Benefits of hosted payload architectures for improved GEO SSA

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ABSTRACT

Maintaining a precise catalog of objects in and near the GEO belt is difficult for a variety of reasons. Optical Hosted Payloads (HP) on commercial satellites have been suggested as a solution to provide accurate, persistent catalog updates to augment existing data or even relieve schedule burden on traditional tracking systems. However, significant questions remain about what architecture requirements are necessary for stable orbit determination solutions, accuracy improvements over traditional tracking systems, and optimal catalog coverage. System trades are performed using COTS software to determine the influence of number, frequency, and accuracy of observations on orbit solution stability and uncertainty. System configurations are also evaluated against catalog coverage metrics such as number and percent of objects observed, number of tracks per day, and revisit times. Initial results show that some assumed configurations can produce stable, accurate orbit solutions for most of the catalog in and near GEO. Fusing observations from HP sensors with traditional ground data may yield dramatic improvements in positional uncertainty of one to two orders of magnitude, often with multiple observations each day.

1. INTRODUCTION

Orbit determination (OD) of satellites near geosynchronous (GEO) orbit is a complex task in general and in particular for uncooperative Resident Space Objects (RSOs). As the population of objects in the GEO neighborhood grows, maintaining a highly accurate catalog of all objects becomes increasingly important to mitigate risks of collision and for security of high value assets. The current Space Surveillance Network (SSN) capabilities for tracking these objects are subject to a number of constraints – particularly weather, scheduling, geographic dispersion and overall capacity – which leave the GEO catalog in significant need of improvement. Although recent efforts in sharing of owner-operator data in the Space Data Association have provided remarkable benefits [1, 2] additional tracking of uncooperative objects will be required.

Many have suggested hosting optical tracking payloads on commercial, civil, or non-dedicated defense GEO satellites as one method to provide additional observations. Similar to ground based optical systems, the geometry of such GEO HP systems may create challenges for OD when used independently. However, they do offer some significant advantages over ground based optical systems in detection range, freedom from the influence of weather, potential observation persistence, and cost. GEO Hosted SSA Payload (GEO HP) system would in general be orthogonal to ground based measurements suggesting that fusing data from both sources could provide dramatic improvements in accuracy.

The goal of this paper is to assist in developing a notional architecture of a GEO HP SSA system that

1. Provides acceptable, or improved, levels of OD accuracy for objects in the GEO Catalog.
2. Provides wide and persistent coverage of the GEO Catalog which can help reduce the level of uncorrelated RSOs among other benefits.
3. Uses heritage sensor and ground processing capability with high levels of technology readiness.

Three key study areas are explored through some simple scenario based studies:

1. **Drivers for Reliability and Accuracy of OD solutions.**
   What are the RSO observation requirements for a single GEO HP to achieve a given level of OD reliability and accuracy for different orbit types (e.g. how often are observations needed)? To what extent does a second GEO HP or ground-based measurements observing the same RSO augment solutions?

2. **Architectural drivers for system performance metrics**. How do key system architectural elements such as number of sensors, sensor field of regard & field of view, etc. influence system performance metrics such as percent of GEO RSO's observed, frequency of observing the same RSO, etc.
3. **Achievable performance.** What are the expected values of the above metrics given some specific sensor and architecture assumptions? What are the key system requirements that most influence the value of these metrics?

2. STUDY OVERVIEW

2.1 General Methodology

All analysis was performed using AGI's Orbit Determination Toolkit (ODTK) and Satellite Tool Kit (STK) to model the population of RSOs in the GEO neighborhood, the host GEO satellites, the ground based trackers, and all sensors. Realistic tracking data for a subset of the GEO population was simulated and processed using ODTK. Sensors included both ground and GEO HP assets and used performance and scheduling assumptions which were considered to be highly representative of heritage sensors and systems. A variety of trades were performed to address the first study area of what quantity and schedule of observations are necessary to achieve reliable OD solutions of a given accuracy. The result of these trades establishes the goal to be achieved by the GEO HP architecture. A separate set of trade studies were performed to address how GEO HP network architectures influence the ability to meet this goal across the greatest percentage of the population. Although the first and second study areas are somewhat decoupled, the results of the OD trade studies were overlaid with the results of the architecture trade studies to find constraints or optimizations that result. The result is a set of notional requirements for configuring such a system to achieve the desired benefits. The very large number of design variables creates a daunting trade space. To limit the scope of the study, results of earlier trades influenced the design boundaries of later trades. An overview of the most significant studies and results are presented here.

2.2 GEO Neighborhood Population

The objects of interest are those in the GEO neighborhood, a region considered to be 300km above and below nominal GEO altitude. There are approximately 1500 objects which pass through or reside in this region which is refered to as "all RSOs". These objects are categorized into three major groupings as depicted in Fig. 1. For the catalog snapshot in December 2010, these groupings consist of 839 GEO, 277 Molniya, and 272 GTO objects and are referred to simply by those names.

