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Modelling of Pico Satellite Network Applications To Maritime Interdiction Operations

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Abstract

The successful command and control of Maritime Interdiction Operations (MIO) depends heavily upon an organization's communications and network platforms. These platforms must provide effective, efficient, affordable communications between operational and tactical commanders in an operating area, among globally distributed expert technical advisors, and especially, between these two groups.

Since 2009, the researchers at the Naval Postgraduate School (NPS) and Lawrence Livermore National Laboratory (LLNL) together with their overseas partners have been exploring the benefits of using very small Picosatellite based, private orbital tactical networking nodes to support expert reachback and coordination in Maritime Interdiction Operations scenarios. The NPS team is currently assembling the first set of three Picosatellites to be launched in late 2011 in conjunction with the first series of field trials of MIO reachback employing orbital tactical nodes.

In order to plan and design integration experiments using Picosatellite nodes, we developed software models for future miniature orbital tactical nodes. These are being assembled using the simulation modeling environment in Satellite Tool Kit (STK). This paper describes the results of simulations of Picosatellite networking nodes and analysis of their implementation in MIO test scenarios.

1. Introduction

In the evolving realities of 21st century network-enabled warfare, it is becoming increasingly evident that space-based tactical networking solutions can facilitate effective synchronous collaboration between on-scene commanders and their supporting technical experts in reachback locations. Many researchers and multilateral security organization participants acknowledge the urgency of finding new approaches to address intractable threats, posed largely from the illicit proliferation and use of weapons of mass effect (WME), weapons and narcotics trafficking and piracy. The need is most visible and urgent in ungoverned and under-governed regions, and across the global commons, such as in Gulf of Aden in the Somali Basin area.

In 2009, researchers at the Naval Postgraduate School (NPS), Lawrence Livermore National Laboratory (LLNL) and several overseas partner nations began to explore the benefits of using very small, Picosatellite based, private orbital tactical networking nodes to support reachback to technical experts and to improve collaboration during Maritime Interdiction Operations (MIO) scenarios. A Picosatellite is typically defined as the smallest category of Cube Satellite (<10kg), with a short life-time in orbit (1-3 months) and an overall weight of 1 kg or less.

Within the framework of the ongoing MIO campaign of experimentation [1], we envision the addition of Picosatellite based orbital nodes as an extension of our existing MIO testbed infrastructure. The infrastructure was originally developed by the NPS and LLNL team to support MIO experimentation to focus on countering maritime sourced nuclear radiation threats. The overseas sites that participate as components of the testbed are operated by academic partners from the University of Bundeswehr, the Swedish Defense Research Agency (FOI) , and the NATO MIO Training Center in Greece. The sites enable research teams to explore challenging solutions to tag and monitor the illicit transfer of nuclear material aboard small craft between the continents.

The Picosatellite orbital ad hoc networking nodes will provide a vital space-based element to strengthen the coordination of detection and sharing situational awareness between the *Foreign Origin* layer, the *Transit* layer, *Foreign Points of Departure*, during *Transit-to-Target* phase, and through to the Target Vicinity layer of the Defense Nuclear Detection Office's (DNDO) emerging nine-layer Nuclear Detection Architecture Model [8]. This architecture model provides a thorough framework on which to orient our research, and gives a bearing to our foreign research partners concerning the potential hand-off of monitoring procedures.

Currently, the tagging and global tracking of illicit material that is being transported by small craft can be accomplished using a combination of low bandwidth Low Earth Orbiting (LEO) satellite links (such as Iridium, GlobalStar), cellular GSM 3G/4G networking to feed a tag's GPS location (or similar methods in GPS denied areas) to a C2 center's situational awareness systems. Such methods have multiple limitations due to their high dependency on access to the LEO constellation, especially in situations when such space assets become unavailable or taken off-line. A Picosatellite based orbital node solution provides a low cost tactical alternative to process detection data and relay it to geographically distributed information fusion centers [2]. It also provides for a "dedicated" ad hoc orbital node that sensor operators and experts could use at their discretion to collect data from unattended sensors, follow small craft over the large distances, etc.

