SDA GEO Location in a GPS Denied Environment

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ABSTRACT

Space is a key component of the national defense structure for multiple countries, and this is expected to continue in the coming decades. Countries with a significant presence in space have an economic and military advantage. Space assets will become increasingly targeted by to potential threats. Due to the reliance on GNSS by most space systems, GPS denial becomes an obvious approach to disrupt an adversary's space-based capabilities. Additionally, future GPS upgrades may reduce sidelobes, potentially impacting the ability of GEO systems to utilize GPS signals. Therefore, development of alternative strategies for orbit determination without GPS is a crucial technology for the future of space domain awareness.

This paper explores the techniques that a satellite can use to determine it's position in GEO without relying on a GPS signal. In ground-based, air and in low-orbit platforms, imagers can locate objects overhead with known locations/ orbital parameters and determine the platform's relative position to those objects. However, at GEO, there are fewer known objects at higher orbits, thus reducing angular diversity in position measurements and drastically increasing positional uncertainty. In this study, we explore the viability of observational techniques for orbit determination of self, which without GPS.

The primary technique is to calculate position based upon the number of known, observable objects using a network of other SDA satellites as a known constellation. If a satellite can image and find the relative position of other SDA GEO satellites and a communication link can provide the precise position knowledge each satellite, then the absolute position of all satellites could be determined. Secondarily, interleaving observations near the earth limb for known objects in MEO will increase the angular diversity of observations and is expected to improve position uncertainty.

The paper will explore the sensitivity to applicable variables to understand what drives positional uncertainty, and what trade-offs would be required to reduce the uncertainty. It also discusses alternate approaches and provides recommendations for architecture to adequately address the problem.

1. INTRODUCTION

1.1 Background

This paper explores the nominal use case of a single space vehicle in GEO trying to determine its own position and velocity uncertainty without the use of GPS signals. This is applicable for any scenario where the satellite is operating in a GPS denied environment, and could be abstracted to cislunar applications, where existing GPS signals would not always be available. Additionally, future GPS constellations may have reduced sidelobes, which are used by GEO satellites for orbit determination. An effective solution for orbit determination without the use of GPS would resolve these technical challenges, and eliminate the cost of the GPS subsystem. It is assumed that the space vehicle still has a communication link and is able to receive accurate position knowledge of Resident Space Objects (RSO) in various orbits.

1.2 Design/Architecture Approach

The primary use case being considered is for a GEO Space Vehicle (SV) monitoring other objects in GEO. Prior studies [1] have shown the viability of determining positional knowledge utilizing objects in LEO and MEO, and the goal is to constrain the methodology to only look within the GEO belt. For this study, the Ansys Orbit Determination Tool Kit (ODTK) is used to assess the feasibility and performance of determining the GEO SV's orbit state: position and velocity. ODTK contains an optimal sequential Kalman filter that predicts the orbit state using a dynamics model and then updates its prediction with measurements over time. Measurements are assumed to be angles-only measurements of the GEO RSOs relative to the GEO SV. For this study, orbit determination performance is characterized based on the filter's uncertainty or variance in its estimation errors; that is, a lower uncertainty in the estimation errors results in a more accurate estimate that is closer to the true orbit state. However, it is possible for the filter to converge on an incorrect solution far from the true orbit state. To check for an incorrect filter solution, the state estimation error is calculated by differencing the true orbit state and estimated orbit state. Performance measures will be presented and analyzed to understand their impact to the position and velocity uncertainties.

The orbit determination performance using GEO RSOs will be compared to a secondary use case, where the sensor intermittently monitors known GPS satellites in their orbit. This use case is presented as GPS satellite positions are well known and have relatively straightforward viewing geometry from GEO. This use case is still applicable in the condition of a GPS denied environment via electronic warfare, where the satellites would still exist in known orbits, even though the GPS signal may not be available. It would also resolve potential technical challenges with improved GPS satellites having reduced sidelobes.

1.3 Performance Measure and Driving Variables

The primary intent is to understand how many RSOs need to be tracked, and for how long, to achieve an adequate orbit determination solution. Based on common ADCS position knowledge requirements, the goal is to achieve <50 m for position RSS and < 0.05 m/s for velocity RSS knowledge. Several variables can affect the accuracy of the proposed orbit determination method, these are defined below in Table 1.

Table 1: ODTK Analysis Variables

Variable	Values
Time period for taking measurements on a given RSO (ex. Every 2 hours)	**2 hours**, 90 minutes, 50 minutes, 20 minutes
Percentage of time period for taking measurements (ex. 50%)	**100%**, 70%, 50%, 10%
Frequency of measurements (ex. 1 Hz)	**1Hz**, 0.1 Hz, 0.05 Hz
Number of GEO RSOs used	**SDO**, SDO & TDRS 5, SDO & TDRS 5/7, SDO & TDRS 5/7/13
GEO RSO orbit state uncertainty	**<75 m & < 0.075 m/s**, <200 m & < 0.2 m/s, <600 m & < 0.6 m/s
Pointing uncertainties (ex. 2 arcsec) * bias and noise have same magnitude	**0.2**, 2, 10, 50 arcsec
Initial state estimate uncertainty	**<10 km & < 0.01 km/s**, <50 km & < 0.05 km/s, <100 km & < 0.1 km/s

Note: **Bolded** values are the baseline set of values used

1.4 System Modeling Approach

The model was developed utilizing ODTK. The Tracking and Data Relay Satellite System (TDRSS) and Solar Dynamics Observatory (SDO) are deployed in GEO and are the RSOs used for the initial analysis. The Global Positioning System (GPS) are the RSOs used during the second iteration of the analysis. A combination of both GEO and GPS satellites are used as RSOs for the third iteration of the analysis.

The assumptions made for this analysis are listed below. These assumptions were necessary to first determine viability of the solution by limiting the number of variables in the trade space. For example, the first assumption is that targets don't have to be Sun-lit. While operationally the GEO SV may require objects to be Sun-lit, this limits the number of variables for initial analysis.

- Target must be lit: False, RSOs are not required to be Sun-lit
- Space background: True, GEO SV cannot track RSOs if Earth is in the way
- Sun and Earth poles do not affect measurements

- Solar power generation is not needed while measurements are taken
- All camera pointing biases and noises disabled, however a bias and noise are added to spacecraft pointing
- Angles-only measurements taken: right ascension, declination
- Within the Kalman filter, measurement noise covariance is zero mean Gaussian white noise and process noise covariance is updated over time
- Kalman filter orbit model includes: 21st degree and order gravity model and cannonball models for aerodynamic drag and solar radiation pressure, applied depending on orbit
- Orbit of RSOs is pre-determined based on ephemerides, and then varied based on constant covariances

ODTK recommends using ground stations to track the RSOs, such that these states and measurements are also estimated and used within the filter; however, we saw near similar results with using ephemerides. The difficulty in using ground stations lies within identifying the correct setup within ODTK that mimics the current date's orbit determination technique of these RSOs.

