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GEOINT Small Satellite Constellation Study for Maritime Domain Awareness

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EXECUTIVE SUMMARY

Project Summary
This executive summary combines the work of three theses that researched the feasibility of a small satellite (SmallSat) constellation to increase intelligence, surveillance, and reconnaissance (ISR) in support of Maritime Domain Awareness (MDA). The three theses each focused on one area of a space systems architecture: orbit and constellation; command, control, and communications (C3); and payload sensor and processing. In addition to these three theses, research was also conducted through a directed study effort into the most efficient means of deploying this notional constellation.

Our research revealed that no commercial satellite architecture is currently available for leverage, therefore a purposed-built constellation is recommended. A constellation of 180 SmallSats using an Electro-Optical (EO) sensor payload can provide the revisit and resolution needed to meet sponsor requirements. At the time of this study, current C3 and image processing capabilities do not meet project requirements. A cross-linked C3 architecture shows more promise than a ground-based architecture, but no such architecture currently exists. While the technology exists to support the ultimate objective of minimize the time between tasking the system and disseminating the data to the end user, the varying maturity levels of these technologies do not currently support on-orbit processing. With currently available technology and taking cost, the number of satellites per launch, and launch tempo into consideration, the Falcon 9 is the recommended platform to deploy this constellation. Potentially, the entire constellation could be placed into orbit in six launches over the span of two to three months, costing roughly $372M.

Our recommended course of action is to invest further research in command, control, and communications; payload sensor; and processing. C3 requires more investigation to identify the optimal system to support the desired constellation's revisit and resolution. The Electro-Optical (EO) sensor restricts imaging to daylight hours, but we recommend researching the potential use of other sensor types such as infrared (IR) or synthetic aperture radar (SAR) for increased imaging opportunity and timeliness. We also recommend further research into automated target recognition because while processing using artificial intelligence (AI) to conduct basic recognition within an image exists, the technology of AI is not mature enough to be completely automated and provide the detailed vessel classification desired by the sponsor. Future research into the optimization of the constellation and launch pattern, as well as the development of smaller launch vehicles with rapid launch tempo capabilities, is also recommended.

Keywords: *artificial intelligence*, *small satellite, constellation, EO, MDA, SAR, space systems, dark vessels*

Background
Planet Labs, BlackSky, Adcole Maryland Aerospace, and UrTheCast own high-resolution small satellites capable of EO (Crawford, 2018). While these SmallSats demonstrate feasibility of an EO SmallSat constellation, none of these spacecraft are in constellations that provide the necessary revisit for MDA, which is typically less than 30 minutes. For example, Planet Labs's constellation provides daily revisit

using a constellation size of 185 satellites (Products, n.d.) and BlackSky provides 90-minute revisit with its planned 60-satellite constellation (BlackSky Transform EO, 2016). Therefore, a purpose-built constellation was designed to meet revisit needs for desired latitudes that are representative of regions often transited by many shipping lanes.

The overall responsiveness of a constellation is affected by the Tasking, Collection, Processing, Exploitation, and Dissemination (TCPED) process. Of these, the collection, processing, and exploitation aspects, to a certain extent, will occur onboard the satellites, but the tasking and dissemination requires a robust C3 architecture. The C3 architecture required to maintain numerous satellites in a Low Earth Orbit (LEO) constellation is more difficult because the required sensor resolution dictates a low orbit which limits the time in view of a LEO satellite relative to a point beneath it on the Earth's surface. The altitude determines the time in view for communications (from the ground) as well as the field of regard (FOR) within which a sensor can be pointed. To achieve the desired resolution with an EO sensor (within a small satellite form factor) implies a very small instantaneous sensor field of view (FOV) which must be pointed within the FOR. This requires a priori knowledge of the expected target's general location and a C3 path to task the sensor. To achieve the desired timeliness, with LEO satellites, means that many satellites are required. Therefore, the C3 architecture needs to provide continuous, or reliable ad hoc, communications to either all of the many satellites, or to those which are approaching the region of interest and which need to be tasked. Using a direct to ground design would require a large number of ground stations in order to both receive data and perform the Telemetry, Tracking and Command (TT&C) mission; Planet Labs uses 30 ground stations for their massive constellation (Orbit Operations, n.d.), and Spire Global uses 30 ground stations to support 57 satellites (Cappaert, 2018), for example. Satellites could instead transmit the data to a satellite outside of the constellation as a relay to the ground. Alternatively, the satellites could cross-link to one another, so each satellite acts as a relay satellite for one another in the constellation.