2. MIO Reachback Requirements

The presence of robust, agile reachback networking solutions enables distributed MIO teams on-the-move to rapidly exchange information with supporting tactical, operational, and strategic centers. Reachback depends upon specific operational characteristics that are critical MIO success. These include, but are not limited to:

Real-Time communications. When a MIO is being conducted on board a suspect merchant vessel, the boarding team commander often requires immediate expert technical collaboration, analyses and recommendations. For example, a boarding team commander may request assistance to accurately identify possible fissile materials based upon alerts from his team member's hand-held sensor on board the vessel. Timely collaboration and assessment is critical in order for the commander to determine whether to proceed with the on board search, maintain a distance in order to avoid a radiation risk to his crew, and ultimately to overall mission success.

In a contemporary scenario, a MIO team commander communicates via radio with his tactical command afloat (e.g. frigate, fast patrol boat) during a mission. The tactical command afloat relays the information to a fusion center ashore and awaits a response, which it then relays back to the team commander on board the suspect vessel. In this C2 decision support loop, the team commander must rely on the tactical command headquarters to accurately relay a volume of detailed, time critical information to the information fusion center ashore, and so on. This method, generally conducted via voice channels, is neither rapid nor adequately reliable, given the volatility of communications afloat. Nonetheless, it reflects the current state of the equipment that is available during MIO operations.

It would be possible for us to give the MIO team commander the ability to communicate directly with his supporting C2 information fusion center and with remotely located technical experts. Such ability would afford him with the synchronous collaboration capability that he needs in order to make mission critical decisions and to minimize health risks to his boarding team. An example vignette follows regarding the localization and tracking of illegal WME materials.

> *During the search of a suspect merchant vessel, a boarding team member with a handheld radiation sensor device receives an indication that he is in the proximity of an unspecified type of fissile material. His sensor only provides information regarding the source's radiation activity. However, the team member is in a cargo space, two decks down from the boarding officer. Unable to transmit from there, the sensor operator returns to the outside deck of the suspect vessel in order to transmit the readings to his tactical command. The sensor data is then forwarded to the fusion center via satellite or another communication mode beyond the boarding team's range.*

Delays can and do occur but there are definite benefits to providing the boarding officer with rapid, reliable, efficient communications directly with the fusion center and technical experts. The team is safer and more efficient in adjudicating the situation. Limited time is available to make decisions on how to board the merchant vessel, manage the vessel's assembled crew and delays in receiving expert assessments. This serious factor can create psychological tension and, can introduce additional risk to the mission. The example above illustrates the critical importance of giving the boarding team commander the capability to collaborate directly with technical experts ashore. By positioning Picosatellites over an operating area, we introduce the capability to use C2 networks to link together the boarding team commander, the tactical afloat headquarters and the fusion center. This approach will significantly improve effectiveness and efficiency to the completion of the overall operational mission, and is a current requirement. It is reasonable to propose that real-time expert advice will not interfere with the progress of a boarding operation; rather, it should add a constructive decision support dynamic.

3. Critical Picosatellite Characteristics in Support of MIO

In our project we use a particular version of the Picosatellite system known as *Tubesat*, developed by the *Interorbital Systems Co*. The NPS experimentation team recently acquired three Tubesat kits, and under the company's assistance, is currently assembling three Tubesats (Fig. 1) , which are expected to enter a low elliptical orbit in the second half of 2011.

Figure 1: Tubesat Pico satellite pictures (courtesy Interorbital Systems Co[1]*)*

Tubesat is a standalone Pico-satellite with a minor capacity for data networking, space imaging, and on-board processing. The Tubesat has a total mass of 0.75 kg, including 0.2-0.3 kg available for the MIO experiment payload. It is designed to operate for up to 3 months, from a 310 km circular polar orbit, with an orbital longevity of 3 weeks to 3 months, depending on the solar weather (orbital decay). To date, no Picosatellite, including Tubesat has any on board propulsion; which is why the orbital decay parameter will affect the lifetime of the orbit.

