Reconstructing Close Proximity Events in Geosynchronous Orbit Using Sparse, Multi-Aspect Observations

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Abstract

The number of close approaches between objects in geosynchronous orbits is increasing as the population of Geosynchronous orbit increases. It can be exceedingly difficult to quickly reconstruct these events using only ground or LEO (Low Earth Orbit) based optical observations due to the lack of angular diversity, sensor lighting constraints and sensor tasking limits. This problem is compounded by objects which are frequently maneuvering. This technique uses sets of space and ground based observations to estimate the orbit state of an unknown object relative to a known RSO (Resident Space Object). The orbit state can be estimated using the angular difference between observations of the unknown object and the RSO and using a basic set of assumptions about the orbit with as few as two observations. A range iteration technique is used to solve for the velocity of the object. As more observations are received, the orbit solution can be improved. This technique can provide a first look characterization of high interest events in GEO in order to determine whether or not to task other sensors or increase coverage on unknown objects in proximity to known RSO's. Analysis will show the limits and results of this algorithm using simulated data.

1. Introduction and Background

Determining the orbit of satellites in GEO using current techniques presents a number of unique challenges. Primarily, ground based observations from optical sensors have very poor observability of the radial component of RSO position. This can be quantified by measuring the angle off of each component of the RSO Radial Intrack Crosstrack (RIC) frame from the observer as shown in Figure 1. In addition, the majority of satellites in GEO maneuver frequently to maintain a stationkeeping box [7]. For the most part the only available observations are from ground optical sites so range data is typically unavailable for orbit determination and due to the time limits on the sites, reduces the number of observations available. These factors make the traditional batch least squares orbit determination used for maintaining a catalog less accurate for objects in GEO, and causes significant lag in updates to orbit states after an RSO maneuvers [5]. This makes reconstructing high interest events which occur in GEO such as conjunctions extremely difficult. One method to alleviate these issues is to place optical sensors on satellites in GEO. As Figure 1 shows, these sensors provide a completely different view point for observations and can be used to reduce the error in the radial component of state. Obviously an optical sensor in a near GEO orbit has a limitation on the intrack observability so they are fundamentally not the complete solution to GEO orbit determination, however by combining observations from the ground, LEO sensors and sensors in

GEO the total observability can be greatly increased. When combined with orbit state data from a satellite operator, the state of an unknown object in close proximity to a known object can be determined very quickly using the proposed technique.