2. MODELING AND ANALYSIS

2.1 Initial Iteration

For the initial iteration of the analysis, one TDRS satellite (TDRS6) is used to represent the GEO SV that is trying to determine its orbit. Three TDRS satellites (TDRS5, TDRS7, and TDRS13) and the SDO are used as GEO RSOs to estimate the GEO SV's orbit state. TDRS and SDO ephemerides are generated using Systems Tool Kit (STK) and used to initialize and propagate the GEO RSOs' orbit states in ODTK.

Figure 1: GEO RSO Orbital Parameters

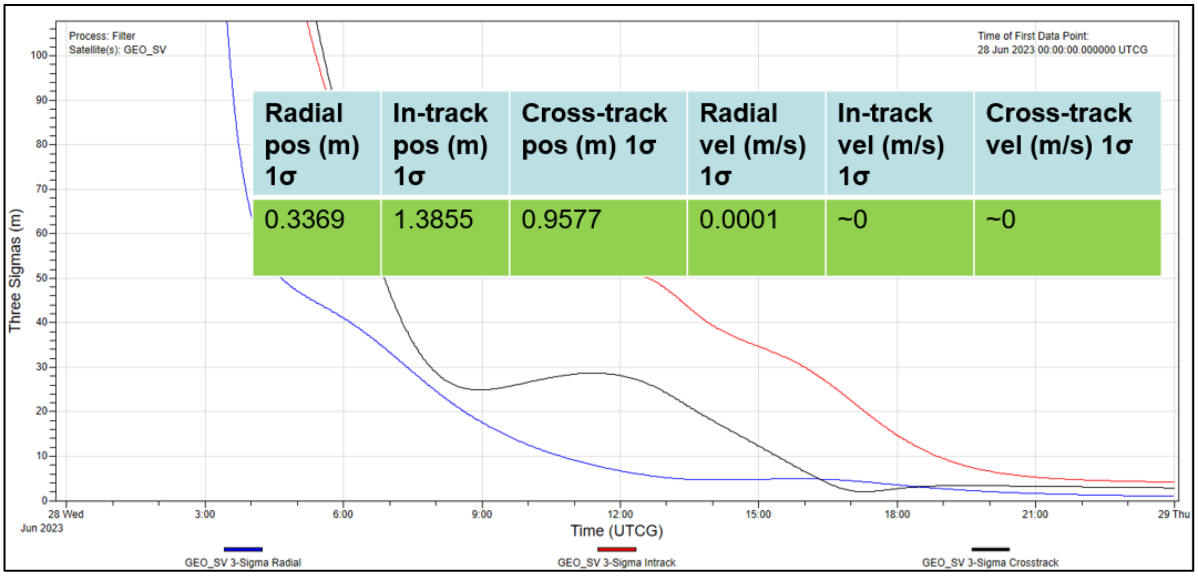
For this iteration, measurements of each GEO RSO, when taken, follow in this order: SDO, TDRS5, TDRS7, TDRS13.

2.2 Sensitivity Analysis

A baseline analysis was completed using the following values:

- Measurement time period: 2 hours
- Measurement percentage: 100%
- Measurement frequency: 1 Hz
- Number of GEO RSOs: 1 SDO
- GEO RSO uncertainty [2] < 75 m & < 0.075 m/s
- Pointing uncertainty: 0.2 arc-sec (bias and noise)
- Initial state estimate uncertainty: <10 km, <0.01 km/s
- Kalman filter has one day to converge on a solution

Using the baseline values above, the orbit determination is checked to understand the potential result of tracking the SDO RSO continuously. The results are shown below in Figure 2.



Radial pos (m) 1σ	In-track pos (m) 1σ	Cross-track pos (m) 1σ	Radial vel (m/s) 1σ	In-track vel (m/s) 1σ	Cross-track vel (m/s) 1σ
0.3369	1.3855	0.9577	0.0001	~0	~0

Figure 2: Baseline Orbit Determination with Continuous Measurement of SDO

The Kalman filter state estimation error was reviewed to understand how the filter was converging on the truth. The filter state estimation error shown below in Figure 3 is taken from the baseline analysis. It shows that the filter state estimation error is near zero, confirming that the filter orbit state estimate is converging on the truth and is correct.

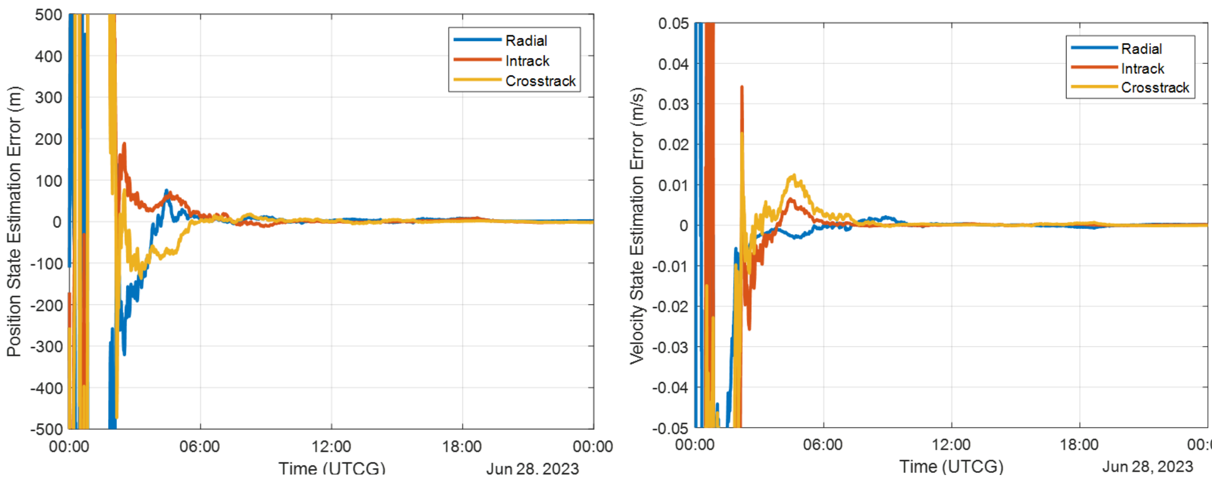


Figure 3: Positional and Velocity Filter State Estimation Errors

The variables were incrementally tested to understand the resulting sensitivity for each variable. An example varying the measurement time period percentage is shown below:

Table 2: Measurement Time Period Percentage Sensitivity Study

Measurement Time Period %	Radial pos (m) 1σ	In-track pos (m) 1σ	Cross-track pos (m) 1σ	Radial vel (m/s) 1σ	In-track vel (m/s) 1σ	Cross-track vel (m/s) 1σ
100%	0.3369	1.3855	0.9577	0.0001	~0	~0
70%	0.4052	1.6741	1.1605	0.0001	~0	~0
50%	0.4796	1.9932	1.3868	0.0002	~0	~0
25%	0.6744	2.8276	1.9837	0.0002	~0	0.0001

A similar analysis was done for all identified variables. The initial sensitivity analysis indicates that the driving factors for orbit determination performance, ranked from highest to lowest, are:

1. Pointing Uncertainty
2. Time period duration of measurements and frequency of measurements in a time period
3. Number of GEO RSOs used.

The results for pointing uncertainty are shown below in Table 3:

Table 3: Pointing Uncertainty Sensitivity Study

Pointing Uncertainty	Radial pos (m) 1σ	In-track pos (m) 1σ	Cross-track pos (m) 1σ	Radial vel (m/s) 1σ	In-track vel (m/s) 1σ	Cross-track vel (m/s) 1σ
0.2 arc-sec	0.3369	1.3855	0.9577	0.0001	~0	~0
2 arc-sec	7.5135	27.4867	21.8921	0.0021	0.0004	0.0005
10 arc-sec	35.9398	95.5525	68.2518	0.0069	0.0022	0.0025
50 arc-sec	70.9226	160.5243	101.4357	0.0112	0.0043	0.0049

Pointing uncertainty magnitudes are varied based on current capabilities in space. For example, a well-placed star tracker with multiple cameras can achieve 0.2 arc-sec pointing knowledge.

2.3 Driving Factors Study

The next step was to vary the driving factors and keep the remaining variables fixed. The following assumptions were made to generate these graphs:

- Measurement frequency: 1 Hz
- GEO RSO uncertainty [2] < 75 m & < 0.075 m/s
- Initial state estimate uncertainty: <10 km, <0.01 km/s
- Kalman filter has one day to converge on a solution
- Measurements of each GEO RSO are taken every 2 hours, but duration of measurements is varied
- Number of GEO RSOs used is varied

Figure 4 below shows the final position RSS uncertainty from the filter. The red line highlights the <50m positional uncertainty target, indicating that the <50m positional uncertainty goal can be met with RSOs being observed for less than 15 minutes out of every 2 hours.

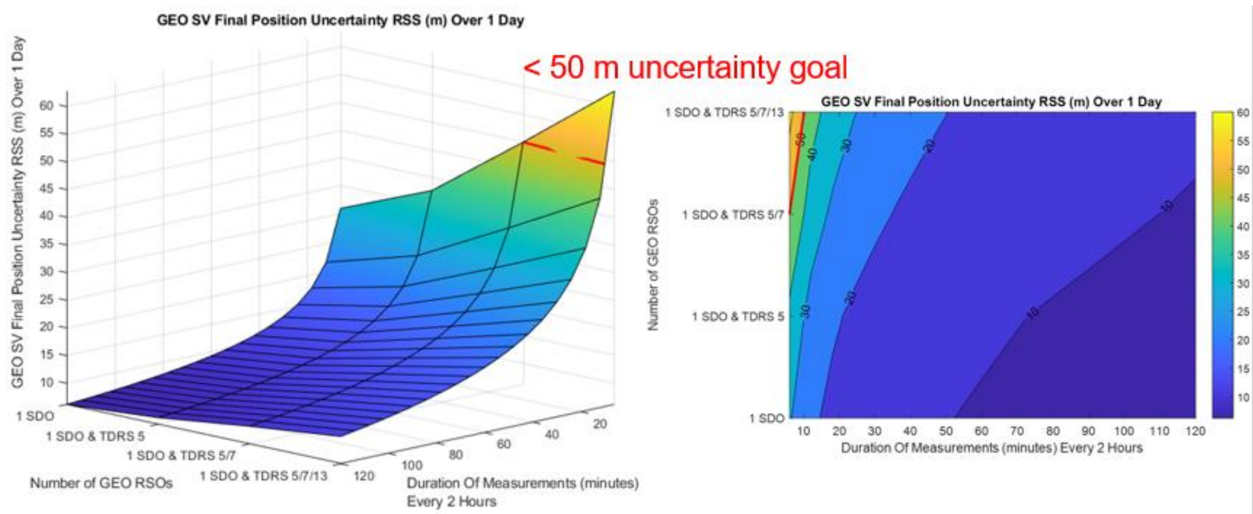


Figure 4: GEO SV Positional Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 2 arc-sec pointing uncertainty

Figure 5 below shows the final velocity RSS uncertainty from the filter. The velocity uncertainty target of <0.05 m/s is not shown, as all resulting uncertainties are less than the target.