Tubesat critical operational capabilities for MIO include**:**

- Operational Lifetime: 20-90 days, depending on solar activity
- Real or Near Real Time Tracking Capability: depending on the selection of orbital parameters and the area of operations.
- Tracking Accuracy: None
- Real time or asynchronous on-the-move data networking
- Reachback Capability: Yes, with connection to MIO expert or C2 team ashore

Correspondingly, Tubesat critical orbital characteristics include:

- Types of orbits that small satellites support: Circular polar orbit at 310 km to maximize coverage with 4-6 satellites.
- Lifetime consideration: 20-90 days, depending on solar weather. Orbital decay parameter impacts lifetime of each Picosatellite and the usable time of the Picosatellite constellation.
- Time of Revisit: a Picosatellite can be accessed every 1.5 hours (refer to the STK analysis below for analytical and detailed results).
- Security that is enabled: There is no security encryption on the Picosatellite.
- Back up satellites: It is relatively easy to place another Picosatellite in orbit
- Ability to crosslink to transfer data in near real time: Future capability, not yet implemented.

The following performance measures could apply to experimental Tubesat implementation for MIO:

- Feasibility to connect for file upload and download
- Feasibility of two-way communications
- Ability of the signal to penetrate materials (such as walls inside ship)
- Signal strength during wall networking
- Signal transmission across oceans and distant sea regions (coverage especially for MIO environments)
- Impact of the meteorological environment on microsatellite transmissions
- Vertical /Horizontal system accuracy, esp. in cargo vessels, searching between decks
  Major data volume and transmission delay constraints associated with Tubesats/Picosatellites as standalone orbital nodes supporting MIO scenarios without commercial or military networks available to support the mission:

4. STK Modeling of Tubesat Support for MIO Activities

The modeling effort that we have described is based on the assumption that the boarding officer needs to communicate in a near real time via Picosatellite nodes, to exchange information with experts in an information fusion center and receive assessments from them. It is assumed that intelligence has been received that a merchant vessel or small craft is transferring WME materials in an area of operation. The detection/boarding team has deployed, and the boarding officer locates the material but does not know how to handle it. In this situation he needs to relay all the information that he has collected to the fusion center, where a technical expert is in a MIO cell advising the boarding officer on how to react, what safety precautions to undertake, etc.

The STK model for Tubesat integration in such an operation was designed based on two modeling options. The first modeling option is based on four Tubesat-type Picosatellites. The second option incorporates six satellites. The orbital characteristics of each model are described in Table 1 and 2. The apogee and perigee altitude remain constant at 310 km, since the Tubesat PICOMIO satellites will obit in this altitude. The inclination for every satellite has been set at 90 degrees, and the true anomaly for the circular orbit is always set to zero. The two parameters that we change are the *Argument of Perigee* and the *Right Ascension for the Ascending Node* (RAAN), which are being changed respectively in order to optimize area coverage.

Orbital Elements	**Apogee Altitude** *Constant for TUBESAT (km)*	**Perigee Altitude** *Constant for TUBESAT (km)*	**Inclination** *(Polar orbit)*	**Argument of Perigee** *(Circular Orbit)*	**RAAN**	**True Anomaly** *(Circular Orbit)*
PICOMIO 1	310	310	90	0	0	0
PICOMIO 2	310	310	90	45	45	0
PICOMIO 3	310	310	90	90	90	0
PICOMIO 4	310	310	90	135	135	0

Table 1: *Orbital Characteristics for TUBESAT mission using 4 Picosatellites*

Characteristics for the six PICOMIO satellites are shown in the Table 2. They are subject to the design considerations used in the four satellite model.