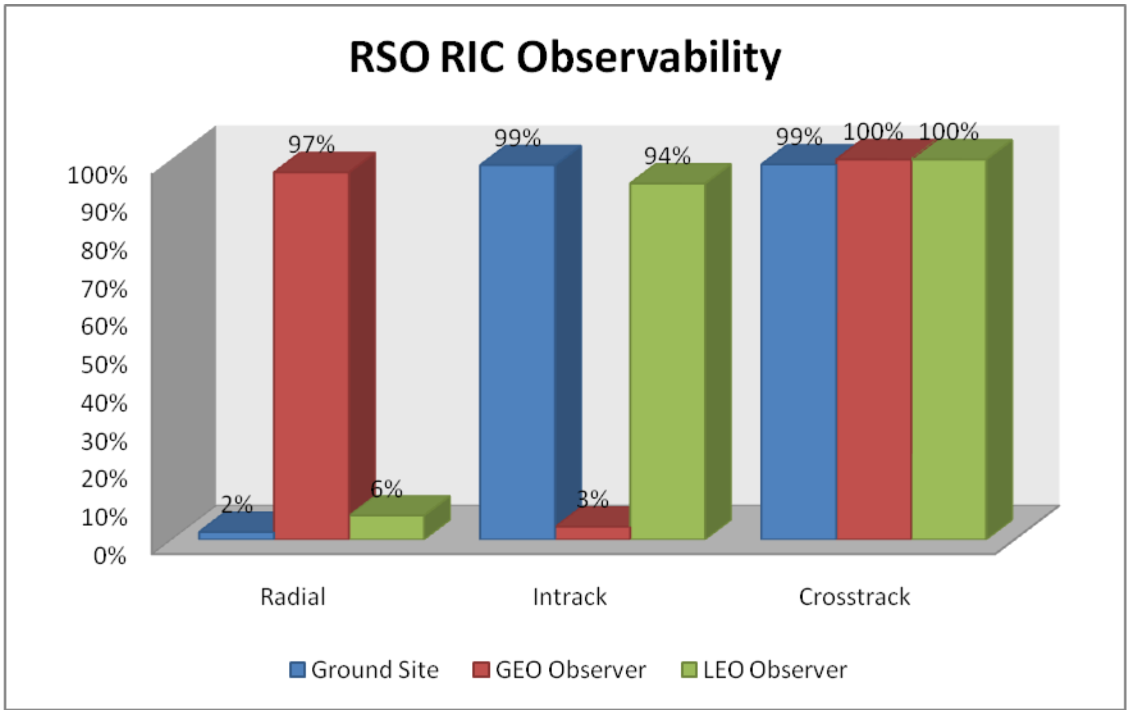


Figure 1: GEO Observability from various geometries

2. High Interest Events in Geosynchronous Orbit

Satellites in GEO orbit are affected by a number of perturbations which cause their orbits to drift over time. Station keeping maneuvers are used to keep a satellite in its assigned longitude and inclination box. A box is typically 0.1° wide in longitude and 0.1° in inclination [7]. Inclination changes are caused by earth oblateness, third body effects from the moon. This causes the inclination to increase at a rate of approximately 0.85° per year [7]. If left unchecked, inclination would increase to 15° over the course of approximately twenty five years. Satellite longitude at GEO is primarily affected by obliquity of earth's equator as well as solar radiation pressure. These perturbations tend to cause satellites to drift towards one of the gravity wells Located at 73°E and 104°W [9]. Eccentricity also tends to increase as a result of these perturbations however current strategies incorporate eccentricity corrections in east / west station keeping maneuvers.

Because of these perturbations, satellites in GEO maneuver very frequently to maintain station. Depending on the satellites propulsion, these maneuvers can occur anywhere from monthly to multiple times per day [3]. These perturbations also mean that satellites and debris which are not controlled will tend to drift and increase in inclination. In many cases, dead satellites and debris can drift and cause conjunctions with active payloads. If the objects are not normally tracked, when a conjunction is detected there may only be a handful of correlated observations with which to perform orbit determination. This technique can help improve the timeliness of the orbit states of the unknown objects and determine an accurate range at the point of closest approach. This enables operators to take action if the conjunction is determined to be dangerous.

3. Assumptions

A number of assumptions were made to simplify the algorithm and increase the ease of analysis. The first assumption is that the RSO's are both near GEO and are located within ±50 km of each other while the observations are being collected. It is possible that this technique would be applicable to highly eccentric orbits which approach GEO but that was not in the scope of the tests performed. This assumption was made because it greatly reduces the search space when determining the unknown RSO state. In other range iteration techniques the delta range used to search starts at the observer position and iterations are performed until convergence [4]. This algorithm also assumes that for each set of measurements for a given observer, there will be measurements for the unknown RSO as well as the known RSO. This requires that both RSO's are in the sensor field of view at the same time. To simplify testing, it is assumed that the known RSO observations are correlated to the known object, while the unknown RSO observation are not correlated to a cataloged object but are correlated to each other.

4. Algorithm Description

This algorithm uses the known position of an RSO combined with observations from a ground site and an observer in GEO to estimate the orbit of an unknown RSO in close proximity to the known RSO. The algorithm is broken down into four sections, initial position estimation, range iteration, orbit verification and residual minimization. This is similar to range iteration techniques for initial orbit determination (IOD) such as Gooding's and Double R iteration [4]. It differs from these techniques in that the initial estimate for the unknown RSO is based on the state of the known RSO. It assumes that the line of sight range only differs from the known RSO range by ±100 km. This significantly shrinks the search space for unknown RSO position compared to other techniques.

The inputs required are observations from a ground observer, observations from a GEO observer and a known RSO state. Observations are required for both the known and unknown RSO. This algorithm outputs an estimated state for the unknown RSO, as well as the relative position of the unknown RSO with respect to the known RSO.

