Relative Cost and Performance Comparison of GEO Space Situational Awareness Architectures

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Background

With the declining budgets and ever increasing competition for the small amount of money available for new developments, many agencies are considering different types of architectures to meet their mission needs. In addition, new missions are being created and a wide range of architectures are being studied to determine the optimum configuration that maximizes performance while minimizing cost. The Space Situational Awareness (SSA) mission area is an example of this approach. The current architecture includes the ground Space Support Network sensors such as the optical and radar systems as well as the Space Based Space Surveillance Satellite (SBSS). The ground SSN primarily focuses on the LEO orbit while SBSS is focused on the GEO surveillance mission. The GEO SSA part of the mission is where new architectures are being studied to support SBSS and these are considering many different types of space based sensors. In addition to declining budgets, the GEO SSA problem is only growing harder as more and more objects are being launched to GEO or being created at GEO. Any type of collision at GEO would only increase the challenges. Also, program execution confidence is at an all-time low with so many acquisitions having severe difficulty. Figure 1 below highlights a number of reasons why new architectures must be considered for GEO SSA. The purpose of this paper is to examine a few of the options and objectively compare the performance against the total cost to field the system. From this comparison, inherent strengths and weakness of the individual options will be identified and these key pieces of information will help to inform future mission developers and industry sensor developers.

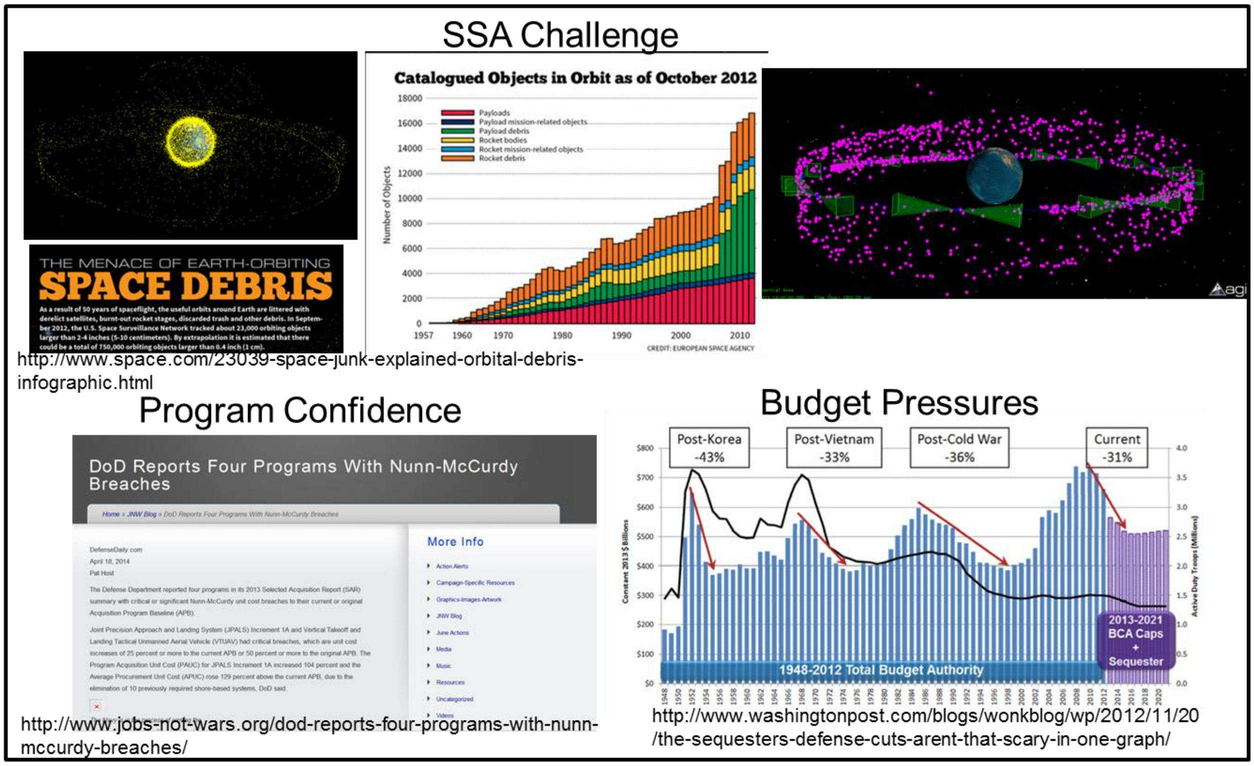

Figure 1 – Internal and External Challenges to SSA Systems

SSA Sensor Concepts

The basic need in the GEO SSA mission is for metric track data of all of the objects at GEO with the main reason being to ensure there are no collisions that could be catastrophic to the rest of the GEO orbit. The sensor trade space involves any number of variations of spacecraft and sensors. The most common options being considered are a monolithic spacecraft that carries complex optical sensors, microsat spacecraft with smaller optical sensors, hosted payloads on commercial or military spacecraft, and simple CubeSats carrying small optical sensors. There are many combinations of these options that could be considered with numerous different payload configurations. Figure 2 below highlights the different options that were focused on for this paper along with a summary of the benefits and disadvantages.