Orbital Elements	**Apogee Altitude** *Constant for TUBESAT (km)*	**Perigee Altitude** *Constant for TUBESAT (km)*	**Inclination** *(Polar orbit)*	**Argument of Perigee** *(Circular Orbit)*	**RAAN**	**True Anomaly** *(Circular Orbit)*
PICOMIO 1	310	310	90	0	0	0
PICOMIO 2	310	310	90	45	45	0
PICOMIO 3	310	310	90	90	90	0
PICOMIO 4	310	310	90	135	135	0
PICOMIO 5	310	310	90	180	180	0

PICOMIO 6	310	310	90	225	225	0

Table 2: *Orbital Characteristics for TUBESAT mission using 6 Picosatellites*

5. Results of Picosatellite Integration Modeling

We conducted simulation runs for both models following the NPS scenario for the upcoming MIO experiment in June, 2011 (Fig.2 and Fig. 3) . Table 3 illustrates the modeling results for the Tubesat passes (Fig. 4) on June 6th and 7th. It highlights the fact that the approximate total time that the PICOMIO satellites will be available for communication is 120 minutes per day.

Date	Satellite	Passes per Satellite	Time (GMT)	Duration (min)
6 June	**PICOMIO 1**	4	**05:09:41 - 05:18:35** **06:43:08 - 06:47:11** **16:14:30 - 16:20:26** **17:44:02 - 17:52:40**	**9** **4** **6** **8**
	PICOMIO 2	3	**07:49:59 - 07:58:18** **09:21:23 - 09:28:11** **20:22:44 - 20:31:42**	**9** **7** **9**
	PICOMIO 3	4	**00:33:12 - 00:38:50** **10:40:23 - 10:48:15** **12:11:05 - 12:18:38** **23:12:53 - 23:21:50**	**6** **8** **7** **9**
	PICOMIO 4	4	**01:51:42 - 02:00:08** **03:22:56 - 03:29:33** **13:30:53 - 13:38:10** **15:00:54 - 15:08:59**	**8** **7** **8** **8**
Total	**-**	**15**	**-**	**113 min**
7 June	**PICOMIO 1**	4	**03:56:26 - 03:58:52** **05:23:18 - 05:32:17** **16:27:31 - 16:35:02** **17:58:00 - 18:05:53**	**2** **9** **7** **7**
	PICOMIO 2	4	**08:01:13 - 08:10:01** **09:33:58 - 09:38:56** **19:05:20 - 19:10:30** **20:34:21 - 20:43:07**	**9** **5** **5** **9**
	PICOMIO 3	5	**00:46:00 - 00:48:47** **10:51:31 - 11:00:03** **12:23:24 - 12:29:36** **21:56:17 - 21:59:38** **23:24:26 - 23:33:21**	**2** **9** **7** **2** **9**
	PICOMIO 4	4	**02:03:04 - 02:11:55** **03:35:14 - 03:40:01** **13:41:52 - 13:50:03** **15:13:02 - 15:20:07**	**8** **5** **9** **7**
Total	**-**	**17**	**-**	**111 min**

Table 3: *Overall MIO scenario results: 4 PICOMIO satellites*

The model identifies the vital time-delay factor for boarding officers to plan their reachback communication availability. On a given day the total passes of the four Picosatellites fluctuate between 12-18 consecutive orbits. Each time a satellite is in orbit over the ground station (Fig. 5) or the operating area, the duration of our access to it also fluctuates between 2-9 minutes. That becomes the optimum timeframe during which to exchange information with a ground station or an area of operations. The total time available to communicate during a 24 hour period via a satellite is approximately 120 minutes (2 hours/day). The following table illustrates the overhead times for 6 and 7 June. 2011. There is a gap of almost 1.5 hours between satellite availability windows. Correspondingly, the total gap in coverage times (using 4 satellites) is approximately 22 hours. These are the results 6 July. Results for the other days are nearly identical; almost no variation. Table 4 shows that the total time that we are without communication with PICOMIO satellites is almost 22.5 hours.

