

Concepts for an Enhanced CubeSat GEO Space Situational Awareness Architecture

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Introduction

Space Situational Awareness (SSA) continues to be a very important national mission with military and civilian interests due to the large number of missions that require the use of space. Space is becoming more congested as more and more entities are launching satellites to both LEO and GEO. Combine that with the ever increasing debris created from those launches, decommissioned satellites, and on-orbit collisions, and the result is the ever increasing need to keep an operational picture of where everything is. The current Space Surveillance Network (SSN) capabilities are quickly becoming over taxed and must devote more resources to track the LEO objects. Because of this, GEO requires additional assets to offset the SSN. Ground based sensors have GEO limitations on access and coverage as well as sensitivities. In addition, ground based sensors provide observations from the same angle that generally have limits on the orbit determination accuracy. On top of the ever increasing debris environment, there are other challenges due to the new environment in the space industry. As many programs have undergone Nunn-McCurdy reviews, confidence in new programs is at an all-time low. Add budget cuts and sequestration to the fold and identifying new ways of doing traditional missions is becoming critical. Figure 1 below highlights the challenging environment. Space based assets can help to fill the holes of the current SSN as well as improve the accuracy of the orbit tracks. CubeSats can provide non-traditional platforms to use as SSA assets and if used appropriately, can provide significant coverage of the GEO belt objects.

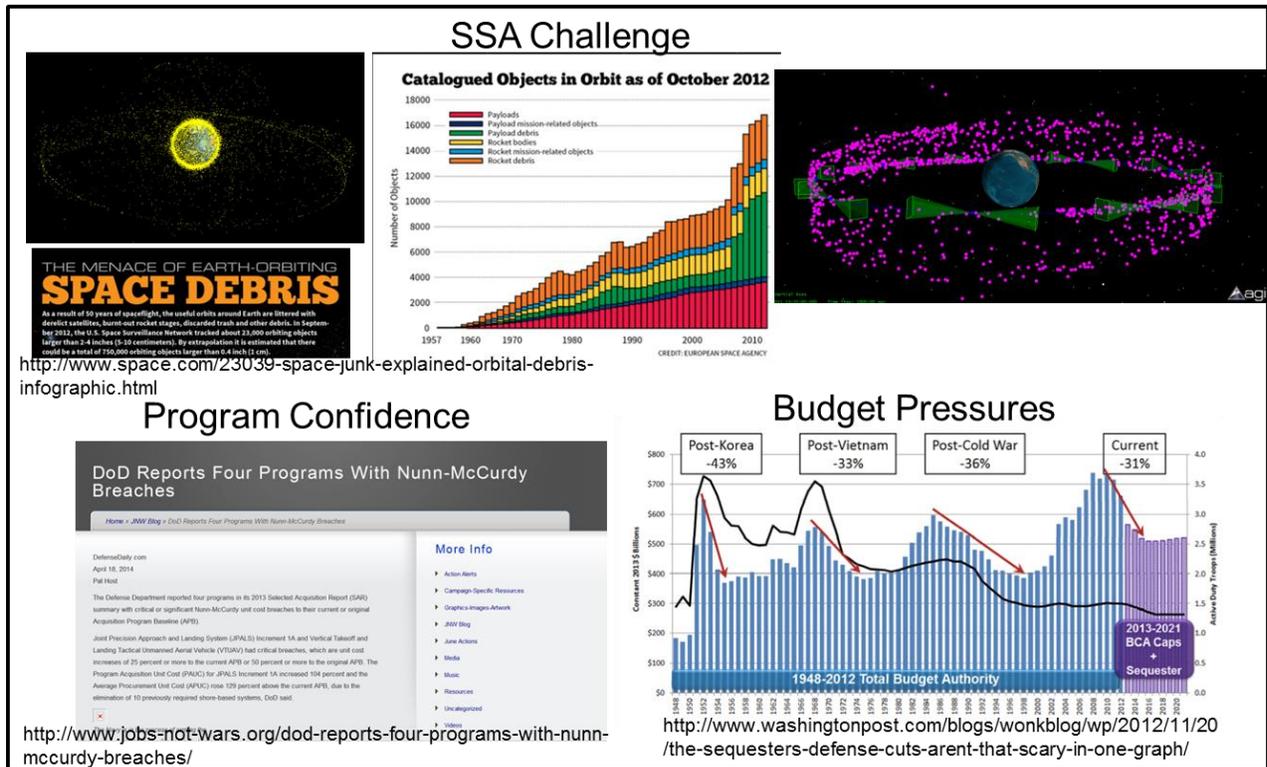


Figure 1 – SSA Challenges to New Architectures

Background

CubeSats have exploded in popularity recently and are being launched significantly more often. Figure 2 below shows the number of CubeSats that have been launched year to year. 2014 has already seen a large number of CubeSats launched through July and is already higher than 2013.