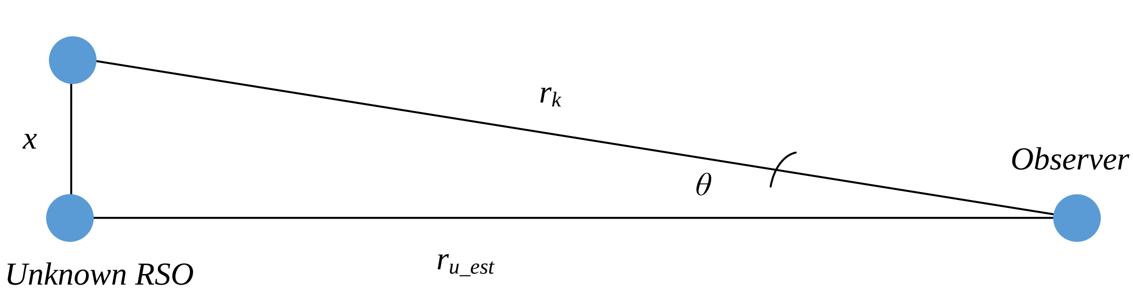
The accuracy of the unknown RSO velocity is somewhat limited, due to short time frames and small numbers of observations. This is acceptable for the algorithm because in many cases either the available observation data is limited or the time span which the state is needed is only a matter of hours, for which the states created by this algorithm are more than adequate. After this algorithm generates a state, if more accurate state knowledge is required additional assets can be tasked.

The algorithm was implemented in MATLAB using both custom functions and those in the NASA's Orbit Determination Toolbox (ODTBX) [9].

4.1 Initial Position Estimate

The first step of this algorithm is to make an initial estimate of the unknown RSO position. First, the vector between the observer and the known RSO (r_k) is calculated using the angle measurements in the observations and the known RSO state. At this point the error in the observation is calculated, obviously any error in the known RSO state will propagate into the estimate of the unknown RSO range. Since this is used only for an initial guess and the final state is verified using observation residuals, errors induced here should drop out. At this point the angle between the known and unknown RSO observation (θ) is calculated and vector between the known and unknown RSO (x). Finally, the magnitude of the vector from the observer to the unknown RSO (r_{u_est}) is determined assuming that x and r_{u_est} are perpendicular. This relative vector is then converted to and ECI position for use in the range iteration step. An ECI position is calculated for each observation from all observers. The variables described and the geometry are shown in Figure 2.

e 2: Initial Position Estimation Geometry



4.2 Range Iteration

Range iteration is used to find a range of possible states which match the observations. In this step, the positions calculated in step one are used as a starting point. At each step, the magnitude of each r_u is varied by an offset in range from the initial estimate. The delta range is varied by ±50 km in 1 km increments. The dotted line shown in Figure 3 shows the ranges which are tested. The range offset uses a middle out approach so that the smallest delta ranges are tested first. Using a function which solves Lambert’s problem for the using the positions calculated using the first and last observation. This function is based on the universal solution to Lambert's problem described in Vallado [9]. The function assumes that the observations all occur within one revolution and the take the short path between the two positions. This produces the estimate for the velocity in each case. Once the orbit state has been calculated it is stored in an array to be checked with the orbit verification and residual minimization steps. Each possible combination of delta range is tested for both the first and the last observations. This constitute coarse range iteration, the results are used in the orbit verification and residual minimization steps. This finds the coarse best fit orbit state, and the range iteration step is rerun from ±2 km in 10 m increments to find the best orbit state possible.