6th June 2011
Total Gap Timeframe in one day

Start Time of Pass	End Time of Pass	Gaps between passes
00:33:12	00:38:50	1 h 10 min
01:51:42	02:00:08	1 h 22 min
03:22:56	03:29:33	1 h 40 min
05:09:41	05:18:35	1 h 25 min
06:43:08	06:47:11	1 h 02 min
07:49:59	07:58:18	1 h 23 min
09:21:23	09:28:11	1 h 12 min
10:40:23	10:48:15	1 h 23 min
12:11:05	12:18:38	1 h 12 min
13:30:53	13:38:10	1 h 22 min
15:00:54	15:08:59	1 h 06 min
16:14:30	16:20:26	1 h 24 min
17:44:02	17:52:40	2 h 30 min
20:22:44	20:31:42	2 h 41 min
23:12:53	23:21:50	-
≈ Total Gap Time during one day		**≈ 22+ hours**

Table 4: *Total Gap Timeframe in one day (4 PICOMIO satellites).*

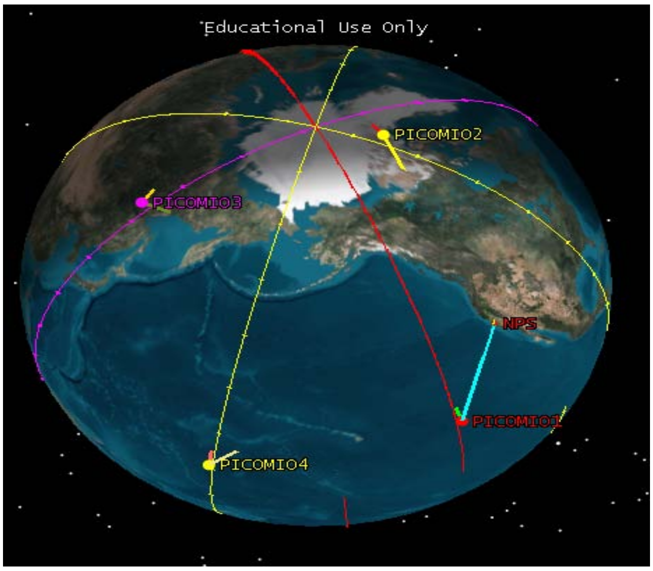

Figure 2: *Total STK Representation and allocation of PICOMIO satellite polar orbits in the scenario.*

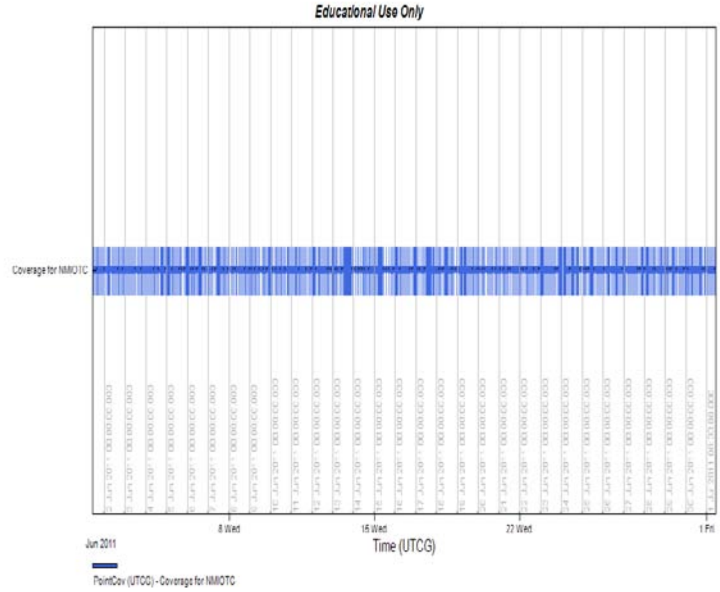

Figure 4: *Total Coverage Time for four PICOMIO satellites and gaps remaining during the total passes timeframe*