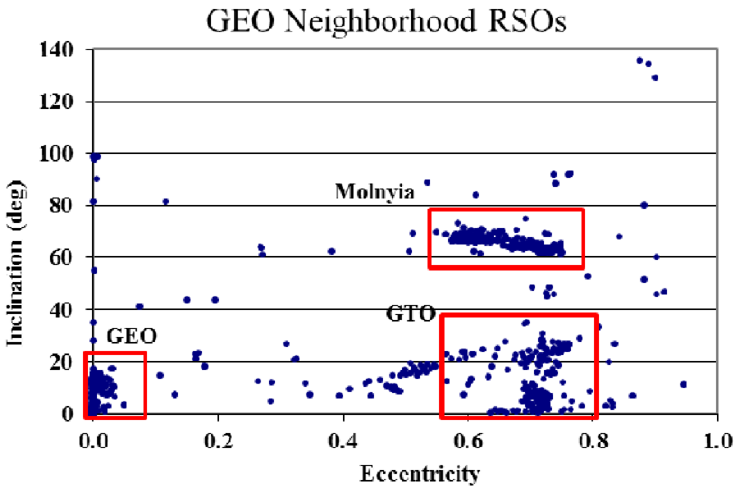

Fig. 1. GEO Neighborhood RSOs shown in an eccentricity vs. inclination distribution.

All orbit information for this study was obtained by searching the publicly available catalog of TLEs from December 2010 and July 2011. All initial states were simply propagated using SGP4 for 5 to 21 days, depending on the study, with no simulated maneuvers. All RSOs were used for architectural level studies, but only a subset was used for the OD studies.

2.3 HP Characteristics

Host satellite orbit. Hypothetical host satellite locations on the GEO belt were selected for OD and architecture studies and are detailed in the appropriate sections. Some architecture studies treated the longitude of the HP satellite as an independent variable.

HP sensor definition and behavior. The optical sensor used by the HP system in this study is a relatively small square Field of View (FOV) which scans within a larger fixed orientation rectangular Field of Regard (FOR) as depicted in Fig. 2.

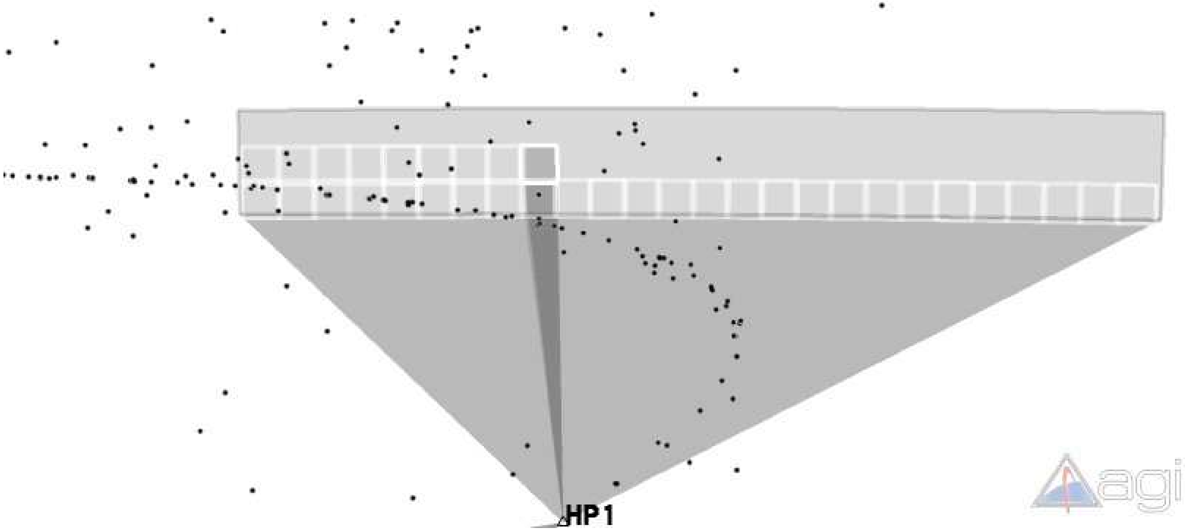

Fig. 2. A sample HP scan pattern

The long dimension, or width, of the FOR was often treated as a variable. FOVs were required to overlap by 0.1°. For simplicity in these initial studies the FOV was assumed to scan through a repeating pattern in rows and columns at a constant rate. No attempt was made to optimize the motion of the FOV for more populated areas of the FOR or for tracking particular objects of interest.

The FOV moves to a particular viewing direction or "location" and remains there for some finite period of time. At each location the tracking data measurements or "observations" are created by acquiring and processing multiple images, each with a finite exposure time in which many RSOs may be visible. Each RSO will be identified by image processing algorithms which extract coordinates from the image to create a single observation. A series of observations will be combined to form a "track". The track starts when the sensor's FOV has no more motion relative to the host spacecraft bus and it begins imaging. The track ends when the sensor takes its last image at that location and begins moving to the next one. The timing of the scan pattern and amount of time the FOV spends at each location was represented by the following equation

*time at location = (exposure time * observations per track) + (image buffering time * observations per track)*

where exposure time = 5 sec, image buffering time = 1 sec, and observations per track varied per study. Note that some analyses only used a FOR and can be thought of as representing a FOV equal to the FOR.

