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THESIS

**THE INTEGRATION OF SMALL SATELLITES IN
MARITIME INTERDICTION OPERATIONS (MIO)**

by

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September 2012

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**THE INTEGRATION OF SMALL SATELLITES IN MARITIME INTERDICTION
OPERATIONS (MIO)**

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The open sea is an area where numerous legal activities occur, such as trade, transportation, and scientific research; but it is also a place that attracts persons with illegal, criminal, and terrorist intentions. Naval nations, often acting in alliance, conduct operations to stop this illegal activity. Maritime-interdiction operations (MIO) are the usual type of operation employed, and, because of their nature, require robust communications and uninterrupted flow of information. Establishing communications and networks in the open seas via terrestrial means is possible only in certain areas and is not feasible around the clock. Therefore, the distribution of the data and information needed for maritime-interdiction operations is significantly limited as to speed, accuracy, and efficiency.

This thesis examines how small satellites can be integrated in an MIO ad-hoc network and how their advantages and disadvantages affect the flow of information among the nodes.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	Automatic Identification system
BER	Bit Error Rate
BGAN	Broadband Global Area Network
bps	Bits per second
CENETIX	Center for Network Innovation and Experimentation
CIP	Counter Infrastructure Protection
CoE	Center of Excellence
COI	Contact of interest
C2	Command and Control
DNOC	Deployable Network Operations Center
FFI	Forsvarets Forskningsinstitut (Norwegian Defense Research Establishment)
GEO	Geostationary Earth Orbit
GGB	Golden Gate Bridge
GNB	Generic Nano-satellite Bus
JCBRN	Joint Chemical Biological Radiological and Nuclear
JROC	Joint Requirements Oversight Council
LEO	Low Earth Orbit
LLNL	Lawrence Livermore National Laboratory
MIO	Maritime Interdiction Operations
MSA	Maritime Situation Awareness
MSO	Maritime Situation Operation
NATO	North Atlantic Treaty Organization

NCA	Norwegian Coastal Administration
NMIOTC	NATO Maritime Interdiction Operations Training Center
NOC	Network Operations Center
OSI	Open Systems Interconnection
RAAN	Right ascension of ascending node
SA	Situation Awareness
SORDE	Special Operations Rapid Decisio-making Environment
TNT	Tactical Network Topology
WMD	Weapons of Mass Destruction

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I. INTRODUCTION

A. BACKGROUND

1. Small Satellites

When Sputnik, the first artificial satellite, was put into Earth's orbit in 1957, very few people imagined the development of the satellite industry as it has occurred over the past 55 years. Today it is feasible to place and control orbital systems with masses from more than 6,000 kg to less than 0.1 kg. Large satellites have masses greater than 1,000 kg; medium satellites have masses from 500kg to 1000kg, mini satellites have masses from 100kg to 500kg, and small satellites have masses of less than 100 kg (Satellite mass categories, n.d.). This research is focused on the last category.

Small satellites are subclassified as microsatellites (10–100 kg), nanosatellites (1–10 kg), picosatellites (0.1–1 kg), and femtosatellites (< 0.1 kg) (Helvajian & Janson, 2008). Because of their size constraints, small-satellites have limited capabilities; but the advance of technology transforms them day by day into a more and more useful tool for various applications.

Over the last 55 years, various entities have launched more than a thousand small satellites, with missions such as space-environment data collection, scientific tests, communications, etc. Although the trend has been towards heavy spacecraft that are highly sophisticated and capable of a wide variety of missions, the advantages of small satellites continue to interest the space industry.

Advancements in technology have significantly improved the capabilities of small spacecrafts in relation to their mass. This progress accords with Moore's law, which observes that the number of transistors on integrated circuits in computing hardware doubles every two years. As microelectronics become more powerful, they need less space and power and become cheaper every year. On the other hand, the modern solar cells that power a satellite can offer more than

twice the energy they produced in the 1960s, and energy-storage density has also vastly improved. Typically, small satellites, and especially nanosatellites and lighter, lack onboard propulsion, but microthruster systems such as cold-gas engines, small solid-rocket engines, solid-rocket thruster arrays, and even electric propulsion, can already be integrated to add propulsion capability.

The significant advantage of small satellites is cost. No matter how expensive the space project envisioned, the actual manufacture, putting in orbit, and control of a small satellite is feasible even for individuals. Picosatellites and cube satellites have long been the tool of choice for university research because of their low cost; but major organizations like the United States Department of Defense are now showing interest in an attempt to reduce operational costs. These satellites have become virtually the only choice for those who need orbital assets for their operations or projects and could not afford them until now.

2. Maritime Interdiction Operations

Today the fight against the asymmetric threat worldwide is of major importance for people's safety around the globe. The term asymmetric threat includes threats or techniques that are "a version of not "fighting fair," which can include the use of surprise in all its operational and strategic dimensions and the use of weapons in ways unplanned. Not fighting fair also includes the prospect of an opponent designing a strategy that fundamentally alters the terrain on which a conflict is fought." An example of asymmetric threat is "terrorism by proxy, used by various Islamic states against U.S. and European interests" (Asymmetric threats, n.d.). All nations try to be prepared for the unexpected. This relatively new threat has no boundaries, no borders, and no ethical laws or constraints. Ten years ago, the September 11 attacks, which killed 3,000 persons, initiated a different perspective on asymmetric threats, and since then countries from all over the world have tried to collaborate to counter the new common enemy.

A product of this collaboration in the maritime environment is maritime-interdiction operations (MIO) (Figure 1). According to Dr. Daniel Goure these

operations traditionally are “activities by naval forces to divert, disrupt, delay, or destroy the enemy’s surface military potential before it can be used effectively against friendly forces” (Goure D., n.d.). Today, MIOs are interrelated with counterterrorism, counter-infrastructure protection (CIP), weapons of mass destruction (WMDs), proliferation, piracy, embargo operations, and law enforcement (NMIOTC Journal, 2011). Countries conduct these operations in a plethora of places, including ungoverned and under-governed regions like the Gulf of Aden, where cooperation among all participants is not only demanded, but extremely challenging.

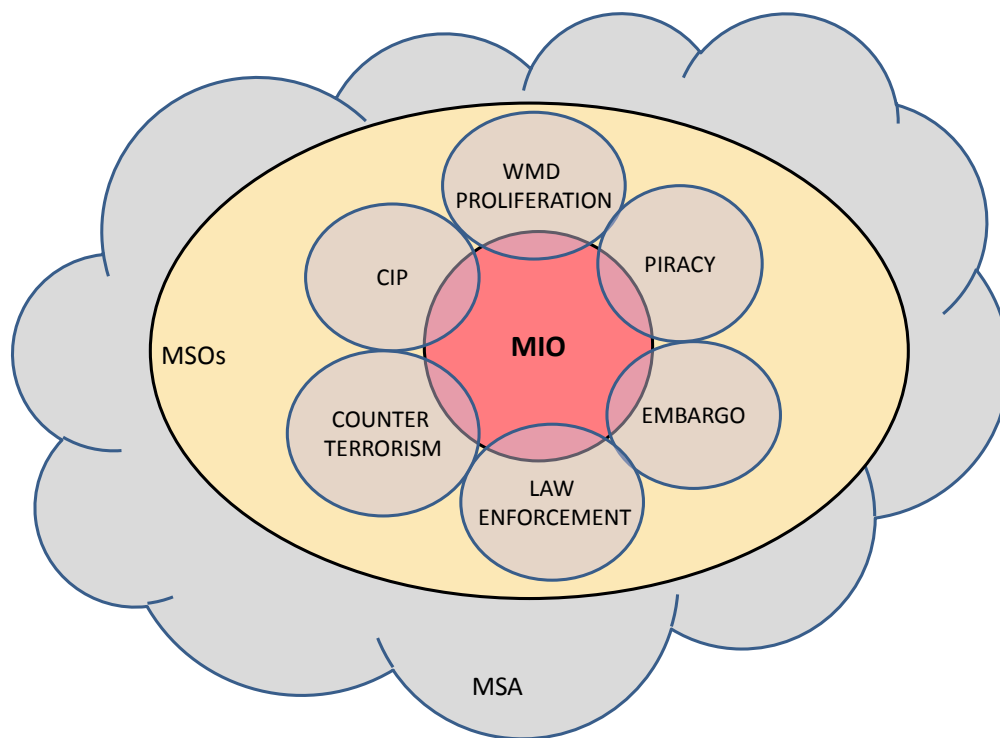


Figure 1. MIO perspective (Adapted from NMIOTC journal)

MIOs cover a plethora of concepts. They can be very sensitive missions, conducted in very different environments such as littoral waters or open seas by a variety of participating services with different cultural, procedural, and technological backgrounds. Any system able to support these operations is

clearly complex and must be studied from a network point of view. Such a network should be robust, reliable, scalable, and efficient to accommodate all this diversity. In addition, it should be able to connect peers with different policies, procedures, and capabilities. Therefore, it is necessary for an MIO network to be adaptive.

This research demonstrates that the integration of small satellites into MIO ad-hoc networks can be a way of solving the need for robustness, reliability, scalability, and efficiency in these networks, which are critical because of the special nature of MIOs. As described above, small satellites are orbital assets that, with the advancement of technology, have many potential capabilities, including operating efficiently as nodes inside networks. Since such integration has never been tested, this paper proposes a large-scale experiment for further research into the advantages and disadvantages of small satellites as nodes in an MIO network.

B. OBJECTIVES

The objectives of this study are to examine the following:

- Which kind of adaptation benefits an MIO environment
- What is the design of a large-scale MIO experiment with small satellites
- How a large-scale MIO experiment with small satellites can be implemented

C. RESEARCH TASKS

1. Adaptation

What are the characteristics an MIO network should have in order to be adaptive, and what does this mean to its structure.

2. Building Blocks and Relationships Among Parts

What are the building blocks an MIO network with small satellites experiment should have, and which relationships must be present among parts for this model to be realistic and functional.

3. Design Parameters

What criteria, design variables, and functional constraints should be taken into account because of the nature of the experiment.

4. Scenario

What type of scenario best fits for exploring in depth the usability of small satellites in an MIO network.

5. Team Composition and Experimentation Roles

Who are the most suitable personnel for the described experiment, and what are their roles.

6. Data Analysis and Collection Plan

What kind of data should be collected by the team, and what volume, frequency, and other parameters will determine the collection plan.

D. SCOPE

This thesis explores implementation of small satellites into fully operational MIO networks. Since the potential integration of these orbital assets into ad-hoc networks such as MIO networks has never been exploited, the author develops an initial design for a large-scale experiment for future research.

E. METHODOLOGY

- Various appreciations of the term “adaptation” in ad-hoc networks are described from the existing literature.
- The author presents the design of the large-scale experiment.

- Based on the aforementioned design, the implementation of the large-scale experiment is described.
- Using different software and hardware tools, an MIO network is modeled and real data is monitored, collected, and analyzed during field experimentation, allowing the effect of orbital assets inside the MIO networks to be assessed and evaluated.

F. THESIS ORGANIZATION

Chapter I includes an introduction to small satellites: advantages, disadvantages, and capabilities, based on current technology. A description of MIO tasks, the organization of missions, and theaters of operation follows, leading to the integration of small satellites into MIOs, which is the purpose of this study. The research objectives, tasks, scope, methodology, and organization of the study complete the chapter.

Chapter II lists definitions and characteristics of ad-hoc networks from the literature. In this chapter, we describe the building blocks, relationships among parts, parameter criteria, space architecture, design variables, functional constraints, and Pareto sets of a large-scale, field-experimentation design. The basic principles of satellite coverage complete the chapter.

In Chapter III, we introduce the research scenario, team composition, and experimental roles, as well as the data analysis and collection plan and the evolution of a large-scale experiment.

In Chapter IV we describe AISSat 1 and the Atlas Craft Target threat-detection and analysis tool. We also describe our models and the results of STK simulations. The possible satellite, with its system and network characteristics, and a look at smart-push vs. smart-pull theory conclude the chapter.

Chapter V presents conclusions and recommendations for future research.

II. AD-HOC NETWORKS, ADAPTATION IN AD-HOC NETWORKS, EXPERIMENTATION, MIO NETWORKS AND SATELLITE COVERAGE

A. AD-HOC NETWORKS

Most MIO operations in open seas are based on a decentralized type of network described as “ad hoc.” These networks are out of range of any terrestrial base station that can support and enhance connectivity. For this paper, the term “ad-hoc network” refers to networks with devices that are free to associate with any other device on the network within link range. Ad-hoc networks do not rely on preexisting infrastructure such as access points or routers. Instead, each node is mobile, acting as a terminal or router, or both, and “participates in routing by forwarding data for other nodes, and so the determination of which nodes forward data is made dynamically based on the network connectivity” (Wireless ad-hoc network, n.d.). These nodes often divide the network into groups or clusters; clustering is a very significant factor in their efficiency. Clustering reduces the amount of data needing to be exchanged for maintaining routing and control information and for the construction and maintenance of “cluster-based virtual-network architectures” (Basagni, n.d.).

The limitations and challenges for these networks are many. Some of them cannot presently be addressed and some have been addressed to a certain degree due to advancements in technology. The limitation and at the same time the challenge of coverage is the most important thing in MIO communications, and satellites can add much benefit. Orbital assets, however, are constantly moving objects, especially LEO satellites, and each time a satellite has the opportunity to participate in an ad-hoc network, it finds that conditions have changed. Thus, the integration of small satellites into MIOs requires adaptability. The network must be always ready to include an orbital asset or to disengage, according to asset position, the weather, atmospheric conditions, and many other

factors that also play a role in the connection of satellites with terrestrial nodes. It is therefore essential that the term “adaptation” be clarified in this paper.

B. ADAPTATION IN AD-HOC NETWORKS

1. Adaptation as a Term

Russel L. Ackoff states that:

A system is adaptive if, when there is a change in its environmental and/or internal state that reduces its efficiency in pursuing one or more of the goals that define its functions, it reacts or responds by changing its own state and/or that of its environment so as to increase efficiency with respect to a goal or goals. (Ackoff, 1971)

Thus, when a system detects less efficiency because of changes to its parameters or environment, it has the ability to alter itself or its environment to regain efficiency (some or all, if possible). Ackoff distinguishes four types of adaptation. “Other–other” adaptation occurs when the system modifies its environment due to external changes (e.g., the tactical command of a group of ships changes the area of an exercise because of bad weather conditions in the designed area). “Other–self” adaptation occurs when the system modifies itself due to external changes (e.g., a group of ships changes the range of operation between units to achieve connectivity). “Self–other” adaptation occurs when a system modifies its environment because of internal changes (e.g., the command of a group of ships decides to divide into two subgroups to perform two-scenario training, so the initial area of the exercise is altered to support the new situation). Finally, “self–self” adaptation occurs when the system modifies itself to compensate for an internal change (e.g., because the ship coordinator of the group’s communication assets is ordered to leave the area and go contribute to a search-and-rescue effort, another ship of the team undertakes coordination of the team) (Ackoff, 1971). It is crystal clear that a truly adaptive system has the ability to sustain its efficiency no matter how many or what kinds of changes occur due to complexity in its environment or itself.

2. Adaptation as a Systems-Thinking Concept

“Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots” (Senge, 2006). Very often, these wholes are very complicated systems—networks with many nodes and numerous links, whose size can change for various internal or external reasons. According to J. H. Holland, “these systems change and reorganize their component parts to adapt themselves to the problems posed by their surroundings” (Holland, 1992) or by themselves. They are grouped under the term, “complex, adaptive systems.” An example of a complex, adaptive system is the immune system. It consists of antibodies, which are the mechanisms that destroy various kinds of invaders entering the body. Because the variety of forms these invaders take is almost infinite and the immune system cannot develop a list of all possible forms and prepare special antibodies for the destruction of every invader, it adapts existing antibodies in order to destroy new, unknown invaders.

Based on interrelationships, complex systems are divided into clusters. According to Barabasi, clustering is a generic property of complex networks. Strong ties are the relationships that produce clusters, and weak ties are relationships that connect clusters together (Figure 2). The concept of weak ties is of critical importance in a complex system because, as Barabasi states, they are the bridges to the outside world. In order for a system to get new information or distribute processed information, weak ties must be activated (Barabasi, 2002, 2003). The way these ties are distributed in a network, and their number, affects the level of system adaptation. A network with many weak ties that connects its clusters in many ways gives flexibility and robustness and helps encountering problems; which all of them end up to an increased capability of adaptation.