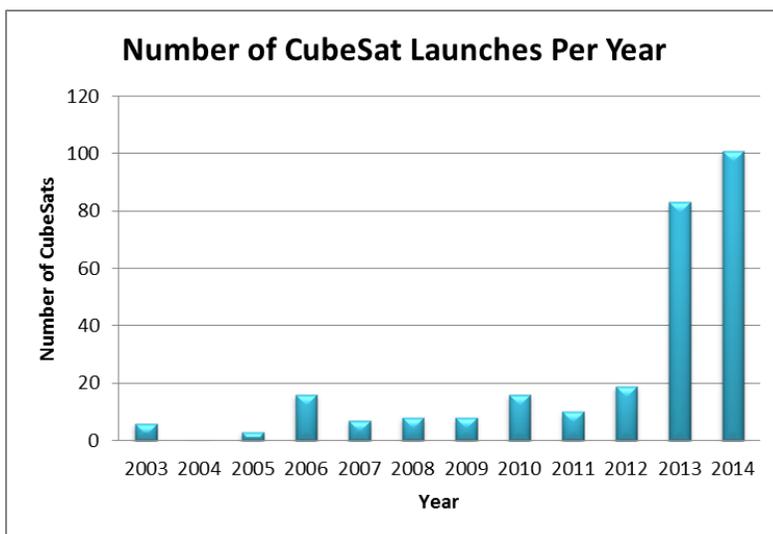


Figure 2 – CubeSat Launches per Year

Everyone from government customers such as SMDC and NASA as well as universities are utilizing CubeSats for missions and education. CubeSats are 10 cm x 10 cm x 10 cm units that can be combined to form larger spacecraft. Standardized components and deployment mechanisms are heavily produced for this form factor and, thus, help to create low cost access to space. The figure below shows the standardized deployers (P-PODs) along with examples of CubeSats.