FOR Elevation. The FOR was considered fixed with respect to the host spacecraft bus with its width lying fixed in the GEO orbit plane, although other orientations are possible. This only considered variations in the elevation angle of the "boresight" of the FOR. Positive elevations are measured from nadir toward the host's inertial velocity vector. Thus, a FOR elevation of +90° points the middle of the FOR East. Host satellites were assumed to have both an east and a west FOR and FOV, one using the positive elevation and the other using the negative elevation. Only one FOR is used at a time depending on the RSO phase angle described below.

Sensor detection constraints. The detection range of imaging sensors is dependent on RSO size, luminosity, and RSO phase angle. The RSO phase angle is defined as the angle from the RSO-HP vector to the RSO-Sun vector. Thus, an angle of 0° means the RSO appears to the HP to be fully lit, 90°is half lit and at 180° the RSO appears fully backlit. The result of the RSO phase angle constraint is that essentially RSOs on a given side of the host satellite will only be visible from that host for approximately half of each day if within the FOR. For simplicity, RSOs were considered visible within a maximum range 60,000 km and a maximum RSO phase angle of 90°.

3. ORBIT DETERMINATION STUDIES

Studies were performed to understand the tracking observation necessary for accurate OD solutions in realistically constrained scenarios. Once this threshold was determined, several scenarios of data fusion were investigated. Simulating observations for the entire GEO catalog was considered unnecessary for this initial study, so only a subset of RSOs was used for the detailed OD analysis.

3.1 Methodology

Although many aspects of the sensor performance will strongly influence the performance of any space-based optical sensor, it was not deemed necessary to consider all of them for this initial OD study. To focus on the RSO orbit, HP orbit, sensor FOR/FOV, RSO phase angle, and lighting geometry, this study assumes fixed measurement accuracy in line with heritage space-based SSA sensors. A parametric scan of observation density and frequency (obs/track and tracks/day) was performed to determine and understand the minimum and desirable thresholds for stable, accurate OD solutions that could be achieved under some representative geometric constraints.

The relative geometry between multiple sensors which observe the same object is one factor of measurement quality. It is well known that orthogonal observations provide more information to the estimation process and can result in substantial improvement to the OD accuracy. Therefore, an additional study was conducted to determine the benefits of fusing multiple GEO HPs and ground based sensors.

For each RSO considered, measurements were simulated, processed by ODTK's sequential filter, and then smoothed. Filter and smoother results were reviewed to confirm stability of the orbit solution. Position accuracy values are reported using values from the smoother. The first 2 days of the smoothed solution were discarded and the remainder was averaged to eliminate filter startup behavior and thus provide a better measure of "steady-state" accuracy.

3.2 Assumptions

Host satellite orbit. The orbit parameters used for the OD studies are detailed in Tab. 1.

Tab. 1. OD study GEO HP orbit parameters

Case	a (km)	e	*i* (deg)	*u*(deg)	Pos uncertainty (m)
One HP	42165.6	.00021	.0278	315.278	1700
Two HPs	42165.8	.00031	.0686	98.617	1700

The orbit uncertainty of the host satellite will impact the predicted accuracy of the space based observations made from that satellite, however some investigation revealed it to not have a strong influence. Processing host and RSO tracking simultaneously provides the best accuracy but this may not always be practical. Instead a reference ephemeris including a constant covariance was used for the HP satellite.

RSO orbits. The RSOs in Tab. 2 were selected for detailed OD studies to provide some variety of GEO orbits and ranges from the host spacecraft. GTO and Molniya orbits were omitted from this study because the non-optimized fixed FOR and FOV scanning or tasking made comprehensive analyses on these orbit types more difficult. When these satellites were visible, the performance was good. However, the encounters were rare. Additionally, priority was placed on investigating the performance of the GEO HP system for GEOs over other orbit types. The initial state for each was obtained directly from the TLE source. A covariance of 0.5 km, 1.4 km, 0.8 km (RIC) was assigned to each satellite, indicating the initial state was relatively well known. This study did not attempt to address the problem of initial orbit determination (IOD) of a RSO from a GEO HP. It is recognized that this IOD process can be challenging and is left for future studies.

Tab. 2. RSO orbit parameters for OD study

Object (SSC)	Orbit Class	a (km)	e	*i* (deg)
2639	GEO	42177.44	0.001194	8.504
2717	GEO	42171.19	0.002233	7.517
4478	GEO	41616.81	0.034785	6.424
858	GEO	42189.84	0.000152	5.255

RSO OD estimation parameters. Solar Radiation Pressure (SRP) and tracking system biases were not estimated in the OD process. This assumes these parameters are known constants and avoids some of the known observability issues with SRP effects. This was done to isolate the effect of geometry and viewing constraints on the GEO HP observations. It is noted that this simplification further leads to some optimism in the performance and that future studies should investigate the effects of biases and SRP on GEO HP solutions.