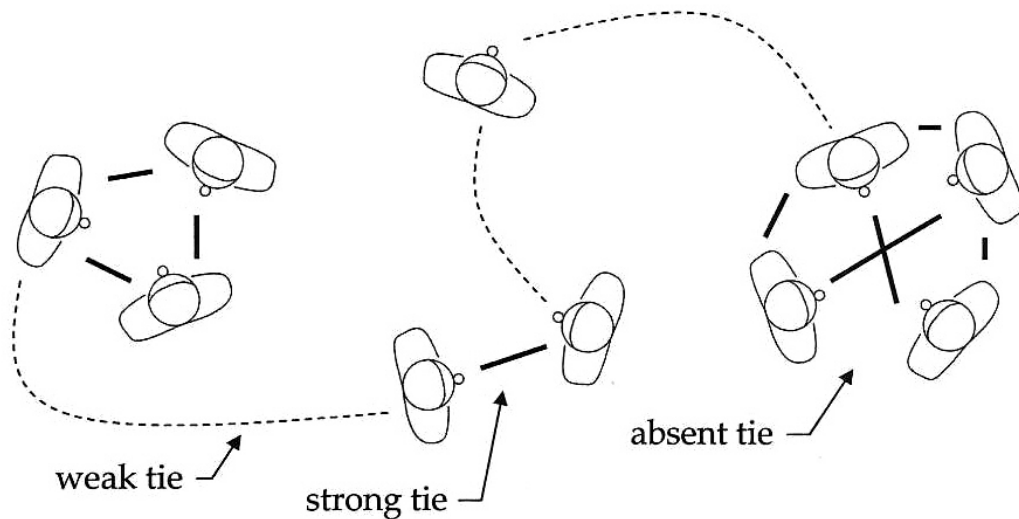


Figure 2. Strong and Weak Ties

According to Holland, an adaptive system must have ways of changing its rules, and to do so must follow certain procedures. First of all, a sense of what good performance is and the development of a reward system for the parts of the system that causing good performance is necessary. The more a rule contributes to good performance, the stronger the possibility that it will be used for future decisions. This procedure can help the system use the best rule from those it has already tried, but it cannot create new rules—for this, the system needs a rule-discovery procedure. With these two procedures, the complex, adaptive system is able to change its rules and increase its adaptiveness (Holland, 1992).

Bordetsky has written many papers suggesting that a key factor for adaptivity in a complex system such as ad-hoc tactical networks is situational awareness.

The concept of a deployable network-operations center (DNOC) offers adaptivity and flexibility to ad-hoc dynamic and tactical environments by supplying tactical units with the needed information, on time, and in an understandable format. Bordetsky and his team built a DNOC with the following criteria:

- Deployable/tactical infrastructure
- Field-deployable kits
- Flexible and adaptable system, with interchangeable parts
- Expeditious set up and tear-down
- Scalability to meet current and future experiments
- Capability for multi-disciplinary collaboration
- Promotion of real-time decision making

Using the TNT testbed and conducting several experiments, Bordetsky concluded the following:

- “Better information-visualization tools increase situational awareness.
- Collaboration and shared information visualizations increase understanding.
- Increased shared awareness and situational understanding increase the likelihood of mission accomplishment” (Bordetsky, 2005).

Moreover, the TNT testbed setup proves that situational awareness is a very important aspect of a complex, adaptive system such as an ad-hoc tactical network. Assuming that this system follows the idea of the seven-layer OSI model and by measuring the performance of the network (video, images, voice etc), the tactical NOC (network operations center) crew or local commanders can adapt easily in the application or in the physical layer to increase the performance of the network (Figure 3). In the application layer, one can reduce video or picture streaming, or allow only voice; in the physical layer, the local commander can move the nodes of the network around to bring them back to line-of-sight with the closest neighbors or change their location for better performance via improved signal strength (Bordetsky, 2010). Bordetsky clearly

suggests that feedback loops like that pictured in Figure 3 support system adaptation. The mechanism for this is situational awareness. As the system receives feedback, it becomes more aware of its current situation. With this knowledge, the system changes. In this particular case, the tactical NOC crew or local commander decides to change to a more preferable and effective form; in other words, the system adapts because the feedback loop results in situational awareness, which in turn causes changes.

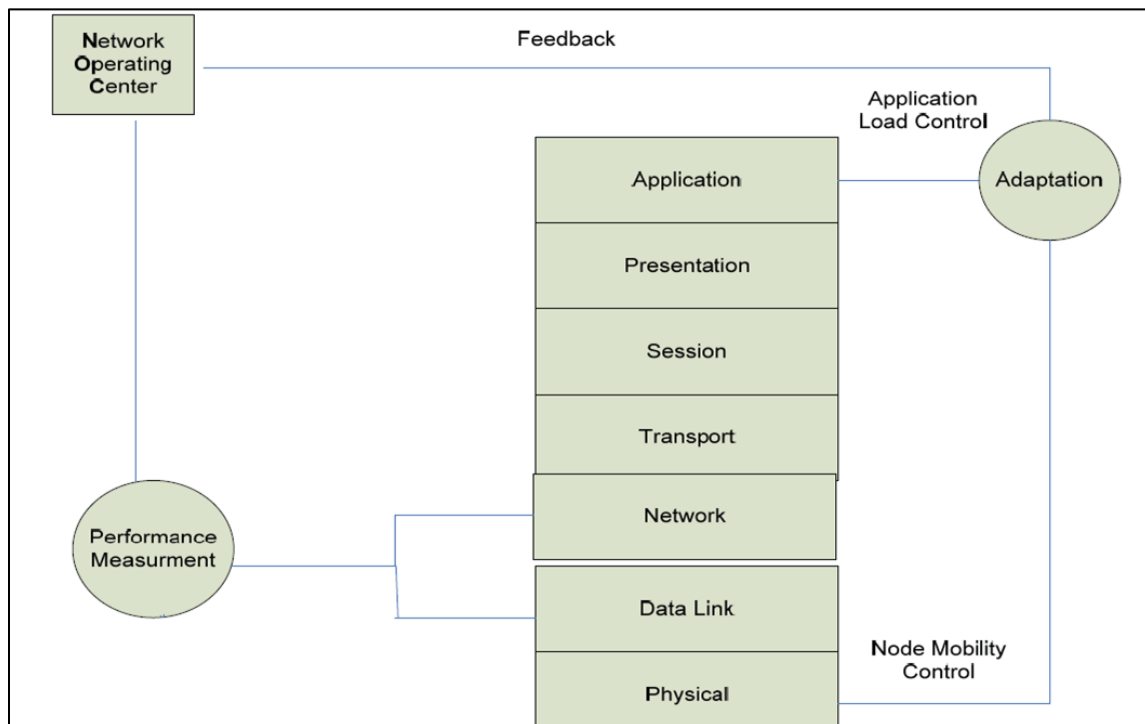


Figure 3. Layers of adaptation in TNT testbed (Adapted from *Testbed for Tactical Networking and Colaboration*. International C2 Journal Vol. 4, No. 3, 2010)

The concept of an “8th layer that extends the well-known seven-layer OSI model implements adaptive networking by giving every critical node” in the tactical network “its own specialized, network-operation center (NOC) capability” (Bordetsky, 2006). This new layer is the means of enabling certain nodes, called hyper nodes, to act as simple NOCs inside the network. In this architecture, every node’s awareness about its neighbors’ status and capabilities is used to form or reform the network for efficiency and robustness. This idea contributes

much to scalability. Hyper nodes are aware of the departures of existing nodes and the arrival of new ones, and offer that knowledge to the system to reallocate the best paths for distributing or gaining information. In this structure, the ability of a network to be adaptive is highly depended on these hyper nodes, which add intelligent, adaptive, self-control to the system.

3. Proposed Application of Adaptation to Ad-Hoc, Tactical MIO Networks, Small Satellites and MIO

Considering the literature on adaptation and how strong and weak ties or situational awareness effect adaptation to large-scale systems, we now focus on MIO ad-hoc tactical networks, and especially on how this adaptation can evolve with the use of small satellites. The reason for focusing on orbital assets and thinking of them as nodes in this complex system lies in the nature of MIOs. The need for monitoring targets, accessing various databases or experts and advisors distributed all around the world while being in open seas is circumscribed when constrained to terrestrial means. Limitations in speed, accuracy, and efficiency can be faced much more effectively with the use of satellites.

After Sputnik, small satellites made their re-appearance as an educational tool, and most of them developed in universities, with applications limited by technical factors such as physical scaling, orbital mechanics, economics, and technology readiness. New technologies, however, improved their capabilities and made them suitable for large programs beyond the scope of education. With their relatively low cost and by potentially using them in constellations, small satellites have become an attractive solution for many commercial, and even military applications, that are impractical or unaffordable with large satellites (Helvajian et. al., 2008).

The scope of this paper is limited, in that it will not capture adaptation in MIO ad-hoc tactical networks as a whole, but instead focus on the use of small satellites and what changes this use will bring to the adaptiveness of MIO systems.

C. LARGE SCALE FIELD-EXPERIMENTATION DESIGN

1. The Design in General

The design of a large-scale field experiment of an MIO with small satellites will include specification of the parts (building blocks) and the scale of the selected networking environment, which is MIO networks. The desired relationships among the parts, which allow the writer to model adaptation for the aforementioned networks, will be identified, and prototype or relevant parameter-criteria space models and TNT 2012-1 experiment descriptions will be explored from literature. Next the parameter-criteria space framework for a desirable system model will be proposed. Finally the writer will identify both a solution for breaking the model down to partial relationships and the meaning of a Pareto set for the expected holistic model.

2. The Building Blocks

The selected networking environment is MIO. The building blocks are individuals, teams, organizations, and orbital assets who operate in order to establish information and knowledge sharing and decision making. These building blocks are the nodes of the network, and they are connected by communication channels, which are the links of the network. The nodes are connected for a particular period with terrestrial or orbital technologies and formulate strong and weak ties. Different clusters can appear over time and this continuously evolving clustering is based on many factors, such as geography, commonly used technology, etc. Figure 4 pictures a configuration of the nodes and links considered in this study.

3. Relationships Among Parts

The nodes of the Figure 4 configuration are interconnected with various communication channels of different technologies. They constitute the strong and weak ties of the system. According to Levin et al, “weak ties provide access to nonredundant information”. They are “typified as distant” and exhibit “infrequent interaction”, and they are “more likely to be sources of novel information” (Levin et al., 2004) (Granovetter, 1973). Calvo et al. support the idea that “weak ties are transitory and only last for one period” (Calvo et al., 2007), so weak ties for this model will be links that are generated for a limited period in allow the nodes to have access to nonredundant information. Small satellites and their footprint will be the source of this model's weak ties. Every terrestrial node that is inside the footprint of the orbital node is considered to always establish a weak tie (link) with it during the time this connection is feasible. On the other hand, strong ties are defined as those that exist for a long, if not constant, time and are used mostly for routine services and information. So for this particular model, no satellite link can be assumed as a strong tie. On the contrary, node connections with terrestrial means such as HF channels are considered strong links.

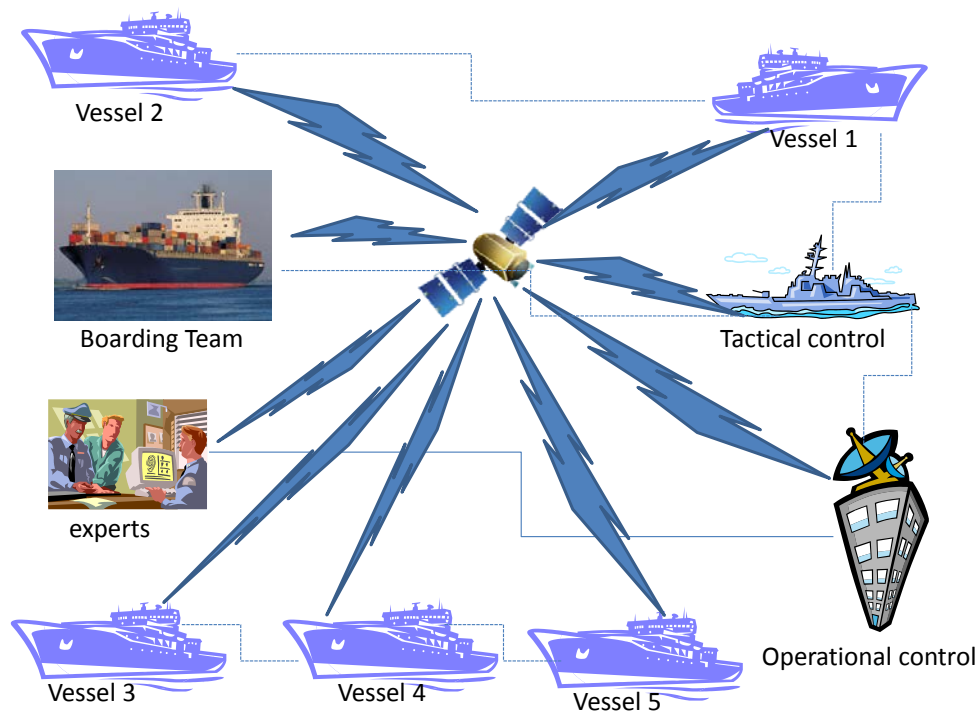


Figure 4. Ad-hoc tactical MIO network

4. Parameter-Criteria Space Architecture

Within the framework of MIO networks, Bordetsky and Mantzouris studied the amount of coverage possible by deploying a number of picosatellites. More specifically, they ran two simulations in the Satellite Tool Kit (STK) for a constellation of four and six picosatellites and concluded that the approximate total time for satellite communications during a day is two hours or three hours and twenty minutes, respectively. This period represents the sum of all time blocks distributed during the day with durations from five to nine minutes, depending on the characteristics of the satellite orbit (Bordetsky et al., 2011). Although the orbit is a design constraint for the model, this paper will not test the effect of the number of satellites in the constellation to the network but rather will use that model (four to six small satellites used as nodes) to test what other characteristics of the network can affect the ability of adaptation. “Adaptation” will

be used in this model as the ability to distribute information among nodes when new arrivals or departures of nodes occur, when strong and weak ties appear or disappear, and when the capacity of the links varies.

A significant aspect of measuring adaptation in MIO networks is also the number of links used for information flow. A robust system is better able to distribute information without flaw if the information makes as few hops to its destination as possible. Barabasi mentions the importance of the degrees of separation between nodes. He states that the real issue isn't the overall size of the network, but the distance between any two nodes. "As we add more links, the distance between the nodes suddenly collapses" (Barabasi, 2002, 2003). So the existence of links in which small satellites are involved affects the degree of separation of the nodes; or in other words, affects the number of links the information needs to use in order to flow. With the establishment of a weak tie, the degrees of separation between two nodes can decrease even to 0. The number of weak ties can affect the system's ability to adapt. A node that has many ways to distribute information or decisions is less likely to fail, so that makes it robust and effective. New nodes that can be embodied in the system via weak links add to the scalability of the system (Table 1). Finally, capacity is always an issue in networks. Small satellites have limits to their download or upload capacity, and confined access time deteriorates even more this problem. On the other hand, strong ties have better chances for maintaining greater capacity. So the combination of strong and weak links used for the distribution of information defines the network's level of effectiveness. As Levin states, "organizations that can make full use of their collective expertise and knowledge are likely to be more innovative, efficient and effective in the marketplace" (Levin, 2004).

Links	Degrees of Separation	Number of Links	Scalability	Capacity
Strong Links	Strong links can increase degrees of separation	The number of strong links has small effect in ability for adaptation	Strong links have not so much power to embody new nodes or to close gaps that occurred of nodes that departed.	The extension of the amount of information can be achieved using collaborative Technologies.
Weak Links	Weak links can decrease degrees of separation	The number of weak links has great effect on the ability of adaptation.	Weak links have great power to embody new nodes or to close the gap of nodes that departed.	Limited capabilities for upload/download. Time is also an issue

Table 1. MIO network links

5. Design-Criteria Similarities With TNT 2012-1 Experiments

Searching for similarities in the TNT 2012-1 set of experiments, “Special Operations Rapid Decision-making Environment (SORDE),” experiment by the company Aptima, presents some common design criteria with MIO experiments, and particularly with the design of this paper’s experiment. SORDE aims to enhance distributed collaboration between tactical operation centers and forward-deployed units by decreasing uncertainty about the actions and status of distributed team members. Distributed warfighting units reduce uncertainty by increasing team and shared situational awareness of mission status and resources. Tools such as e-mail, text messages, chatrooms and file-sharing systems enable instantaneous information sharing across globally distributed teams. Forward-deployed warfighters have the opportunity for real-time reach-back with operation centers, enhancing their situational awareness.

Similarly, in an MIO environment, there is extended collaboration between forward-deployed units such as boarding teams or vessels farther away from line

of sight (LOS) and tactical operation centers, or even distributed experts, all around the world. The tool for this collaboration, this paper asserts, is the use of small satellites. Small satellites promise to decrease the uncertainty of boarding teams, for example, and increase situational awareness by connecting forward-deployed units directly with distributed experts and providing the ability to upload and download data such as voice, pictures, or even videos. Just like warfighters, forward-deployed units in an MIO have opportunities for real-time reach-back.

Moreover, SORDE is intended to improve warfighter decision making process in environments with great uncertainty because of their restricted access to communications channels. The result is a measurable increase in mission effectiveness and overall reduction of uncertainty about the status of critical blue forces. For their part, small satellites are intended to improve the decision-making process for distributed units in environments where there is no way to communicate and exchange information except through orbital assets. The result will also be a measurable increase in MIO effectiveness and in situational awareness among the nodes of the network.

6. Design Variables

Design variables are those quantities or choices that are under the control of the model's designer. They are system's independent variables and determine what needs to be measured to understand the responses of a system undergoing testing. For this particular study, design variables are those that define nodes and links. For the nodes of this model, there are two states: orbital and terrestrial. The variables for the links are the number of links for each node and capacity.