The processing aspect of the mission architecture is inextricably linked to the C3 architecture given the current state of technology, where satellite imaging payloads mostly operate in a store-and-forward mode. The satellite captures the image of interest, and then when it can establish a connection to a ground site to link to, it sends the data. The use of Field Programmable Gate Array (FPGA) technology has garnered recent attention for use in software-defined radios (SDRs) for SmallSat communication systems (Varnavas, n.d.). For image processing, using FPGA SDR technology on board SmallSats would allow for on-the-fly, overhead programming capabilities (Mcgowan, 2018). This allows more flexibility for SmallSats to upgrade to new algorithms, for example, which would help with offloading processed data to ground sites and the user to meet MDA needs.

Potential launch solutions were down-selected from 24 identified platforms using the following criteria: the ability to carry one to two planes, or 10 to 20 satellites; the ability to deploy the entire constellation for less than $1B; and the number of launches required. The remaining launch platforms were then analyzed for specific orbital maneuvers to determine the minimum number of launches required, the cost, and the estimated launch tempos for each feasible solution. In the launch analysis, we assumed that every upper stage will reach 500 km altitude with the advertised payload capacity; that all of the fuel on the upper stage will be expended; that the available mass-to-orbit only counts toward payload fuel or mass; and that all velocity changes will occur instantaneously.

Findings and Conclusions

Conducting online research and interviews facilitated the development of the trade space of current SmallSat sensors capable of providing high-resolution imagery and onboard satellite imaging processing. High-resolution EO sensors compatible with SmallSats are commercially viable; Harris's SpaceView offers a variety of low cost high-resolution EO payloads. This sensor's staring mode, which provides sub-one-meter resolution at 525 km (Crawford, 2018), was used as the baseline imaging capability for this study.

We used Satellite Tool Kit (STK) software simulations to design the optimal constellation. The simulations use the satellite's access area to consider opportunities for imaging with the assumption that the satellite is tasked to point within the access area. The access area was restricted to provide no worse than one-meter resolution imagery. Simulation average revisit times ranged from 5 to 20 minutes depending on the constellation design, but there are gaps in access and maximum revisit (Crawford, 2018). These gaps can be predicted; however, to improve MDA utility, we designed a constellation that minimized their occurrence and duration. The simulations revealed that increasing the number of satellites within an orbital plane did not minimize the occurrence and duration of access gaps, but increasing the number of planes did accomplish this objective (Crawford, 2018). The optimum constellation, which minimizes frequency and gaps in excess of 60 minutes that occurred several times throughout the day, uses a triple Walker design of three different inclinations where each inclination has six planes and ten satellites in each plane at an altitude of 525 km; the total constellation consists of 180 satellites in 18 planes with a rough cost estimate of $2B (Crawford, 2018). The inclinations of the triple Walker vary from 17° to 34° because the best opportunity for revisit occurs when the orbital plane's inclination matches the latitude desired for coverage (Wertz, 2010). The triple Walker only provides coverage between latitudes 34° North and 34° South due to the selected inclinations and nature of orbital mechanics. While global coverage and an average revisit time of 22 minutes can be achieved with the 80-satellite, polar constellation, the resulting maximum revisit time on the order of two to three hours would not meet the desired MDA requirements (Crawford, 2018).

We researched various C3 methods, via online sources and interviews, and analyzed their ability to support a 180-satellite constellation in Low Earth Orbit (LEO). The constellation requires at least 480 kbps for data transfer, and we concluded that Mobile User Objective System (MUOS) or Inter-Satellite Links (ISLs), also known as crosslinks, are both potential options for continuous data relay (Begley, 2018). This data rate is calculated per satellite for 50 accesses at 9.6 kbps each, assuming that 50 satellites will be in view of each MUOS satellite (or three to four satellites per Wide Code Division Multiple Access (WCDMA) beam), which can provide a minimum data rate of 9.6 kbps. Based on the estimated image size of 400 KB, MUOS would be sufficient to support the minimum data rate required of 1.2 kbps per image. MUOS as a data relay system requires technology maturity; Space and Naval Warfare Systems Command (SPAWAR) is set to launch a CubeSat demonstrator of MUOS as a relay no earlier than July 2018 (Yoo & Mroczek, 2015). MUOS was also designed for a doppler shift at aircraft speed, so development is underway by the MUOS program office to increase the design to the speed of a satellite, with implementation expected in 2019 (Begley, 2018). ISLs requires at least one ground station and adds complexity to the design of the satellite, which could require up to four additional pointing antennas. Viable command and control options include Naval Research Lab's Neptune Common Ground Architecture (CGA) or Harris Corporation's OS/COMET program (Begley, 2018). Neptune's primary ground station, Blossom Point Tracking Facility (BPTF) in Washington, D.C. requires few additional antennas to support the 180-satellite constellation and can provide ad-hoc tasking to satellites if there is an available communication path (Begley, 2018). OS/COMET has proven utility through use by Global Positioning System (GPS) and Iridium; this system can provide more automation within the constellation and allow for a true network in space.

