elsevier.

78. J.H. Piddington, “The magnetosphere and its environs, Planet Space Science, 1965, Vol 13, pp. 363-376, Pergamon Press, Sydney Australia.

79. Guenther Reitz, Characteristic of the Radiation Field in Low Earth Orbit and in Deep Space, German Aerospace Center, Koln, Germany, 13 March 2008, Science Direct.

80. G.D. Badhwar, D.E. Robbins, Decay rate of the second radiation belt, Advances of Space Research, Vol. 17, pp. 151-158, 1996, Pergamon.

81. Alfred L. Vampola, The Hazardous Space Environment, IEEE transactions on plasma science, Vol. 28, No. 6, December 2000.

82. Development and Modeling of a microwave excited microplasma thruster, Yoshinori Takao and Kouinchi Ono, Kyoto University, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 11-14 July 2004, Fort Lauderdale, Florida

83. A miniature electrothermal thruster using microwave excited plasmas: a numerical design consideration, Yoshinori Takao, Kouinchi Ono, Institute of Physics publishing, Plasma sources science technology 15 (2006) 211-277, March 2006, Kyoto University, Department of Aeronautics and Astronautics.

84. Performance testing of a miniature electrothermal thruster using microwave excited microplasmas, Yoshinori Takao and Kouinchi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 9-12 July 2006, Sacramento, California (AIAA 2006-4492)

85. A miniature electrothermal thruster using microwave – excited microplasmas: Thrust measurement and its comparison with numerical analysis, Journal of Applied Physics 101, 123307, June 2007, Yoshimori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Japan.

86. Microwave – excited microplasma thruster with helium and hydrogen propellants, Takao Takahashi, Yoshinori Takao, Yugo Ichida, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan, Physics of Plasmas 18, 063505, June 2011.

87. Microwave – excited microplasma thruster with applied magnetic field, IEPC 2011-262, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11-15, September 2011, Tetsuo Kawanabe, Takeshi Takahashi, Yoshinori Takao, Koji Eriguchi, Kouichi Ono, Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan

88. Design and Initial testing of a miniature microwave electrothermal thruster, Penn State, AIAA 2007-5293, Michael Micci, 2007

89. Final Report, Plasma stabilization in low power C band microwave arcjets, Michael Micci, Penn State, DTIC, 31 Oct 1999

90. Development of a Microwave Excited microplasma thruster, Yoshinori Takao etal, Kyoto University, Japan, IEPC 2005-056

91. Optimization of GEO using electric propulsion based on genetic algorithm, Han Xianwei etal, Xian Polytechnic University, China

92. Modeling and Direct Thrust Measurements of a 8 GHz Microwave Electrothermal Thruster, Jeffrey Hopkins and Michael Micci, Penn State, AIAA 2011-5885, 47TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 31 July – 03 August 2011, San Diego, California.

93. "Decision by Objectives", Ernest Forman DSc,Professor of Management Science at George Washington University, Mary Ann Selly, Expert Choice Inc.

94. "Cost Benefit Analysis", Project co-financed by the European Commission, Directorate General Transport Energy 16/10/2009

95. "European Maritime Safety Agency", Annual Report 2011

96. "The business of pirate protection", Economic of Security Working Paper 75, Anja Shortland and Federico Varese, August 2012

97. "Enabling technologies for distributed picosatellite missions in LEO", Tanya Vladimirova etal, Department of Electronic Engineering, University of Surrey

98. "Practice Standard for project risk Management", Project Management Institute, 2009

99. "Survey and assessment of the capabilities of Cubesats for Earth Observation", Daniel Selva and David Krejci, Acta Astronautica 74(2012) 50-68.

100. “Survey of worldwide pico and nano satellite missions distributions and subsystems technology” J. Bouwmeester and J. Guo, Acta, Delft University, Astronautica 67 (2010) 854-862

101. “Treasure Mapped: Using Satellite Imagery to track the development Effects of Somali Piracy”, Dr Anja Shortland, David Stephen, Brunel University, 12 Jan 2012.

102. “The eye and the fist: Optimizing research and interdiction” M. Kress etal, European Journal of Operational Research, 220 (2012) 550-558.

103. http://www.n2yo.com/

104. http://www.satview.org

105. http://www.pe0sat.vgnet.nl/satellite/frequencies/

106. http://www.ne.jp/asahi/hamradio/je9pel/satslist.htm