HP sensor definition. A scanning FOV of 2.8°x2.8° in a fixed FOR of 6°x30° with a FOR elevation angle of 50° was used for the OD studies. An accuracy of 2 arcsec (white noise sigma) was applied to the space-based Right Ascension and Declination angle measurements in line with heritage space-based SSA sensors.

Ground sensor parameters and scheduling. It was necessary to provide representative simulated measurements from traditional ground-based sensors to validate the method used here and provide a basis of comparison. Ground sensor observations were generated by using a custom scheduling algorithm designed to produce a tracking schedule that is somewhat realistic, described in [3]. Tab. 3. below shows the GEODSS (Socorro, Maui, Diego Garcia, and Moron) and radars (Altair, Clear, Ascension, Millstone Hill, and Kaena Point) used with similar parameters. The real radar systems, although likely able to observe GEOs, probably have lower tasking rates for these satellites than used in this study. These additional range observations may result in somewhat optimistic performance of ground sensors. Globus II is listed separately due to unique weather constraints. The default ODTK sensor accuracies were used: Range 5m, Az 0.03 deg, El 0.02, RA 20 arcSec, Dec 20 arcSec.

Tab. 3. Ground sensor tracking parameters

	Track length (min)	Obs Step (sec)	Revisit time (hr)	Inter-revisit time (hr)	Missed-Track Probability	Type
GEODSS	6.0	20	23	18	35%	Optical Trackers
Radars	5.0	20	16	12	10%	Mechanical Steered (Dish) Radars
Eglin	3.0	30	24	12	15%	Mechanical Steered (Dish) Radars, Deep Space Mode
Globus II	5.0	20	23	24	75%	Optical Tracker

3.3 Orbit Determination Results

Study of Orbit accuracy vs. tracking density and schedule. This study used one GEO HP with all lighting and sensor constraints for the FOV. The first independent variable studied was the obs/track, used to define the scan rate of the FOV and the number of OD measurements simulated for each FOV location. The motion of the FOV and the relative motion of a particular RSO in its orbit determine the actual tracks/day simulated for that object. However, to establish a more thorough understanding of the nature of OD from GEO HP tracking, it is helpful to think of tracks/day as another independent variable since it is highly dependent on the FOV motion. To accomplish this, passes were removed or sometimes manually added (still subject to lighting and range constraints) to achieve various average values of tracks/day.

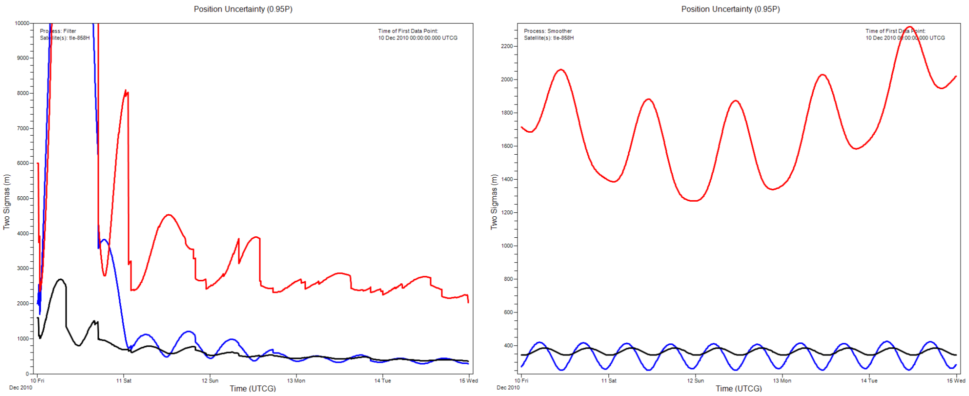

Fig. 3. Filter (left) and smoother (right) position uncertainty results showing typical convergence

In most cases, the filter converged and the smoother uncertainty showed the traditional bathtub shape as depicted in Fig. 3. These stable solutions are indicative of a sufficient amount of tracking data. However, in cases which had insufficient tracking, the filter never clearly converged and the smoother output was either flat or generally growing over time. The average uncertainty was generally greater and these results were considered an unreliable OD.

Results for each GEO examined showed trends similar to Fig. 4. A slight knee in the curve is apparent around 3 tracks/day and 5 obs/track. Below this rate of tracking the filter does not usually have sufficient knowledge to converge on a solution. Increased tracking does improve the solution, but not indefinitely because of the inherent observability limitations of a single observer. It is noted that Fig. 4 represents slightly above average performance for single HP tracking for the GEOs studied. Some cases had higher uncertainties but exhibited the same general behavior. Based on this analysis, a conservative recommendation for requirements in our notional system is to average at least 6 tracks/day and 10 obs/track across the GEO population of interest. This conservatism is warranted since simulated data was used and IOD in a real system was not addressed.