We found that one-meter resolution is required for processing software to determine not only the type but also the class of ship (Mcgowan, 2018). The technology exists for classification of imagery, but a complete automated processing solution for SmallSats does not. The Rapid Image Exploitation Resource (RAPIER) Ship Detection System (SDS) software owned by SPAWAR is the most promising for ship type classification (Mcgowan, 2018). An interview with a RAPIER SDS team representative, Mr. Bowes, highlighted its ability to process high-resolution satellite imagery and detection of up to 10,000 ships. While the software is ready for deployment at ground stations, it is only at Technical Readiness Level (TRL) 8 as a terrestrial system and is not ready for deployment onboard satellites (M. Bowes, personal communication, April 1, 2018). To increase the accuracy of classification, the RAPIER SDS team has identified that a processor using multiple machine learning algorithms is a critical component in having the capability of onboard processing to classify ships, which currently requires further development (Mcgowan, 2018).

Through the calculations performed for inclination and right ascension of the ascending node (RAAN) changes, we found that the most efficient launch campaign is to launch into an inclination of 17° at a given RAAN, then to conduct a burn to 25° inclination, followed by a second burn to 33° while maintaining the same RAAN. Finally, a RAAN change of 60° is conducted at the steepest inclination, with a deployment of the desired satellites at each new orbit. Consequently, we determined that both the Falcon 9 and Atlas V are capable of performing the desired inclination and RAAN changes. Initially, the Atlas V was the preferred launch platform; however, it would still require five launches (one launch would contain only two planes of satellites vice four) to deploy the constellation, and the Falcon 9 would require six. The total cost for the Atlas V is estimated to be around $545M while the Falcon 9 would only cost $372M, which essentially renders launch timing as the critical factor. In 2017, there were six Atlas V launches and eighteen Falcon 9 launches, indicating SpaceX has demonstrated the more robust launch tempo required for such a large constellation. While the Atlas V and Falcon 9 are the two primary considerations, there are a number of smaller launch companies focusing exclusively on SmallSats. Most notably, the Firefly β is capable of delivering 4,000 kg to 500 km at a cost of $15M per launch. The β is able to deliver 1.5 planes (15 180-kg satellites) to orbit, meaning it will require a total of 12 launches to deliver all 180 satellites. At $15M per launch, this totals $180M for the total constellation. However, the β is not considered a viable option at this time because it has only completed four launches so far and has not been proven as a reliable platform, nor does it have the operational support to perform 12 launches in a timely manner. Firefly β should be watched as its infrastructure develops further; as they begin to conduct routine launches, Firefly β could be the most cost effective means of deploying the desired constellation. With currently available technology and taking cost, the number of satellites per launch, and launch tempo into consideration, the Falcon 9 is the recommended platform to deploy this 180-satellite, Triple Walker constellation of SmallSats. Potentially, the entire constellation could be placed into orbit in six launches over the span of two to three months, costing roughly $372M.

Recommendations for Further Research

We recommend an investment in the following research:

1. Payload research for IR and SAR sensors.
2. Spacecraft design upon payload selection.
3. C3 for maintaining a responsive constellation to meet TCPED requirements for MDA needs.
4. Target recognition through the use of fully-automated AI processing.
5. Optimization analysis of the constellation to include different methods, such as street of coverage.
6. Detailed cost analysis to build, implement, and maintain the constellation.

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Acronyms

artificial intelligence (AI)
Blossom Point Tracking Facility (BPTF)
command, control, and communications (C3)

Common Ground Architecture (CGA)
electro-optical (EO)
field of regard (FOR)
field of view (FOV)
Field Programmable Gate Array (FPGA)
Global Positioning System (GPS)
infrared (IR)
synthetic aperture radar (SAR)
intelligence, surveillance, and reconnaissance (ISR)
Inter-Satellite Links (ISLs)
Low Earth Orbit (LEO)
Maritime Domain Awareness (MDA)
Mobile User Objective System (MUOS)
Rapid Image Exploitation Resource (RAPIER)
right ascension of the ascending node (RAAN)
Satellite Tool Kit (STK)
Ship Detection System (SDS)
small satellite (SmallSat)
software-defined radios (SDRs)
Space and Naval Warfare Systems Command (SPAWAR)
Tasking, Collection, Processing, Exploitation, and Dissemination (TCPED)
Technical Readiness Level (TRL)
OS/COMET = Telemetry, Tracking and Command (TT&C) software
Wide Code Division Multiple Access (WCDMA)