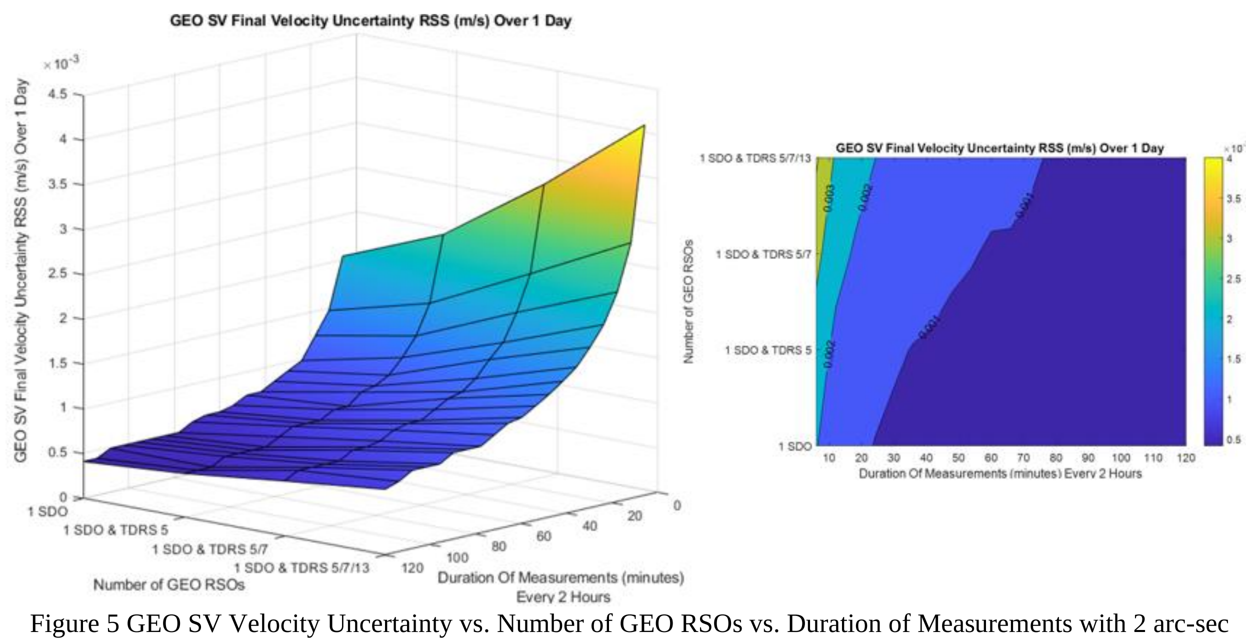


Figure 5 GEO SV Velocity Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 2 arc-sec pointing uncertainty

These cases were re-run with a 10 arc-sec pointing uncertainty. Figure 6 below shows the final position RSS uncertainty from the filter. The red line highlights the <50m positional uncertainty target, which has shifted relative to Figure 4.

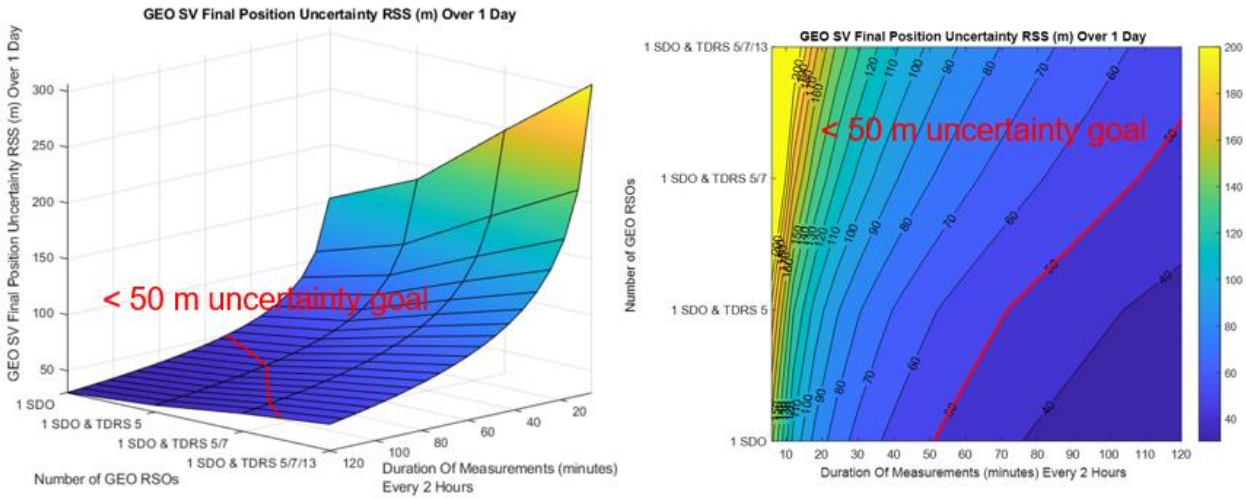


Figure 6: GEO SV Positional Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 10 arc-sec pointing uncertainty

Figure 6 shows that only tracking SDO provides <50m uncertainty in 50 out of 120 minutes. Figure 7 below shows the final velocity RSS uncertainty from the filter. The velocity uncertainty target of <0.05 m/s is again not shown, as all resulting uncertainties are less than the target.

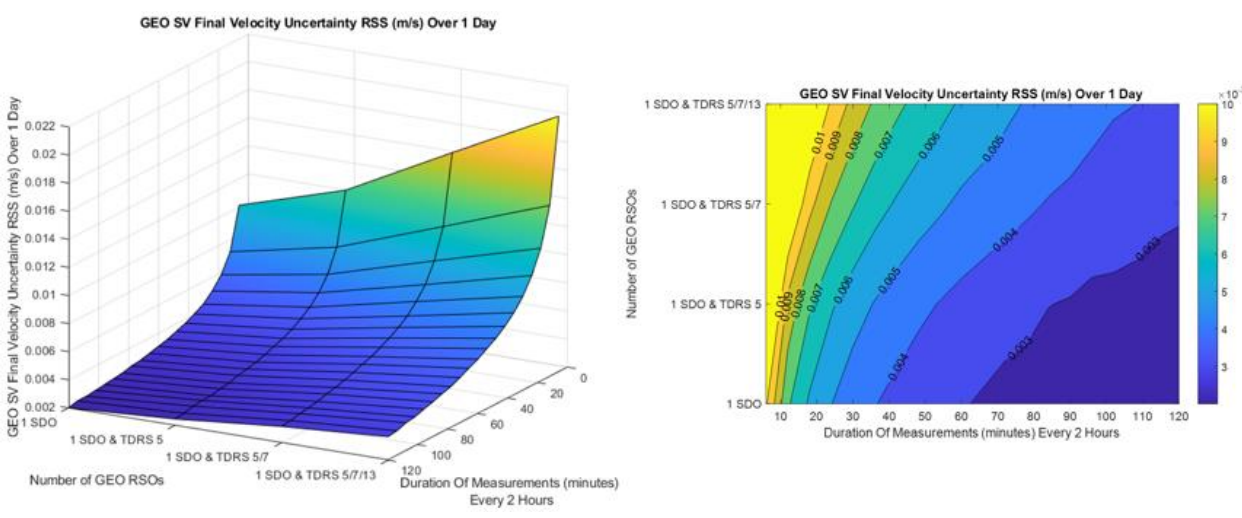


Figure 7: GEO SV Velocity Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 10 arc-sec pointing uncertainty

The initial results imply that the number of RSOs tracked is critical to achieving an acceptable level of performance. It also confirms that 10 arc-sec pointing uncertainty is unlikely to be feasible unless a secondary sensor were available to track the known RSOs 100% of the time, as the best-case scenario required tracking of the RSO for about 40% of the mission time. However, at 2 arc-sec pointing uncertainty, we can track <3 GEO RSOs for 6 minutes and maintain the <50m positional uncertainty. Analysis was run for a 50 arc-sec pointing uncertainty as well (not shown), and all positional uncertainty was greater than the <50m target.