7. Functional Constraints

Functional constraints are variables assigned by environmental factors. Considering the nature of an MIO, functional constraints can be many and can vary significantly. To understand adaptation in an MIO network with orbital assets, the constraints to consider are the characteristics of the orbit, time, and participant training. Since in this paper only small satellites are tested, the orbital

nodes use only low-earth orbits (LEO). So apogee and perigee altitude, inclination, argument of perigee, right ascension for the ascending node (RAAN) and true anomaly are restricted to values that represent LEO. By the term “time,” the writer means the amount of time that an orbital node is available to the network. Lastly, because participant attitudes can affect the validity of measurements, it is assumed that all are professionals in their roles (e.g., boarding teams, WMD experts, nuclear/radiation experts) and equally well trained. Table 2 provides a consolidated view of variables and constraints.

Variables	Description	Range
Nodes		
Node State	A node can be a terrestrial unit or a small satellite	Orbital-Terrestrial
Links		
Number of links	The number of links a node has in a particular moment	Numerical
Capacity	Maximum amount of distributed information	bps
Functional Constraints		
Apogee Altitude	Orbit characteristic	300 Km-1500Km (LEO)
Perigee Altitude	Orbit characteristic	300 Km-1500Km (LEO)
Inclination	Orbit characteristic	0-180 degrees (by convention)
Argument of Perigee	Orbit characteristic	0-359 degrees (by convention)
RAAN	Orbit characteristic	0-359 degrees (by convention)
Time	Amount of time that every orbital node is available to the network	Varied
Participants' Training	Self explanatory	

Table 2. MIO network variable and constraints

8. Meaning of the Pareto Set for the Expected Holistic Model

When we are searching for optimization in a holistic model, tradeoffs have to be made. This is because not all solutions always apply, as every model has its own constraints. The Pareto set of feasible points is the set of solutions in which one or more constraints have been taken into account. For this study, four Pareto sets will be investigated. In the x-axis (horizontal), strong and weak links appear, and in y-axis (vertical), scalability and degrees of separation are plotted (Figure 5).

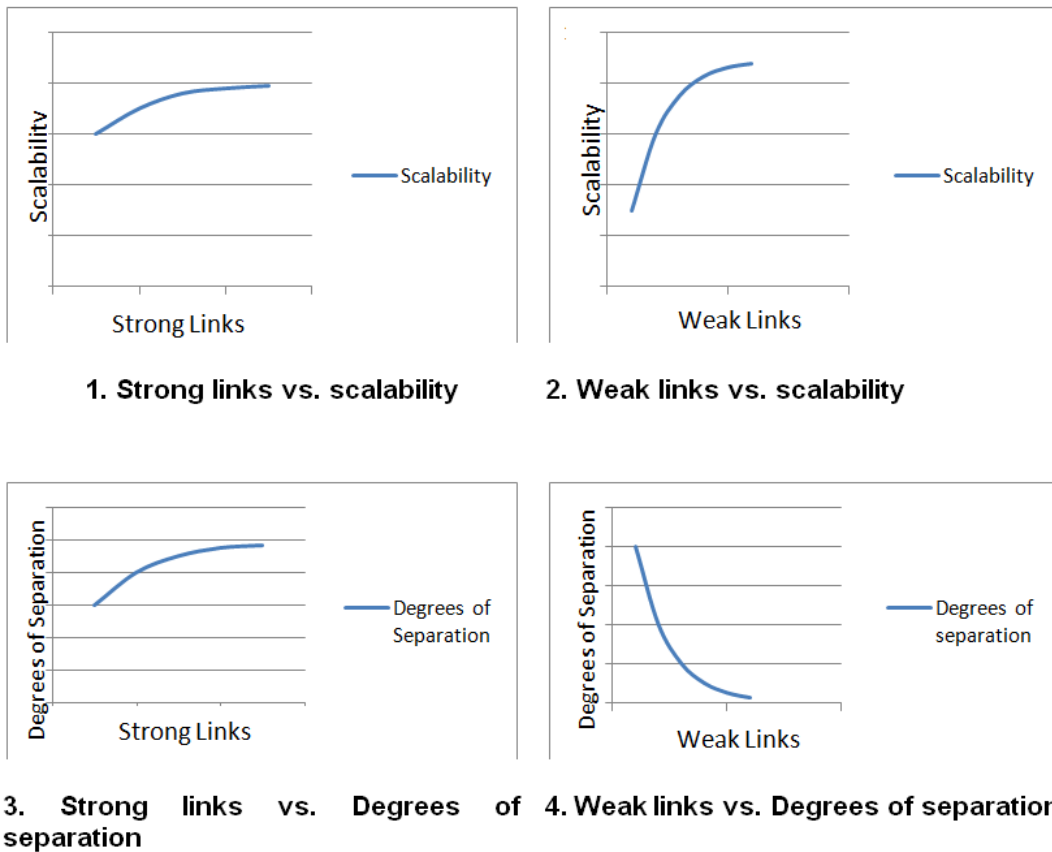


Figure 5. The Pareto set

D. MIO NETWORKS

Mesh networks are the most common type used in MIOs until now. These networks are characterized by a constant change of location of their nodes, the

number of nodes participating, and the tactical and environmental conditions during operation. In a real MIO environment, almost nothing is constant, and this makes ensuring functionality of such a network a very challenging issue.

To clarify the concept of an MIO network, the wave relay mesh infrastructure of the Center for Network Innovation and Experimentation (CENETIX) tactical-network topology (TNT) testbed in San Francisco Bay provides a good example. The cluster consists at this time of one fixed node on the Golden Gate Bridge (GGB) and two or more nodes on San Francisco Police Department patrol boats. All nodes are equipped with quad radio routers and sector antenna (SA) arrays from Persistent Systems, LLC (Figure 6). This small network provides the NPS CENETIX SA server with spectral uploads from ARAM sensors, GPS tracking, and video feeds. The GGB node is connected to the TNT backbone network, and every node connected to the GGB node can provide connectivity to any neighbor node that is out of range of the GGB node. This ability to expand provides scalability, flexibility, and adaptability in the network, ingredients extremely important for the success of a mission.



Figure 6. Sector Antenna Array and Quad Radio Router

On February 28, 2012, a trial took place with two patrol boats and the GGB node. During the trial, whenever one of the boats was out of range of the GGB node, the second boat relayed the signal and kept connectivity. The problem was when both boats were in the blind regions of the GGB node: the whole network collapsed, making it obvious that the existing fixed node was a bottleneck for the system and that an extra node was necessary. This extra node could be a fixed node with coverage in the blind area or an aerial node such as a UAV or satellite. The latter option seems exotic for coastal waters, but in open seas probably represents the most effective, if not the only, solution.

E. SATELLITE COVERAGE

To place small satellites over an area of interest in a way that can provide extended coverage for an MIO network relies on many parameters, based on tactical situation and strategic plan. When this thesis mentions orbits in general,

only low-earth orbits (LEO), which are “the region of space to 2000km altitude” (Office of Safety and Mission Assurance, 1995), are referred to, because this is where small satellites typically live and operate. Continuous LEO satellite coverage over an area, although technologically possible in reality, would be extremely expensive and, as a practical matter, not achievable. Thus, the operation command has to decide first on the area of coverage. With this information, some of the parameters of the orbit can be decided; but for an MIO, the area of coverage is an issue, because although you can limit the area of operations, illegal activities can take place, theoretically, everywhere on the open sea. It is difficult to exclude regions when designing a safety net around countries. A highly inclined orbit can cover most of the earth’s surface and, if the north and south poles should be included, a polar orbit is the only solution. Another important parameter that must be taken into account for the coverage plan is what part of the day the orbital assets are needed over a specific region. Most of the satellites in LEO revisit a place more than once a day. The frequency depends on the period of the orbit, but not on a specific time of the day, except those that follow sun-synchronous orbits. “Sun-synchronous orbits are those whose orbital plane makes a constant angle α with the radial from the Sun to the Earth” as can be seen in Figure 7 (Curtis, 2010, p.237). In other words, the asset is able to make passes over a particular region of the earth at the same time every day. This parameter can be very important for particular types of MIO operations. For example, usually boarding operations happen during daytime, so an orbital node is needed then and not during night hours. With sun-synchronous orbits, this is achievable.

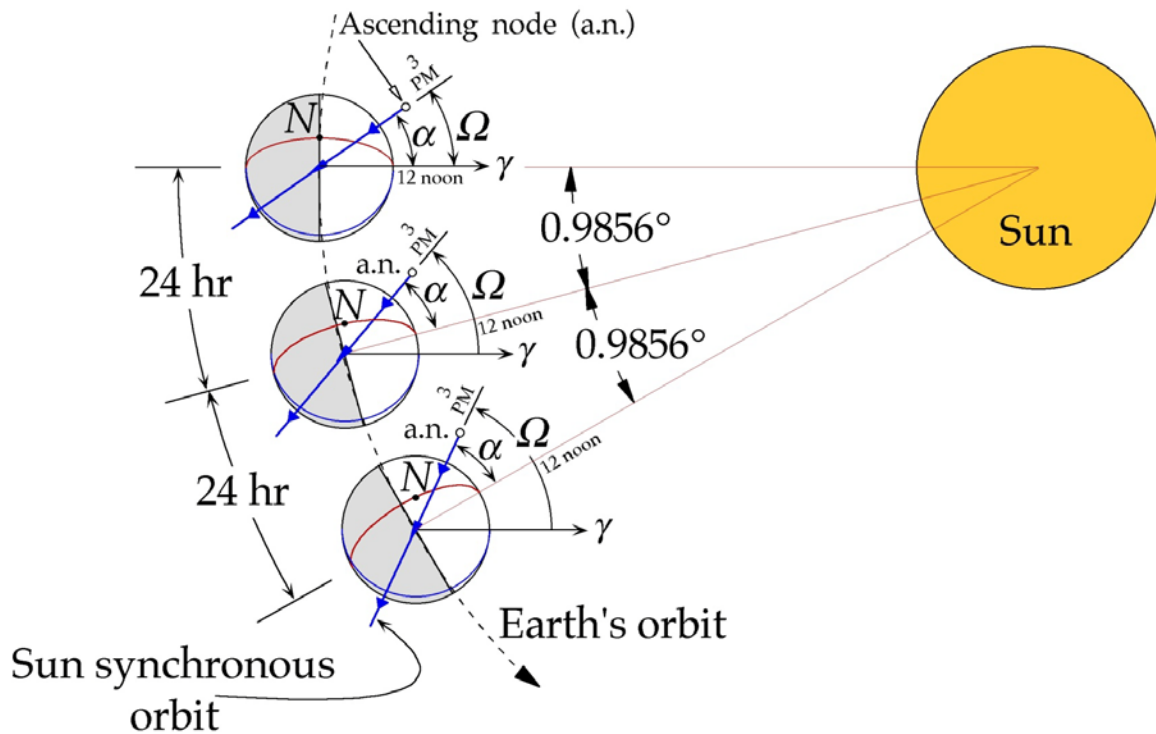


Figure 7. Sun-synchronous orbit (Adapted from *Orbital Mechanics for Engineering Students*. Second edition. Burlington, MA:Elsevier. p.237)

A satellite, to be sun-synchronous, must follow the formula:

$$\dot{\Omega} = - \left[\frac{3}{2} \frac{\sqrt{\mu} J_2 R^2}{(1-e^2)^2 \frac{7}{a^2}} \right] \cos i \quad (1)$$

Where

$\dot{\Omega} = 1.991 \times 10^{-7}$ rad/s (change in Ω , RAAN)

$J_2 = 1.08263 \times 10^{-3}$ (second zonal harmonic)

$\mu = 398600 \text{ km}^3/\text{s}^2$ (gravitational parameter for Earth)

$R = 6378 \text{ km}$ (Earth radius)

$e = 0$ (eccentricity for a circular orbit)

$a = \text{altitude (km)} + R \text{ (semi major axis)}$

$i \text{ (inclination)}$

Because the inclination of a satellite is difficult and expensive to change from the initial orbit, and all other values are constants for one altitude only, the satellite can be sun-synchronous for a range of inclinations. For example, for an inclination $i=96.33^\circ$, the satellite, to be sun-synchronous, should remain at 200-km altitude. This means that only when the satellite is at 200-km altitude will it make a pass according to design, and this will last a limited number of days because of atmospheric drag. After that, the time of revisit will start to drift, and this must be taken into account in the design of the operation. The drawback for small satellites is that their altitude is not constant. Since they do not usually have their own propulsion systems, atmospheric drag reduces the satellites' altitudes, until they reenter the atmosphere.

In real operations, extended coverage of an area requires not just one, but a constellation of small satellites. The number of assets will be, determined by the operational requirements. The way to increase the area or duration of coverage is to increase the number of orbital assets. Constellations are principally defined by the number of planes, the RAAN of each plane, and the number of satellites in each plane. True anomaly is the angle between the direction of periapsis and the current position of the satellite, as seen from the center of the earth (true anomaly, n.d.). Keeping the orbit elements of the constellation identical and changing true anomaly, one can disperse or concentrate the access time above a region for a particular period during a day.

As an example, simulating in Satellite Tool Kit, a sun-synchronous, two-satellite constellation with the same orbital elements, and with the Gulf of Mexico as the area of interest, a change in true anomaly of 70 degrees to the second asset has the result of accessing the whole area with only two satellites every night at the same time (Figure 8).

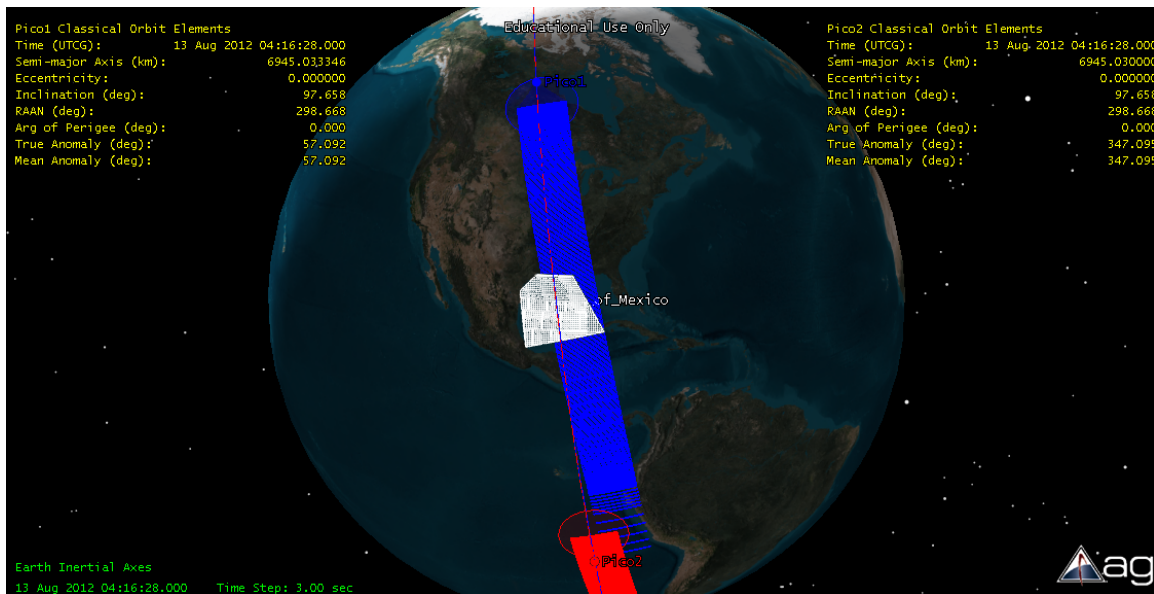


Figure 8. Coverage of Gulf of Mexico

Bordetsky and Mantzouris simulated in STK a four- and a six-satellite constellation and chose to disperse the assets by using different arguments of perigee.

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III. LARGE SCALE EXPERIMENT AND SIMULATION

A. LARGE SCALE EXPERIMENT

1. The Experiment in General

The nature of MIOs is so complex—and at the same time, the satellite world is so advanced technologically—that it is impossible for a single experiment to examine and prove the level of integration that can be achieved between MIOs and small satellites, and the interactions that occur between the two. So this experiment may be considered part of an experimentation campaign that includes hypothesis generation and testing efforts. Alberts et al. defines an experimentation campaign as “a series of related activities that explore and mature knowledge about a concept of interest” (Alberts et al., 2002). As illustrated in Figure 9, “experimentation campaigns use the different types of experiments in a logical way to move from an idea or concept to some demonstrated military capability” (Alberts et al., 2002).