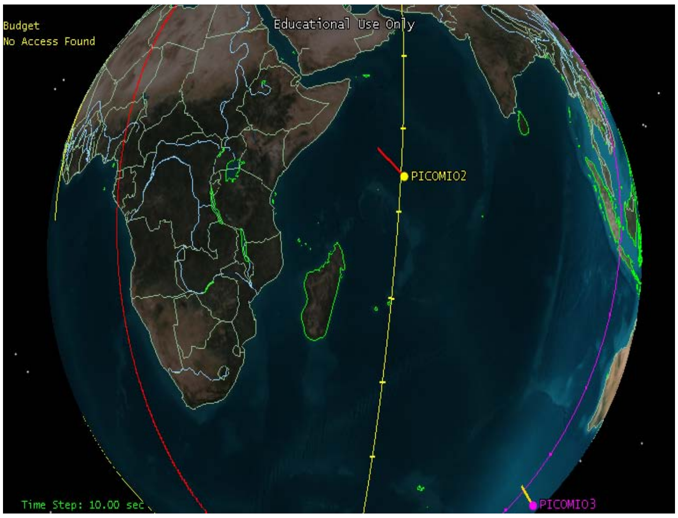

Figure 3: *PICOMIO 2 passing over the area of MIO in the Somali Basin; acquiring data from a boarding officer and sending it to a reachback ground station on the U.S. West Coast*

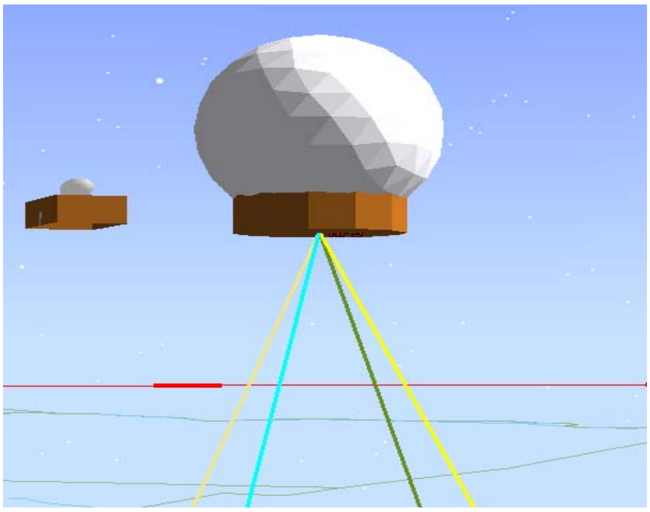

Figure 5: *Type of sensor used for the ground station to communicate with the PICOMIO satellites*

Table 5 represents the modeling results for expected coverage time in the footprint of the MIO experimentation sites, as provided by four(4) or six(6) Tubesat type Picosatellites between 4-12 June,

2011. The results clearly illustrate that by adding two more satellites to support orbit, the total daily time coverage increases by 3 - 4 %, or approximately 1 hour and 20 minutes more per day.

Dates June 2011	Daily Percent Time Covered 4 Pico-Satellites	Daily Percent Time Covered 6 Pico-Satellites
4	**7.00**	**11.32**
5	**7.17**	**11.84**
6	**8.10**	**11.81**
7	**7.92**	**11.66**
8	**7.96**	**11.66**
9	**7.77**	**10.14**
10	**7.23**	**10.15**
11	**7.52**	**11.51**
12	**7.62**	**11.67**

Table 5: *Daily Percentage of Time Covered using 4 and 6 PICOMIO satellites, 4-12 July, 2011*

6. Picosatellite Orbital Decay Effects

Finally, we refer to the Orbital Decay Characteristics of the Picosatellites because our TUBESAT solution does not incorporate any type of on board propulsion, so it’s duration in orbit will depend on the solar activity. In our STK model we insert the parameters in the following table.

Orbital Decay Characteristics	Value
Cd	2.033
Cr	1.33
Drag Area	0.01365 m^2
Area Exposed to Sun	0.01543 m^2
Mass	1 kgr
Atmospheric Density	Jacchia 1970 model
Solar Flux sigma level	0

Table 6: *Orbital Decay Characteristics (without on board propulsion)*

We acquired the following results after running the model with these orbital decay characteristics (Table 6). The PICOMIO satellites will remain on orbit for a little over a month, ranging from 30–33 days).