However, it was surprising that additional satellites resulted in higher positional uncertainty. An analysis case was run assuming all RSOs could be measured simultaneously rather than in sequence. This produced the expected result, where additional RSO data continuously improves the uncertainty estimate. Figure 8 below shows the final position RSS uncertainty from the filter.

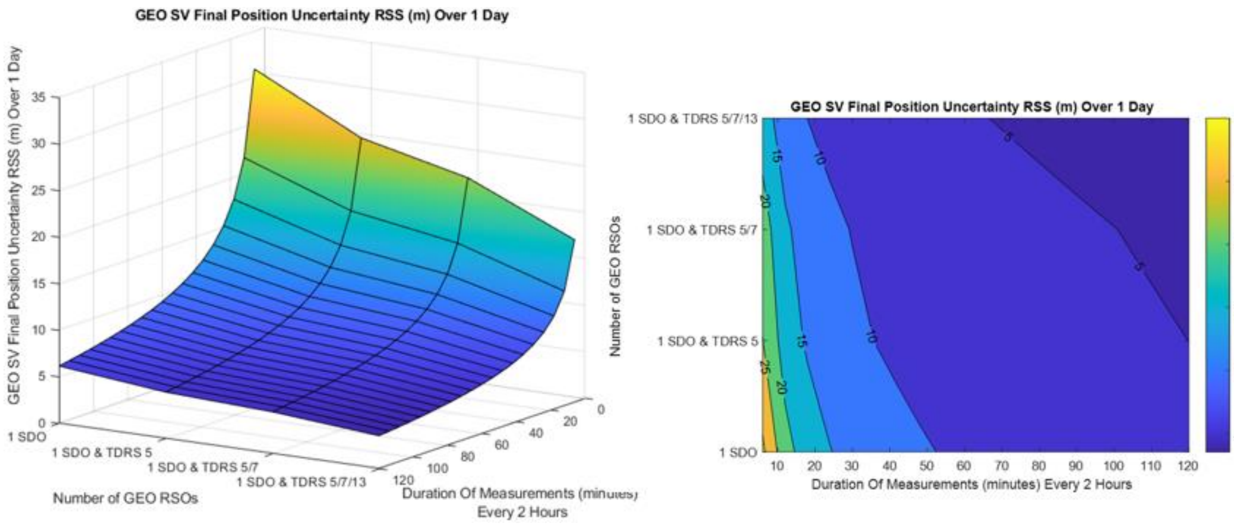


Figure 8 GEO SV Positional Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 2 arc-sec pointing uncertainty, Simultaneous Measurements

Figure 9 below shows the final velocity RSS uncertainty from the filter.

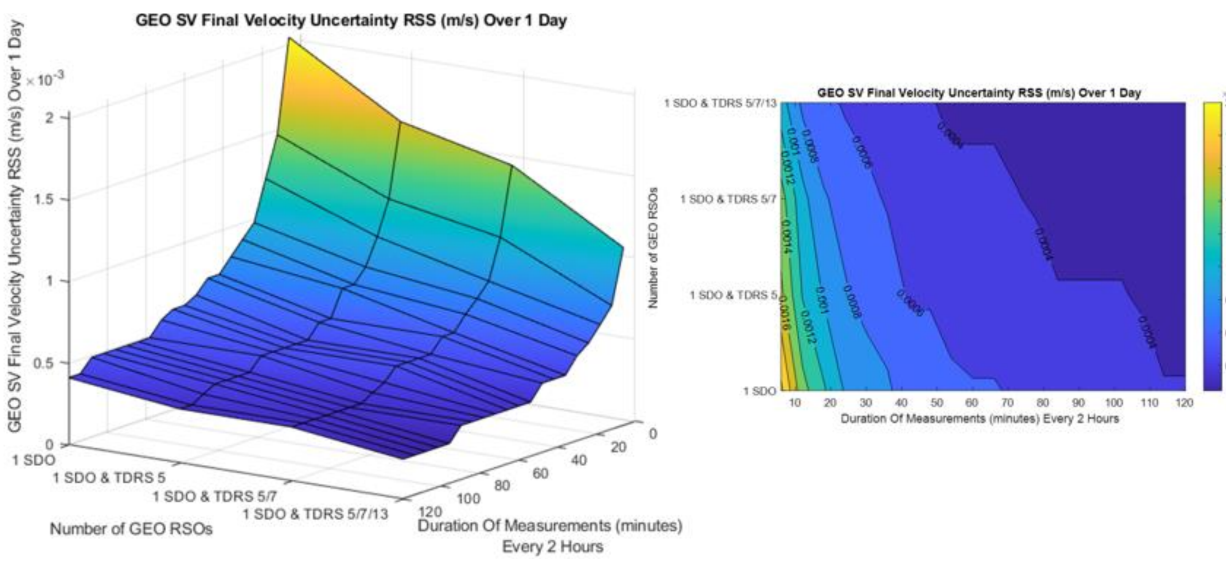


Figure 9: GEO SV Velocity Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 2 arc-sec pointing uncertainty, Simultaneous Measurements

The assessment for why additional RSOs increased the uncertainty (in Figure 4 through Figure 7) is because those analysis cases are stepping through the different RSOs one at a time for the applicable measurement duration (6-120 minutes), so increasing the number of RSOs being tracked reduces the measurement time on the initial RSO (the SDO satellite). To confirm this, each RSO was analyzed individually (only one RSO being measured). The results are shown below in Figure 10, and indicate that measurements of TDRS7 and TDRS 13 result in significantly increased uncertainty. This explains reduced performance in earlier analysis (Figure 4 through Figure 7), as when TDRS7 is added as an RSO it introduces higher uncertainty into the Kalman filter with less frequent measurements of SDO and TDRS5. This causes the covariance to increase, as viewing a sub-optimal RSO reduces the amount of time viewing the optimal RSO.