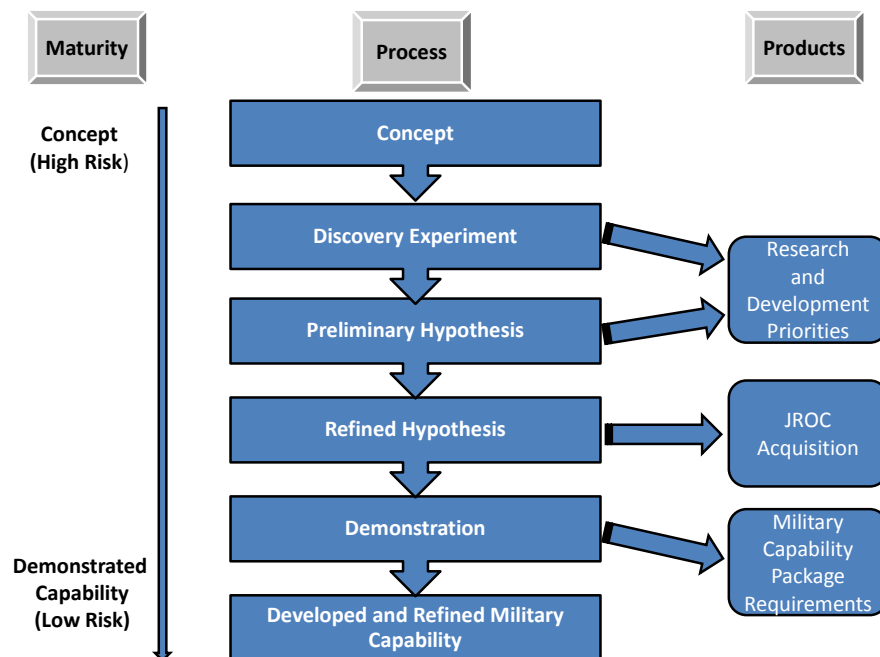


Figure 9. From theory to practice (Adapted from Code of Best Practice for Experimentation)

Discovery experiments, according to Alberts, lead to hypothesis generation. “They generate rich insights and knowledge, they will not ordinarily provide enough information (or evidence) to reach a conclusion that is valid (correct understandings of the cause-and-effect or temporal relationships that are hypothesized) or reliable” (Alberts et al., 2002). Since the integration of small satellites in a military operation environment such as an MIO has never been tried before, a discovery experiment can become very useful for hypothesis generation. The simulations that Bordetsky et al. conducted with picosatellite constellations are in the discovery track. They demonstrated that small satellites in general can become a valuable tool for MIOs and these simulations can be the start for an experimentation campaign that can test hypotheses like that in this research (Table 1).

This research moves one step forward from theory to practice (Figure 9). In this experiment, “preliminary hypotheses” are those related to the aforementioned relationships between the creation, use, and disbandment of strong and weak ties, and their effect in the adaptation of the model, as described in Table 1. The “refined hypothesis” is focused on evaluating the use of small satellites in the creation, use, and disbandment of strong and weak ties, and also in evaluating new parameters that appear in the information-distribution loop. Alberts states that “Hypothesis testing experiments are the classic type used by scholars to advance knowledge by seeking to falsify specific hypotheses (specifically if...then statements) or discover their limiting conditions. They are also used to test whole theories (systems of consistent, related hypotheses that attempt to explain some domain of knowledge) or observable hypotheses derived from such theories. In a scientific sense, hypothesis testing experiments build knowledge or refine our understanding of a knowledge domain. In order to conduct hypothesis testing experiments, the experimenter(s) create a situation in which one or more factors of interest (dependent variables) can be observed systematically under conditions that vary the values of factors thought to cause change (independent variables) in the factors of interest, while other potentially

relevant factors (control variables) are held constant, either empirically or through statistical manipulation.” (Alberts 2002). In this experiment adaptation, strong and weak ties are observed while the values of the aforementioned independent variables vary, keeping orbit, time, and training constant.

This experimentation campaign can be completed by a number of demonstrative experiments. According to Alberts et al., “in such demonstrations, all the technologies employed are well-established and the setting (scenario, participants, etc.) is orchestrated to show that these technologies can be employed efficiently and effectively under the specified conditions.” (Alberts 2002). For this situation, after hypothesis-testing results are clear and well understood, the experimenters can focus their attempts to attract support for the adoption of this innovation. For a successful demonstration, the team has to correct all the factors that caused problems to the system or discrepancies in the results and to investigate the settings that best describe the concept.

2. Experiment Scenario and Initial-Plan Structure

a. Scenario Overview

NATO launched a constellation of six small satellites in polar orbits as a communication aid for a large-scale exercise to be conducted south of Crete. Experiment intelligence indicates that a terrorist organization wants to transfer fissile materials from Ukraine to Iran. A container ship (Figure 10) departed from the port of Odessa, Ukraine, and declared as last port of call Alexandria, Egypt. After leaving the Aegean Sea, and after NATO received information from the AIS system of the ship, the last port of call changed to Imam Khomeini port in Iran. NATO decided to start an MIO for this incident and ordered a group of four ships to proceed to the area of the contact of interest (COI). The COI is 150 nautical miles southeast of Crete. This MIO experiment will be conducted in two phases.

Phase 1. Arriving in the area, no radioactive source is detected from sensors employed by the four warships, so the local command decides to

send a boarding team to further investigate cargo, crew, manifest, route of travel, and biometrics. For this investigation, the boarding team maintains network connectivity via terrestrial means of communication with their command-and-control center aboard one of the four ships. They are equipped with hand-held active and passive nuclear/radiological detectors, cameras, and other advanced biometric data-collection devices. Detection results, including those from visual and verbal descriptions, are downloaded and stored into computers. A fast-deployable ground station for small satellites, including SmallSat antenna, control, and tracking displays, is also part of the boarding team's equipment. Information in the form of simple data, voice, picture, and video recordings are gathered by the team and sent to Europe (NATO Joint Chemical Biological Radiological and Nuclear Center of Excellence in Czech Republic) and the US (Lawrence Livermore National Laboratory), where technical nuclear/radiological experts will conduct analysis and adjudication. The team also sends information to their command-and-control center. The amount and type of data transferred will vary greatly, according to the availability and capacity limits of the communication assets and the data consumers' requirements. Finally, the team decides on further actions in the boarding operation after receiving the expert results via satellite link (Figure 11).



Figure 10. Iranian container ship

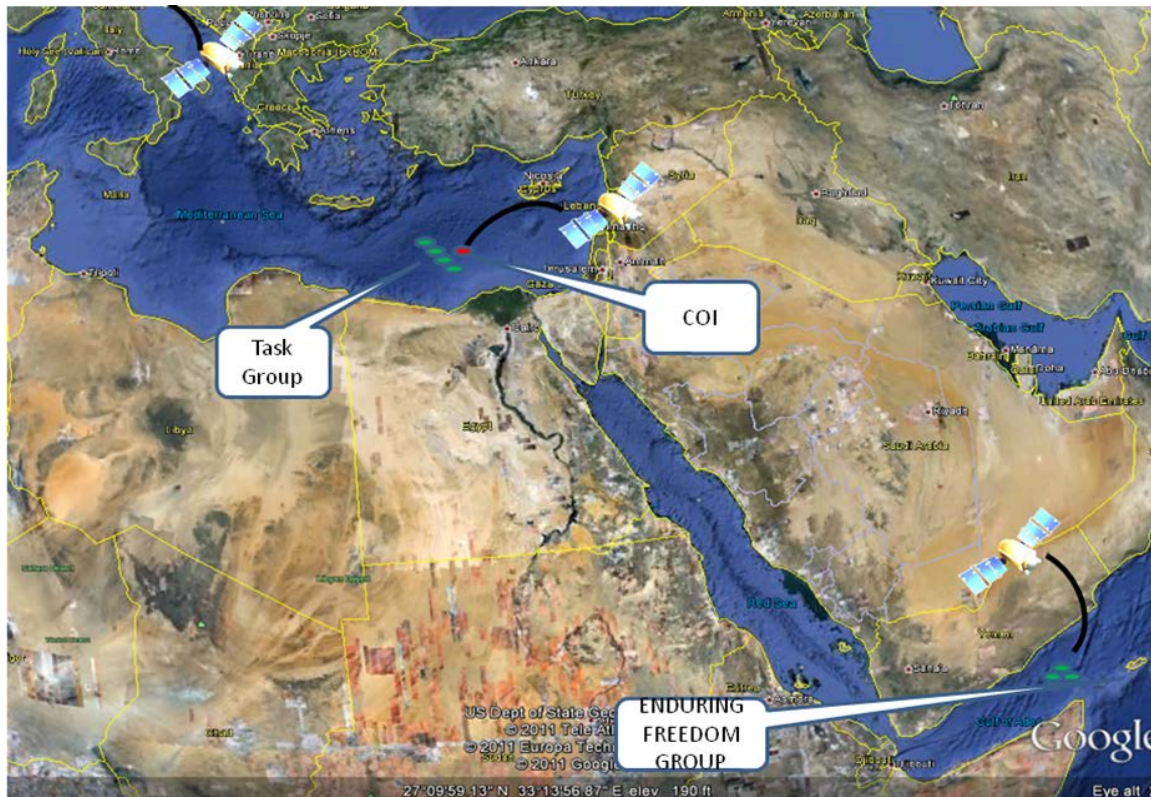


Figure 11. Scenario overview

Phase 2, the Iranian container ship continues her route to Imam Khomeini port. NATO decides that warships participating in Operation Enduring Freedom at the Horn of Africa area will escort the COI to a safe port for further investigation, and they will need all related information. The command-and-control center (one of the four warships in the Mediterranean) uploads information (data and results from the boarding operation) to the orbital assets and a unit of Operation Enduring Freedom uses a downlink to receive the information. Two more fast-deployable ground stations for small satellites are required for the execution of this phase of the experiment: one on the local command-and-control center and one on the ship at the Horn of Africa that is collecting the pertinent information (Figure 11).

3. Team Composition and Experimentation Roles

The design of this experiment requires the involvement of people with a variety of expertise. Military experts, operators familiar with the functions involved in the scenario, academic experts involved in the experiment design, data analysis and modeling experts, individuals with knowledge of scenario development, and those with technical expertise in generating and instrumenting a realistic environment (Alberts, 2002) will together orchestrate this experiment.

The team comprises the following sub teams (Table 3):

- Academic experts. These will be mostly from NPS and will be responsible for the control of the experiment. Principal Investigator, experiment plan, design and execution, a network-operation-center officer, ground-station controllers, and data-capturing-tools controllers are some of the basic responsibilities of this sub team. These experts will be distributed to the various sites of the experiment; some will be in the CENETIX room at NPS. They will handle the design variables and make sure that functional constraints are held constant. Finally, people located at NPS will observe the measurements that explain the dependent variables
- Nuclear/radiological experts. For this model, NATO JCBRN Defense CoE in Czech Republic and LLNL in US will receive the packets of information, analyze them, and send the results back to the boarding team on site.
- Military experts will staff the various positions on site and be responsible for the realistic conduct of the scenario. They will be provided by NATO Maritime Interdiction Operations Training Center (NMIOTC) in Crete.

SUB TEAM	ORGANIZATION	LOCATION	RESPONSIBILITIES
Academic experts	NPS	NPS/ on site	Principal Investigator, experiment plan, design and execution, network operation center officer, ground station controllers, data capturing tools controllers
Nuc/Rad experts	NATO JCBRN CoE / LLNL	Czech Republic / US	receiving the packets of information, analyzing them and sending the results back to the boarding team on cite
Military experts	NMIOTC	on site	realistic conduction of the scenario

Table 3. Team composition, location, and responsibilities

4. Data Analysis and Collection Plan

The data analysis and collection plan is the heart of the experiment. The efforts involved are highly linked, and although it is intuitive first to collect and then to analyze, in reality things are much more complicated. The purpose of collecting data is to feed the data-analysis plan, so it is obvious that the data-analysis plan determines what kind of data is needed for every situation. Alberts mentions that “while the data analysis plan should be posited first, the process of developing the two plans will be iterative. The initial data requirements from the posited data analysis plan will have to be put into the context of the experiment setting, the collection means available (pre-experiment, automatic, observer based, SME based, etc.), and the scenarios being used.” This means that data-analysis plan will be modified to accept only available data and, on the other hand, the collection process may reveal needs for analysis not described in the initial data-analysis plan (Albert et al., 2002). The categories of data that the experiment team will capture are shown in Table 4.

Categories of data	
1.	Number of nodes involved in each packet of information distribution
2.	Bit error rate
3.	Number of strong and weak links that exist at any particular time
4.	Degrees of separation between the sender and the receiver of each packet of information
5.	Network performance when there are only terrestrial nodes inside the network
6.	Network performance when there are orbital nodes inside the network

Table 4. Categories of data

a. Data-Analysis Plan

The data-analysis plan includes descriptive, bivariate, and multivariate analysis. In the descriptive phase of the plan, data anomalies are identified and corrected or excluded from analysis. After the identification of data anomalies, the distribution of each variable is examined. The purpose of this action will be twofold: to find any invariant variable and remove it from the analysis plan, and to discover the number of outliers, and thus know what kind of statistics should be used.

Since most hypotheses include if-then terms such as “if A occurs then B happens under condition of C”—and because of the relationships explained in Table 1 and the four Pareto sets (strong/weak links vs. scalability and strong/weak links vs. degrees of separation)—bivariate analysis for this model is essential and is expected to uncover important dynamics within the data. According to Alberts, “in order to identify the relationships between the various factors and variables, the order for conducting bivariate analyses is:

- Dependent variables

- Control factors
- Control factors and dependent variables
- Independent variables
- Control factors and independent variables and
- Independent variables and dependent variables.” (Alberts et al., 2002).

Particularly for this experiment, criteria and constraints from Table 2 and the Pareto sets will be analyzed. Scalability and degrees of separation should be independent. If correlated, the design should need some changes such as redefinition or merging or splitting the variables (Alberts et al., 2002). Association (if any) between orbital characteristics, time, and participant's training will be determined, and after that relationships between them and dependent variables will be identified. Because the design of the experiment is supposed to exclude effects of functional constraints by keeping them constant, if any relationship between functional constraints and dependent variables are identified, “the analytic team would know that the design had been unsuccessful and these factors would need to be included in the later multivariate analyses and considered in the process of refining the conceptual model.” (Alberts et al., 2002).

Like dependent variables, the independent variables of this model are assumed unrelated. If not, changes to the design are needed. If there is any relationship between the independent variables and functional constraints, that will indicate that the design is probably flawed.

Finally, independent and dependent variables are examined for relationships among them. At this point, Alberts mentions that “these are true tests of the strength of association for the direct propositions of hypotheses posited in the conceptual model.” (Alberts et al., 2002). It is important that the team test all possible bivariate combinations because this project belongs to an

early experimentation domain, and there can be relationships not considered in the design.

Finally, multivariate analysis will test the whole data as a system.

b. Data-Collection Plan

The data-collection plan for this experiment is based on “automated collection, recording for later reduction and human observation” (Alberts et al., 2002). It is essential for the team to ensure that the aforementioned data-collection mechanisms impact the functionality of the systems as little as possible. Also, because time is critical, time synchronization for everybody and for all assets of the experiment is necessary. Automated collection enables the team to monitor easily and accurately certain data during the experiment without too many people involved, eliminating human error. Recording for later data reduction is the safe method for capturing data, because it eliminates errors from too few observers or incorrect understanding of what to record and what not to. Audio and visual recordings, enriched with meta-data, will be used for later analysis after reduction. Human observation is an important data-capturing technique, especially for data that other tools cannot capture, because it captures data from a higher-level, human view. This method can give very useful information, but on the other hand, can be extremely inaccurate because of observer subjectivity; for this to be avoided, observer selection and training is important.

Table 4 depicts the data to be collected. For categories 2, 5 and 6 automated collection will be used; for category 4, recording for later reduction and human observation will be used, and for categories 1 and 3, human observation (Table 5). Only select people from the team will have access to each variable, to avoid conflicts in measurements. It is assumed that three to four days of measurements are enough for extraction of useful conclusions from the gathered data, and that deep knowledge of equipment handling by the team will ensure quality data collection. CENETIX resource portal tools will be used for

capturing events, anomalies, useful information, meta-data, collaboration between the members of the team, and data reduction and assembly.

Collection Plan	Data Category
Automated collection	• Bit error rate • Network performance when there are only terrestrial nodes inside the network • Network performance when there are orbital nodes inside the network
Recording for later reduction	• Degrees of separation between the sender and the receiver of each packet of information
Human observation	• Number of nodes involved in each packet of information distribution • Number of strong and weak links that exist at any particular time

Table 5. Data-collection plan

5. Experiment Evolution

“In a present day scenario, an 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 channel 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” (Bordetsky et al., 2011). The evolution of MIOs by adding orbital nodes to the network can limit the problems described above; thus operational risk for the boarding team can be minimized and rapid decisions made. Small satellites include a variety of orbital assets, with different advantages and disadvantages. So testing and comparing different kinds of small satellites may be the next step for this campaign. Because, generally speaking, this kind of satellite lacks onboard propulsion, they can only

be put in the lower LEO altitudes, to avoid creating long-lived debris at higher altitudes. This affects many factors in this experiment. It would be an appropriate challenge for a team to investigate the use of different LEO orbits to realize what results may be derived, because it is possible that in the future some small satellites will have onboard propulsion.

IV. INTEGRATION OF SMALL SATELLITES TO MIO NETWORKS

A. AISSAT 1 AND ATLAS CRAFT TARGETR

1. AISSat-1. An Existing Asset as an Example of a Possible MIO Satellite.

As of this writing, there have been no known attempts to build a small satellite dedicated to MIO operations. The reason stems more from limited interest among nations that conduct MIO operations than from any lack of technology. Countries are not well informed of the advantages a small satellite can offer in such operations, or of their relatively small cost of deployment. The technology required for an attempt of this kind is already here, and a living example is AISSat-1. “AISSat-1 is believed to be the first low cost nano-satellite to provide an observational service to governmental authorities. The mission objective is to perform maritime observations in the Norwegian high north and high south” (Narheim et al., 2010).

