AN/FSY-3 Space Fence System Support of Conjunction Assessment

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ABSTRACT

The Space Fence System is a ground-based space surveillance radar system designed to detect and track all objects in Low Earth Orbit the size of a softball or larger. The system detects many objects that are not currently in the catalog of satellites and space debris that is maintained by the US Air Force. In addition, it will also be capable of tracking many of the deep space objects in the catalog. By providing daily updates of the orbits of these new objects along with updates of most of the objects in the catalog, it will enhance Space Situational Awareness and significantly improve our ability to predict close approaches, aka conjunctions, of objects in space. With this additional capacity for tracking objects in space the Space Surveillance Network has significantly more resources for monitoring orbital debris, especially for debris that could collide with active satellites and other debris.

1. INTRODUCTION

The activation of the Space Fence System (SFS) in late 2018 will usher in a new era for Space Situational Awareness. By detecting and tracking all objects the size of a softball or greater in altitudes ranging from 250 km to 3000 km with its Low Earth Orbit (LEO) surveillance fence, the SFS will greatly increase our knowledge of objects in a critical region of space. Knowledge of objects in this region is crucial to the planning of space launches, to the operation of civilian and military satellites in this region, and to manned spacecraft operations. In addition, the SFS has sufficient power and aperture for detection and tracking of objects beyond the LEO regime out to the geosynchronous belt (GEO) [1].

While the Space Surveillance Network (SSN) includes a number of very capable sensors, Space Fence represents the only S-band surveillance radar operated entirely for the purpose of detecting and tracking objects in space. The catalog of known orbiting objects, or Resident Space Objects (RSO), contains about 17,000 [2] entries and identifies most, if not all, objects in Low Earth Orbit (LEO) larger than about the size of a basketball. Objects are identified by the characteristics of their orbits in the form of Keplerian element sets, an object number, and an estimate of the impact of the atmosphere on the orbit over time. The radar is expected to detect many small LEO objects not currently in the catalog. Estimates place the number of uncataloged objects that could be detected by the Space Fence System at IOC between 30,000 and 60,000. When an object is detected and tracked but cannot be correlated with an RSO, the track is designated as an Un-Correlated Track (UCT). After a UCT has been tracked enough times to establish a reasonably accurate element set, it can be promoted by the Joint Space Operations Center (JSpOC) to an RSO and is then added to the catalog.

As the catalog of objects in orbit expands, the task of predicting close approaches of two objects, also known as Conjunction Assessment (CA), becomes more computationally difficult because the assessment of conjunctions between any two objects scales at n^2. Currently, CA are only completed between a small number of key satellite assets and the current catalog. This information is given to satellite operators so they can decide if they should initiate a debris avoidance maneuver. While this meets the requirements needed by asset owners, there are valid reasons for performing conjunction assessment across the entire RSO population. This All-Versus-All assessment of the entire catalog helps to predict debris creating events which could potentially affect functioning satellites soon after impact. Collisions between large spent rocket bodies and small debris objects are of particular interest because of the large amount of new debris that could be created in one collision [3].

Conjunction Assessment of the catalog after the inclusion of the many small LEO objects expected to be detected by Space Fence will likely flag many more possible collisions or close approach events [4]. Objects identified as candidates for possible collisions can be tasked to the radar to provide more accurate and timely information for collision avoidance analysis. This additional information will help prevent unnecessary satellite maneuvers and minimize avoidable collisions.

In general, the probability of a conjunction can be estimated more accurately with more precise measurements of the two orbits of the objects, especially nearer to the time of closest approach. Timely observations are fundamental to accuracy because observational uncertainties and atmospheric effects compound over time. Errors in orbit determination grow when propagated and compared to the object's actual position. For objects in LEO, the major source of uncertainty when propagating orbits forward in time is due to the impact of the atmosphere. The atmosphere imparts a drag force on these objects that is defined by the density of the atmosphere (ρ), the drag coefficient of the object (C_D), its cross section (A) and the velocity of the object relative to the atmosphere (V). We divide by the object's mass (M) to get the acceleration.

$$a = \frac{1}{2} \rho \frac{C_D A}{M} V^2$$

Atmospheric effects, such as solar wind, become more important to objects at higher altitudes, but for the LEO regime fluid dynamic effects dominate. For most objects in space the terms ($\frac{C_D A}{M}$) are combined to form a ballistic coefficient that can be estimated based data collected by tracking the object.

Atmospheric drag is difficult to predict, and future predicted positions are affected by the longer time the atmosphere affects the object in unknown amounts. Conjunction assessment for LEO objects is complicated by the impact and variability of atmospheric drag. Newer models of the atmosphere, such as JBH09, along with efforts to use calibration satellites for near-real time estimates of the state of the atmosphere are helping to reduce the uncertainty. Propagation of satellite orbits more than a few days into the future has the potential for significant errors as the state of the atmosphere is dependent on solar activity which can change over that time period [5].

The density of the atmosphere at LEO altitudes varies diurnally due to solar heating over the course of days and longer due to variations in the solar output. New high precision models of atmospheric density in the LEO regime use measurements of solar activity to predict the state of the atmosphere over the next few days. Weather prediction information is provided by the National Oceanic and Atmospheric Administration (NOAA). Fig. 1, below, shows a 27 day outlook of the 10.7cm Radio Flux which has a direct impact on satellites both due to solar drag and its effects on expanding the atmosphere. Note that the prediction does not capture the actual values well as time progresses.