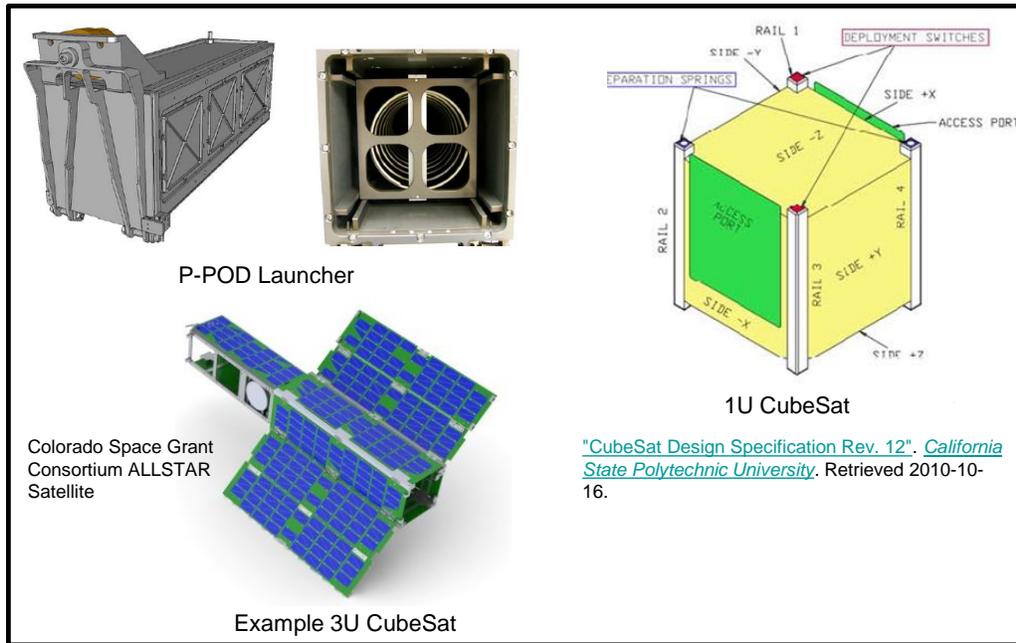


Figure 3 – CubeSat Hardware and Deployer Options

By utilizing the CubeSat as an SSA platform, the hardware costs associated with the SSA data collection can be minimized. Software and hardware components for CubeSats are readily available and the technology is being pushed to higher quality and higher reliability parts. However, there are still concerns associated with CubeSats such as access to space (especially GEO), fault tolerance, orbit selections, and payload accommodations. These concerns drive how the CubeSats can be used and forces new architecture approaches. When CubeSats fail before their End of Life Sequence, it creates new pieces of debris and increases the SSA problem. For GEO, the orbit becomes increasingly important because failed satellites will drift along the GEO belt creating potential collisions and increase the number of objects that must be tracked. Because of this, orbits above or below the GEO belt are the preferred orbits to use for SSA as the CubeSats can be disposed of in that orbit and it creates a relative drift with respect to GEO. However, getting CubeSats to GEO requires direct insertion launches that are not very frequent and will begin to have high competition for the limited rideshare slots. Because there are many more launches into a GEO transfer orbit where the primary spacecraft provides its own insertion maneuver, these launches are prime candidates for rideshares. Staying in the GTO orbit also provides opportunities to image the GEO belt at apogee. With an apogee slightly lower than GEO and a perigee that will eventually force the CubeSat to re-enter, this orbit provides a safe location to perform SSA. Finally, there are opportunities to rideshare on commercial satellites going to GEO that can help fill in the launch availability gaps. Several developments are currently in work including the DARPA Phoenix program to leverage the commercial market for rideshare space to GEO. All of these available options for access to the GEO belt are enhanced with the advancements in CubeSat propulsion systems. Currently, CubeSats have flown limited propulsion systems but many more are in development. These range from simple cold gas systems to complex hydrazine systems with higher thrust and delta V. Since each launch opportunity will allow for multiple CubeSats, a propulsion system allows for phasing in each orbit to maximize the coverage. Also, the

injection locations of direct injections to GEO and hosted on commercial satellites will vary and a propulsion system is key to getting into the correct location to perform the SSA mission. In addition to reliability and orbit selection, the size, weight, and power (SWaP) available for payloads is less than traditional satellites. To help mitigate this constraint, larger numbers of CubeSats can be deployed to meet the same mission performance as traditional satellites. Figure 4 below shows a CubeSat concept that can be used for GEO SSA.