AISSat-1 is a nanosatellite, a 20-cm cube. Its platform is based on University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS-SFL)’s generic nanosatellite bus (GNB), a low-cost spacecraft bus weighing around 6 kg and equipped with three-axis attitude determination and control components, which provide high-precision pointing. This asset carries an AIS (dual-channel VHF) receiver developed by Kongsberg Seatex AS, Norway, a UHF receiver, and an S-Band transmitter (Figure 12) (Eriksen et al., n.d.).

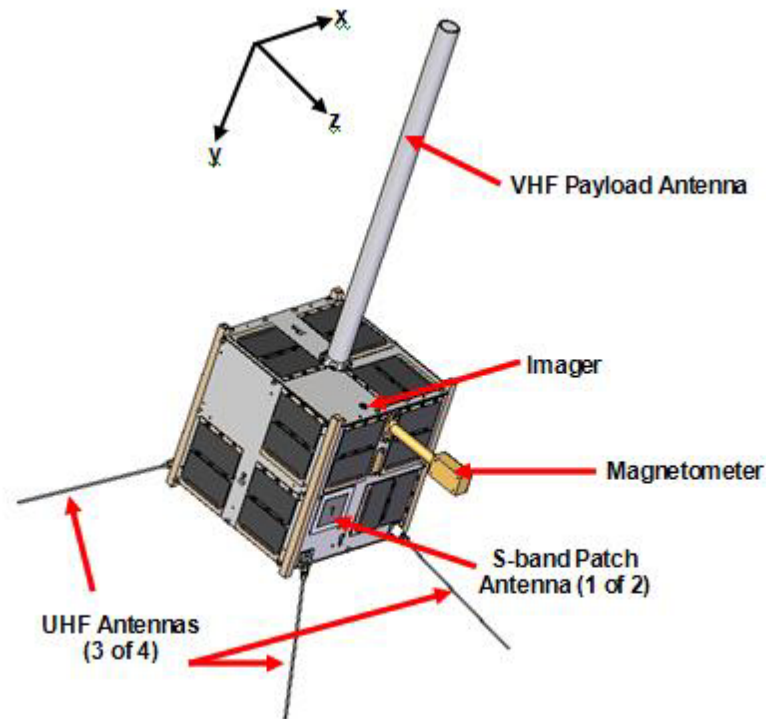


Figure 12. AISSat-1 External Layout(Adapted from AISSat-1 Early Results)

Moving on a sun-synchronous orbit at 630-km altitude, the AISSat-1 collects AIS signals from vessels, decodes them, and either downloads directly to the ground station at Svalbard, if within line of sight, or stores the data on board in order to download at first opportunity. For data downlink, an S-Band transmitter is used, capable of data rates from 32 to 256 Kbps, and two patch antennas are mounted on the satellite in such a way that near-omnidirectional coverage is achieved. Data latency is reduced to a minimum, as the AISSat-1 can communicate with the ground station on every orbit. The real-time or recorded data from all daily orbits are stored at Svalbard to forward to a mission-control center located at FFI in southern Norway. Finally, the Norwegian Coastal Administration (NCA), which is the main recipient of the data, makes it available to the rest of AIS system (Figure 13) (Narheim et al., 2010). For data uplink from

the ground station, a UHF receiver is used, operating at 4 kbps. The antenna setup is four phased, quad-canted, monopole antennas, for near-omnidirectional coverage.

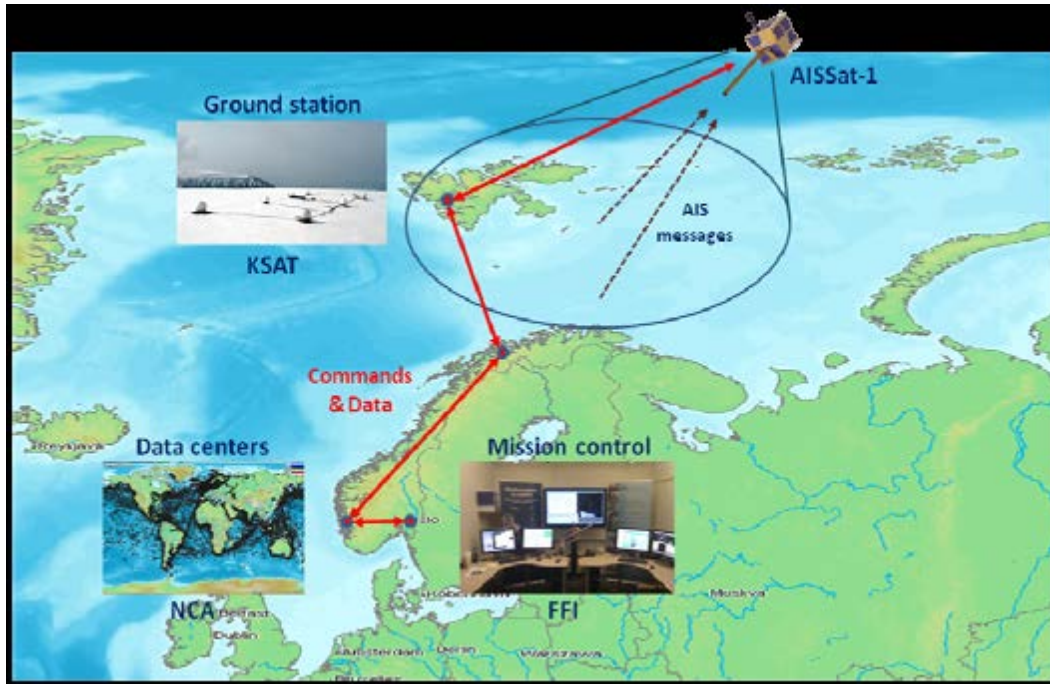


Figure 13. AISSat-1 communications architecture(Adapted from Tracking Ship Traffic with Space-Based AIS: *Experience gained in first months of operations*)

2. TARGETR: Atlas Craft Threat Detection and Analysis Tool.

A very accurate illustration of AISSat-1 data can be had with an Atlascraft next-generation, threat-detection and analysis tool called Targetr. Using web services, Targetr gathers and correlates data from every available source, such as satellite data feeds, terrestrial collection stations, historical databases, published reports, RSS feeds, web sites, and third-party providers. Fusion of this data enables the tool to provide “proactive situational awareness, enabling rapid maritime anomaly detection, threat identification, and reaction.” “Targetr addresses movement, identification, metadata, and relationships for vessels, cargo, companies, people, and the interactions between them” (Targetr, n.d.).

For this research, the author requested that Atlascraft create a special account in their website where AISSat-1 is the only source that provides information for any target. With AISSat-1 as the only source of data, the user can understand, using Targetr, how the satellite operates, its effectiveness and quality of service, and similarities to and differences from future MIO satellites. In addition, the user can easily visualize and exploit the available data via analytical maps, tables, pictures, and other convenient tools.

For the date May 30, 2012, between 0600 and 0800, Targetr retrieved from the FFI database the targets in Figure 14. The reason for acquiring data from this short, particular period only is that choosing longer periods would make the picture too loaded with tracks and difficult to analyze. It is obvious from Figure 14 that the AISSat-1 orbit covers the higher latitudes more efficiently, which is logical, as the purpose of this satellite is coverage of the Norwegian Sea. Every yellow triangle on the map represents a track whose AIS signal is received from the satellite during that period. The position of every track and all other available data such as name, place of origin, destination, etc., are retrieved from the transmitted signal.

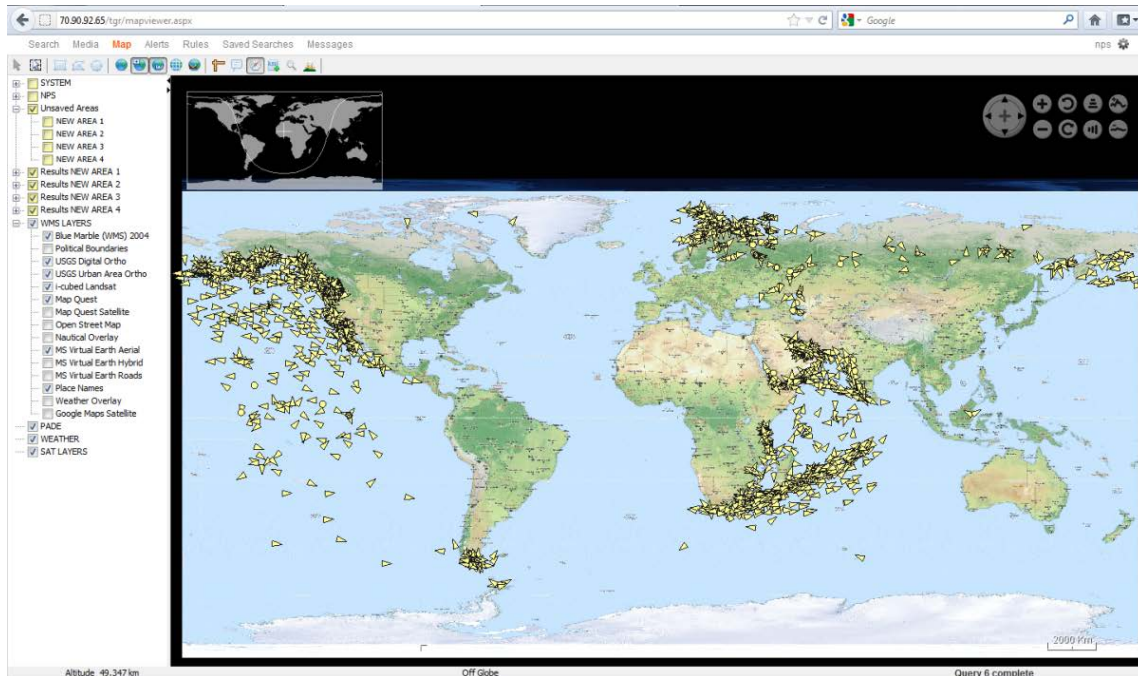


Figure 14. Targetr platform

For a clearer look at the type of data the satellite can receive from an AIS source and then transmit to a ground station, either directly or when downlink is feasible, we zoom in on the Norwegian Sea and arbitrarily selected a track. The area of coverage of the satellite is displayed in light green. Theoretically, every vessel inside this area transmitting AIS signals is captured and stored in the satellite's memory. In reality, the quality of reception for each signal is the combined result of many factors, such as environmental conditions, the position of the vessel, traffic in the area (causing message collisions), condition and status of the AIS transmitter; but the measured performance on detection probability is within acceptable levels (more than 90%). Clicking on the selected track, information about the identification of the vessel, heading, speed, latitude, longitude, and time of the position of the track are automatically displayed. Selecting to expand the track, the tool illustrates in red all the vessel positions the satellite received on every orbit (Figure 15).

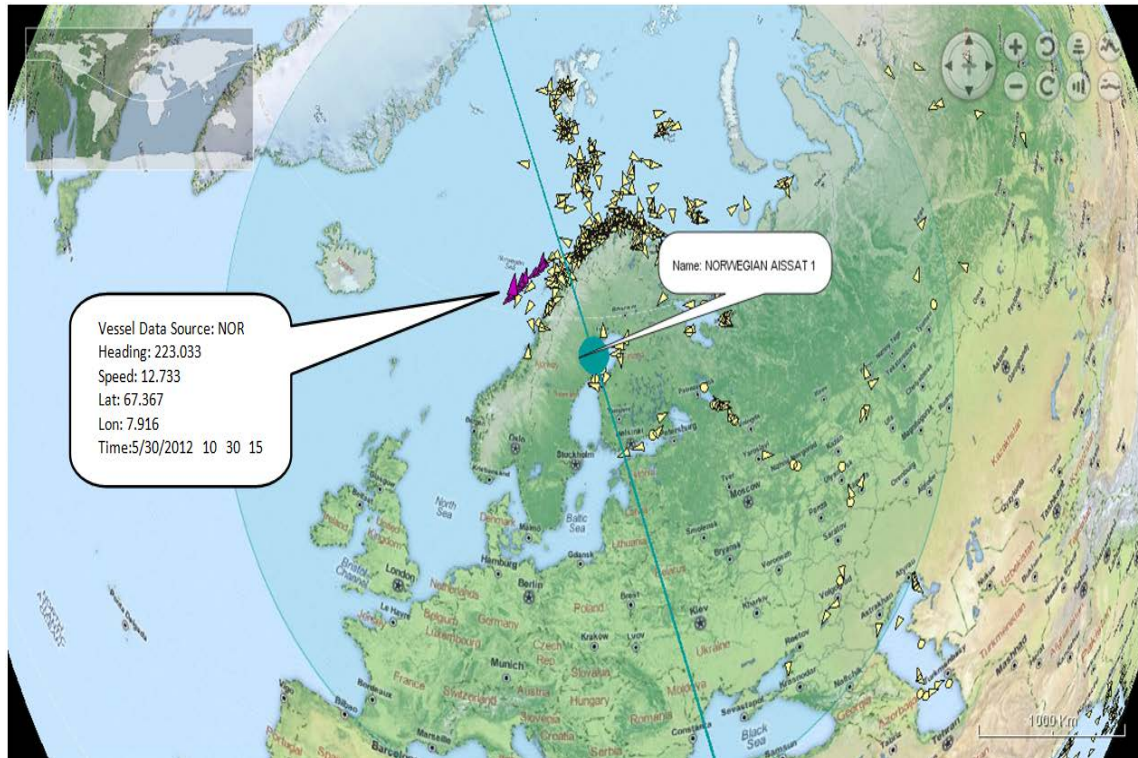


Figure 15. Track expansion and AISat-1 area of coverage

Selecting “show details page,” one can draw some interesting conclusions about the received data (Figure 16). For the aforementioned track, it is obvious that the AISat-1 received twelve different sets of data. Examining the time between receptions, one can easily derive that the satellite received AIS signals from the particular vessel from eight of a total of fifteen passages above the given area in one day. At some passages, more than one signal was received. After checking the receptions of many vessels, the author observed that generally, for every track, there is from one to seventeen or more receptions in a day. This observation leads to the conclusion that there can be many opportunities for a track positioned at a convenient place, under optimal environmental conditions, to upload a significant amount of data to the satellite. The downlink of the data to Svalbard is not difficult as the station is located to a high latitude (78.216 N) and so the satellite has many chances to see the ground station while orbiting during a day.

▼ METADATA

	NOR U 12 POSITIONS
▼ IDENTIFICATION INFORMATION	
MMSI	265936000

▶ INTERACTIVE MAP

▶ AIS MESSAGE TRAFFIC TO VESSEL

▼ POSITIONS

LATITUDE	LONGITUDE	OBSERVATION TIME	SOURCE	STATUS
67° 22' 02.09"N	07° 54' 58.07"E	2012-05-30 22:30:15Z	NOR	Active
67° 22' 02.09"N	07° 54' 58.07"E	2012-05-30 22:30:15Z	NOR	Active
67° 36' 59.32"N	08° 31' 02.97"E	2012-05-30 20:54:35Z	NOR	Active
67° 51' 32.88"N	09° 07' 20.11"E	2012-05-30 19:18:06Z	NOR	Active
67° 51' 32.88"N	09° 07' 20.11"E	2012-05-30 19:18:06Z	NOR	Active
68° 05' 13.44"N	09° 41' 28.50"E	2012-05-30 17:42:46Z	NOR	Active
68° 05' 13.44"N	09° 41' 28.50"E	2012-05-30 17:42:46Z	NOR	Active
68° 45' 36.89"N	11° 37' 17.27"E	2012-05-30 12:47:06Z	NOR	Active
68° 59' 13.67"N	12° 20' 46.51"E	2012-05-30 11:10:35Z	NOR	Active
68° 59' 13.67"N	12° 20' 46.51"E	2012-05-30 11:10:35Z	NOR	Inactive
69° 14' 04.52"N	13° 04' 43.76"E	2012-05-30 09:34:21Z	NOR	Active
69° 28' 17.11"N	13° 47' 16.00"E	2012-05-30 07:57:33Z	NOR	Active

▼ SEVERE ALERTS

▼ HIGH ALERTS

▶ ELEVATED ALERTS

▶ GUARDED ALERTS

▶ LOW ALERTS

▶ HYPERGRAPH

▶ FUSION EVENTS

Figure 16. The “show details” page

B. STK

1. STK Modeling of AISat-1

The following modeling efforts are based on the scenario described in the previous chapter. A boarding team onboard a ship of interest located southwest of Crete conducts an MIO and a constellation of small satellites is used for the transfer of information between the team and radiological/nuclear experts in the data-fusion center. For simplicity, this scenarios takes into account two terrestrial nodes of the network only: the boarding team on the ship and the JCBRN Defense CoE. The ship is moving in circles with a speed of 12 knots (Figure 17). The constellation consists of six identical nanosatellites and follows the pattern Bordetsky and Mantzouris introduced in their work with the following differentiation: in the first model, the altitude of the assets is 630 km and in the second, 310 km (Table 6).