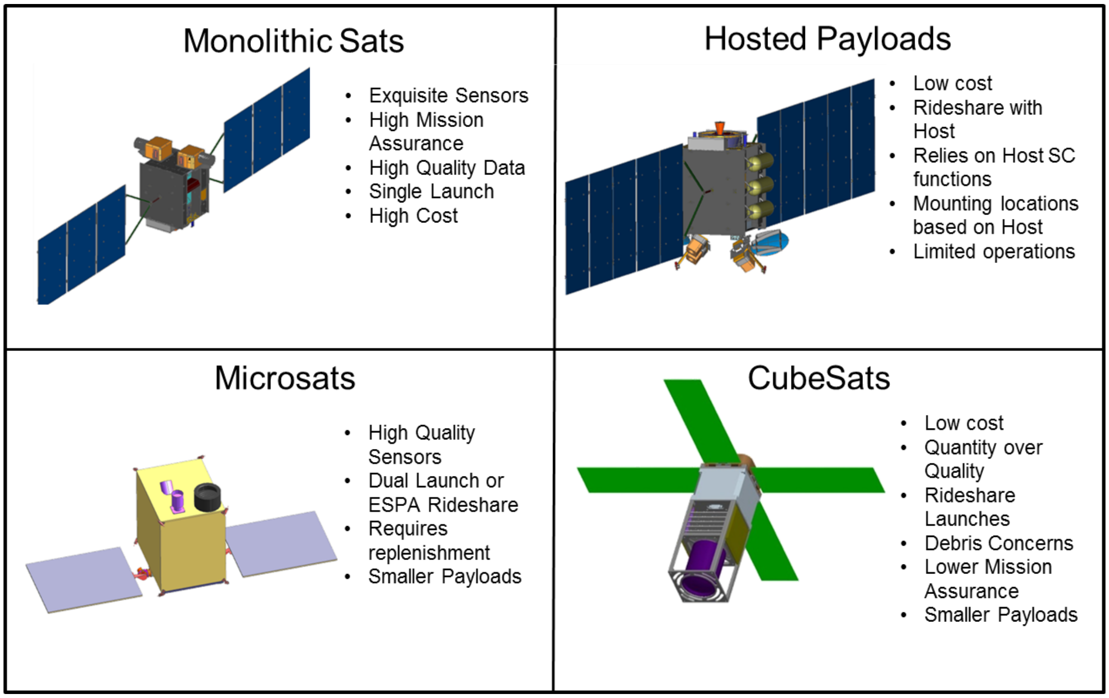

Figure 2 – Spacecraft Platforms Considered for this Study

The large, monolith spacecraft are in the 1000 kg class of vehicles similar to existing commercial satellite lines. These spacecraft can carry large payloads that take a lot of power and can operate them with high duty cycles. The spacecraft are primary payloads on the launch vehicle and can last up to 15 years on orbit. This minimizes the number of vehicles required to perform the mission and minimizes the number of replenishment launches and spacecraft to meet the full mission life of the architecture. However, the disadvantages of this option are the high launch costs and the one for one spacecraft to launch ratio. In addition, these spacecraft tend to be much more expensive and require a more complex ground system. To achieve more resiliency within the architecture, more features will need to be built in such as more satellites, higher assurance ground systems, more communications paths among others.

The microsat spacecraft are in the 200 or 300 kg class of vehicles. These are much smaller than the larger monolithic spacecraft and can be launched two at a time instead of one. This helps to save on launch costs. The sensors that can fly on these types of spacecraft are smaller; however, the individual spacecraft costs are smaller. These types of spacecraft generally have a 5 year design life so replenishment spacecraft must be launched in order to meet the mission design life. Different launch options can exist if the spacecraft can be made small enough such as launching more than two at a time on an ESPA ring.

Hosted Payload sensors are mounted to commercial or military spacecraft going to GEO. This provides, in essence, a free launch to GEO. The optical sensors can be used to look up and down the GEO belt from their position on the host vehicle. The costs of the system can be low because only the sensors and their integration with the host are cost drivers as you can take advantage of the host's support infrastructure. The disadvantages include having to potentially include two sensors to cover both sides of the host vehicle unless placed on the more desirable nadir or zenith deck. The integration costs are usually higher as these sensors must not interfere with the primary mission of the host satellite. These sensors are also limited to the orbital slot that the host vehicle prefers and creates more challenges to coverage of the entire GEO belt.

CubeSats offer a very inexpensive option and are in the 3 to 5 kg class of satellites. They can be launched in large numbers as rideshares on GEO launches. The concept with CubeSats is to utilize quantity over quality. The CubeSats can host smaller optical sensors and the larger numbers in the constellation can offer similar performance at the lower cost point per vehicle. However, rideshares directly to GEO are not always common and generally occur on military missions. This limits the opportunities to place the CubeSats into the GEO orbit. The CubeSats are generally designed for a one year mission life and so many replenishment launches are required in order to maintain the architecture. Also, the small size limits the optical payloads that can be used.

Architecture Concepts

A large monolithic satellite can have large optical sensors to do the object search mission. In addition, narrow field of view sensors or additional phenomenologies such as Infrared could be added to significantly increase detection capabilities after being queued by a wider field of view sensor. The combination of these types of sensors creates a complex and very capable SSA sensor system. For this analysis, a detection range of 42,000 km of 1 meter size objects is used with a 3 degree field of view. This sensor is also on a two-axis gimbal system in order to maximize coverage of the GEO belt. Four of these satellites will be equally spaced around the GEO belt with coverage of east and west. For this paper, only the wide field of view sensor is used in the analyses for the comparison. In reality, the data provided from all of the sensors would add to the architecture's performance. Figure 3 below shows this architecture and an example spacecraft configuration.