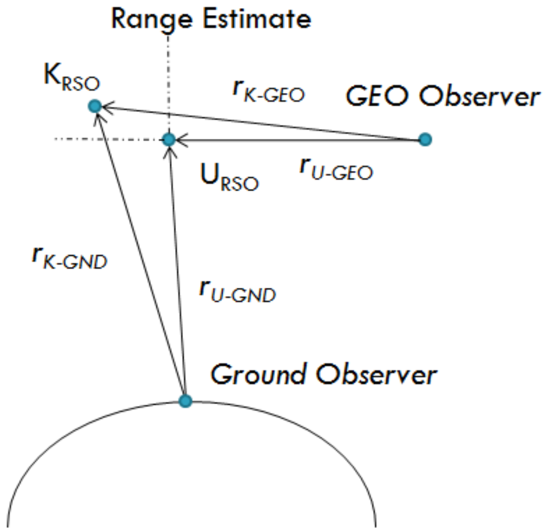


Figure 3: Observer and RSO Geometry

4.3 Orbit Verification

In this step the orbit state produced in the range iteration step is checked for validity. This step verifies that the unknown RSO is in a reasonable orbit with respect to inclination and eccentricity. To perform these checks the ECI state vector is converted into Keplerian elements. The eccentricity check verifies that the eccentricity of unknown RSO is less than 1.0 making the assumption that the orbit is not parabolic or hyperbolic. The next check verifies that the inclination of the unknown RSO is less than 15˚ if the eccentricity is less than 0.3. Because uncontrolled satellites in GEO tend to drift to approximately 15˚ inclination and then back down in a predictable cycle [7], it is reasonable to assume that the solved for orbit is invalid if it reports a near GEO orbit with greater than 15˚ inclination. The checks used here are very basic however they are user configurable in the algorithm, so any inputs can easily adjusted if desired by the user.

4.4 Observation Residual Minimization

Observation residual minimization is used to find the best fit orbit from all of the cases run in the range iteration step. This checks angle between the propagated orbit from each case against all the available observations.

In order to do this, the orbit state is propagated from the epoch of the first observation to the last, using a two body propagator implemented in MATLAB. This propagator is somewhat in accurate however the time of propagation is typically between 30 seconds and one hour, so the error induced is minimal. This propagator was chosen purely for speed, because it is run within the range iteration loop and therefore is called thousands of times. Next, the angular difference between the estimated orbit and the observation is calculated and added to an array. Once the angular difference has been determined for all of the observations the algorithm stores the mean of the errors for each case. From there, the case with the minimum mean error is selected and used as the final unknown RSO orbit state. Calculating all of the possible cases is more computationally intensive, but it avoids producing a state which is a local minimum and improves the chance of returning the global minimum.

5. Test Data and Limitations

In order to test the algorithm a number of test scenarios were created and used to generate simulated observations. Observations were generated using the rrdotang function from ODTBX [9] which generates azimuth and elevation measurements from a given observer to a satellite. The observer can be either a ground or space based observer. As this was a preliminary functional test of the algorithm, sensor constraints and performance characteristics were ignored. For these tests, sensor error and process noise were not added to the simulated observations.

The following tests were performed to verify the function of the algorithm and determine sensitivity. For all cases the known RSO was located at 80˚ Longitude with 0˚ inclination and a circular GEO orbit. The observer longitude varied but in most cases it was a circular orbit drifting west at 1˚ of longitude per day. The ground site location was set at Diego Garcia. Four measurements were used for each observation from each site at 30 second intervals, and the observations were separated by 15 minutes unless otherwise noted. Orbit propagation was done with the 8th order Runge-Kutta numerical propagator included with ODTBX.

Initial position errors were typically on the order of 100 m, and the primary source of error was the initial velocity error which was typically on the order of 0.2 to 0.5 m/. This causes the estimated orbit state to diverge from truth with time. This error growth was acceptable for the purposes of this algorithm, and it should only be used in situations where an initial estimate is needed.

5.1 Varied Unknown RSO Geometry

In order to determine that the unknown RSO geometry did not significantly affect the performance of the algorithm the unknown RSO geometry was varied with the following conditions.

- Pure radial separation from the known RSO
- Pure intrack separation from the known RSO
- Pure crosstrack separation from the known RSO
- Unknown RSO and known RSO in a simulated cluster

The pure component cases used a positional separation of 30 km, with a relative velocity of zero, so the unknown RSO was drifting away from the known RSO. Figure 4 shows the Radial separation case geometry in the Radial – Intrack Plane. The radial Intrack error over the 12 hours of propagation was minimal in this case.

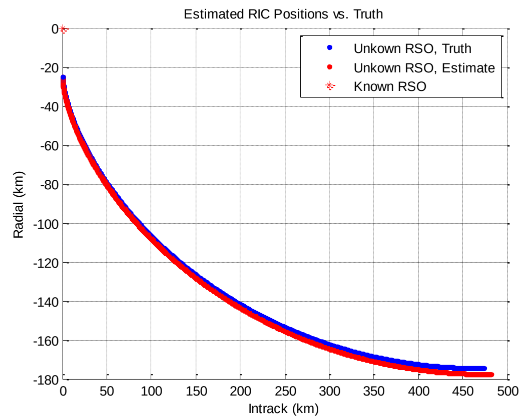


Figure 4: Radial Separation Case, Radial vs. Intrack Position

This test showed that the algorithm was not significantly impacted by differences in the initial relative state of the unknown RSO. Positional errors were on the order of tens of meters from the truth positions, and velocity errors were on the order of 0.2 to 0.5 m/s. In twelve hours the positional error grew to between 3 and 6 km from the truth state. Figure 4 shows the position error growth for the radial and intrack cases. It is worth noting that this testing does not take into account the fact that if the RSO's do not have sufficient separation in the line of sight vector it will be impossible to collect observations. This is highly sensor dependant and therefore has not been explored further.