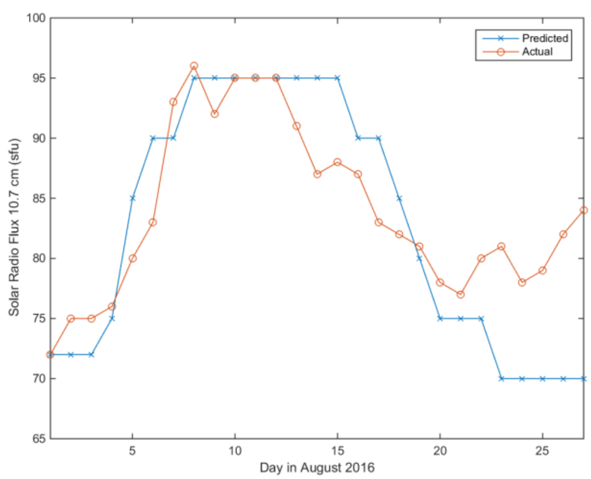


Fig. 1. Forecasted verus actual solar flux in August [5]

Using a cost function that accurately reflects the resource requirements for various sensors in the Space Surveillance Network and the relative value of their observations, it is possible to prioritize the tracking resources of those sensors such that the limited available resources for improving the accuracy of conjunction probabilities are applied effectively and efficiently. The Space Fence System sensor sites are located near the equator thus they are able to view almost all types of orbits; however, observations from radars at higher absolute altitudes would be beneficial for more accurate determination of an orbits inclination and of the apogee of highly elliptical orbits. Using the capabilities and locations of sensors in the SSN, the JSpOC could optimize the tasking of those sensors to best estimate the orbits of objects in the catalog and the probability of conjunctions.

2. SPACE FENCE TRACKING CAPABILITIES

The Space Fence System is designed to perform un-cued surveillance of objects in LEO and to track all detected objects to determine an estimate of their orbit. The un-cued LEO surveillance fence is a fan-shaped search volume aligned in an east-west direction with different revisit rates for different altitudes that detects objects as they pass through. When a detection event occurs, the scheduler queues a sequence of transmit pulses, independent from those of the un-cued fence, to track the object long enough to determine its observed locations. The observations are then combined to estimate its orbital element set. This is compared to the catalog to determine if the object's element set correlates with one already cataloged or if it is an uncorrelated track (UCT).

The Space Fence System is designed to run the un-cued surveillance mission with the majority of the radar's transmit power. A portion of the radar's remaining resources are available for precision tracking of objects of interest and to generate temporary mini-fences at higher altitudes to support ad hoc tasking, such as in support of a new space launch. The radar's tasked tracking schema is configurable by object, where the user may request a track duration defined by time or number of observations. Additionally, the user can request tracks to be performed on optimal passes or every pass among other settings. Tasked tracks, with default values, begin shortly after the object enters the SFS field of regard and include more observations than an un-cued track which is triggered only when the object passes through the fence. This tasking capability provides the opportunity to maintain coverage outside of LEO and into geosynchronous orbits (GEO) with minimal impact, if any, on un-cued surveillance.

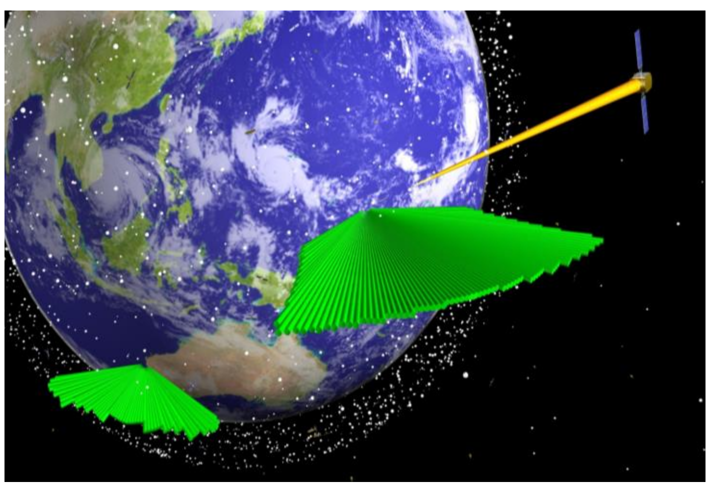


Fig. 2. Visualization of the Space Fence Radar beams from sites in Kwajalein and Australia

Because the SFS uses element level digital beam forming for both transmit and receive, the radar is capable of performing both un-cued surveillance and cued tracking simultaneously. Fig. 2 depicts the radar at Sensor Site 1 tracking a satellite while maintaining the surveillance fence. The figure also includes the proposed Sensor Site 2 in Australia, which would be part of the LEO assured coverage mission. The Australian site would provide important surveillance over the lower sector of LEO, with additional capability to track into GEO. The two assets combined would nearly double the amount of tracks per day.

3. RADAR MODEL IN A NASA 2030 CATALOG ENVIRONMENT

Lockheed Martin's high fidelity model of the Space Fence System is actively used for capability analysis. The model runs using Mission and Radar control software used in the actual system, executing functions to point beams, analyze returns, determine orbits, and report observation data. Therefore, the model functions as a very accurate representation of the actual system. A modeling and simulation scenario is run by populating the simulated environment with orbiting objects both cataloged and uncataloged, then executing the simulated SFS with both a surveillance fence and optional taskings reporting on detections, observations and tracks as the operational system would.