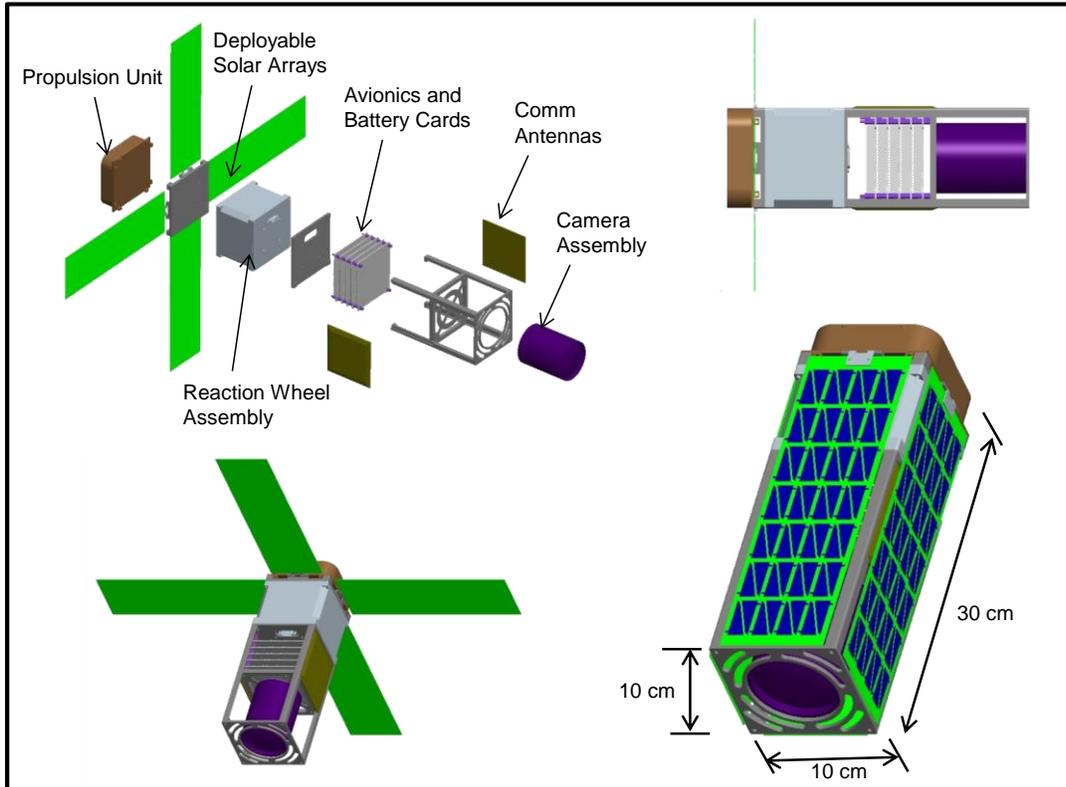


Figure 4 – CubeSat Concept to Perform GEO SSA

Collection Architecture

GEO +500km

Previous papers have shown the validity of using a GEO +500 km orbit to collect imagery of the GEO belt. This orbit creates a relative drift with respect to GEO of 6 deg/day. Utilizing a visible imaging camera to take images of GEO belt objects, a constellation of CubeSats equally spaced around the belt can provide a significant amount of the required images for the SSA mission. Figure 5 below shows an overview of the orbit and shows the percent coverage and access (at least one observation per object per day) for different numbers of CubeSats. It also shows the average maximum gap period between observations of a single object. Obviously placing hundreds of CubeSats into this orbit would provide substantial coverage but is not practical due to the available GSO launches, competition for the rideshare slots on these few launches, and failure rates of the CubeSats. Also, the sun creates exclusion zones throughout the day where the CubeSats cannot image. The CubeSats would be designed to slew between imaging the velocity and anti-velocity vector to account for the Sun. Figure 5 does show that this collection location can provide significant access to all of the GEO objects when you get to closer to twenty CubeSats.