The characteristics of the asset platform are based on AISSat-1. This choice is made because this particular design has been tested while in orbit since 2010, and the products of its two-year operation are very promising for the integration of a similar spacecraft into an MIO network. It is assumed that the platform is equipped with three-axis attitude determination and control components. The communications packet consists of a 1dbW transmitter and a receiver, both operating at 2.4 GHz. The antennas are patch antennas with 3dB main-lobe gain and they provide a hemispherical operating pattern. Additional gains and losses are assumed to be zero. The assumption is that the two ground stations (the ship and the JCBRN center) operate with identical equipment with an operating frequency of 2.4 GHz and transmitter power of 30dBW. They use a pencil-beam antenna with 40dB main-lobe gain and there are no other gains or losses in the system (Table 7). The reader can find details of this scenario in the appendix of this paper.

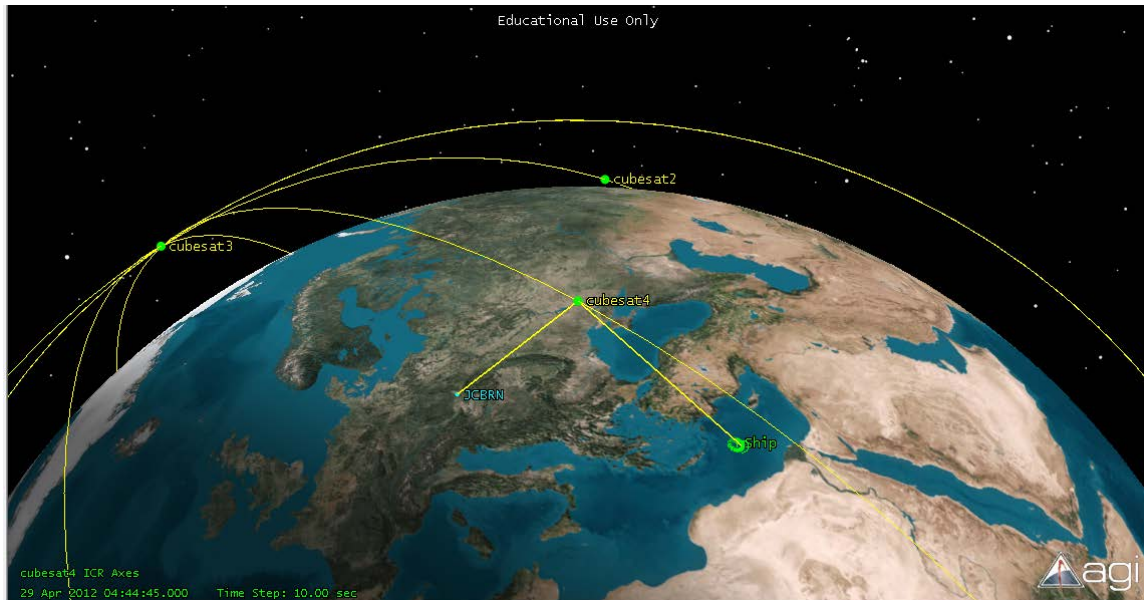


Figure 17. The two nodes of the network communicating via satellite

Orbital Assets	Apogee Altitude Model1/Model2 (Km)	Perigee Altitude Model1/Model2 (Km)	Inclination (degrees)	Argument of Perigee (degrees)	RAAN (degrees)	True Anomaly (degrees)
Cubesat 1	630/310	630/310	90	0	0	0
Cubesat 2	630/310	630/310	90	45	45	0
Cubesat 3	630/310	630/310	90	90	90	0
Cubesat 4	630/310	630/310	90	135	135	0
Cubesat 5	630/310	630/310	90	180	180	0
Cubesat 6	630/310	630/310	90	225	225	0

Table 6. Constellations set up

	Nanosatellite	Ship	JCBRN
Pointing Equipment	three-axis attitude determination and control components	-	-
RF Output Power (dBW)	1	30	30
Frequency (GHz)	2.4	2.4	2.4
Type of Antenna	patch	Pencil Beam	Pencil Beam
Main Lobe Gain (dB)	3	40	40
Miscellaneous gains/losses	0	0	0

Table 7. Nanosatellite/ground-station characteristics

2. Integration Modeling Results

We ran the simulations of the two models for a twenty-four hour period. The date of the scenario is April 28–29, 2012. We focused our interest on two basic factors: the duration every orbital asset available to the network and the quality of service these assets can provide to the network. Because different assumptions translate into different results, and differences in the technology

employed can mislead as to what is appropriate or not, we derive results comparing the two models with their only difference being the altitude of the orbit. With comparison, we tried to eliminate most other factors that relate to our assumptions and technology used.

The higher a satellite's orbit, the bigger the possible area of coverage on the surface of the earth. Therefore, it is expected that at 630 km altitude, the access duration of the orbital assets should be improved as compared with that at 310 km. Tables 8 and 9 illustrate the results for access time for the two constellations from JCBRN station. It appears that doubling the altitude of the asset causes the access time to increase from 70% for Satellite 4 (minimum increase: from 38.3 at 310 km altitude to 65.3 minutes at 630km altitude) up to 126% for Satellite 1 (maximum increase: from 32.6 at 310 km altitude to 73.7 minutes at 630km altitude). The duration of every access increased from a range of 4.6–9 minutes at an altitude of 310 km to a range of 5–13 minutes at an altitude of 630 km. Also, the number of accesses was more at 630 km and the total duration showed an increase of 92% in access time during a day. The results presented in Tables 8 and 9 are for the location of the JCBRN center and are different for every spot on the globe.

	At 630 km					At 310 km			
	Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)		Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)
Satellite 1	1	4/28/12 19:28	4/28/12 19:41	12.8		1	4/28/2012 19:28	4/28/2012 19:36	8.1
	2	4/28/12 21:06	4/28/12 21:18	12.6		2	4/28/2012 20:59	4/28/2012 21:07	8.3
	3	4/28/12 22:45	4/28/12 22:50	5.3		3	4/29/2012 7:15	4/29/2012 7:23	7.4
	4	4/29/12 6:31	4/29/12 6:41	9.8		4	4/29/2012 8:45	4/29/2012 8:54	8.7
	5	4/29/12 8:06	4/29/12 8:19	13.3					32.6
	6	4/29/12 9:45	4/29/12 9:56	11.1					
	7	4/29/12 18:14	4/29/12 18:23	8.8					
				73.7					
Satellite 2	Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)		Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)
	1	4/28/12 20:56	4/28/12 21:02	5.9		1	4/28/2012 22:19	4/28/2012 22:27	7.7
	2	4/28/12 22:31	4/28/12 22:44	12.9		2	4/28/2012 23:49	4/28/2012 23:58	8.6
	3	4/29/12 0:08	4/29/12 0:21	12.5		3	4/29/2012 10:06	4/29/2012 10:13	6.9
	4	4/29/12 1:48	4/29/12 1:53	4.6		4	4/29/2012 11:36	4/29/2012 11:44	8.9
	5	4/29/12 9:34	4/29/12 9:44	10.0		5	4/29/2012 13:11	4/29/2012 13:12	1.2
	6	4/29/12 11:08	4/29/12 11:22	13.4					33.2
	7	4/29/12 12:48	4/29/12 12:59	11.0					
				70.2					
Satellite 3	Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)		Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)
	1	4/28/12 23:58	4/29/12 0:05	6.4		1	4/29/2012 1:09	4/29/2012 1:17	7.2
	2	4/29/12 1:34	4/29/12 1:47	13.0		2	4/29/2012 2:40	4/29/2012 2:48	8.8
	3	4/29/12 3:11	4/29/12 3:24	12.4		3	4/29/2012 12:57	4/29/2012 13:03	6.2
	4	4/29/12 4:51	4/29/12 4:55	3.8		4	4/29/2012 14:26	4/29/2012 14:35	9.0
	5	4/29/12 12:36	4/29/12 12:46	10.2		5	4/29/2012 16:00	4/29/2012 16:04	3.8
	6	4/29/12 14:11	4/29/12 14:25	13.4					35.0
	7	4/29/12 15:50	4/29/12 16:01	10.8					
				70.0					

Table 8. Satellite 1, 2, and 3 access times and duration at 630km and 310km

At 630 km					At 310 km				
Satellite 4	Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)		Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)
	1	4/29/12 3:01	4/29/12 3:08	6.9		1	4/29/2012 4:00	4/29/2012 4:07	6.5
	2	4/29/12 4:36	4/29/12 4:49	13.0		2	4/29/2012 5:30	4/29/2012 5:39	8.9
	3	4/29/12 6:14	4/29/12 6:26	12.3		3	4/29/2012 7:03	4/29/2012 7:06	3.4
	4	4/29/12 7:54	4/29/12 7:57	3.0		4	4/29/2012 15:48	4/29/2012 15:53	5.4
	5	4/29/12 15:39	4/29/12 15:49	10.5		5	4/29/2012 17:16	4/29/2012 17:25	9.0
	6	4/29/12 17:14	4/29/12 17:27	13.4		6	4/29/2012 18:50	4/29/2012 18:55	5.1
	7	4/29/12 18:53	4/29/12 19:00	6.2					38.3
				65.3					
Satellite 5	Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)		Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)
	1	4/28/12 19:55	4/28/12 20:08	13.2		1	4/28/2012 19:53	4/28/2012 20:02	8.7
	2	4/28/12 21:33	4/28/12 21:45	11.8		2	4/28/2012 21:25	4/28/2012 21:32	7.3
	3	4/29/12 6:03	4/29/12 6:11	7.3		3	4/29/2012 6:51	4/29/2012 6:56	5.7
	4	4/29/12 7:39	4/29/12 7:52	13.1		4	4/29/2012 8:20	4/29/2012 8:29	9.0
	5	4/29/12 9:17	4/29/12 9:29	12.2		5	4/29/2012 9:52	4/29/2012 9:57	4.8
	6	4/29/12 10:58	4/29/12 10:59	1.8		6	4/29/2012 18:39	4/29/2012 18:43	4.3
	7	4/29/12 18:41	4/29/12 18:52	10.7					39.9
				70.0					
Satellite 6	Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)		Access	Start Time (UTC)	Stop Time (UTC)	Duration (min)
	1	4/28/12 21:24	4/28/12 21:33	9.1		1	4/28/2012 22:44	4/28/2012 22:52	8.5
	2	4/28/12 22:58	4/28/12 23:11	13.3		2	4/29/2012 0:15	4/29/2012 0:23	7.8
	3	4/29/12 0:36	4/29/12 0:48	11.6		3	4/29/2012 9:42	4/29/2012 9:46	4.6
	4	4/29/12 9:06	4/29/12 9:14	7.7		4	4/29/2012 11:11	4/29/2012 11:20	9.0
	5	4/29/12 10:42	4/29/12 10:55	13.1		5	4/29/2012 12:42	4/29/2012 12:48	5.8
	6	4/29/12 12:19	4/29/12 12:31	12.1					35.7
				66.8					
Total duration of access				416		215 min			
				6.9		3.6 hours			

Table 9. Satellite 4, 5, and 6 access times and duration at 630 km and 310 km

Generally, the higher the latitude of a location, the more accesses and greater access duration this location has when the orbital assets follow polar orbits. This is the reason for the small differences in Bordetsky and Mantzouris' findings and the findings of this research. The results of the comparison of the access between the constellations and the ship are similar. At these two simulations, the vessel is set to a 12-knot speed. As a moving node, the ship has different access time from the JCBRN ground station, but because the two terrestrial stations are not on the same latitude (the JCBRN station is far north of the vessel) the difference in their results is a product of movement and latitude. For this scenario, ship-to-satellite access is reduced approximately 25% in

comparison with JCBRN-to-satellite access. Comparing the numbers of the two simulations, one can assume that the higher the orbit of a satellite, the more coverage. In Chapter III of this thesis, we mention that because small satellites lack propulsion systems, they fly in the bottom limits of LEO to avoid becoming long-lived debris. However, even if they had propulsion, these spacecraft would not be able to operate at high LEO because of other technical reasons.

Available power and volume are two major considerations in putting small satellites in high-altitude orbits. Limited power equals limited signal-transmission power and limited volume translates to limited antennas size, and thus limited gain. Transmission power and antenna type and size are two of the most important parameters for successful communication between stations. A 20-cm cube is able to produce from a couple of Watts up to a couple of tens of Watts electric power (with deployable solar arrays) (Helvajian H. and Janson S., 2008) and carry whatever antenna can be stored inside the cube initially and mounted outside the cube after achieving orbit.

Satellite 1	Time (UTCG)	Rcvd. Iso. Power (dBW) at 630km	C/N (dB) at 630km	BER at 630km	Time (UTCG)	Rcvd. Iso. Power (dBW) at 310km	C/N (dB) at 310km	BER at 310km
	4/28/2012 19:28	-166.454	-23.9677	1.73E-01	4/28/2012 19:28	-163.377	-18.54	3.89E-02
	4/28/2012 19:29	-165.271	-20.3968	7.72E-02	4/28/2012 19:29	-161.671	-15.9869	8.99E-03
	4/28/2012 19:30	-163.921	-18.2598	3.43E-02	4/28/2012 19:30	-159.755	-13.7855	1.15E-03
	4/28/2012 19:31	-162.412	-16.4737	1.26E-02	4/28/2012 19:31	-157.927	-11.8863	7.42E-05
	4/28/2012 19:32	-160.782	-14.7538	3.19E-03	4/28/2012 19:32	-156.961	-10.9187	1.11E-05
	4/28/2012 19:33	-159.207	-13.1611	5.27E-04	4/28/2012 19:33	-157.596	-11.5876	4.31E-05
	4/28/2012 19:34	-158.143	-12.1044	1.08E-04	4/28/2012 19:34	-159.318	-13.4254	7.42E-04
	4/28/2012 19:35	-158.161	-12.1477	1.16E-04	4/28/2012 19:35	-161.255	-15.6644	7.03E-03
	4/28/2012 19:36	-159.252	-13.3009	6.33E-04	4/28/2012 19:36	-163.041	-18.0969	3.17E-02
	4/28/2012 19:37	-160.835	-15.0358	4.15E-03	4/28/2012 19:36	-163.217	-18.3696	3.60E-02
	4/28/2012 19:38	-162.467	-16.986	1.75E-02	4/28/2012 20:59	-163.379	-19.487	5.69E-02
	4/28/2012 19:39	-163.975	-19.0979	4.91E-02	4/28/2012 21:00	-161.52	-15.972	8.89E-03
	4/28/2012 19:40	-165.325	-21.5099	1.05E-01	4/28/2012 21:01	-159.323	-13.3506	6.75E-04
	4/28/2012 19:41	-166.334	-23.9529	1.72E-01	4/28/2012 21:02	-156.966	-10.9209	1.12E-05
	4/28/2012 21:06	-166.454	-24.6531	1.91E-01	4/28/2012 21:03	-155.392	-9.3561	1.92E-07
	4/28/2012 21:07	-165.254	-20.2791	7.44E-02	4/28/2012 21:04	-156.048	-10.0614	1.43E-06
	4/28/2012 21:08	-163.885	-18.1052	3.19E-02	4/28/2012 21:05	-158.238	-12.4141	1.78E-04
	4/28/2012 21:09	-162.362	-16.3599	1.17E-02	4/28/2012 21:06	-160.555	-15.165	4.65E-03
	4/28/2012 21:10	-160.732	-14.6858	2.99E-03	4/28/2012 21:07	-162.577	-18.0961	3.17E-02
	4/28/2012 21:11	-159.2	-13.1644	5.29E-04	4/28/2012 21:07	-163.216	-19.2166	5.14E-02
	4/28/2012 21:12	-158.253	-12.2443	1.36E-04	4/29/2012 7:15	-163.232	-17.9944	3.02E-02
	4/28/2012 21:13	-158.421	-12.4633	1.93E-04	4/29/2012 7:16	-161.631	-15.945	8.71E-03
	4/28/2012 21:14	-159.594	-13.7518	1.10E-03	4/29/2012 7:17	-160.027	-14.115	1.67E-03
	4/28/2012 21:15	-161.187	-15.5928	6.64E-03	4/29/2012 7:18	-158.819	-12.8115	3.24E-04
	4/28/2012 21:17	-164.278	-19.9434	6.67E-02	4/29/2012 7:20	-159.515	-13.4764	7.91E-04
	4/28/2012 21:18	-165.602	-22.5097	1.32E-01	4/29/2012 7:21	-161.04	-15.0934	4.36E-03
	4/28/2012 21:18	-166.338	-24.2993	1.82E-01	4/29/2012 7:22	-162.675	-17.0997	1.87E-02
	4/28/2012 22:45	-166.443	-20.532	8.04E-02	4/29/2012 7:23	-163.376	-18.1738	3.29E-02
	4/28/2012 22:46	-166.041	-20.0288	6.87E-02	4/29/2012 8:45	-163.206	-20.3582	7.63E-02
	4/28/2012 22:47	-165.802	-19.7565	6.26E-02	4/29/2012 8:46	-161.239	-16.4267	1.22E-02
	4/28/2012 22:48	-165.762	-19.7239	6.19E-02	4/29/2012 8:47	-158.775	-13.1086	4.91E-04
	4/28/2012 22:49	-165.929	-19.926	6.64E-02	4/29/2012 8:48	-155.805	-9.8401	7.87E-07
	4/28/2012 22:50	-166.279	-20.3409	7.59E-02	4/29/2012 8:49	-153.239	-7.2029	3.88E-11
	4/28/2012 22:50	-166.401	-20.4869	7.94E-02	4/29/2012 8:50	-153.902	-7.8555	7.99E-10
	4/29/2012 6:31	-166.365	-21.1155	9.49E-02	4/29/2012 8:51	-156.852	-10.8458	9.49E-06
	4/29/2012 6:32	-165.489	-19.9265	6.64E-02	4/29/2012 8:52	-159.667	-13.9088	1.32E-03
	4/29/2012 6:33	-164.649	-18.8775	4.49E-02	4/29/2012 8:53	-161.954	-17.1302	1.90E-02
	4/29/2012 6:34	-163.939	-18.0362	3.08E-02	4/29/2012 8:54	-163.38	-20.5192	8.01E-02
	4/29/2012 6:35	-163.467	-17.4847	2.32E-02		-159.956	-14.5324	1.45E-02
	4/29/2012 6:36	-163.329	-17.3018	2.10E-02				
	4/29/2012 6:37	-163.558	-17.5121	2.36E-02				
	4/29/2012 6:38	-164.102	-18.0703	3.13E-02				
	4/29/2012 6:39	-164.856	-18.9066	4.54E-02				
	4/29/2012 6:40	-165.717	-20.0107	6.83E-02				
	4/29/2012 6:41	-166.451	-21.2304	9.79E-02				
	4/29/2012 8:06	-166.33	-40.3051	4.43E-01				
	4/29/2012 8:07	-165.013	-24.5384	1.88E-01				
	4/29/2012 8:08	-163.468	-19.4946	5.71E-02				
	4/29/2012 8:09	-161.623	-16.3862	1.19E-02				
	4/29/2012 8:10	-159.385	-13.6445	9.72E-04				
	4/29/2012 8:11	-156.713	-10.7717	8.04E-06				
	4/29/2012 8:12	-154.121	-8.1096	2.31E-09				
	4/29/2012 8:13	-153.732	-7.704	4.12E-10				
	4/29/2012 8:15	-158.795	-12.7601	3.01E-04				
	4/29/2012 8:16	-161.136	-15.0951	4.37E-03				
	4/29/2012 8:17	-163.063	-17.0169	1.78E-02				
	4/29/2012 8:18	-164.67	-18.6268	4.04E-02				
	4/29/2012 8:19	-166.036	-20.1705	7.19E-02				
	4/29/2012 8:19	-166.454	-43.215	4.59E-01				
	4/29/2012 9:45	-166.35	-21.4312	1.03E-01				
	4/29/2012 9:46	-165.373	-20.0032	6.81E-02				
	4/29/2012 9:47	-164.374	-18.7076	4.18E-02				
	4/29/2012 9:48	-163.432	-17.5838	2.45E-02				
	4/29/2012 9:49	-162.663	-16.7099	1.47E-02				
	4/29/2012 9:50	-162.216	-16.2061	1.05E-02				
	4/29/2012 9:51	-162.209	-16.1701	1.03E-02				
	4/29/2012 9:52	-162.643	-16.5968	1.37E-02				
	4/29/2012 9:53	-163.401	-17.3809	2.19E-02				
	4/29/2012 9:54	-164.335	-18.408	3.67E-02				
	4/29/2012 9:55	-165.329	-19.6462	6.02E-02				
	4/29/2012 9:56	-166.311	-21.2353	9.80E-02				
	4/29/2012 9:56	-166.451	-21.5199	1.05E-01				
	4/29/2012 18:14	-166.448	-20.8232	8.76E-02				
	4/29/2012 18:15	-165.742	-19.8541	6.48E-02				
	4/29/2012 18:16	-165.118	-19.118	4.95E-02				
	4/29/2012 18:17	-164.648	-18.6072	4.01E-02				
	4/29/2012 18:18	-164.398	-18.3536	3.58E-02				
	4/29/2012 18:19	-164.41	-18.3872	3.63E-02				
	4/29/2012 18:20	-164.683	-18.7065	4.18E-02				
	4/29/2012 18:21	-165.171	-19.2747	5.26E-02				
	4/29/2012 18:22	-165.809	-20.0399	6.89E-02				
	4/29/2012 18:23	-166.37	-20.7475	8.57E-02				
		-163.404	-18.4465	5.82E-02				