For this study, the model was run using an environment based on the NASA 2030 Simulated Catalog, which is an estimate of the future space enviornment consisting of over 150,000 objects of differing sizes down to 1cm and in a wide variety of orbits. The catalog was created in 2006 using two high-fidelity models, LEGEND (the NASA long-term orbital debris projection model) and NaKModule (the NASA sodium potassium droplet deposit model) [7]. The simulation environment lasted five days, where Space Fence Sensor Site 1 in Kwajalein was able to track the majority of the 14,011 objects in its reference catalog (a simulation of the current day NORAD two-line element set catalog) and discover 51,227 objects which were seen at least two times and correctly correlated between those passes. Thus, the radar maintained a steady state catalog of 65,238 objects over the course of the five days.

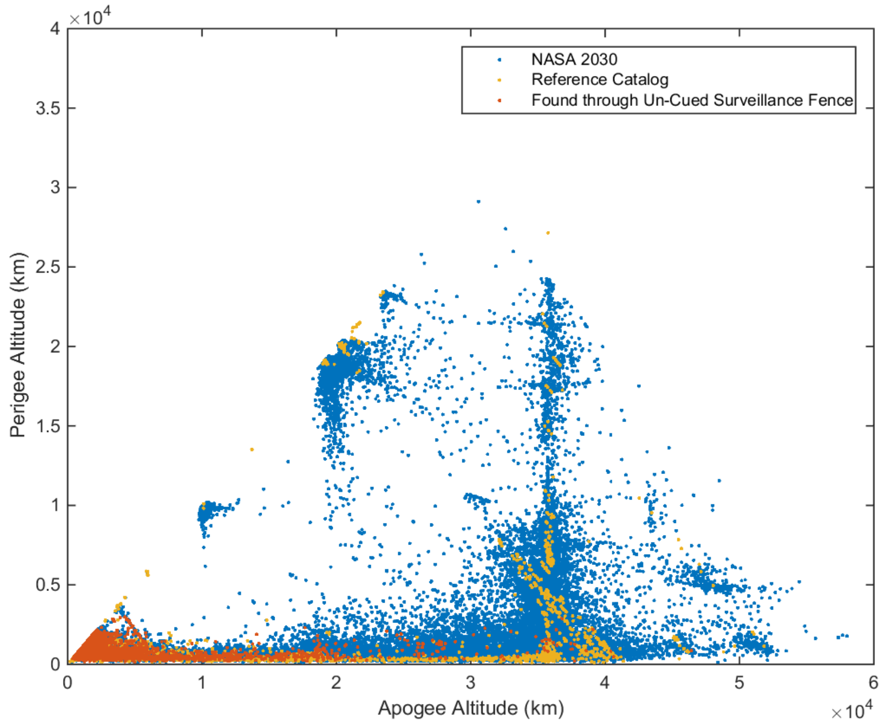


Fig. 3. Apogee and perigee altitudes of scenario objects

The Kwajalein radar's LEO fence was modeled for the entirety of the simulation, detecting objects with an altitude below 3000km. Above, Fig. 3 shows the apogee and perigee of objects the radar discovered and maintained of the modified NASA 2030 catalog. Notice all objects found by the SFS had a perigee whose altitude was within the fence. Also, note that the simulation only reported objects it could see; there were many instances where objects' orbits did not pass through the fence. The majority of the objects in the reference catalog were in LEO, with a sampling through MEO (Medium Earth Orbit), HEO (Highly Elliptical Orbit), and GEO.

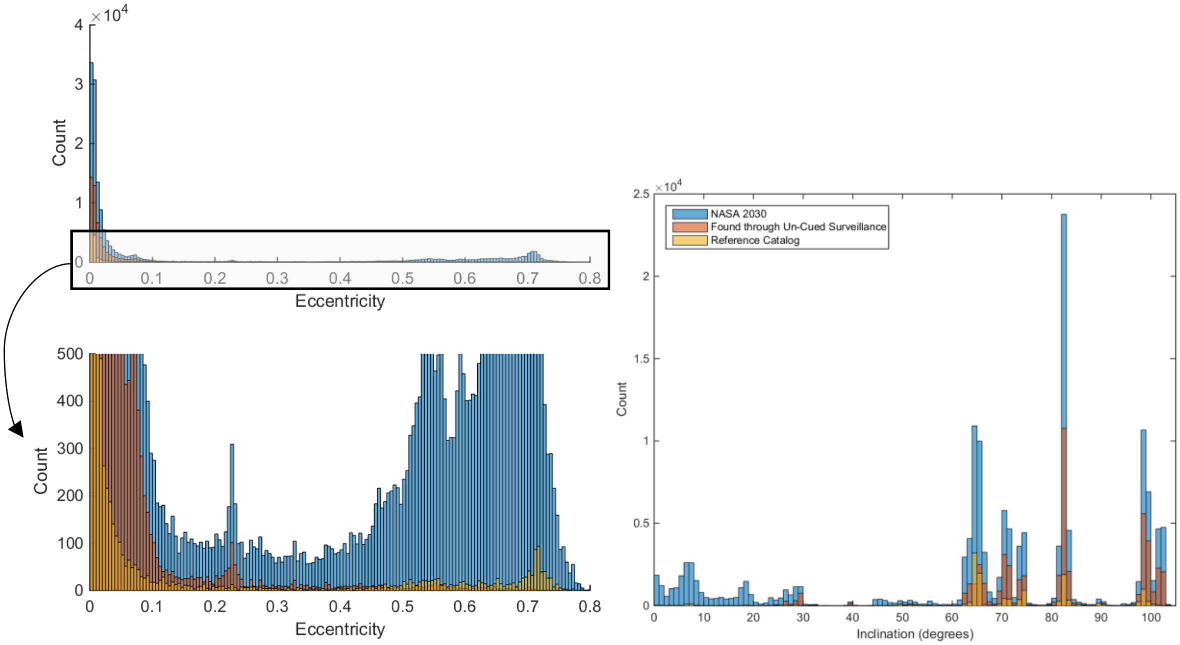
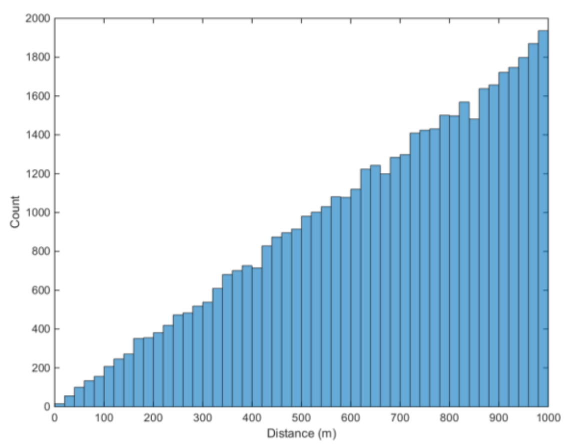