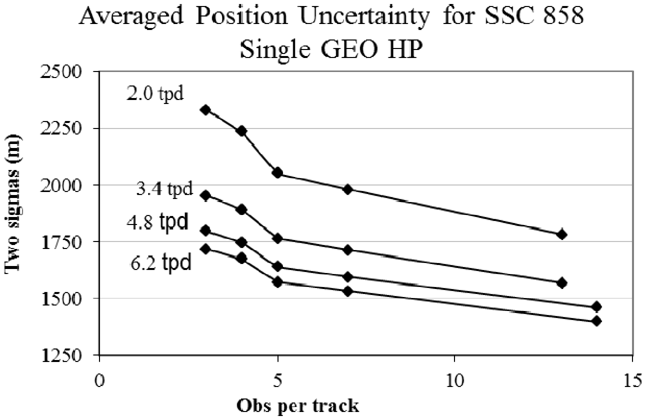

Fig. 4. Sample OD accuracy variation for one GEO HP

Data fusion study. When simulating data fusion, observations from ground and GEO HP sensors were processed together in the filter and smoother in several combinations: Ground only, One GEO HP only, Two GEO HPs only, One GEO HP and ground, and Two GEO HPs and ground. This study used a value of 10-15 obs/track. The combination of different geometries, realistic constraints and ground sensor tasking means that each tracker had a consistent, but not identical, tracking schedule averaging about 4 tracks/day. This was a consequence of lighting constraints and non-optimized sensor tasking. These tracks were additive, so that the 2 HP + Ground case did have the most measurements. Position uncertainty results are shown in Fig. 5 and show improvements over ground-only tracking of one to two orders of magnitude. Note the logarithmic scale and the fact that data fusion improves the average uncertainty of a solution as well as how much that uncertainty varies. For example, for 2 GEO HPs and ground tracking, SSC 2717 had an average uncertainty of 335 m that varied by ± 74 m. In the cases shown, the single GEO HP performed better than the ground because of the closer proximity, the higher accuracy of the observations, and the larger observation density of the GEO HP compared to the ground sensors.

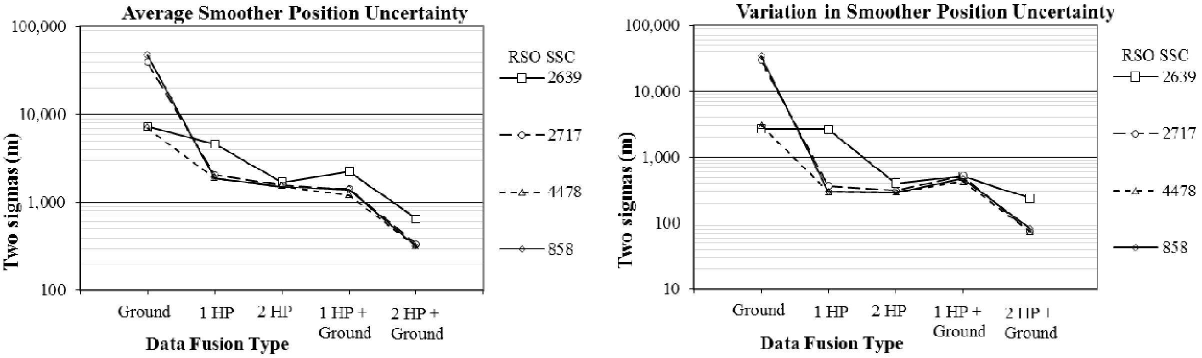

Fig. 5. Smoother position uncertainty average and variation (2 sigmas, meters) using data fusion

4. HP ARCHITECTURE STUDIES

These studies explored how key system architectural parameters influenced the ability of the GEO HP sensor to observe the RSOs in the GEO Catalog.

4.1 Methodology

The dynamic natures of orbits together with lighting and sensor geometry constraints make observing the GEO catalog from a GEO orbit a more complicated and constrained task than may be first imagined. Fundamental architectural choices will dramatically affect how much of the GEO catalog is observed and how well it is observed. A series of parametric scans of the trade space was executed to evaluate the influences of these choices. For each trial, constrained visibility intervals were computed from the sensor FOV or FOR to each of the ~1500 RSOs for a time span of 5 days. A number of performance metrics and statistics on these metrics were computed for each RSO. A detailed description of the variables and metrics used is in following sections.

4.2 Architecture inputs and Assumptions

GEO HP sensor parameters. A scanning FOV of 1.4°x1.4° in a fixed FOR of 1.4° height was used unless otherwise noted. FOR width and elevation were often used as the independent variables in these studies.

GEO HP orbit. All host satellites used the orbit parameters in Tab. 3, except when the longitude of ascending node (μ) was used as a variable.