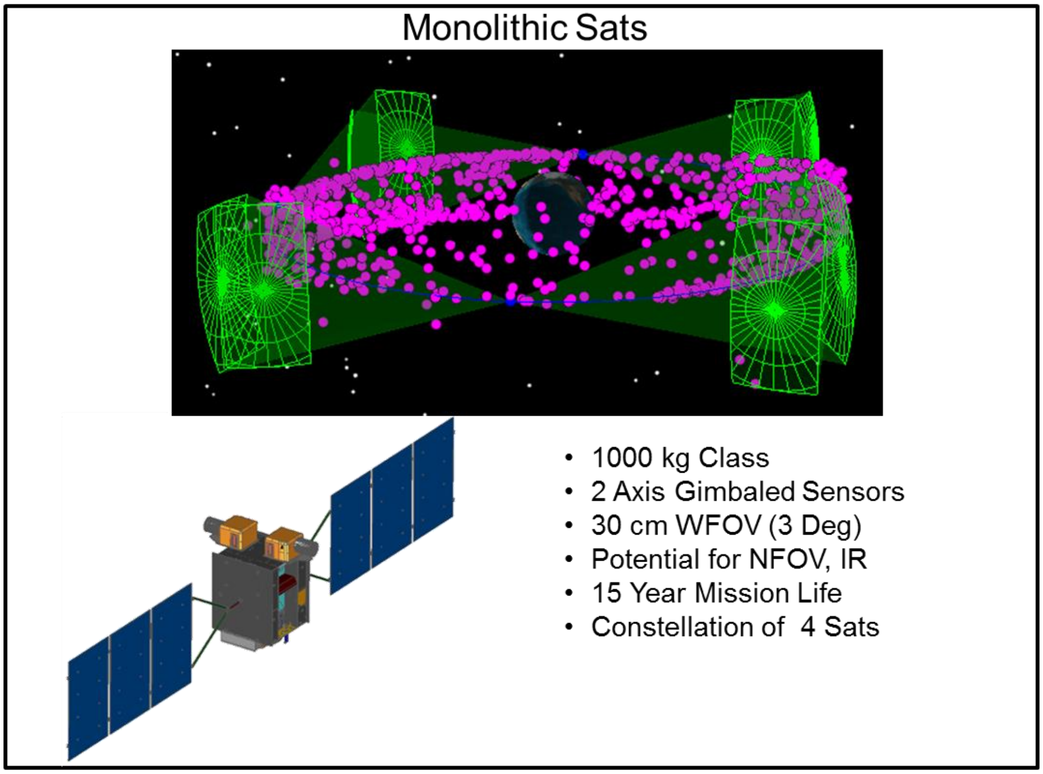

Figure 3 - Monolith Satellite Architecture and Concept Design

The small satellite configuration consists of a smaller visible telescope for the object search mission. A second narrow field of view sensor could also be added with a similar operations concept to the monolithic satellite. Since these sensors will be smaller than the monolithic satellite, the performance will be lower as well. For this analysis, a

15 cm telescope was chosen with a 3 deg field of view that has a detection range of 20,000 km of 1 meter objects. This sensor on the microsatellite bus will be fixed to the body and will require the vehicle to slew in order to look east and west. Since these spacecraft will be lower in cost and less capable than the monolithic, 16 microsats will be equally spaced around the GEO belt in order to get similar performance. Figure 4 below shows the microsat architecture and an example spacecraft configuration.