Fig. 4. Histograms of Keplerian elements of scenario objects

The simulation showed Space Fence's ability to collect observations on elliptical and high inclination objects. Fig. 4 shows how the radar expanded the catalog with trends similar to those in the modified NASA 2030 catalog. The radar's un-cued fence is able to detect mainly semi-circular orbits. Due to typical inclinations of highly elliptical orbits, the object is unlikely to pass through the fence even though its altitude is within the fence's detectable range. However, these objects could be tasked for tracks beyond the fence as the object moves towards or away from perigee. The figure also shows few objects were found at very low inclination, because the radar is geographically located at 9 degrees North latitude and the objects never passed through the fence. The radar did find many objects in typical LEO orbits with inclinations ranging from 60 to 110 degrees.

4. CONJUNCTION ASSESSMENT OF EXPANDED CATALOG

Conjunction Assessment was conducted on a representative internal SFS catalog in steady state. Roughly 65,000 objects were analyzed using COMBO V5.4.2, the "Computation Of Miss Between Orbits" module in the Astrodynamic Standards Software suite. The program performed All-Versus-All CA over a 7 day period, calculating the time, distance, and relative speed of closest approach. The count of closest approaches showed a linear relationship with closest approach distance [7], shown below in Fig. 5.



Separation Distance (m)	***Count***
1000	46,868
500	11,690
100	467
50	109
5	1

Fig. 5. Closest approach count by distance

There were 46,868 occurrences when the objects came within 1 km of each other. The closest two objects came was within 5 meters in that simulated week. While the objects were modeled as discrete points, many would be roughly ten centimeters in diameter or larger. This could mean that debris-causing events, whose debris cloud would be in Space Fence's view, may occur weekly. While these events are unfortunate, Space Fence would aid in the scientific analysis and model development of impacts by collecting observations of the debris cloud multiple times per day. In these instances, the radar operator could create a micro fence in the path of the debris cloud to find the new objects including those much smaller than the un-cued fence would naturally detect.

As seen in Fig. 6 below, there will be a periodicity associated with conjunctions, not a steady amount per day. Debris fields like those caused by the Iridium and Cosmos collision or the Chinese anti-satellite test would require more taskings if an object were to pass through the cloud. While many of the close approaches/collisions would not be between operational satellites, a plethora of objects flagged for close passes could be tracked to create a database of object interactions. This dataset could be used for probability of collision analysis and refinement. The radar scheduler can handle tens of thousands of taskings per day without interrupting LEO surveillance, thus the entirety of the objects with a possible conjunction under 1 km could be tasked to the radar to collect additional passes and observations.

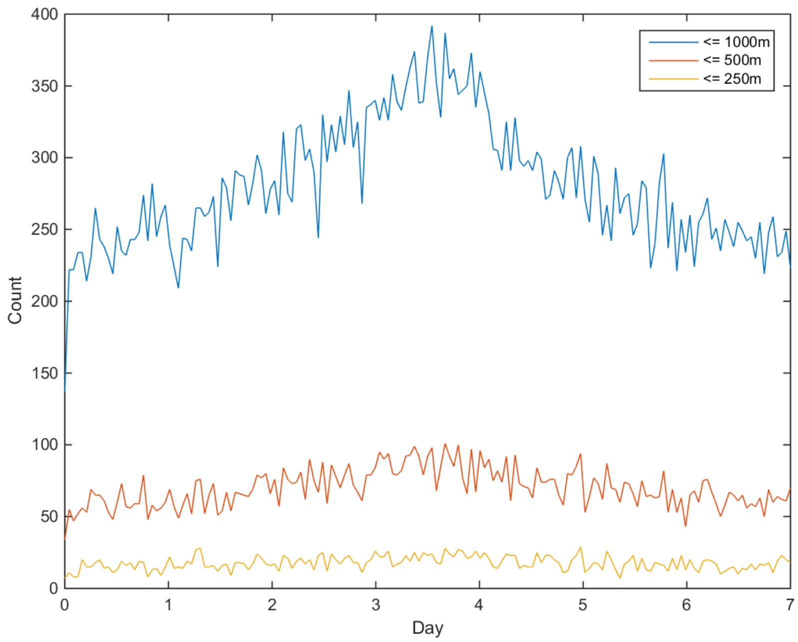


Fig. 6. Hourly closest approach count for varying separation distances

The impact speeds are shown below in Fig. 7, where the count increases exponentially with speed. Notice the peak at 14 km/s. This derives from objects in high inclinations impacting each other moving in opposite directions; this instance is visualized in the figure where the conjunction was flattened into a plane. The majority of the objects found by Space Fence in the simulation existed in LEO where orbit speeds are around 7 km/s and many of the objects' inclinations were 80 degrees. At such a high inclination, the objects' north-south speed is roughly 98.5% of its total speed. Thus, two objects approaching each other with the majority of their speed in antiparallel directions would collide at 14 km/s as seen in the histogram.