Tab. 3. Architecture study HP orbit parameters

a (km)	e	*i* (deg)	*u* (deg)
42166.3	0.0	0.0	300

4.3 GEO catalog coverage metrics

All metrics were computed both for all objects in the GEO neighborhood, referred to simply as all RSOs, and for the subset of those objects classified GEOs (see Fig. 1). Note that many metrics are computed as averages across the population of RSOs which was actually observed at least one time. The primary metrics evaluated are described below, though only a subset of resulting values is presented here.

1. **Number and percent of objects observed.** The number of objects observed at least one time during the analysis period and that number reported as a percentage of all objects. This is perhaps the most basic measure of coverage.
2. **Tracks/day.** The total number of tracking intervals divided by the analysis period. When computed for a FOV study, this represents the number of actual tracks and how frequently objects in the catalog are observed by the FOV scan pattern. When computed for a FOR study, this represents the number of times favorable viewing conditions exist within the FOR, each of which could be from minutes to several hours long.
3. **Track duration.** The sum of the durations of each track during the analysis period.
4. **Track duration/day.** The track duration divided by the analysis period.
5. **Average maximum tracking gap.** The time from the end of one track to the beginning of the next track. For each RSO, the maximum gap over the analysis period is computed, then averaged across the population.
6. **Average minimum tracking gap.** Similar to the average maximum tracking gap, but the minimum gap is computed. This is an indicator of the best-case revisit times from a given architecture.

4.4 Results

FOR elevation and width. This study had two independent variables: the elevation and width of the FOR. Only the FOR from a single GEO HP was evaluated. Fig. 6 summarizes the results of this study. For GEO RSOs, there is a clear optimal elevation of about 65°, regardless of the width of the FOR. For all RSOs, if there is a clear optimum it is at a smaller elevation angle. Note that no other FOR shapes or orientations were evaluated for this study. It is also noted that this result is for a host at 300° E longitude and that the result may vary by longitude due to local RSO densities (see GEO HP longitude study below). Additional optimization may be achieved by selecting different elevation angles on the east and west facing sensors.

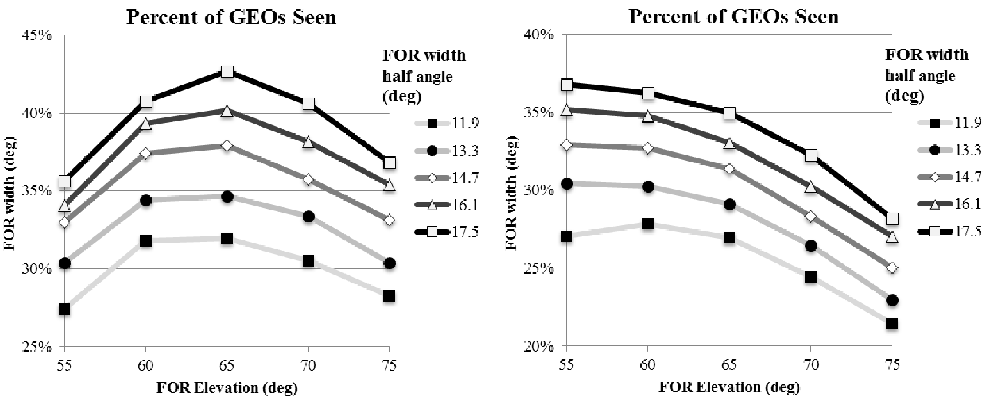

Fig. 6. Percent of GEO RSOs seen (left) and all RSOs seen (right) from a single GEO HP

FOV obs/track and FOR width. This study had two independent variables: the width of the FOR and the obs/track of the scanning FOV. It used a FOR elevation angle of 65° since the first study suggested this was optimal for GEOs. The simple scan pattern means larger FORs and obs/track necessarily reduce the number of times a given RSO is observed.

The results shown in Fig. 7 are especially useful for identifying what size FOR will meet the recommended obs/track and tracks/day for an accurate OD solution. This figure indicates that given a 10 obs/track requirement, any FOR width below 34° will exceed the recommended 6 tracks/day. The uneven nature of this chart is an artifact of the interaction between the RSO orbits and the scanning rate varying as the obs/track is changed.