Table 10. Satellite-1 to JCBRN downlink, link-budget analysis

Table 10 depicts the major link-budget parameters for Satellite 1 downlink at 630km and at 310km, with JCBRN station. The numbers show that the signal received from a spacecraft at 310 km is much stronger with much fewer errors. Moreover, the strength of the signal is not constant through the whole duration of the access period. As the satellite flies above the horizon at the beginning and at the end of the access period, the signal is worse than in the middle. This is because the distance between the satellite and the station, called the slant range is not constant. The slant range when an asset starts or finishes accessing the station can be many times the minimum slant range that appears when the satellite is exactly above the station. This phenomenon can change the quality of the signal by many orders of magnitude and is highly related to the characteristics of the satellite orbit. So it is not correct one to state that access time equals communication time, because the signal at the borders of the access time might not be strong enough for successful transmission or reception. The absolute numbers for received isotropic power, signal-to-noise ratio (C/N), and bit-error rate (BER) that appear in our simulations might not be optimal for a realistic transmission, even for a constellation orbiting at 310km altitude, because of certain characteristics of the satellite platform we chose in an attempt to keep our models simple. The example of AISat-1 proves that in reality, technology can amplify these parameters to values that ensure successful uplinks and downlinks but the construction of such a model is out of the scope of this research.

Table 11 is the fusion of six sets of data as they appear for Satellite 1 in Table 10. It depicts the average values of the three aforementioned link-budget parameters for the downlink of the six satellites for both altitude situations with the JCBRN station. The numbers clearly present the advantage of 310km-altitude constellation as regards the quality of the transmitted signal. All six satellites succeed at almost the same level of efficiency for every situation and the difference between the two transmissions can exceed one order of

magnitude regarding the BER (Table 11). The link-budget analysis for the downlink between the satellites and the boarded vessel yields results similar to those we came up with the satellite-to-JCBRN connection.

	Rcvd. Iso. Power (dBW)		C/N (dB)		BER	
	630km	310km	630km	310km	630km	310km
Satellite 1	-163.4	-160.0	-18.4	-14.5	5.8E-02	1.5E-02
Satellite 2	-162.4	-159.0	-16.3	-13.0	2.4E-02	3.74E-03
Satellite 3	-162.4	-159.1	-16.3	-13.0	2.4E-02	4.2E-03
Satellite 4	-162.2	-159.4	-16.2	-13.4	2.34E-02	4.99E-03
Satellite 5	-162.3	-159.4	-16.2	-13.3	2..29E-02	4.56E-03
Satellite 6	-162.3	-159.1	-16.2	-13.1	2.3E-02	4.1E-03

Table 11. Link-budget comparison

The transmitted power and the size and type of the antenna for terrestrial stations, though not unlimited, do not follow the restrictions of a small satellite. The uplink of a terrestrial station (mobile or not) can be powerful enough to transmit signals that can transfer uncorrupted information to an orbital asset. This means that for successful transfers of information among the nodes of an MIO network using small satellites, special attention must be paid to the selection of the downlink parameters between the orbital assets and the terrestrial stations. The rest of the connections between nodes are much easier to implement.

C. A POSSIBLE SOLUTION

1. Integration

The simplicity of an MIO network is the factor that best enables the integration of small satellites. MIO operations do not necessarily require large

space systems with extreme capabilities. What is really needed is an efficient relay of information, a means that can get, store, and transfer data and make it available to distant entities that are critical nodes of the MIO network.

Naval forces or coalitions typically decide that they need to investigate a ship because intelligence indicates illegal activities that endanger national or global security. An MIO boarding team on a vessel of interest, equipped with biometric devices and radio-nuclear or other sensors obtains measurements all over the ship. The team gets strange spectra of unknown materials and lack the expertise to interpret specific measurements. They take photographs of the materials, video of possible changes in their condition, and video of the area where materials are located. This data needs to be transferred to distributed laboratories around the world, where experts can analyze them and databases can be searched. The results of this analysis need to return quickly back to the team to inform further actions. Wireless means of communication are needed for the flow of information, and every kind has its limitations. Without orbital assets, the operation can proceed in littoral waters only, where, using some variety of technology, the team can communicate with shore and all information can be further transmitted. TNT MIO 12-2, experiment (June 6-15, 2012) that took place in Baltic sea between the Swedish port of Karlskrona and the Polish port of Gdynia, in Bydgoszcz Poland and in Souda Bay, Greece models the aforementioned scenario. Especially in Souda Bay, wave-relay receivers, transmitters, and the GPRS network relayed information to the NMIO TC NOC, and from there the information reached places distributed all around the world via internet. One of the tools used for distribution of information was the Broadband Global Area Network (BGAN), a global-coverage network that uses three satellites in geostationary orbits and is provided by Inmarsat (Broadband Global Area Network, n.d.)(Figure 18).

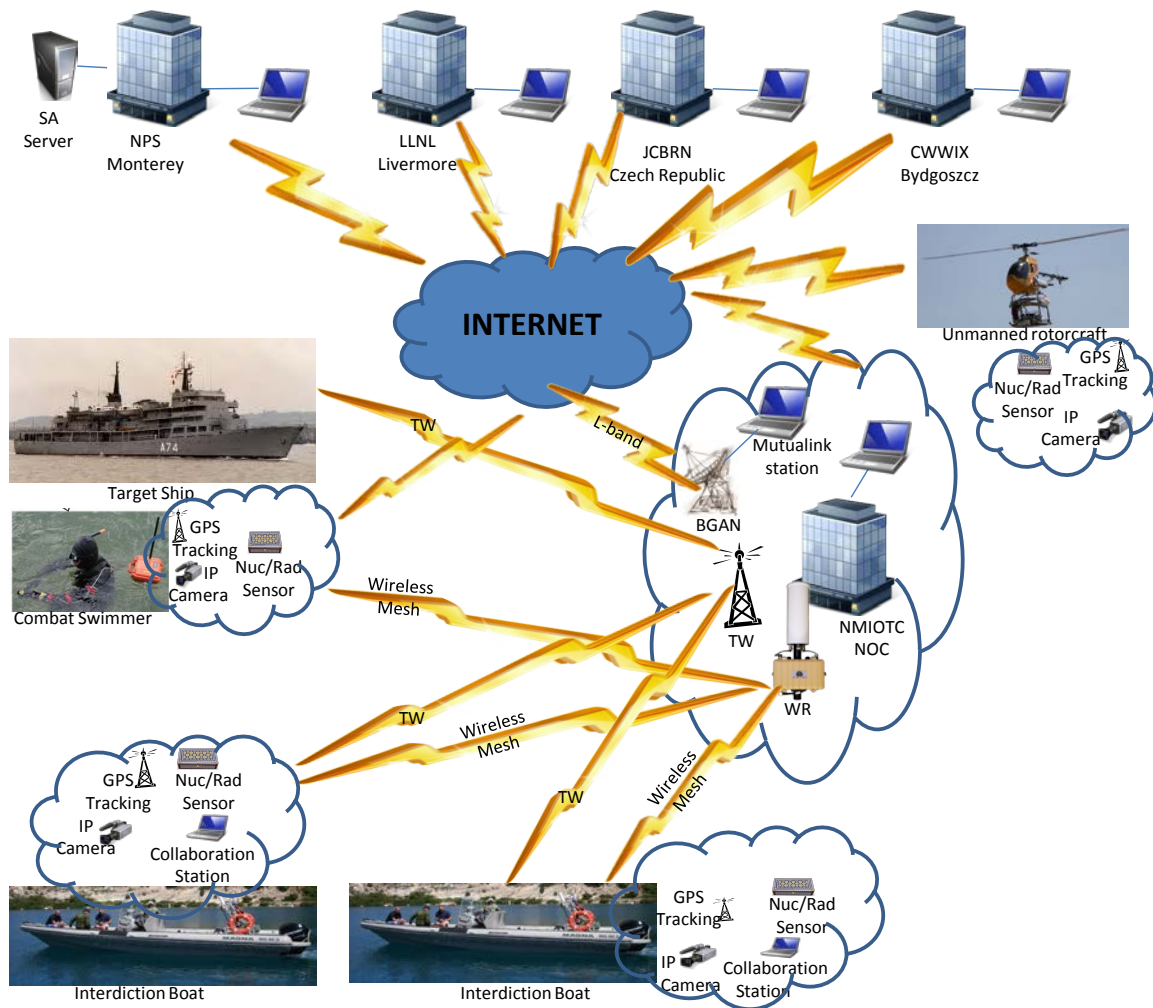


Figure 18. MIO 12-2 network diagram

For operations on the open seas, orbital assets must be used in transmitting and receiving data. Highly capable GEO/LEO satellites are in orbit and cover certain areas of the globe around the clock. If specific needs occur, some satellites can change orbit by their own means to cover areas of interest. The technologically advanced communication systems aboard these assets can transfer vast amounts of information reliably and swiftly, just like BGAN did in the TNT MIO 12-2 experiment. It looks like everything that can make an MIO in open seas successful is already in place. So why are small satellites such an interesting asset?

One reason is cost. Most GEO/LEO satellites are commercial, and the cost for transferring data is high. Owning these assets is a privilege affordable to only powerful countries, and not a possibility for most navies or coalitions. Small satellites provide an alternative. Another reason for the interest in small satellites is that they do not need the launch platforms the bigger satellites need—they can be launched easily even from a combat aircraft (Socher and Gany, 2008). This characteristic offers great flexibility to MIOs. There is no need for an existing constellation in orbit to design an operation using these assets. The command of an operation can deploy a constellation of small satellites only when and where needed.

As seen in the research scenario, the volume of information that needs to travel between the nodes of a MIO network is relatively trivial. Data without high quality or real-time video is the most a node will try to upload or download. In addition, small satellites nowadays can meet the requirements for data transfer in terms of data rates in MIO networks. Helvajian H. and Janson S. quote a table (Table 12) with indicative data rates for small satellites when 2m- and 4m-diameter ground-station antennas and a 10-dBi transmit spacecraft antenna are used at 2500-km range (Helvajian H. and Janson S., 2008).

Satellite Class	RF Output Power (W)	Data Rate for 2m Diameter Receiver (Mbps)	Data Rate for 4m Diameter Receiver (Mbps)
Microsatellite	1.4-12	2.8-24	11-97
Nanosatellite	0.30-2.5	0.61-5.1	2.4-20
Picosatellite	0.065-0.53	0.13-1.1	0.53-4.3
Femtosatellite	0.015-0.12	0.031-0.24	0.12-0.97
Attosatellite	<0.025	<0.051	<0.20

Table 12. Small satellites indicative data rates (Adapted from *Small Satellites: Past, present and future*. Reston, VA: AIAA)

According to Table 12, microsatellites, nanosatellites, and even picosatellites can have data rates more than suitable for MIO networks. AISSat-1 achieves data rates from 32 to 256 Kbps and represents a working example of this idea, showing that data rates should not be an issue in the future. Rather, the main problem is availability. Living in LEO orbits, these assets can have contact

with a ground station for only a few minutes per orbit and for limited passes per day, depending on the kind of orbit selected. This shortcoming can be solved by deploying constellations of small satellites to provide a number of passes and enough time for uplinks and downlinks.

The more assets a constellation has, the more time a node can use for uploading and downloading data. Obviously, increasing the number of orbital assets raises the cost of the whole mission, so the maximum number of assets can grow up to the point where the cost is meaningful for an MIO operation. This number is far less than that which would be needed to provide continuous coverage. On the contrary, access time will always be a small cluster within the 24-hour day. This research examined another way to increase availability: increasing the altitude of orbit. This solution can also work up to the point where the signal is not strong enough for successful transfer of data, so, again, continuous coverage is far from possible. Moreover, as long as these spacecrafts are not equipped with propulsion, orbital altitude is also a regulator of their operational life and can change the cost effectiveness of the system dramatically. So the tradeoffs concerning coverage, signal strength, and operational life of small satellites include: low orbital altitude offers poor coverage, stronger signal, and short operational life is achieved, while higher orbital altitude offers greater coverage, weaker signal, and longer operational life (Figure 19).