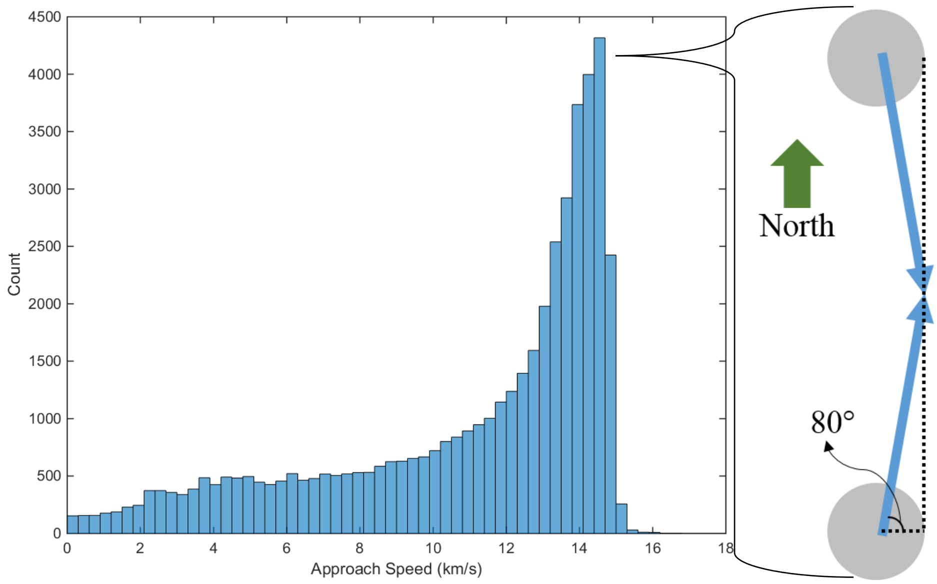


Fig. 7. Conjunction approach speeds and visualization

5. CA OF EXPANDED CATALOG ON NASA SATELLITES

There is a concern that when Space Fence becomes operational, current analysis tools and scripts will be overburdened by the massive increase in cataloged objects. This catalog increase is visualized below in Fig. 8. To understand the extent of the impact, a set of roughly sixty two-line elements (TLEs) was analyzed for conjunctions against both a catalog of recently (within 30 days) updated RSOs from 13 July, 2016 and the expanded catalog of well-maintained objects from the simulation. The TLEs were representative of satellites actively monitored for conjunctions by NASA, which included all orbit regimes: LEO, MEO, HEO, and GEO. The catalog contained 10,626 objects whose TLEs epoch were sufficiently current for COMBO to analyze. Over a seven day period, there were 17 close approaches where two objects passed within 1 km of each other. These instances would be flagged by JSpOC and a notification would be sent to NASA for further analysis on the probability of collision between the debris and their satellites of interest. Compare this to the scenario where the NASA representative catalog was run against the expanded catalog. Over a seven day period, there were 48 conjunctions when objects came within at 1 km of each other. On average, it could be expected that seven instances per day satellites would be in danger of a collision and would require intensive probability of collision calculations conducted long beforehand. This is nearly a 300% increase in workload once the catalog expands.

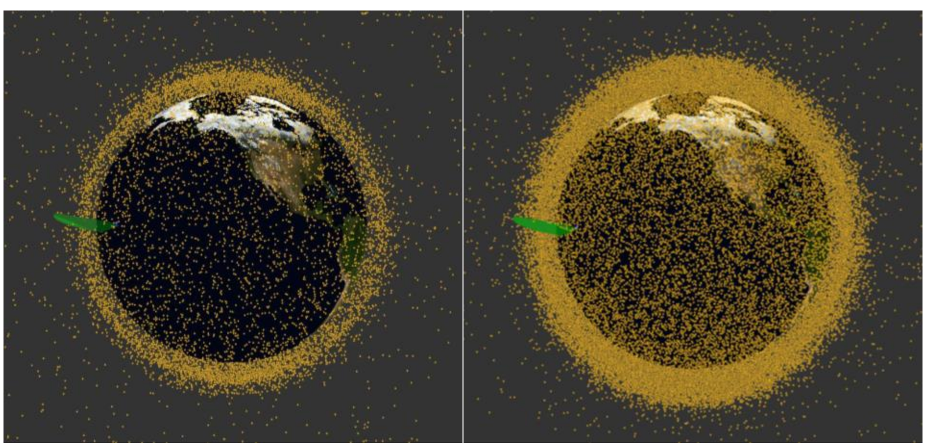
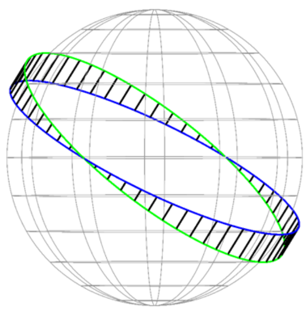


Fig. 8. Juxtaposition of the current LEO catalog (as of 13-July-2016) versus the current catalog with an estimate of the SFS detected objects

6. ORBIT DETERMINATION ACCURACY WITH DIFFERING TRACK MODES

Orbit determination can be improved in a multitude of ways including obtaining longer tracks on objects, obtaining more frequent tracks, and lowering the uncertainties of individual measurements so as to increase the accuracy of generated observations. This is critical for conjunction assessment where the stakes are so high, and where the most important question of the day is not “Where is the object now”, but “Where will the object be in 24 hours when we expect this collision might occur?”