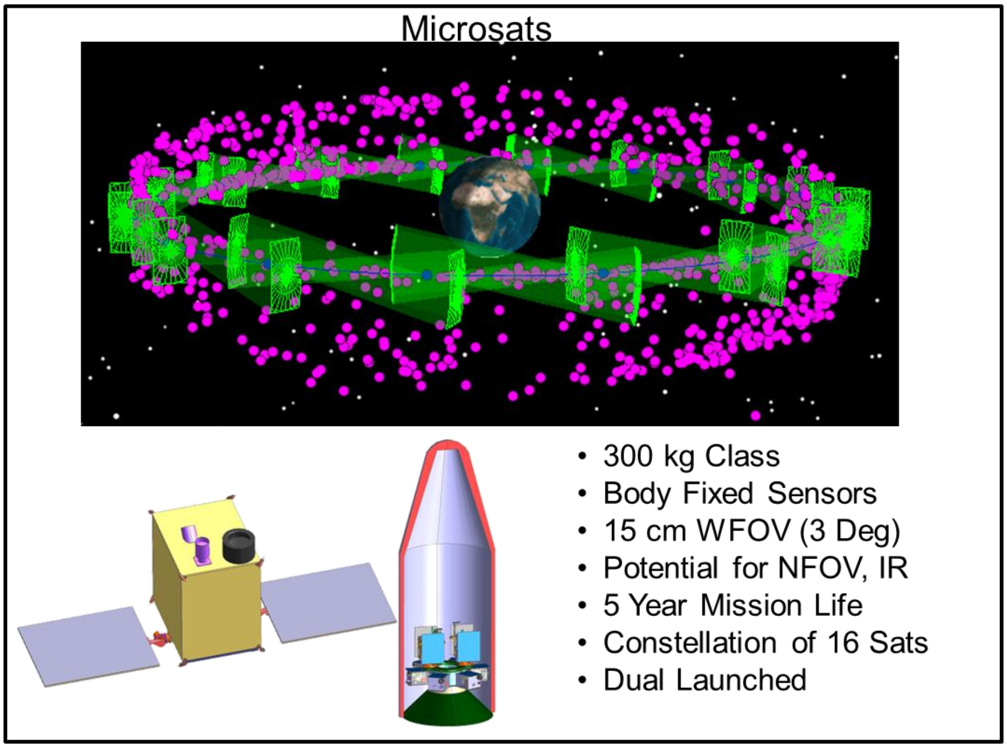

Figure 4 - Microsat Architecture and Concept Design

The hosted payload configuration consists of a single wide field of view sensor on one side of the vehicle along with a companion sensor on the other side. Since hosted payloads must be smaller in size and cannot interfere with the host satellite, the sensor will need to be gimbaled to cover the GEO belt. There is some potential for these gimbals to interfere with the primary spacecraft. The detection range of this sensor is 20,000 km detecting 1 meter objects with a 3 degree field of view similar to the microsat concept. They will be positioned on the host spacecraft looking east and west along the GEO belt. It is assumed that 16 satellites have hosted payloads on them at GEO but not equally spaced around the GEO belt due to available ride shares. Figure 5 below shows this architecture and concept.

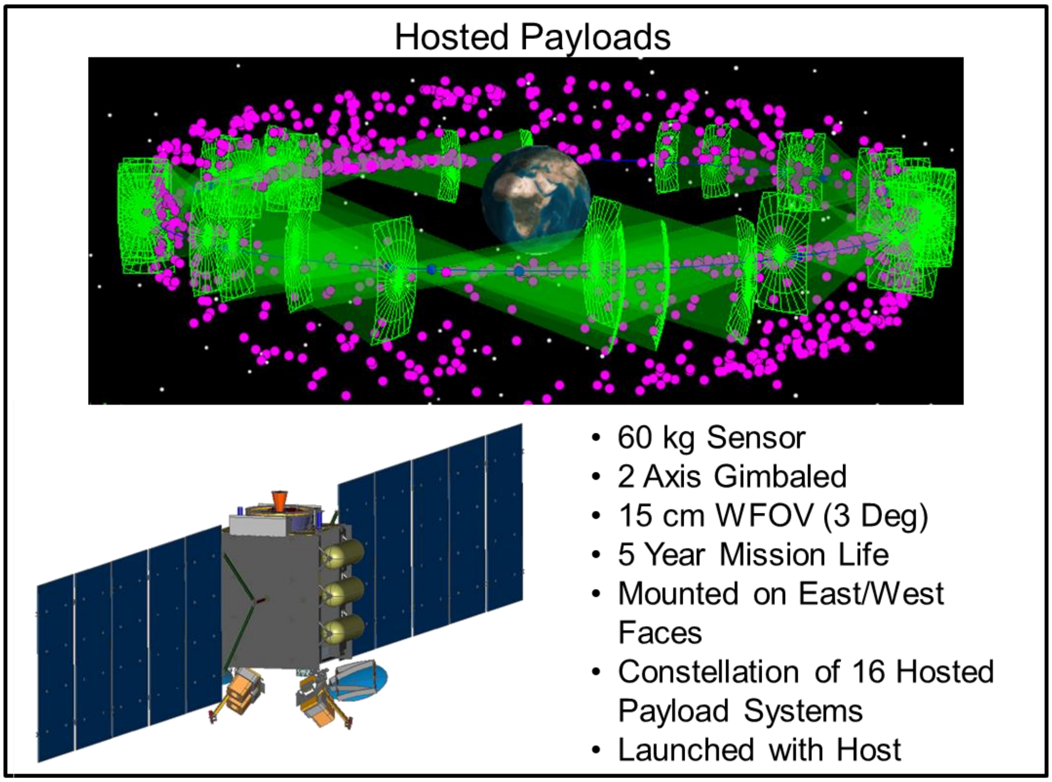

Figure 5: Hosted Payload Architecture and Concept Design

The CubeSat architecture consists of small 3U CubeSats with a small star camera sensor for a wide field of view camera. CubeSats cannot carry much of a payload so the detection ranges will be lower. For this analysis, it is assumed that a 5000 km detection range of a 1 meter object utilizing with a 30 degree field of view. The sensor is body fixed but small reaction wheels will allow for the CubeSat to change the pointing vector. Because the reliability of these CubeSats will be low, they will be placed in a GEO +500 km orbit to ensure failures do not create uncontrolled debris at GEO. For this architecture, 27 CubeSats will be placed in orbit. Several CubeSat deployers can load and deploy 9 CubeSats so an ESPA ring with three slots taken up with CubeSats will put 27 in orbit each time. Since the lifetime of these CubeSats will be one year, replenishment CubeSats will have to be launched every year to maintain the architecture. Figure 6 below shows this architecture.