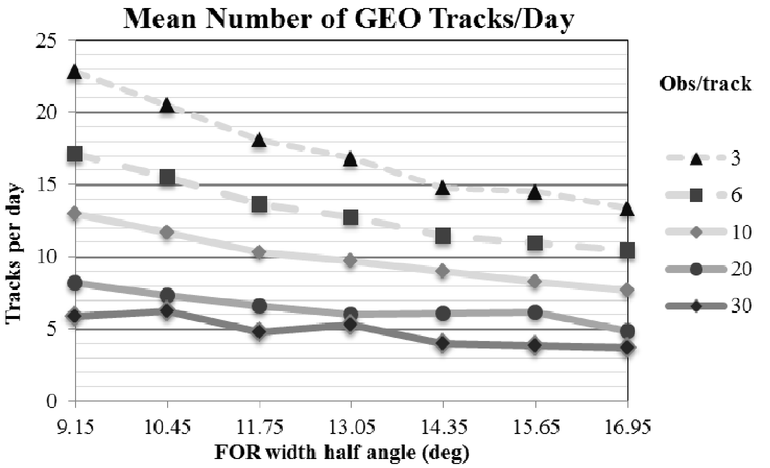

Fig. 7. GEO tracks/day variation with obs/track

GEO HP Longitude and FOR elevation. The purpose of this study is to determine if certain longitudes are more optimal than others because of the local density of RSOs along the GEO belt. Only the FOR was considered. Longitude of ascending node and FOR elevation were varied. FOR width was constant at 34°. Fig. 8 indicates notable variations in the coverage of RSOs ranging from 30-45% from a single location, although greater than 40% coverage is quite common. The drop at 240-270° longitude is because the West-facing FOR mostly observes the relatively empty spaces over the Pacific ocean. Future studies should examine a broader range of FOR elevations and seek to optimize total catalog coverage for each FOR (east &West).

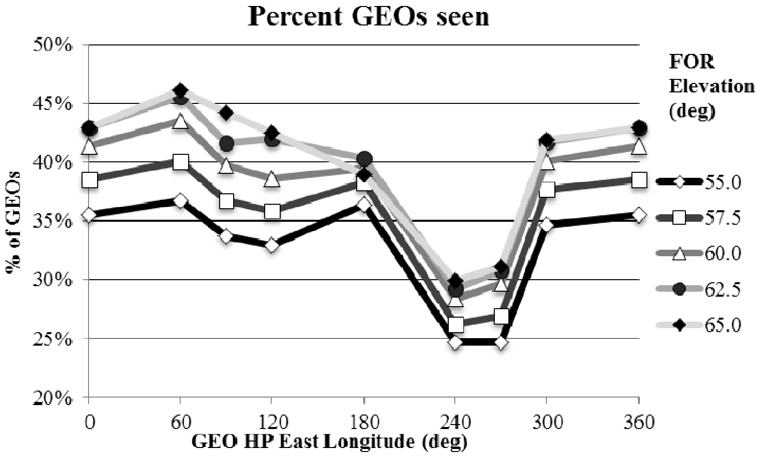

Fig. 8. GEO coverage variation with GEO HP longitude

Number of HPs. To determine what GEO HP constellation size is necessary to maximize observability of all ~1500 objects in the GEO catalog, sample constellations are being studied. To date, constellations of 2 and 3 GEO HPs were evaluated considering only the FOR. For 2 GEO HPs, the hosts were located at 120° and 300° East longitude. For 3 GEO HPs, the hosts were located at 60°, 180°, and 300° East longitude as illustrated in Fig. 9. The FOR elevation angle was varied, but the same value was applied to each GEO HP. Different ranges of FOR values were visually inspected in a 3D depiction as in Fig. 10 to determine reasonable inputs. A FOR width of 34° was used for all cases. Fig. 9 shows results for GEOs only and all RSOs using each sample constellation size Note that these metrics do not report if a given RSO is seen by one or more GEO HPs nor the persistence of the observations. Future studies should evaluate double and single coverage against larger constellation sizes and persistence of observations using a scanning FOV.

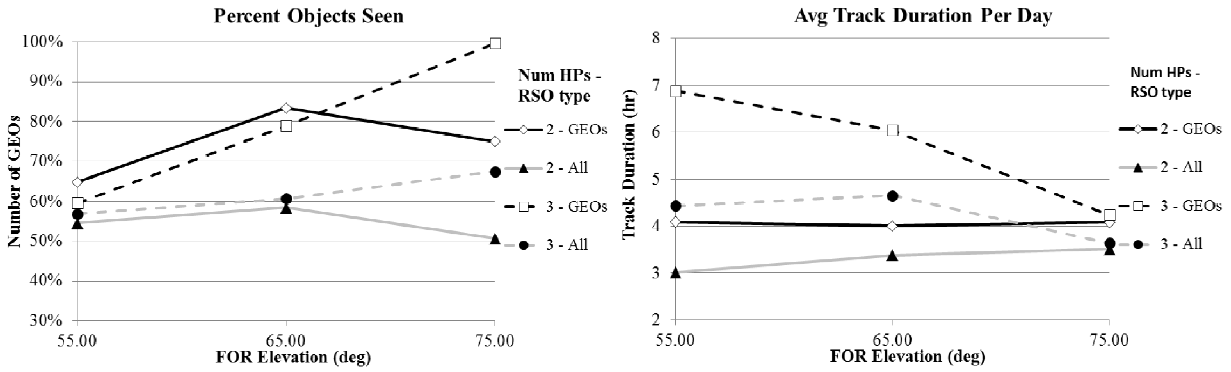

Fig. 9. GEO catalog coverage metrics for GEOs and all RSOs using two notional GEO HP constellations