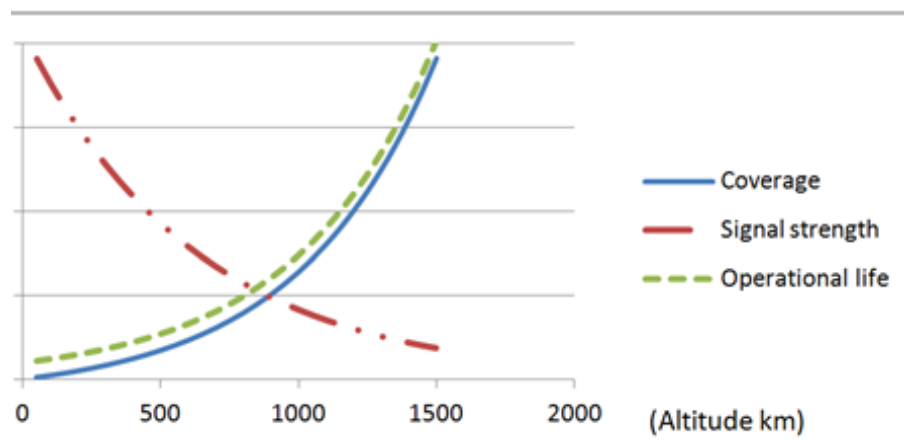


Figure 19. Tradeoffs between coverage, signal strength, and operational life of small satellites

2. System and Network Characteristics

MIO networks using small satellites as nodes need to be adaptive. Since small satellites have limited capabilities, the architecture of terrestrial stations should be efficient enough to counter all orbital limitations. High-gain antennas, sophisticated filters, powerful transmitters, and sensitive receivers are some of the needed characteristics. Moreover, terrestrial stations need to be intelligent enough to estimate when the next satellite will be accessible, for what duration, and with which satellite of the constellation it will be connected. They should be the hyper-nodes of the system, which, according to the 8th-layer concept and their NOC capability (Bordetsky, 2006), have the ability to be aware of the orbital traffic and so help the system reallocate the best paths for distributing or gaining information.

No matter how intelligent and effective the hyper-nodes of an MIO network are, continuous real-time information exchange between a boarding team and nuclear/radiation experts is not feasible, since continuous coverage cannot easily be achieved with small satellites. With a six-satellite constellation orbiting at 630 km altitude, the JCBRN center has a chance for access to almost two orbital assets (on average) for every one-hour period during the day (tables 8 and 9) while the boarding team can have access to more than one orbital asset, on average, for the same period. This translates to an access period of 10–26 minutes and 5–13 minutes per hour, for the JCBRN and the boarding team respectively, for uploading or downloading data. Taking into account the data rates of Table 12, we conclude that small satellites can provide the network with the ability to send and receive significant volumes of information in near-real time. With the constellation orbiting at 310 km altitude, the aforementioned results are reduced to a period of 6–11 minutes' access for the JCBRN center and 5–9 minutes' access for the boarding team.

The need to exchange real time data between the nodes of an MIO network depends on the nature of the MIO operation and the current conditions in every task. In this situation, it is clear that small satellites can play a backup

role in the communication plan of an operation. Very often, an MIO operation lasts for hours, and time is not so much critical to the conduct of its tasks. In these instances, small satellites can play a key role in the efficient and fast exchange of accurate and important information.

D. FACING LIMITED CAPABILITIES

1. Smart-Push vs. Smart-Pull Theory

One of the important questions an MIO network architect has to answer when integrating small satellites into a network is what kind of information can be exchanged between nodes. Simple data, pictures, voice, and video are all available, but can a network of this kind support the exchange of them all? What are the limits? In the previous paragraphs, we tried to face the problem technically. Smart-push vs. smart-pull theory is a completely different approach to the problem. It is based on the culture one brings to handling the important bits of information.

Smart-pull theory supports the idea that all relevant data to a task or a mission must be accessible, and from the pool of data, the decision maker pulls, after critical thinking and judgment, the bits that are important for building the information. An example of smart pull would be to interpret all available data for a terrorist group such as personal skills, education, expertise, training, recent movements, affiliations, etc., and produce valuable information such as the place and time of a planned attack. On the other hand, smart-push theory supports the idea that only the most important bits should reach the decision maker, giving him time to process the data efficiently and make appropriate decisions. An example of smart-push theory would be a fighting jet pilot who needs to know only what is really important for his mission, since his processing capability is very limited in comparison to all the tasks he has to accomplish during his flight (Hayes-Roth, 2006).

Implementation of smart-push theory on an MIO would help solve the problem of limitations on the volume of information the network can handle. At

the level of the boarding team, using as high-quality video as necessary for interpreting the current situation or uploading pictures instead of video whenever possible are small examples of how data can be processed before sending to the decision maker—in our case, the experts. This attitude follows smart-push theory and reduces significantly the volume of transmitted information without killing important bits. The experts, on the other hand, can process the information they have available for the boarding team and send them only what is really critical.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Adaptation in MIO networks is an aspect of great importance. Due to the various conditions that may exist in their environment and because most of the time they are formed as ad-hoc networks, they need to be robust, reliable, scalable, and efficient. Adaptation can add to all these four factors.

Satellites are the tools that can increase the level of adaptation in MIO networks. The problem in the utilization of commercial orbital assets is their cost. Small satellites can be a solution to this problem, but there are some constraints that must be taken into consideration by the architect of the network. Continuous coverage is practically unachievable. Our models showed that a six satellite-constellation can offer less than ten hours of total coverage per day. Additionally, their operational life is very limited in comparison with commercial satellites, because they usually do not have a propulsion system onboard and are LEO assets. Low altitude, lack of propulsion, and solar activity are the major factors that determine their operational life. The amount of power a small satellite can generate and the onboard storage space available limit the strength and quality of a transmitted signal and confine data rates.

An effective way of using small satellites in a MIO network is as weak links. These assets can connect the clusters of the network, but the links break and are reestablished continuously. The clusters of an MIO network can be distributed across the globe, and weak ties are the bridges between them. These links cannot support the exchange of real-time data, but the achieved data rates using current technology are sufficient to support the amount of information exchanged in an MIO. AISSat-1 is the active proof that, technologically, we are able to move from conceptualization to real-world trials. AISSat-1 provides

successful maritime observational services to Norwegian governmental authorities. We showed in our models that this kind of platform can be used effectively as an MIO-network orbital node.

Depending on the nature of the operation, small satellites can play a backup or key role to the communication plan of an operation. If there is a need for real-time data exchange, then, because these orbital assets do not provide continuous coverage, they must be used as backup platforms. When time is not critical, as often happens with MIOs, small satellites provide an efficient, cheap, and effective way of distributing information among the clusters of a network.

Since small satellites have limited capabilities, terrestrial stations' architectures should be efficient to counter the limitations. High-gain antennas, sophisticated filters, and powerful transmitters are some of the characteristics a terrestrial station should have in order to support the network.

For our simulations to be tested in a real environment, an experimental campaign—not a single experiment—is needed, because of the complex nature of MIOs and the variety of technological solutions the space industry can provide. The team for such an experimental campaign should comprise academic, nuclear/radiological and military experts who will be responsible for data collection following automated, recording for later reduction and human-observation collection plans.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Large-Scale Experimentation

We were not able to proceed with a real, large-scale MIO experiment that integrates small satellites, because at the present time there are no orbiting small satellites available to us. The TNT test-bed environment can provide the experimental team with a suitable facility for the experimentation, with a variety of tools for data capturing and analysis. The cooperation of the Space Systems Academic Group and the Information-Technology department at NPS can contribute to significant results in the area of small satellites and achieve

connectivity at ad-hoc networks like MIOs. The implementation of a large-scale experiment would test our designs and verify our simulations. Moreover, the analysis of environmental conditions and orbital-decay effects during the experiment could provide valuable insight about the real efficiency and effectiveness of these spacecrafts over time.

2. Different Small-Satellite Types

In this paper there is very little distinction made between small-satellite types. We built our models with the assumption that the assets we are using belong to the nanosatellites category. According to their generic characteristics and to Table 12, microsatellites and picosatellites are also capable of participating as nodes in a MIO network. For future work, examining the different characteristics of small-satellite types would afford comparison between them and their measure of suitability in different MIOs and MIO networks.

3. Orbits and Terrestrial Stations

Only one kind of orbit and two specific sites as terrestrial stations were selected for our models. The theoretical ease—it is not easy yet—of launching small satellites on demand and for various missions, even using a combat aircraft as a launching vehicle instead of ground-based rocket launchers (Socher and Gany, 2008), gives the ability to select the most appropriate orbit for every mission. This is why it would be interesting in future work to compare different kinds of orbits, combining them with multiple sites around the globe in different latitudes. Such a study would give a more complete picture of achieved connectivity for these kinds of networks in association with different orbits.

4. Bursty Behavior

In this paper, we examined small satellites as weak links of MIO ad-hoc networks. A different approach would be examine these networks from a burst-attitude perspective. Barabasi states “most of our actions are driven by laws, patterns and mechanisms” (Barabasi, 2010). The footprint, and so the availability

of a satellite, is not a random phenomenon—it is driven by very specific laws. The network is aware of when an orbital asset is available. Time is limited, and because the volume of information is greater than the volume that can be handled by a small satellite, there is a need to prioritize. The most important and time-critical parts of information are uploaded or downloaded in bursts—that is, whenever an orbital asset is connected to the network—postponing, cancelling, or choosing another means of distribution for quantities of insignificant information.

APPENDIX

A. HOW TO CREATE THE MIO SCENARIO IN STK

1. Create the Six Satellites

- Create a scenario and name it.
- Click the “insert object” button and select “satellite” from the “scenario objects.” Select “insert default” from “select a method” area.
- Name the satellite “cubesat1” and double-click it at the object browser to open its menu.
- Open the “orbit” page and enter the following settings:
 - o Propagator: J2Perturbation.
 - o Click the “use scenario analysis period.”
 - o Apogee Altitude: 630km/310km.
 - o Perigee Altitude: 630km/310km.
 - o Inclination: 90 deg.
 - o Argument of Perigee: 0 deg.
 - o RAAN: 0 deg.
 - o True Anomaly: 0 deg.
 - o Click OK to save changes.
- Click the “insert object” button. Select “receiver” from the “attached objects.” From the “select Object” catalog that appears, choose cubesat1 and click OK.
- Name the receiver “satrcv1” and double-click it at the object browser to open its menu.

- Open the “definition” page, and enter the following settings:
 - o Select “model specs” tab.
 - o Frequency: 2.4GHz.
 - o Click “auto track.”
 - o Antenna to LNA Line Loss: 0dB.
 - o LNA Gain: 0dB.
 - o LNA to receiver Line Loss: 0dB.
 - o Select “Antenna” tab and then “Model Specs” tab.
 - o Type: Hemispherical.
 - o Design Frequency: 2.4 GHz.
 - o Main-lobe Gain: 3dB.
 - o Efficiency: 100%.
 - o Select “system noise temperature” tab.
 - o Click on “constant” radio button and enter 1000K.
 - o Select “filter” tab and enter for “receiver bandwidth” 0.002MHz.
 - o Click OK to save changes.
- Click the “insert object” button and select “transmitter” from the “attached objects.” From the “select Object” catalog that appears, choose “cubesat1” and then click OK.
- Name the transmitter “satxmtr1” and double-click it at the object browser to open its menu.
- Open the “definition” page, and enter the following settings:
 - o Select “model specs” tab.
 - o Frequency: 2.4GHz.

- o Power 0dBW.
- o Select “Antenna” tab and then “Model Specs” tab.
- o Type: Hemispherical.
- o Design Frequency: 2.4 GHz.
- o Main-lobe Gain: 3dB.
- o Efficiency: 100%.
- o Select “polarization” tab, click “use”, and select “linear.”
- o Select “modulator” tab, put for “data rate” 0.009Mb/sec and select BPSK for “modulation type.”
- o Click OK to save changes.
- Create the other five satellites with the names cubesat2, cubesat3, cubesat4, cubesat5, cubesat6 and use the same settings with cubesat1, except the values for argument of perigee and RAAN which should be both values 45, 90, 135, 180, and 225 deg respectively. The receivers and the transmitters should have the same characteristics and be named after the number of every satellite.

2. Create the Facility and the Ship

- Click the “insert object” button and select “facility” from the “scenario objects” and “insert default” from “select a method.”
- Name the facility “JCBRN” and double-click it at the object browser to open its menu.
- Open the “position” page and enter the following settings:
 - o Type: Geodetic.
 - o Latitude: 49.3581 deg.

- o Longitude: 17.1526 deg.
 - o Altitude: 0km.
 - o Altitude Reference: WG84.
 - o Height Above Ground: 0km.
 - o Click OK to save changes.
- Click the “insert object” button and select “receiver” from the “attached objects”. From the “select Object” catalog that appears choose JCORN and then click OK.
- Name the receiver “stationrcv” and double-click it at the object browser to open its menu.
- Open the “definition” page, and enter the following settings:
 - o Select “model specs” tab.
 - o Frequency: 2.4GHz.
 - o Click “auto track.”
 - o Antenna to LNA Line Loss: 0dB.
 - o LNA Gain: 20dB.
 - o LNA to receiver Line Loss: 0dB.
 - o Select “Antenna” tab and then “Model Specs” tab.
 - o Type: Pencil Beam.
 - o Design Frequency: 2.4 GHz.
 - o Main-lobe Gain: 40dB.
 - o Back-lobe Gain: -3.0103dB.
 - o Beamwidth: 1.62062deg.
 - o Select “system noise temperature” tab.

- o Click on “constant” radio button and enter 90K.
 - o Select “filter” tab and enter for “receiver bandwidth” 1MHz.
 - o Click OK to save changes.
- Click the “insert object” button and select “transmitter” from the “attached objects. From the “select Object” catalog that appears choose JCBRN and then click OK.
- Name the transmitter “stationxmtr” and double-click it at the object browser to open its menu.
- Open the “definition” page, and enter the following settings:
 - o Select “model specs” tab.
 - o Frequency: 2.4GHz.
 - o Power 30dBW.
 - o Select “Antenna” tab and then “Model Specs” tab.
 - o Type: Pencil Beam.
 - o Design Frequency: 2.4 GHz.
 - o Main-lobe Gain: 40db.
 - o Back-lobe Gain: -3.0103dB.
 - o Beamwidth: 1.62062deg.
 - o Select “polarization” tab, click “use”, and select “linear.”
 - o Select “modulator” tab, put for “data rate” 0.09Mb/sec and select BPSK for “modulation type.”
 - o Click OK to save changes.
- Click the “insert object” button and select “ship” from the “scenario objects” and “insert default” from “select a method” area.
- Double-click ship at the object browser to open its menu.

- Open the “route” page and insert points on the provided table. The first point at the MIO scenario is latitude 34.05745091deg, longitude 28.93466478, and speed 0.00617328 km/sec. The ship sails in circles in this scenario.
- Click OK to save changes.
- Click the “insert object” button and select “receiver” from the “attached objects”. From the “select Object” catalog that appears choose ship and then click OK.
- Name the receiver “shiprcv” and double-click it at the object browser to open its menu.
- Open the “definition” page, and enter the following settings:
 - o Select “model specs” tab.
 - o Frequency: 2.4GHz.
 - o Click “auto track.”
 - o Antenna to LNA Line Loss: 0dB.
 - o LNA Gain: 20dB.
 - o LNA to receiver Line Loss: 0dB.
 - o Select “Antenna” tab and then “Model Specs” tab.
 - o Type: Pencil Beam.
 - o Design Frequency: 2.4 GHz.
 - o Main-lobe Gain: 40dB.
 - o Back-lobe Gain: -3.0103dB.
 - o Beamwidth: 1.62062deg.
 - o Select “system noise temperature” tab.
 - o Click on “constant” radio button and enter 90K.

- o Select “filter” tab and enter for “receiver bandwidth” 0.002MHz.
 - o Click OK to save changes.
- Click the “insert object” button and select “transmitter” from the “attached objects”. From the “select Object” catalog that appears choose “ship” and then click OK.
- Name the transmitter “shipxmtr” and double-click it at the object browser to open its menu.
- Open the “definition” page, and enter the following settings:
 - o Select “model specs” tab.
 - o Frequency: 2.4GHz.
 - o Power 30dBW.
 - o Select “Antenna” tab and then “Model Specs” tab.
 - o Type: Pencil Beam.
 - o Design Frequency: 2.4 GHz.
 - o Main-lobe Gain: 40db.
 - o Back-lobe Gain: -3.0103dB.
 - o Beamwidth: 1.62062deg.
 - o Select “polarization” tab, click “use”, and select “linear.”
 - o Select “modulator” tab, put for “data rate” 1Mb/sec and select BPSK for “modulation type.”
 - o Click OK to save changes.

3. Create Constellations and Chains of Events

- Click the “insert object” button and select “constellation” from the “scenario objects” and “insert default” from “select a method” area.

- Name the constellation “cubesat_rcv” and double-click it at the object browser to open its menu. “Definition” page should already be selected.
- Select all the satellite receivers in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.
- With the same way create two more constellations and name them cubesat_sats and cubesat_xmtrs.
- For cubesat_sats, select all the satellites in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.
- For cubesat_xmtrs select all the satellite transmitters in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.
- Click the “insert object” button and select “chain” from the “scenario objects” and “insert default” from “select a method” area.
- Name the chain “JCBRN_to_cubesat” and double-click it at the object browser to open its menu. “Definition” page should already be selected.
- Select station xmtr and cubesat_rcvs constellation in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.
- With the same way create three more chains of events and name them JCBRN_to_ship, ship_to_cubesat and ship_to_JCBRN.
- For JCBRN_to_ship select the JCBRN facility, cubesat_sats constellation and the ship in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.

- For ship_to_cubesat select the ship xmtr and the cubesat_rcvs constellation in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.
- For ship_to_JCBRN select the ship, the cubesat_sats constellation and the JCBRN facility in the scenario at the “available objects” table, move them to the “assigned objects” list and click OK.

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