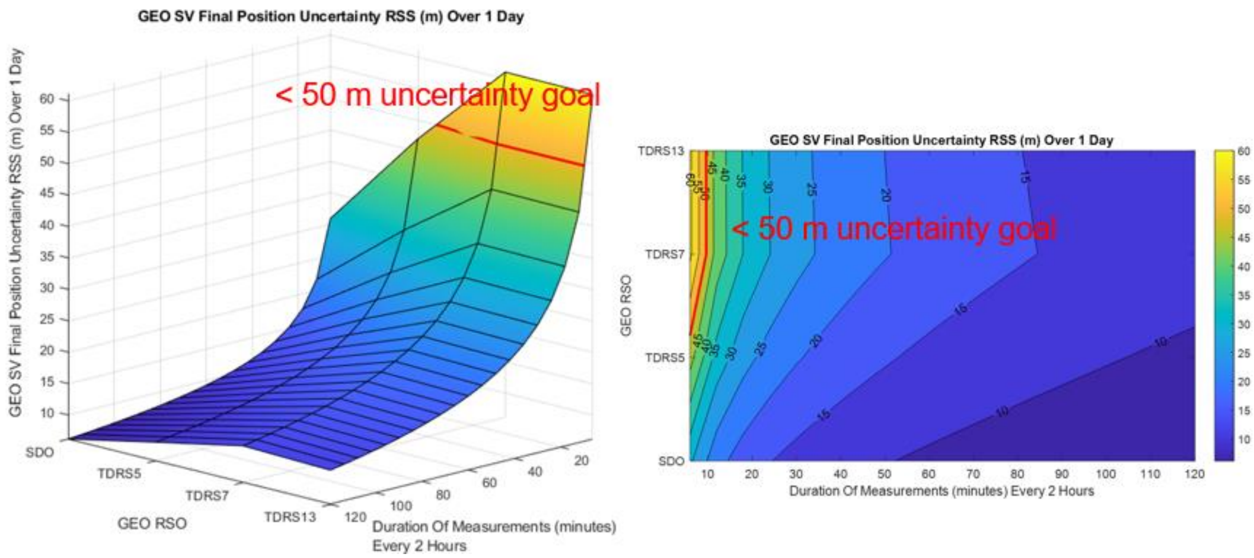


Figure 10 GEO SV Positional Uncertainty vs. Number of GEO RSOs vs. Duration of Measurements with 2 arc-sec pointing uncertainty, Single GEO Measurements

This data indicates that TDRS 7 and 13 provide sub-optimal data and should not be used. A review of the orbits indicates that TDRS 7 is the furthest GEO RSO (red orbit in Figure 1), and results in higher uncertainty because the angular uncertainty has a larger impact for distant RSOs. TDRS 13 is in a trailing orbit (green orbit in Figure 1) and does not provide good angular diversity, which is expected to impact the result. The SDO satellite orbit provides better quality measurements in 3D space due to its inclination and distance. In practical terms, this indicates the selection of RSOs for angles only tracking is critical to achieving the desired uncertainty.

2.4 Secondary Use Case

The initial results show that some GEO RSOs are not ideal. The accuracy achieved was also greater than the <50m goal at 10 arc-sec pointing uncertainly unless significant time was spent looking at the target. It is expected that RSOs with better orbit diversity will improve measurement quality. For this reason, MEO satellites were used instead of TDRS. TDRS6 is still used to represent the SV trying to determine its orbit, while GPS satellites SVN43, SVN56, SVN57, and SVN63 were used as GPS RSOs. GPS satellite ephemeris are well known and provide the desired orbital diversity.

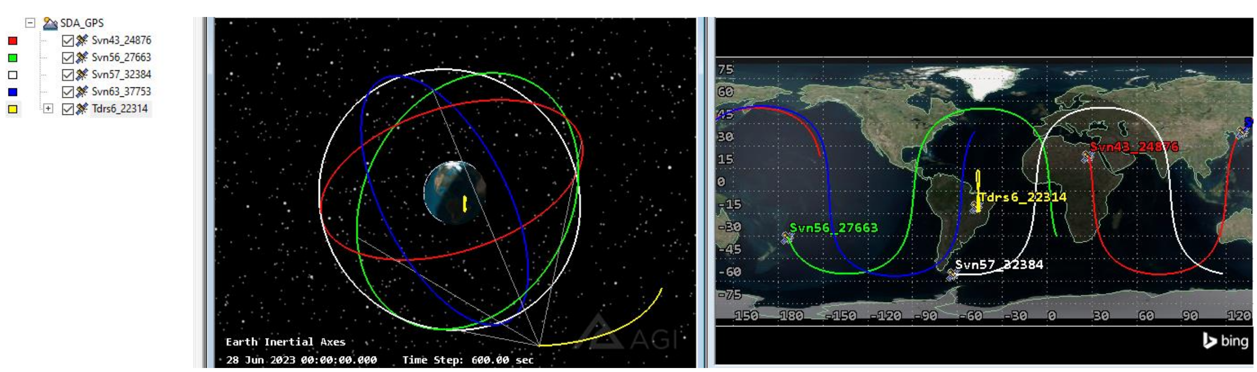


Figure 11 GPS Satellites Used for Orbit Determination

The plots below in Figure 13 and Figure 13 show the positional uncertainty using the same assumptions and analysis as TDRS but using the GPS satellites instead. It shows that at 2 arc-sec uncertainty , this can be done in under 10 minutes for all GPS satellites. Even at 10 arc-sec uncertainty, some GPS satellites (SVN43 and 57) can achieve the <50m uncertainty target with about 30 minutes of measurement time (every 2 hours), compared to 50 minutes when using the GEO SDO satellite.

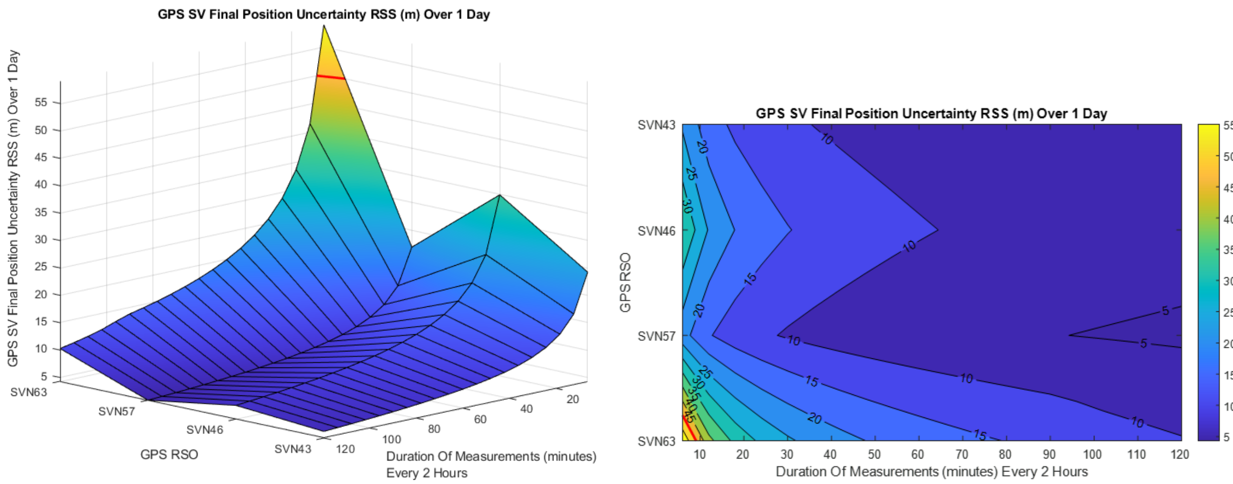


Figure 12 GEO SV Position Uncertainty vs. Number of GPS RSOs vs. Duration of Measurements with 2 arc-sec uncertainty