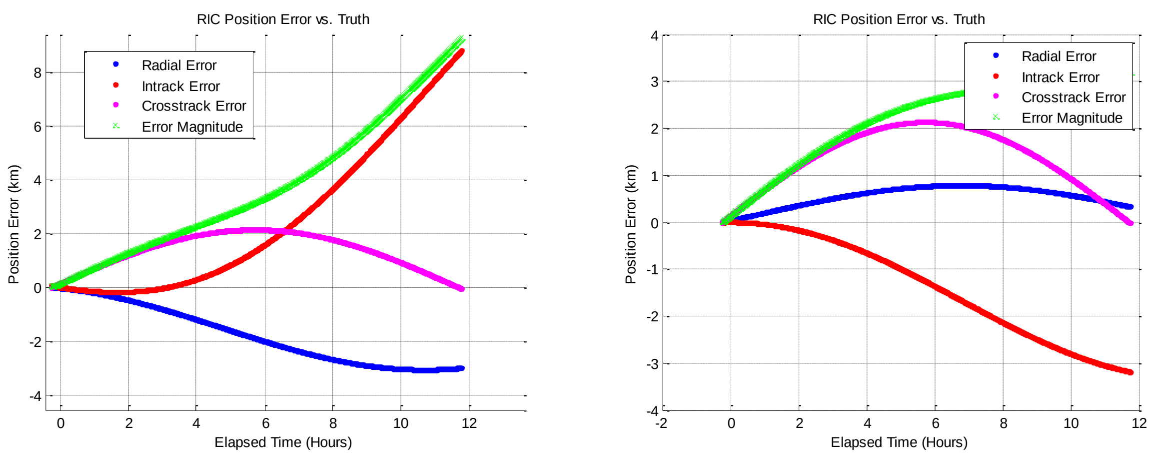


Figure 5: Radial and Intrack Separation Case, Position Error vs. Time

5.2 Varied Observer Longitude

The purpose of this test was to determine the effect of longitude of the GEO observer on the accuracy of the orbit state produced by the algorithm. This test was run using the same RSO states for each case and varying the longitude of the GEO observer. In all cases the GEO observer was in a sub-GEO orbit drifting west at one degree per day with all other orbital parameters being held constant. The observer delta longitude to the known RSO is varied from 2˚ to 90˚. Figure 6 shows the ground tracks of the observers and RSO's used for these test cases.

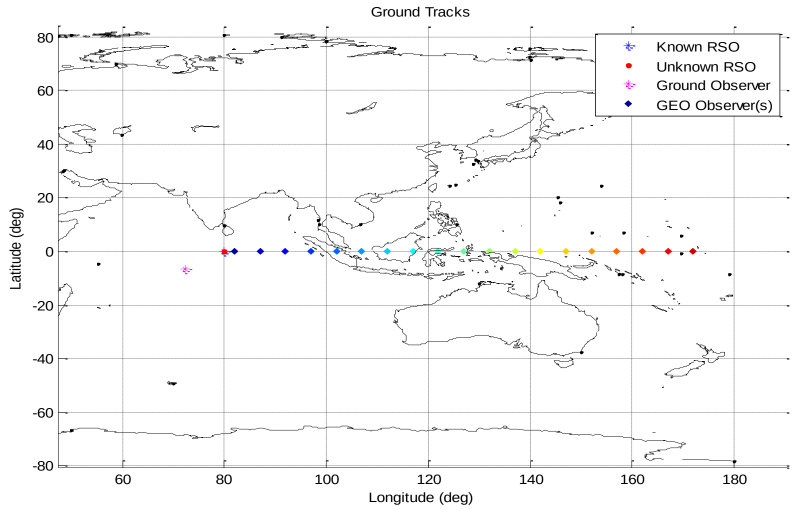


Figure 6: Varied Observer Longitude Ground Tracks

The results of this test showed that the initial position and velocity errors decreased as the delta longitude increased. Figure 7 shows this trend. This is primarily due to the fact that as the range from the GEO observer to the known RSO decreases, the radial observability also decreases. This reduces the total observability of the ground and GEO observer and induces additional errors. However the initial error in the worst case examined here is approximately 87 m from the truth state which is still adequate to provide a usable orbit state for one to two hours past the state epoch. For best performance it seems that 30˚ to 50˚ delta longitude is optimal for this algorithm. However, this is dependent of the sensors ability to resolve the objects at these ranges, which was not investigated as part of this testing.