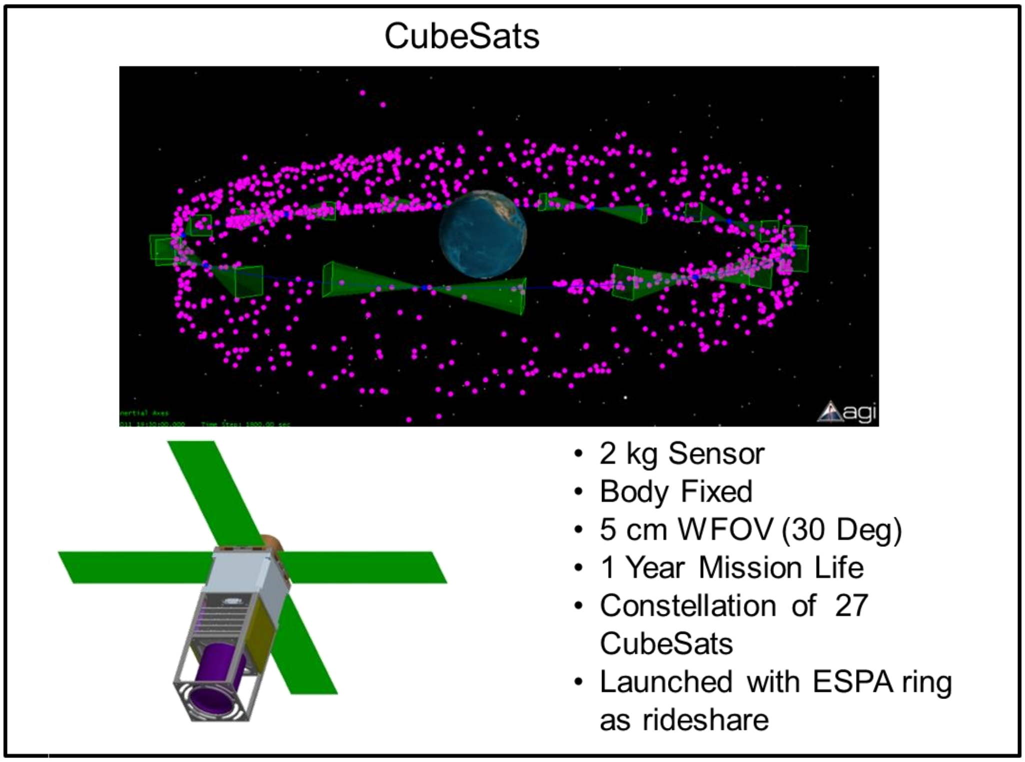

Figure 6 – CubeSat Architecture and Concept Design

Architecture Performance and Cost Analysis

To compare the performance of the various architectures, coverage, access, and maximum time between observations will be used. These parameters are important for SSA because coverage is the amount of time an object is viewed while access means how many objects are getting at least one observation. These sets of observations will be used to update the two line element set. The mean coverage percentage describes on average, the amount of coverage the architecture provides. The maximum time between observations is important in case objects maneuver or change orbits and to ensure timely observations for collision avoidance concerns. These architectures were constructed in Systems Took Kit and linked with Matlab to perform the analyses and generate the data. All of these scenarios were run for a single day. Obviously, the performance will improve for multiple day runs but a single day is enough to compare the performance between the architectures. Figures 7-11 below show the performance of the four different architectures.