Propagating an object’s position forward in time with any kind of accuracy requires an accurate assessment of the objects current orbital state. As the object is propagated forward in time, two general effects of any error in this orbital state can be observed. The first is a periodic effect that might be caused by an inaccurate measure of an orbit’s inclination, eccentricity, or argument of perigee. With every orbit the object’s predicted path departs from the object’s actual path in a cyclical fashion whose frequency is directly related to the objects period. For example in Fig. 9 (left), one might predict the object will follow the path of the green line, but due to an error in inclination, the object is instead following the blue line.



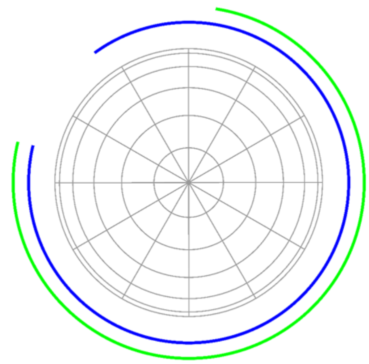


Fig. 9. Periodic Effect (left) and Drift Error (right). Enlarged for visualization

The second type of observed error is a drifting error wherein the error appears to build over time. This type of error might be caused by an inaccurate assessment of the object’s period or drag. In this error the predicted position of the object closely matches that of the actual position when the object is observed, but due to an inaccurate measure of period or drag, the objects begin to slowly move away from one another as seen in Fig. 9 (right). It should be noted that this error is also periodic, as eventually the lead (predicted or actual) object will begin to ‘lap’ the lagging object and the two will approach each other once again. However, since the examination of orbital states is usually conducted over hours or days instead of months or years, this error will present itself as a gradual departure of the predicted position from the actual position.

To examine how Space Fence will contribute to the improvement of orbit accuracy, 33 satellites of interest to NASA were used in a five day scenario to see what improvements might be discovered. The objects varied in inclination from approximately 20 to 99 degrees, with the majority having a nearly polar orbit. The altitudes of the objects varied from about 370 to 1350 kilometers.

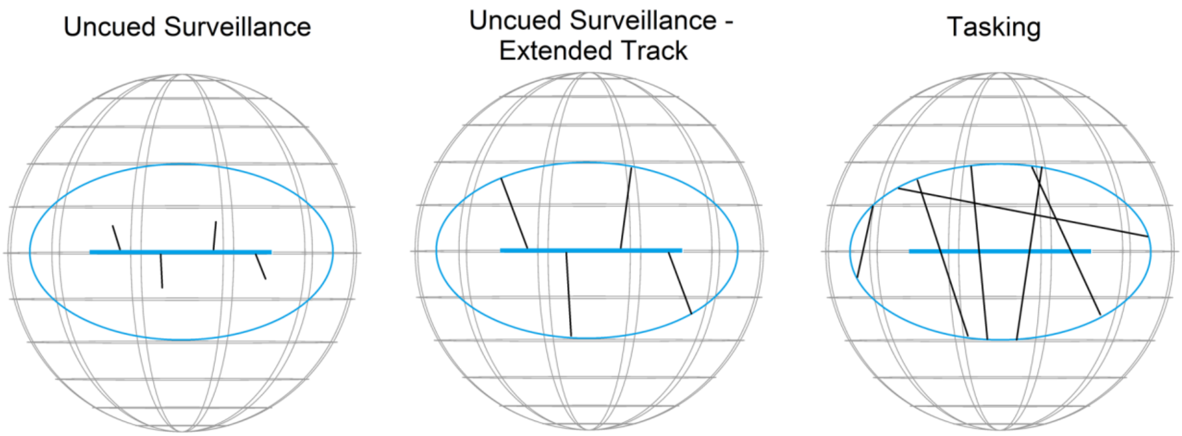


Fig. 10. Tracks (black) within a notional field of regard (blue oval) for differing modes with the un-cued surveillance fence (blue line) running

The scenario was run three times, with Space Fence set up to track the objects in three different configurations as shown in Fig. 10. The first configuration was basic un-cued surveillance, where only objects that pass through the fence are tracked, and are only tracked long enough to collect about three observations. The second configuration was un-cued surveillance with extended tracking, where only objects that pass through the fence are tracked, but are then tracked further to collect as many observations as possible from the time of passing through the fence until eventually leaving the field of regard. The third configuration was tasking, in which up to 18 observations were attempted to be collected on every pass regardless of whether the object crossed the fence or not. The Space Fence radar allocates the majority of its resources using the un-cued surveillance fence and its resultant tracks. The resource usage for the two modes which feature the use of the surveillance fence to track the target as an RSO or provide extended tracking capability is captured under this allocation. The remaining portion of the radar resources is allocated for searching and tracking the tasked targets, which is further discussed later in the paper.

The 33 objects were represented by TLE's. These TLE's were propagated forward in time for five days using an SGP4 propagator built on a MATLAB platform to create a truth data set. The truth data set consisted of a satellite number, an RUV position/velocity vector (from the perspective of the Space Fence Kwajalein radar site), and the satellite's radar cross section (RCS) value.