Pico Satellite	Date *(June)*	Time *(GMT)*	Orbits *(one month)*	Lifetime *(in days)*
PICOMIO1	4	07:39:32	527	**33**
PICOMIO2	3	19:28:47	528	**32**
PICOMIO3	2	05:54:02	503	**31**
PICOMIO4	2	07:29:36	504	**30**

***Table 7:** Results for the Lifetime of PICOMIO satellites.*

Changing Cd or Cr coefficients in the model to be identical as 2 and 1 (best case scenario) changes the orbital path by only one orbit. For example, for PICOMIO1 if we change the Cd and Cr to identical values of 2 and 1 respectively, it will change the orbital value by only one orbit, from 527 orbits to 528. The change is neither critical nor serious. Lifetime parameter influences the orbital path and the satellites to be up there for almost a month and this is the important fact for our scenarios.

Conclusions

It is evident that to apply real time networking applications using Tubesat Picosatellites, we must use more than 6 Picosatellites in Polar Orbits. With the scheme of 4-6 Tubesat type Picosatellites we will have an operationally effective communication period that is limited to almost four hours/day, depending on the satellite configuration. However, with the above run scenarios using four Picosatellites, we obtain almost 2.5 hours of availability for communications. This may be sufficient time to applying reachback methods in operational use. Field officers need this capability to enhance their mission success rate and safeguard their teams while performing work on board suspect vessels through the tactical orbital reach back to C2 fusion centers and technical experts. The proposed Picosatellite based networking model contributes directly to the emerging concept of Space Operations to Counter Maritime Terrorism (Fig. 6) by populating the “funnel” part of the diagram below.

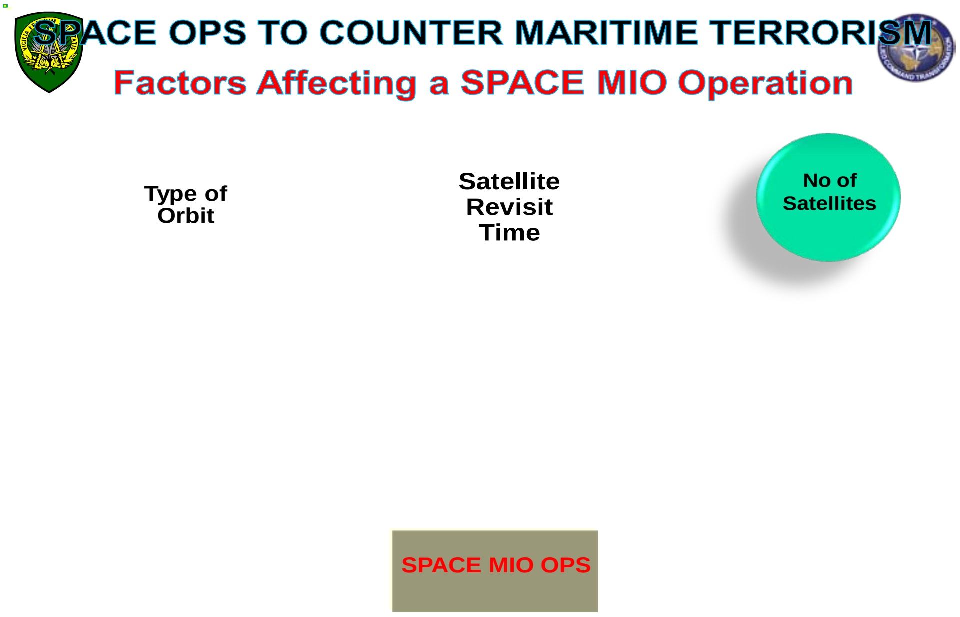

***Figure 6:** Concept of Space Operations executed for supporting the Maritime Interdiction activities*

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