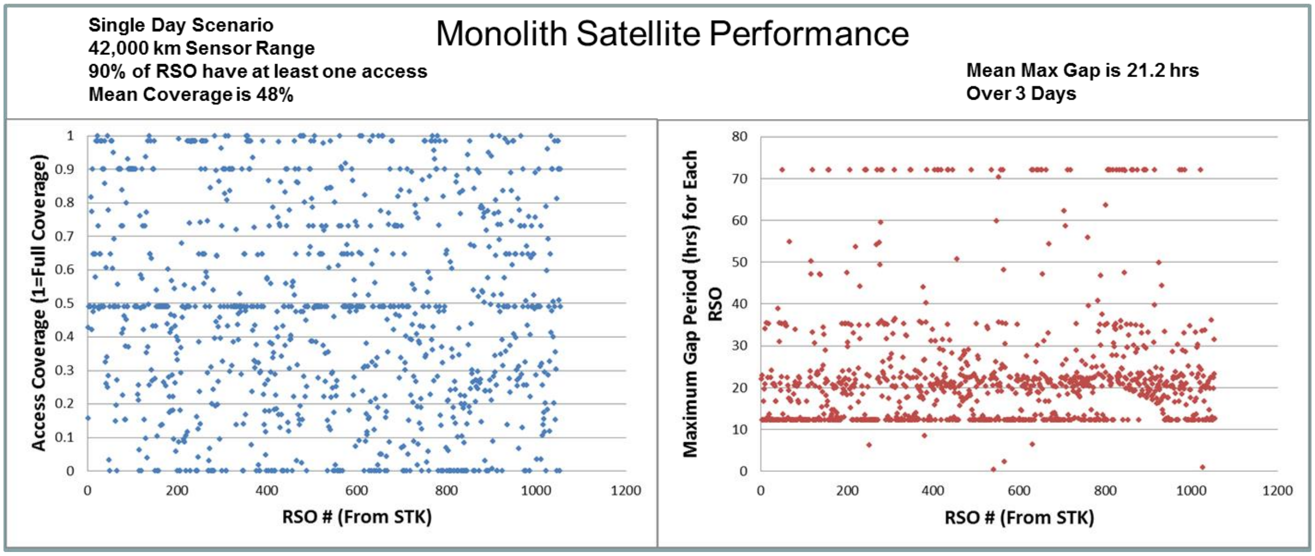

Figure 7 – Monolithic Architecture Performance

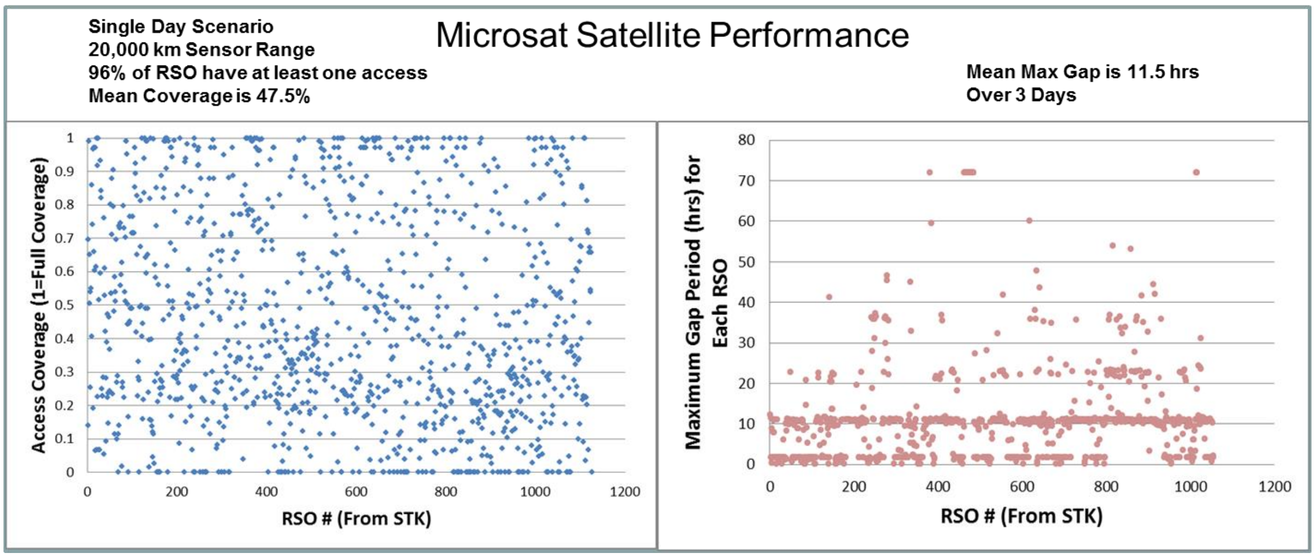

Figure 8 – Small Sat Architecture Performance

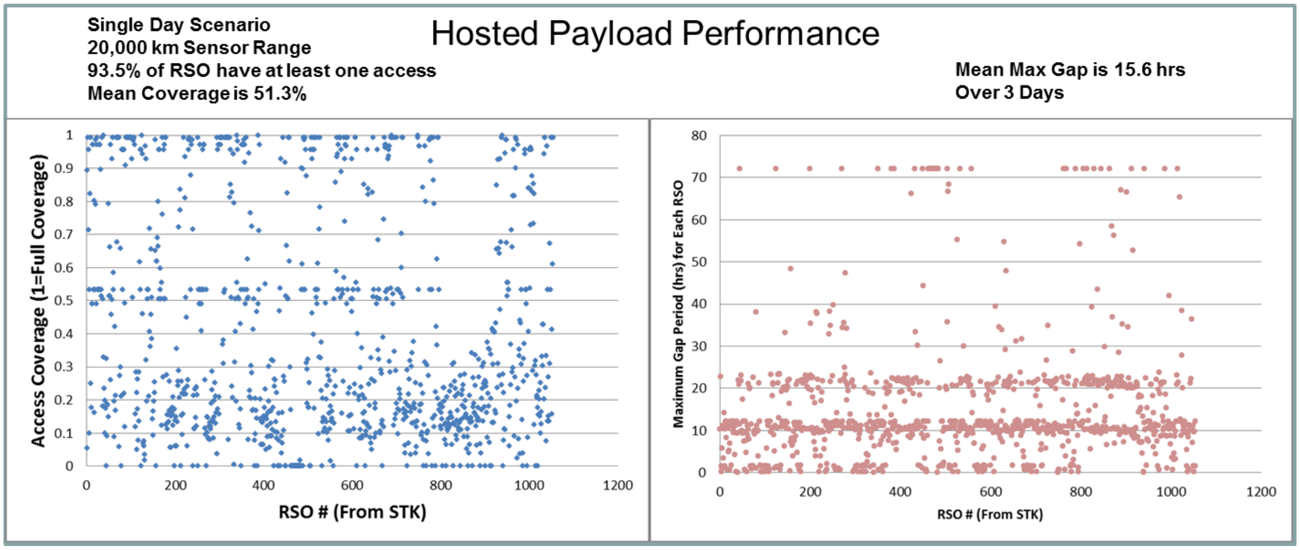

Figure 9 – Hosted Payload Architecture Performance

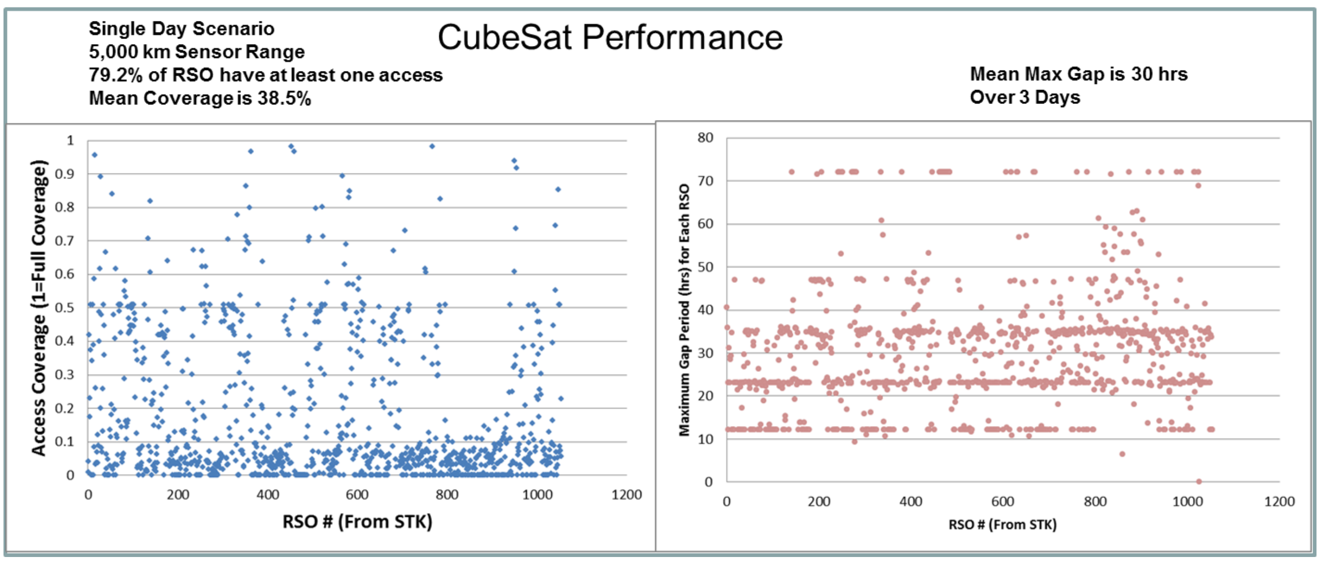

Figure 10 – CubeSat Architecture Performance

The results from the performance analysis show that the microsat and monolithic architectures provide similar SSA performance. The main difference lies in the average time between observations as the monolithic architecture has less overlap in coverage based on the constellation. The hosted payload option also provides significant performance; however, there are some objects in the belt that do not get any observations due to gaps in coverage based on the potential hosts available for ridesharing. The CubeSat architecture provides less performance compared to the other three architectures but still adds capability that could help to offset the current SSN.

To compare the relative costs of these architectures, it is important to consider the spacecraft and ground costs, both non-recurring and recurring on top of the launch costs. In addition, operations costs for the constellation through the mission lifetime and any replenishment costs including additional launches