The propagated TLE data was then fed through radar models to add a representative measurement error to produce simulated radar measurements that approximate actual operating conditions. Two sets of radar measurement data were created, one set for simulated surveillance measurements, and the second set for simulated tasking measurements. These radar data sets were then utilized by the Space Fence Tracker to generate observations for each pass during the five day scenario. Differential correction was performed by Space Fence during this process to generate refined orbital data that represented the actual Space Fence System. This is also the data that would be utilized by conjunction assessment analysts investigating the potential collision event.

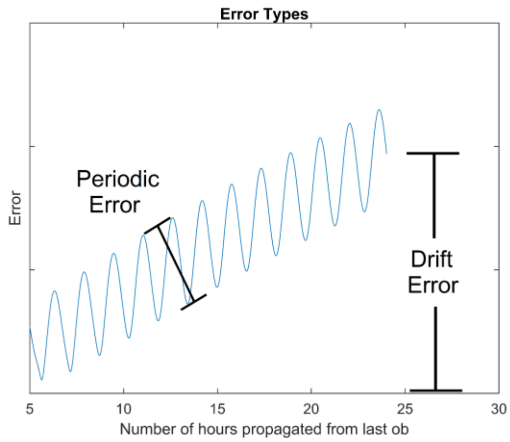


Fig. 11. Example error growth over time

After the five day scenarios were complete, the final TLE for each object that was generated by Space Fence was collected. These TLEs were then propagated forward in time from their respective epochs in one minute increments for 24 hours. The TLEs were propagated into an Earth Centered Inertial (ECI) coordinate frame, and their position was then compared to that of the original NASA TLE. The measurement error was calculated as the distance between the ECI position of the propagated Space Fence TLE, and the original NASA TLE. The error was then examined separately as a periodic error and a drift error as shown in Fig. 11.

For this initial assessment, only one Monte Carlo run was completed in each tracking configuration due to time constraints, but the analysis results set the basis for expected performance trends and future analyses. Out of the 33 satellites examined, 32 satellites naturally crossed the un-cued surveillance fence and thus were used as the basis of the time in track study. Out of the 32 satellites crossing un-cued surveillance, 28 satellites had very consistent tracking trends in each of the system configurations so this subset was used as the basis of the initial drift and periodic average error assessments.

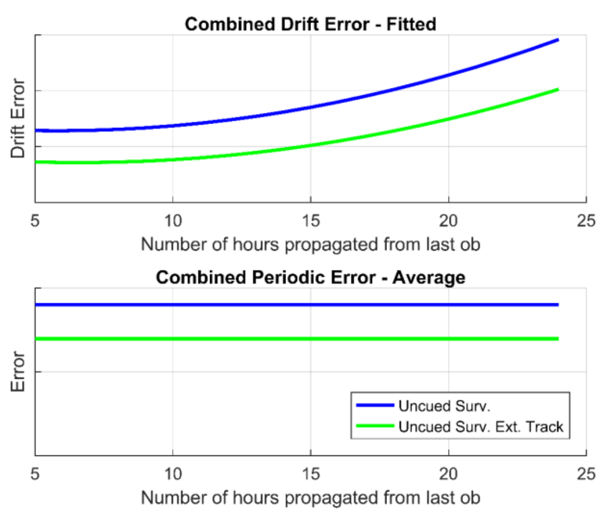


Fig. 12. Drift error (top) and periodic error (bottom)

One can see in Fig. 12 that a visible improvement could be obtained in the drift and periodic errors when additional observations were collected via extending the track. It should be noted that the drift error chart contains effects of the periodic error within it, however the fitted chart is intended to help remove those effects. The track data from the analysis is summarized in Table 1, which quantifies the increased track duration achieved via extended tracking. Additionally, the total number of passes and track duration are included for the tasked scenario, which shows significantly more passes and track time than for un-cued surveillance.

	Un-Cued Surveillance	*Un-Cued Surveillance, Extended Track*	*Tasked*
Total # of Passes	260	260	438
Total Time Tracked (min)	167	691	1116

Table 1. Summary of differing modes' results

Tasks are typically requested for geometries that do not cross or would not be detected by the un-cued surveillance fence or to provide longer tracks than the un-cued surveillance fence is capable of providing (as the fence is centered in the field of regard). The Space Fence radar has a subset of the total radar's resources dedicated to performing these tasks without interrupting the surveillance mission. Fig. 13 shows the increased radar resource usage from the tasking case over the 5 day analysis. As an object is tracked across the sky, the effects of its range loss and scan angle loss will increase and the accuracy of the measurement decreases. To combat that, the radar will dedicate more transmit resource on the object to both account for the increase losses as well as providing a stronger signal-to-noise ratio (SNR) on the object to maintain the accuracy of the object. Fig. 13 shows this effect as the tail end of the track requires more radar resources than the earlier part of the track. Despite increased demands on the radar as a result of the tasks, resource usage is not significant as the radar was sized to perform routine surveillance using highly spoiled beams, whereas tasking utilizes unspoiled/low spoiled beams to service its needs. If simultaneous tasking requires more than the allocation, the Space Fence radar will dynamically allocate more resources to the higher priority activity, as required.