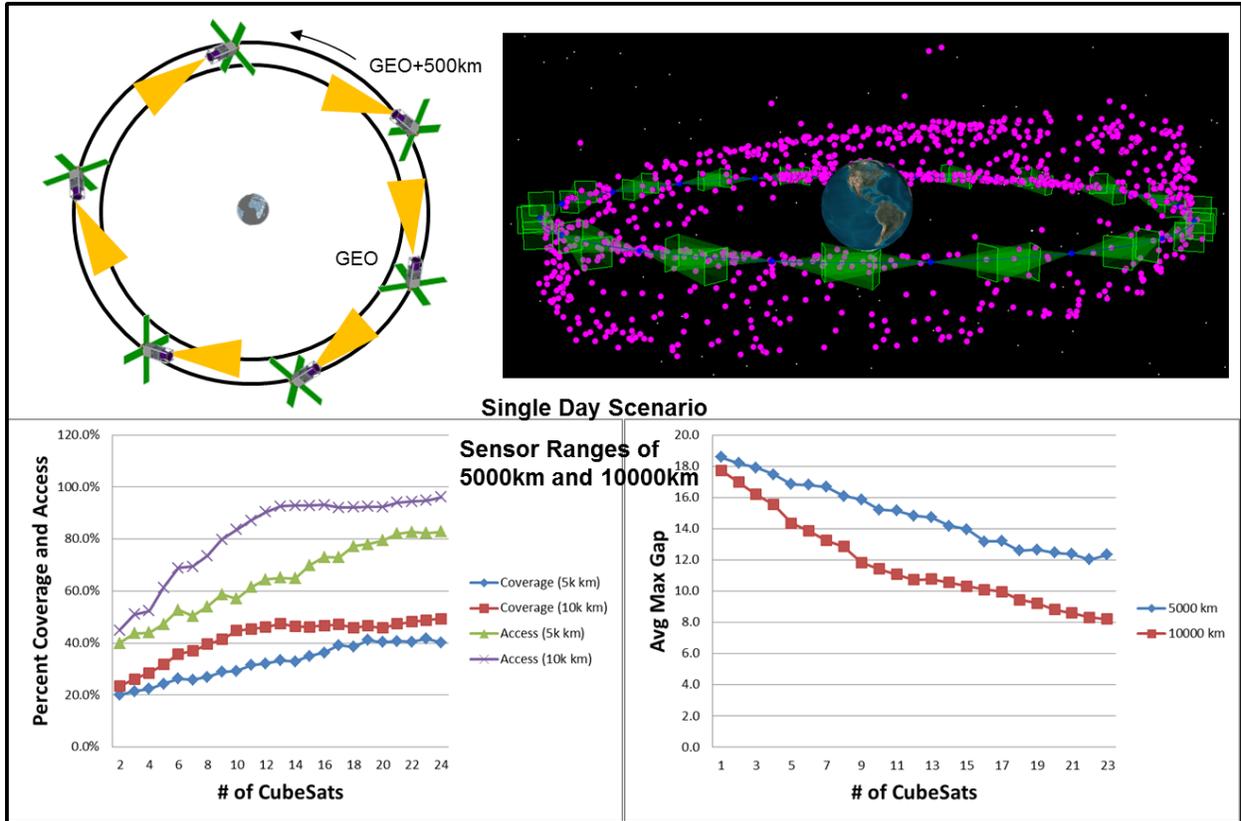


Figure 5 – Overview of GEO+500km Orbit

Highly Elliptical Orbits

The second orbit in the mission architecture is to utilize the highly elliptical orbits (HEO) such as GEO transfer orbits. These orbits provide imaging opportunities at apogee in an inclined orbit that provides a different view point than coplanar with GEO. Due to orbit perturbations, the Right Ascension of the Ascending Node and Argument of perigee rotates around the Earth and this moves the apogee away from the GEO belt north or south for a period of time. An option to prevent this is to keep as low an inclination as possible. However, the higher inclinations provide the different viewing angle and lighting conditions that increase the tracking accuracies and limits sun outages. Adding multiple planes of CubeSats in these HEO orbits will also help to minimize the outages caused by the perigee walk. Figure 6 below shows the orbit and collection area of the orbit.

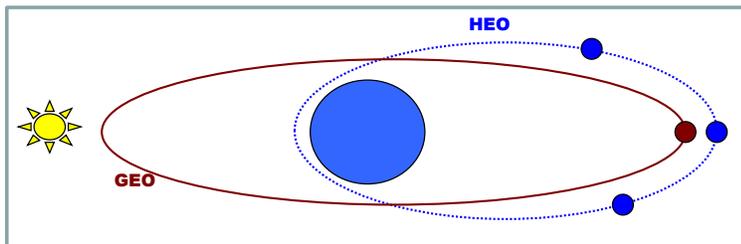


Figure 6 - GTO/HEO Mission Orbit

Because the image collection opportunities exist around apogee, which is the lowest velocity of the orbit, they represent roughly 30% of the orbit period. The remaining part of the orbit can be used to downlink the data. In addition, the range advantage at perigee allows for much higher data rates than at GEO. Figure 7 below shows the collection opportunities of a single CubeSat over the course of one week. It shows that access to the entire belt is achieved after 4 days. However, this analysis does not account for inclined objects at GEO.

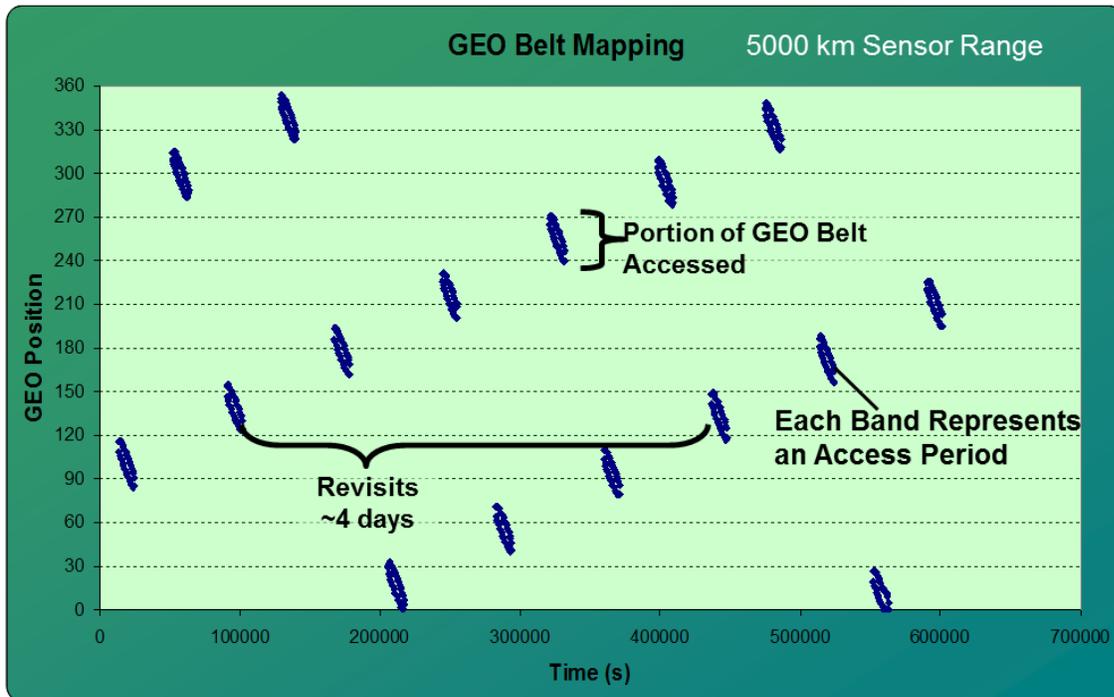


Figure 7 – HEO Access to the GEO Belt

There are several advantages to utilizing HEO orbits with CubeSats. First, propulsion can be minimized to just the phasing within each plane of CubeSats because reentry will naturally occur within a year or two due to the low perigee. This helps to minimize the complexity of the CubeSat. Also, there is no risk to creating new debris in orbit because of this. There are some disadvantages to the orbit which are the perigee walk that will temporarily take the apogee of the orbit above or below the GEO belt so there are potentially no imaging opportunities. This can be mitigated, partially, by the phasing within planes as well as with adding more CubeSats on additional launches. Also, the lower inclination orbits will reduce this perigee walk. Figure 8 below shows the coverage of five planes of HEO CubeSats with an inclination of 12 degrees.