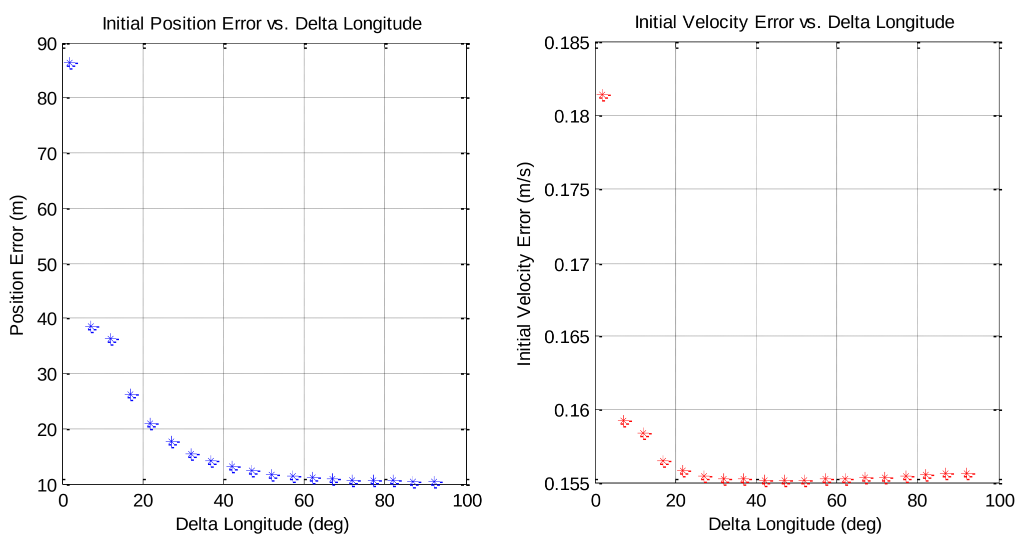


Figure 7: Position and Velocity Error vs. Delta Longitude

5.3 Varied Time Between Observations

This test used the same initial geometry and conditions as the simulated cluster test performed in section 4.1. Time between observations was increased from 30 seconds to one hour in 30 second increments. Results show that as time between observations increases the position and velocity errors also decrease. This is shown clearly in Figure 8, which shows the propagated position and velocity error over four hours for all the cases which were run. The color of the lines indicates the time between observations. The graphs clearly show that the longer separation times produce more accurate results.

This is most likely due to the way the residual minimization works, if the angular difference between the observations is greater, as it would be with more separation, the residual minimization can reduce the error in the state more than it could with shorter separation times since there is more error introduced in the rejected states.

There may be a point at which this fails however separation times longer than one hour were not explored because they would defeat the purpose of this algorithm. It seems that after approximately 15 minutes of separation the returns on increased observation separation diminish significantly. At this point it becomes a tradeoff between the timeliness of the orbit state and the accuracy of the orbit state produced.