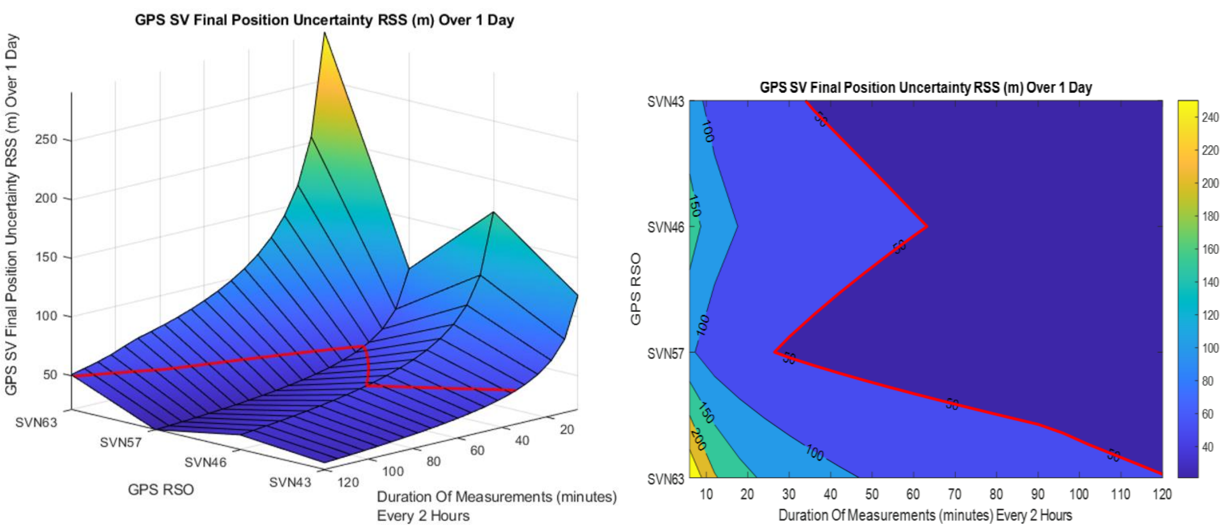


Figure 13: GEO SV Position Uncertainty vs. Number of GPS RSOs vs. Duration of Measurements with 10 arc-sec uncertainty

2.5 Tertiary Use Case

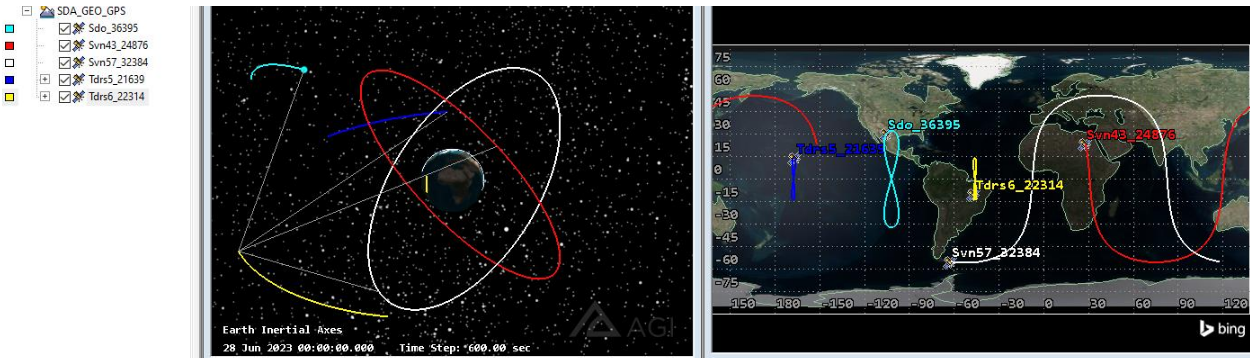


Figure 14 GEO and GPS Satellites Used for Orbit Determination

Lastly, a combination of GPS and GEO RSOs were used. The expectation is that this combination will provide higher angular diversity and result in better performance. The secondary use case (GPS only) would likely require a more sensitive EO instrument. To minimize potential cost and complexity, the orbits are mixed to improve performance.

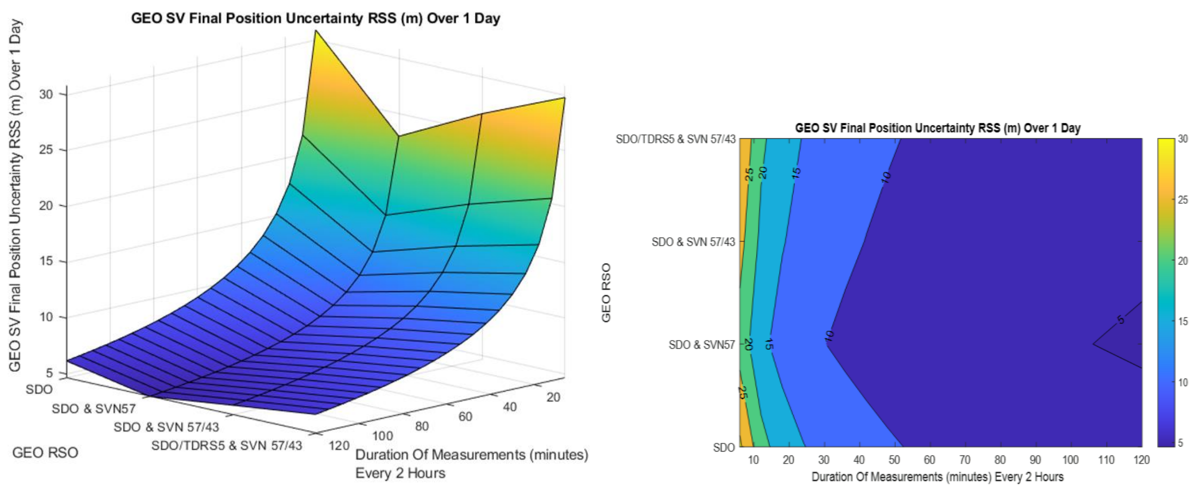


Figure 15: GEO SV Position Uncertainty vs. Number of GEO & GPS RSOs vs. Duration of Measurements with 2 arc-sec uncertainty