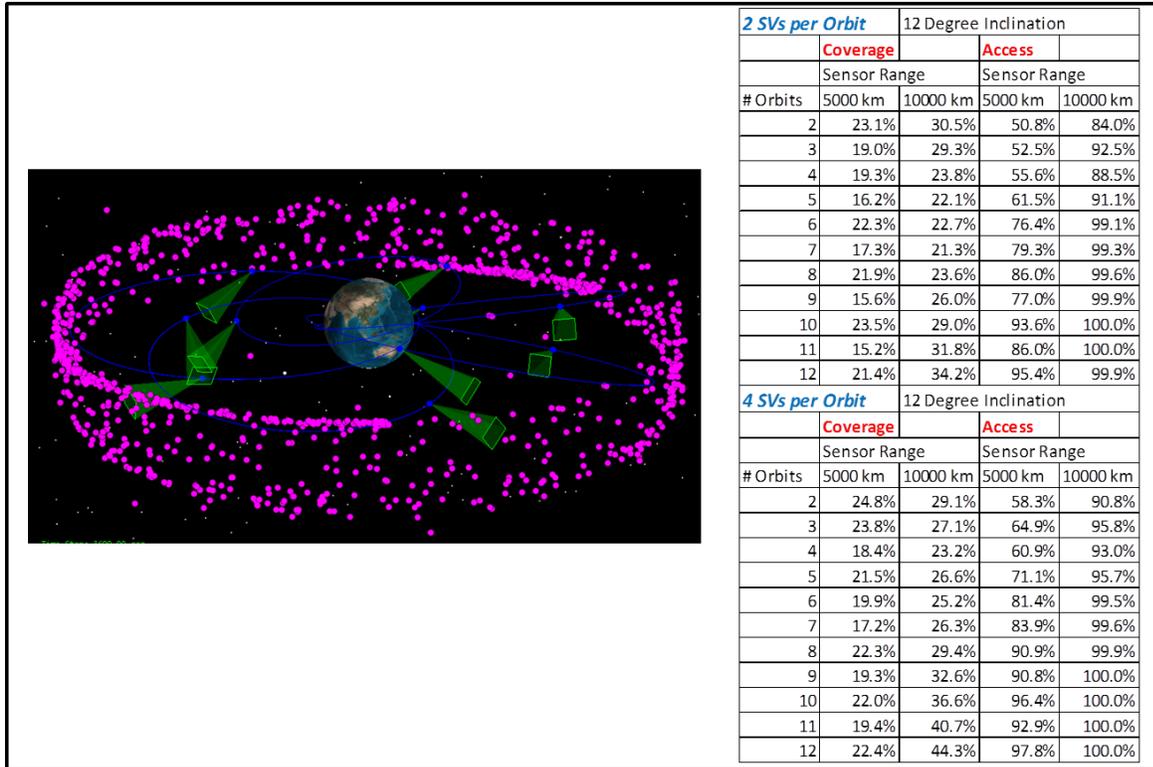


Figure 8 - Coverage for HEO CubeSats

Geopotential Wells

The final piece of the architecture is to utilize the western and eastern Geopotential wells. These are the areas where the Rocky Mountains and the Himalayas create extra forces that tend to capture very slow moving objects relative to GEO. Therefore, if a CubeSat were to fail while near one of the wells, the CubeSat would remain there and not begin to drift along the GEO belt. Figure 9 below shows the locations of the wells and how objects tend to drift back and forth within a few degrees. It also shows, as expected, that there are a significant number of objects near the wells as it image up to 21% of the total GEO objects.