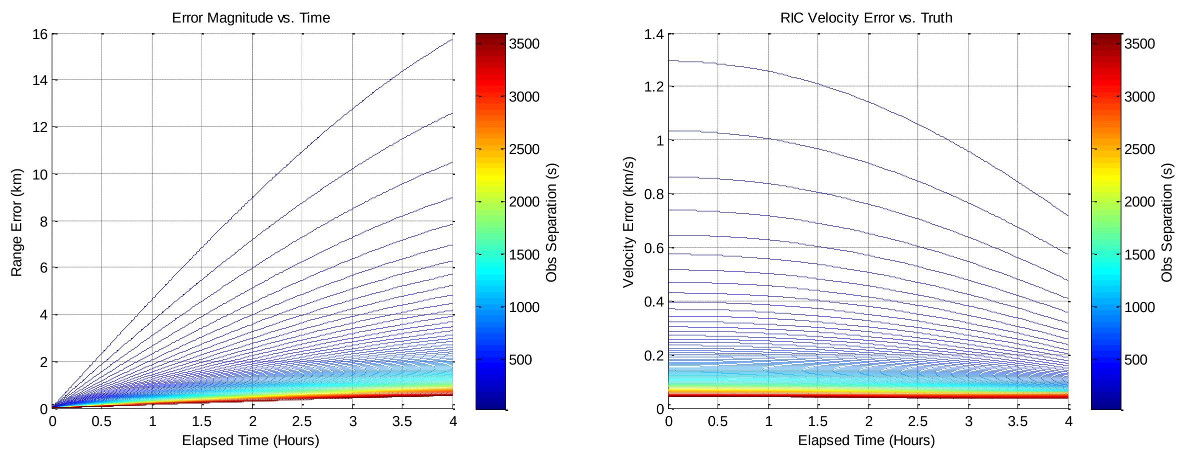


Figure 8: Position and velocity error with varied observation temporal separation

5.4 Test using LEO observer and ground observer

The final test demonstrates that this technique will only be effective if there are observations from multiple perspectives. It also shows that RSO observability from an observer in LEO is not significantly different that one on the ground, as shown in Figure 1. The test was performed using the simulated cluster case from section 4.1 replacing the GEO observer with one in a sun synchronous orbit with an apogee altitude of approximately 800 km.

This test case shows that while the initial position error is similar to other cases tested, the velocity error is so much higher that the resulting orbit is essentially useless. After five hours the propagated orbit state contained 50 km of position error from truth as shown in

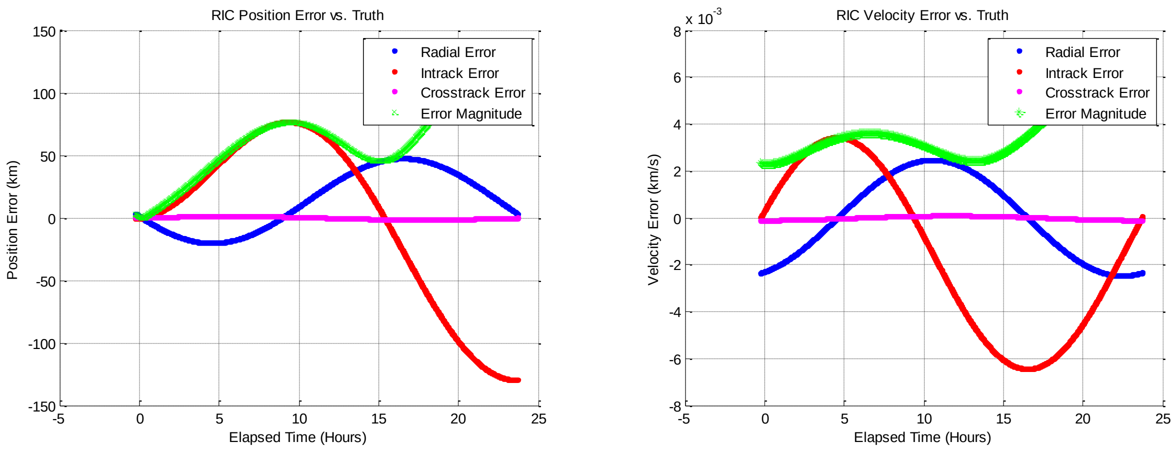


Figure 9: Position and velocity errors for LEO observer case

6. Conclusions

This technique demonstrates the utility of SSA sensors in GEO to increase the accuracy of initial orbit determination of unknown objects. It allows rapid initial orbit determination to be performed in order to reconstruct high interest events in the GEO and near GEO environment. Given the right conditions this algorithm can produce an orbit state with as few as two observations and a state for a known RSO. Obviously this technique is limited in that the unknown object must be spaced closely with a known object, and the GEO observer must be in the correct position to make the observations. Also the orbit state produced is typically only valid for a few hours after the epoch of the last observation, and to increase that accuracy after that would require further tasking of sensors. Despite these limitations, this technique allows decision makers to evaluate high interest events which occur in GEO by providing timely and accurate orbit states during such events. A capability that will be key as space becomes a more congested and dynamic environment.

7. References

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