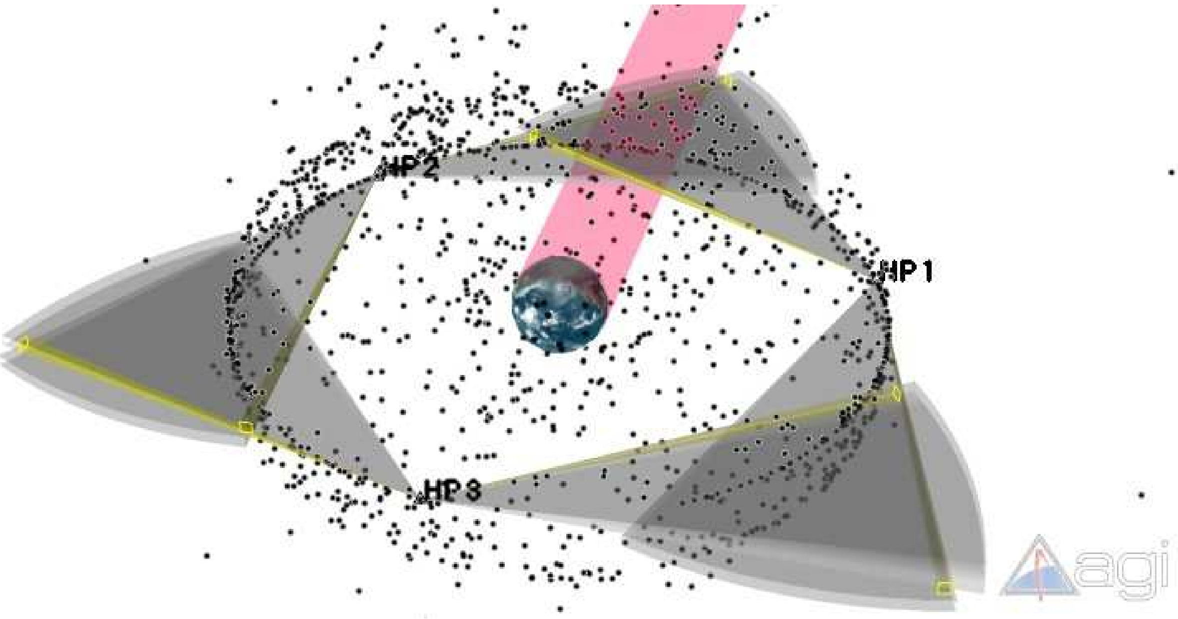

Fig. 10. Sample architecture using 3 host satellites with a 65° FOR

5. CONCLUSIONS

The scenario based studies described in this paper have provided some insights to the architectural requirements necessary to provide adequate OD of GEO RSO's from sensors hosted on GEO satellites. Models and scripts were successfully developed using AGI's Orbit Determination Toolkit (ODTK) and Satellite Tool Kit (STK) that allow parametric studies of various sensor architectural configurations to be performed. From these tools, notional requirements were established to obtain adequate OD results and architectural design parameters were evaluated for impact on catalog coverage.

The studies indicate a conservative notional imaging density of 10 observations per track and 6 tracks per day from a single GEO HP will provide an adequate OD accuracy for typical GEO RSOs. Improvements in OD accuracies of more than one order of magnitude can be gained when data fusion with ground sensors is used to resolve observability limitations of the different available sensors. Position uncertainties well under 1 km are possible with data from 2 GEO HPs fused with ground measurements.

Only a few introductory studies of optimizing sensor configurations and constellation architectures have been completed, but they have indicate that GEO HPs can make a significant contribution to the SSN. It was shown that even a simple, narrow FOR sensor can achieve observations on as much as 45% of all GEO RSO's in the GEO neighborhood.

This effort has suggested a number of areas as important for further study in both detailed orbit determination and architectures.

1. Orbit Determination Requirements
    a. OD requirements for GTOs and HEOs. Obs/track and tracks/day requirements should be established for accurate OD of GTOs and HEOs. Data fusion test cases for these orbit classes should also be investigated.
    b. Initial Orbit Determination. The IOD problem should be thoroughly investigated to determine what level of tracking is generally sufficient to come up with initial orbit estimates and recover from orbit perturbations.
    c. Data Fusion from other sources. The benefits of fusing data from other optical trackers in LEO, MEO, GTO, HEO, and inclined GEO orbits should be investigated.
2. Optimizing GEO HP Architecture
    a. Larger GEO constellation sizes. Networks of 6 or more GEO HPs should be investigated with the goal of attaining double coverage of and meeting or exceeding the recommend tracking targets for every GEO RSO
    b. Variations on FOR. Many possibilities exist for the size, shape, and orientation of the sensor FOR, which may have a significant impact on the observability of more highly inclined GEOs as well as GTOs and HEOs.
    c. Variations on FOV scanning. Different scan patterns and optimized tasking for the FOV should also be evaluated as this can also have a significant impact on the observability of all objects.

6. REFERENCES

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