must be included. Assuming that the mission lifetime requirement is 15 years, that sets the total operations costs and the number of replenishment spacecraft and launches required. The larger satellites have more electronics and complex payloads so the operations costs are higher than the hosted payload and CubeSat options. Data quality will be much higher for the larger satellites but was not factored into this cost calculation. Figure 11 below shows the relative costs of the four architectures normalized against the Microsat case that is the most expensive.

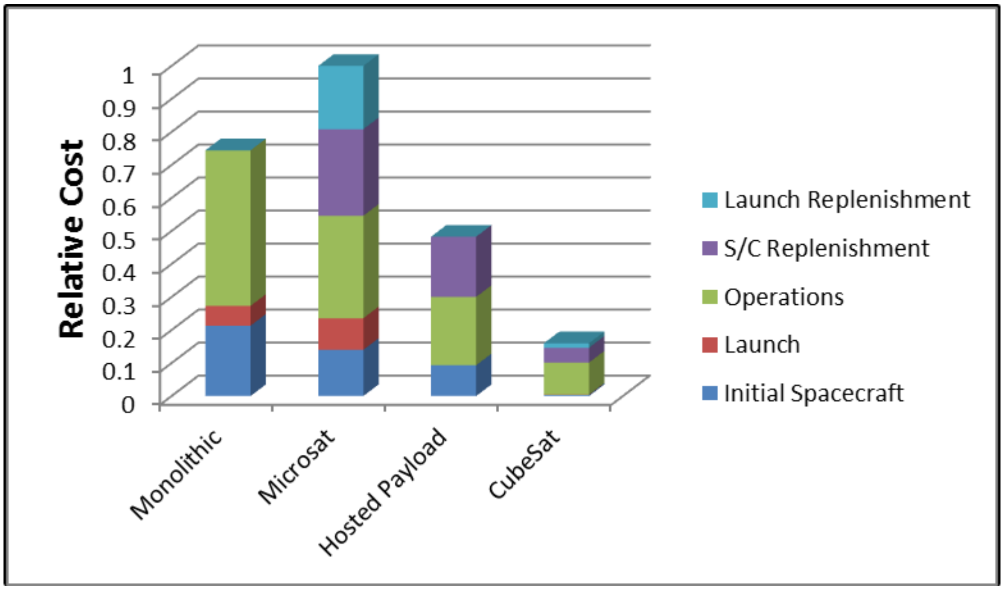

Figure 11 – Normalized Cost Comparison the Four Architectures

By taking the relative cost and comparing them against the SSA performance helps to show which architectures are providing the best value. Figure 12 below shows performance versus relative costs. The ideal architectures would show up in the upper left meaning they have the highest SSA performance with the lowest costs. To calculate the relative performance, coverage, access, and average maximum gap period were normalized for the highest concept in each category. The three scores were then summed together. There are many potential ways of comparing the performance of these architectures and this was a simple way to highlight some of the key benefits and regrets.