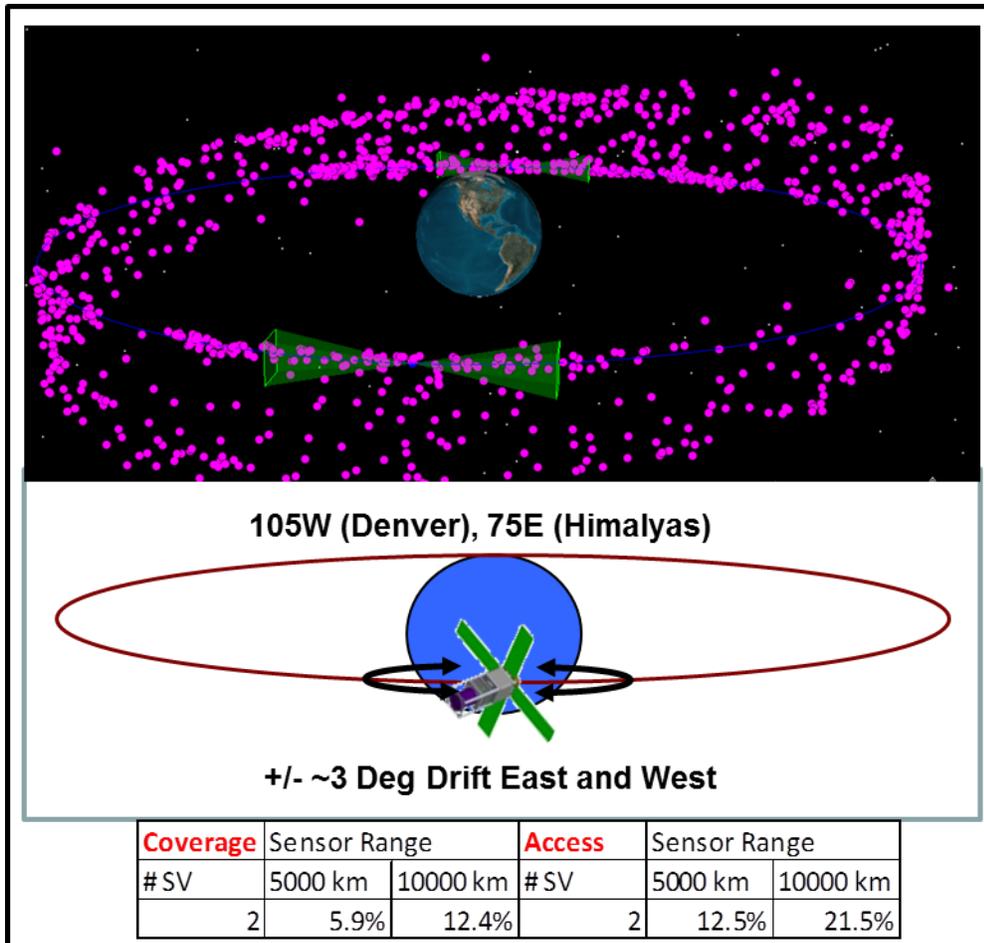


Figure 9 – Western and Eastern Wells

To get to these orbits, a potential option is to rideshare with commercial communications satellites. Programs such as DARPA’s Phoenix are attempting to build pods that can be hosted by these commercial satellites to carry small spacecraft and insert them into GEO. Once circularized at GEO, the CubeSats could be deployed from the host and use the propulsion system to make maneuvers to drift to the western and eastern wells. Once stationed at these wells, the CubeSats would be tasked to image up and down the GEO belt with the primary objective of looking for drifting satellites incoming or outgoing. The benefit of these orbits is to track the drifting satellites that might be harder for the GEO+500 km CubeSats to image as well as the HEO CubeSats. However, tracking the objects around the wells is also a priority. Figure 10 below shows the DARPA Phoenix concepts for rideshares to GEO.