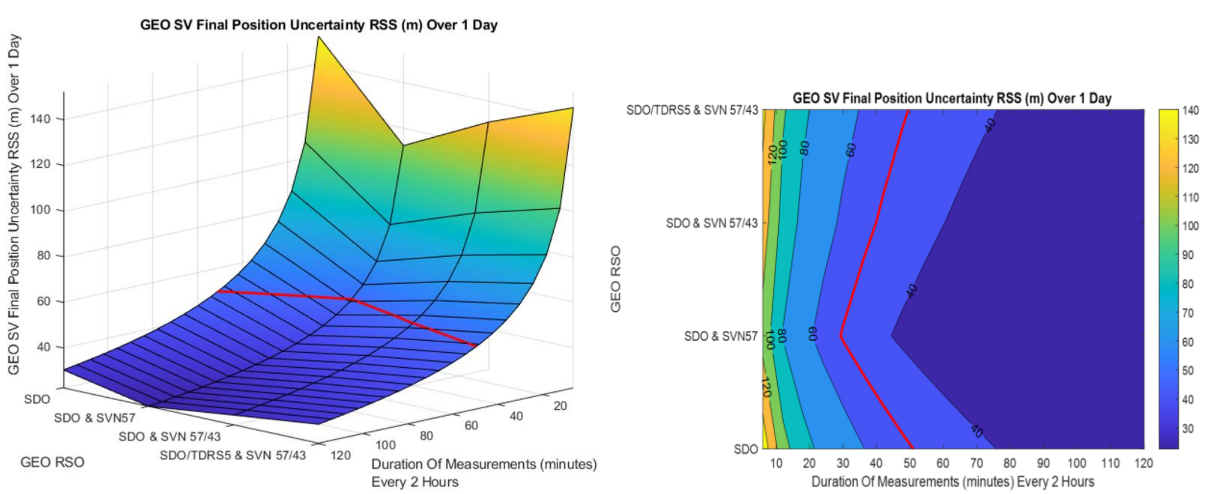


Figure 16: GEO SV Position Uncertainty vs. Number of GEO & GPS RSOs vs. Duration of Measurements with 10 arc-sec uncertainty

By alternating between tracking of GEO RSOs and GPS RSOs, it's possible to achieve <50m positional uncertainty in about 30 minutes of measurement time every two hours, compared to 50 minutes of measurement time when only viewing the SDO (GEO) satellite. This is for the case with 10 arc-sec of pointing uncertainty. If the sensor can achieve 2 arc-sec of pointing uncertainty, then either tracking the SDO by itself or in combination with the SVN57 meets the positional uncertainty with only 6 minutes of tracking time.

3. DISCUSSION

Overall, the various use cases indicate the pointing uncertainty of the SV's sensor is the most critical component to performing angles only orbit determination. Also significant is identifying a diverse set of RSOs that can be tracked, and being selective about which RSOs are used. For a real mission, an analysis of which RSOs will be tracked (and for how long) during normal mission operations should first be considered. Then, committing mission time to track select RSOs may be required, depending on the SV's pointing uncertainty and the positional & velocity uncertainty requirements. It's possible that utilizing RSOs seen during normal mission operation would be enough to meet particular mission requirements. This needs to be analyzed over longer time periods to understand the relative orbits between RSOs and the SV, and to better understand how to utilize angular diversity to RSOs to select which RSOs should be used in the OD filter. Overall, careful selection of RSOs in diverse orbits is the best method for solving the OD problem.

3.1 Future Consideration

Additional steps to take to further this analysis can first involve focusing on a smaller region of pointing uncertainty and measurement time duration. The increased resolution in the driving factors can further reveal the requirements needed for adequate orbit determination. Secondly, a deeper understanding on the optimal type of RSO can be gained by evaluating the observability of the GEO SV based on angles-only measurements. Further analysis can focus on trying to determine the geometrically optimal orbit for the filter state estimator. The initial analysis assumption that targets don't need to be Sun-lit would also be toggled to understand the impact, and would be part of the trade space for identifying ideal RSOs to track.

Future studies can integrate additional data sources and compare their relative performance to capability discussed herein, both as singular methods and also in combination. The first such method to be considered would be to look at the Earth, assuming the space vehicle contained an IR payload that could pick up large, significant sources of heat. In this scenario, there time to look from GEO to the Earth and back would have to be considered.

An additional method that could be used in GEO is to look at the Moon itself and the stars near the Moon. The ephemeris of the Moon in the Earth fixed system is quite stable and would not require updates for a long time. Therefore, an accurate direction to the Moon's center might provide good information about the satellite's location relative to the Earth. Also, precise timing of the winking out or the sudden appearance of a star at the limb of the Moon could provide precise information about the observing satellite's location in the Earth fixed system. This use case would be particular useful for any Earth orbit satellites monitoring cislunar space, and also could extend to orbital determination for satellites in cislunar orbit.

4. SUMMARY

These results indicate it's possible to gain acceptable positional and velocity knowledge without directly utilizing a GPS signal in GEO. There is an obvious trade against the primary mission objective for any applicable space vehicle implementing this method, and how much time can be allocated to looking in GEO and MEO. Additional analysis is needed on specific uses cases, both to understand driving factors for RSO selection, and also to increase model fidelity (such as requiring targets to be Sun-lit).

The analysis indicates that with good knowledge of RSOs, a sensor meeting the ~2 arc-sec pointing uncertainty can achieve typical positional and velocity uncertainty targets. At ~10 arc-sec pointing uncertainty, the angular and orbital diversity of satellites being tracked becomes critical to achieve target positional knowledge. This supports potentially removing GPS receivers from GEO SVs, both saving cost during SV procurement and addressing potential GPS denial scenarios.

5. REFERENCES

[1] R Mamich, D Kucharski, R Zanetti, M Jah, E Silva, J Griesbach, J Fine. Navigation Using Serendipitous Star-tracker Observations and On-Board Data Processing, *Texas Aerospace Engineering and Engineering Mechanics*, February 2022.

[2] Oza, Dipak & Bolvin, D. & Lorah, J. & Lee, Taemoon & Doll, C.. (1995). *Accurate orbit determination strategies for the tracking and data relay satellites*. -1. 59-72.