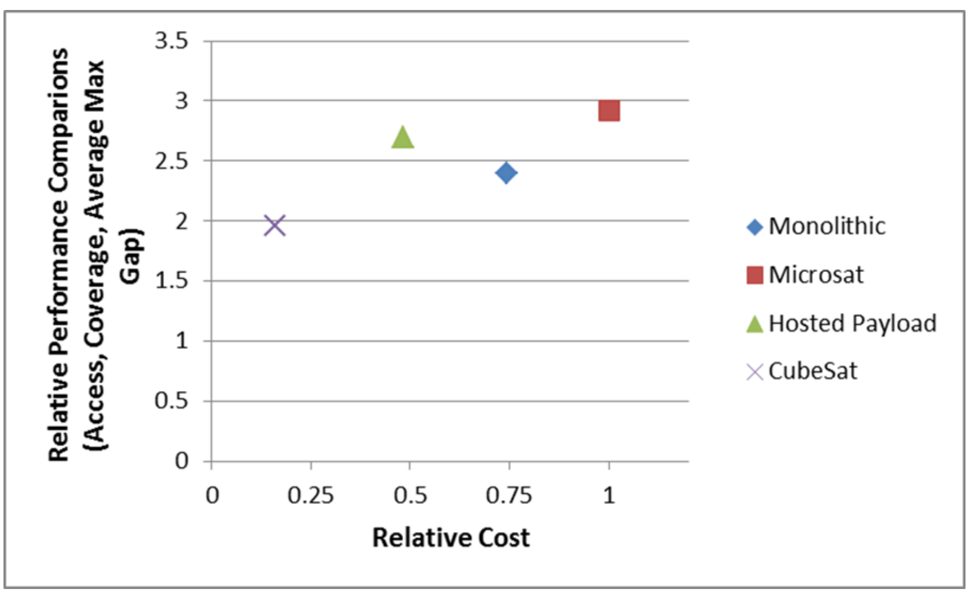

Figure 12 – Performance versus Relative Cost

The CubeSat architecture had the lowest performance as well as the lowest cost while the Microsat had the highest performance and highest cost. One conclusion from that is these architectures could be optimized more to bring them more in line with the other two. For example, adding more CubeSats will increase the performance and could reach the same level as the other three. Conversely, Microsats could be removed from the architecture to reduce the performance as well as cost to remain in line with the other three. The hosted payload concept offers a significant amount of capability at a reduced cost. The monolithic spacecraft concept provides slightly less performance based on the amount of satellites in the constellation. More satellites could be added to increase the performance but it will also increase the cost.

Conclusions and Recommendations

When performing this initial top level study, it is not important what the absolute cost is of each architecture is because there are many different ways you could design the architectures, spacecraft, and sensors that would change the cost and performance. A different sensor mix or adding more spacecraft into the architecture could increase performance and cost. For example, employing a significant amount of autonomy on the monolithic satellites could reduce operating costs and keep them more in line with the microsat concepts. Without spending a significant amount of time optimizing each architecture, a simple relative cost and performance comparison helps to illuminate key advantages and disadvantages of each concept. Table 1 below highlights the key conclusions for each concept.

Table 1 – Key Conclusions from the Study

Monolithic Concept	Microsat Concept	Hosted Payload	CubeSat
2nd Highest Cost with the 2nd highest performance	Highest cost and highest performance	3rd highest performance with the 2nd lowest cost	Lowest performance against the lowest cost
15 year mission life eliminates replenishment, cannot update technology	Opportunities to reduce launch costs including replenishment by going to ESPA launches	Architecture is driven by host and may not be optimal. Creates gaps in coverage that may not be ideal	Lower quality data and lower data integrity
Resiliency measure must be built in or buy spare sats	Can utilize updates to sensors on replenishment spacecraft to increase performance over time	Performance can be increased with larger, more sophisticated sensor, with higher integration costs	Upcoming competition for rideshare launches direct to GEO limits architecture performance
Operations costs are highest, look for autonomy	Operations costs are significant and can be reduced with more autonomy	Integration costs can be reduced by hosting on the same type of spacecraft	One GSO launch required per year to maintain architecture
Potential for enhanced data, IR, NFOV, others	Less data to the ground but still maintains data integrity	Operations costs are low without having to control entire satellite	No ability to add IR, NFOV to all CubeSats, could replace sensors on some CubeSats
Highest Data Integrity, highest data to the ground	Overlap in coverage reduces gap period between observations	Limited in access by mounting locations on the host. Can be drive to less than ideal locations	Lower coverage statistics could be mitigated with increased architecture size
Less overlap in coverage for higher inclined objects	Roughly equal coverage of most objects at GEO	Some objects will never be imaged due to architecture	

Many of these conclusions do not come from the cost and performance comparison but are derived from the process of developing the metrics. This study does prove that there is a wealth of options available when developing the next generation GEO SSA system and the optimum answer is most likely a mix of all of these options. By understanding each concept's strengths and weaknesses, one can develop an architecture that enhances the strengths but covers the weaknesses.