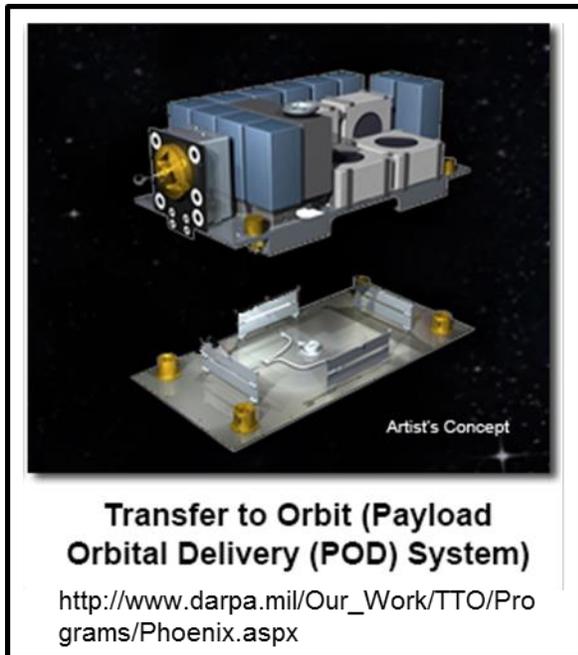


Figure 10 – DARPA Phoenix Rideshare Option

SSA Performance Assessments

The primary sensor for this analysis is a Star Camera like optical sensor for visible imaging with a 10000 km range of 5 m targets. The smaller objects will still be detected with the imaging camera at closer ranges. The CubeSat will also have small reaction wheels to go along with a chemical propulsion system. The reaction wheels allow for rapid slewing to track higher inclination targets or faster objects while the propulsion system provides the maneuvering and phasing capability. The SSA performance analysis is based on several metrics. First, the coverage of all GEO objects is important as this dictates the total time that objects are tracked. Access is important as one observation a day is enough to help maintain the current catalog. Finally, the time between observations is important in case the objects are drifting or maneuvering. STK was utilized with the GEO satellite database as well as Matlab to calculate these metrics for the CubeSat. Figure 11 below shows the coverage of all three CubeSat orbits combined. From these plots, it shows that this architecture can significantly aid the SSN as nearly 100% of the objects are imaged once per day, while 44% of the objects are covered. This means that, on average, an object is imaged 44% of its orbit in a single day. The mean maximum gap is 8.6 hours that shows that most of the time, the revisit rate sits below 12 hours. This will aid in the detection of moving objects.

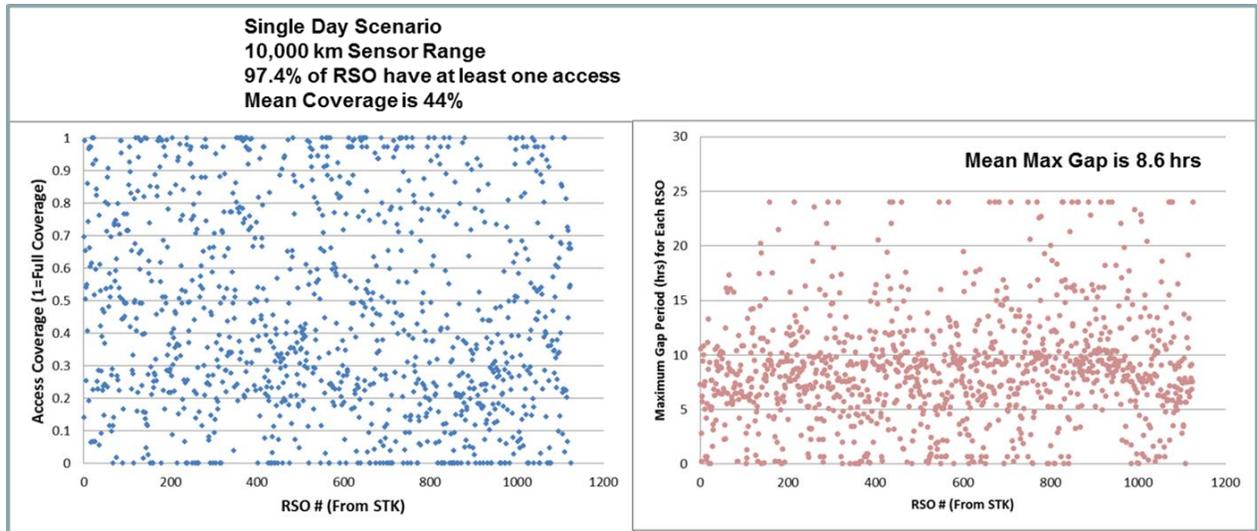


Figure 11 – CubeSat Coverage for Baseline Architecture

Conclusions

Based on the results from this study, a constellation of CubeSats can provide significant coverage of the GEO belt. By utilizing these three orbits, different viewing angles are provided to counter the sun outages, higher accuracy tracks are produced, and custody of nearly all of GEO objects can be performed. There are many different variations on the architecture and this specific one was selected to show the validity of CubeSats to SSA. For an operational system, optimization of the architecture will need to be performed. With the CubeSats' low price point to produce and using rideshare launches, this architecture can be developed very affordably compared to more traditional architectures. This creates a new paradigm in development of emphasizing quantity over quality to accomplish the mission. This architecture shows that CubeSats can begin to augment the current SSN systems and provide quality SSA data for relatively low cost. The GEO +500 km orbit provides the significant performance of the total architecture while the HEO orbits provide more opportunities for rideshare launches and provides different viewing angles to GEO than coplanar. The Geopotential wells provide an ideal location to place CubeSats at GEO due to the natural forces that capture slow moving objects. Overall, this CubeSat architecture does highlight that CubeSats should be considered in future SSA architecture concepts and their performance will not be limited.