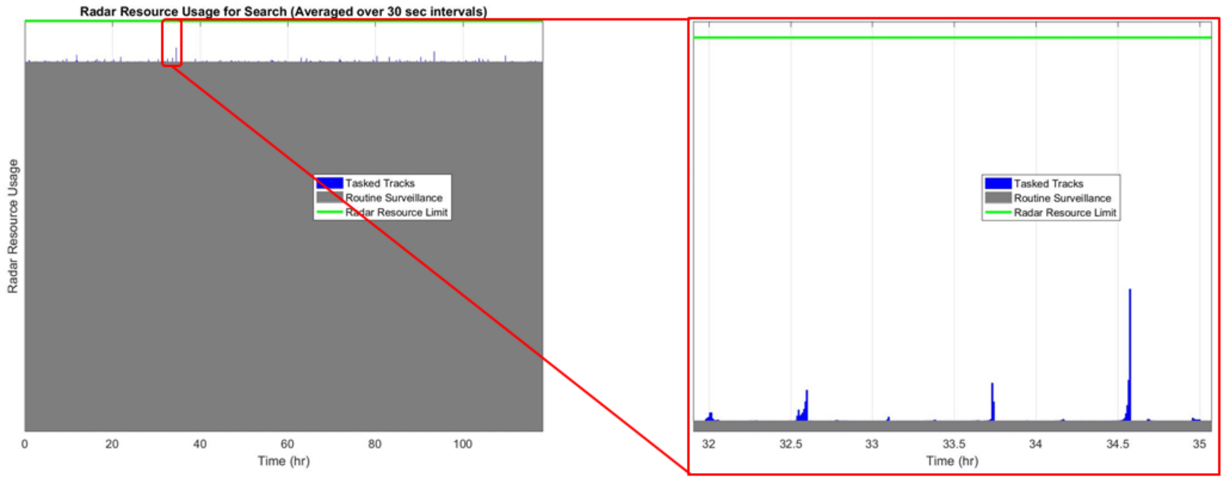


Fig. 13. Additional radar resource usage by tasks

A summary of all passes from un-cued surveillance and tasking is shown in Fig 14. For un-cued surveillance, assured coverage above 800 km altitude provides consistent number of passes over all LEO object whereas pass opportunities at lower altitude are limited by geometry constraints. However, with the addition of tasking, there are more opportunities at nearly all altitudes and many times more opportunities for low inclination objects (for example, the few objects with 20+ passes over the 5 day scenario all had inclinations 20-40 degrees).

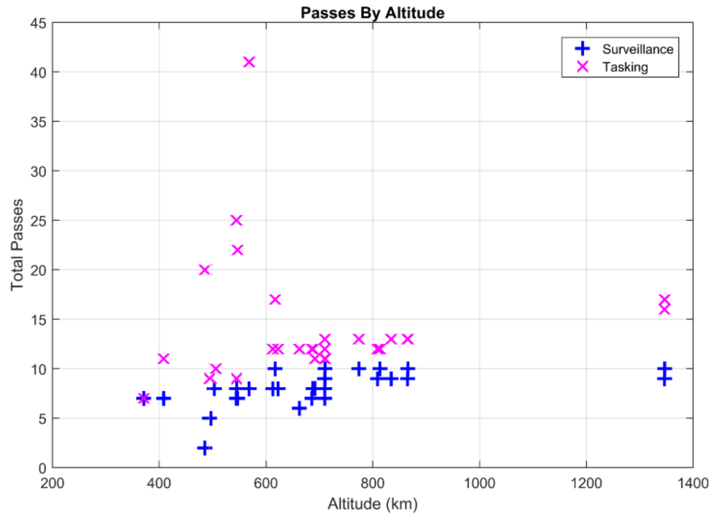


Fig. 14. Total number of passes by orbital altitude over the 5 day scenario

This focused analysis indicates that for conjunction assessment situations, Space Fence could be utilized to improve orbit accuracy by obtaining a larger number of observations than what normally be captured by the fence thus leading to a more accurate orbit determinations. While based on a small set of data run, there were dominant trends that appeared. This study suggests that the manner in which to obtain these observations differs. For low altitude objects with polar orbits, the preferable option would be to utilize surveillance with extended tracking. For high altitude objects with polar orbits, tasking might be utilized to some advantage to supplement the fence and task those satellites that might miss the fence but still travel through the field of regard, and or those satellites that are traveling over the fence. Finally, tasking is suited well for low inclination objects that travel parallel to the fence, and in fact are able to collect many more passes and observations of these objects than the fence normally collects for polar objects.

As can be seen from this study, Space Fence provides the ability to continuously monitor the space domain. Considering that Space Fence will only be one component of the entire space surveillance network, the combined observation capability of these systems working together will surely improve the accuracy of orbit determination even further.

7. CONCLUSION

When the Space Fence System begins operations and increases the number of objects tracked, the management schema for conjunction assessment must evolve. Higher precision tracks could be requested by the SFS and other sensors, which would decrease uncertainty in measurements reported to JSpOC. More sensors could be tasked to track objects of interest, which would increase the amount of observations used for orbit determination. Higher fidelity atmospheric models could be combined with improved drag estimates for satellites and orbital debris to improve the accuracy of multi-day orbital propagation [9]. With the Space Fence System providing updates on essentially the complete LEO catalog for all objects the size of, or larger than, a softball, there will be a wealth of data from which to evaluate different models of atmospheric drag. Additionally, there is a potential for developing more accurate estimates of objects' drag coefficients. SFS will be tracking the bulk of the LEO objects in the catalog, which frees other radars in the SSN to be tasked to collect higher resolution data or to expend more resources on searching for and tracking deep space objects.

The radar will open entirely new avenues for SSA. Space Fence will expand the tasking ability of the SSN and open the possibility for tasking beyond the critical needs of asset operators. Organizations will see a large increase in their collision avoidance workload, which will demand a combination of optimization and resource increase, but this radar will provide a wealth of data for probability of collision refinement. Instead of analyzing solely operational satellites colliding with debris, the radar will be able to look closer at debris on debris conjunctions. Advance, accurate, and reliable warning of these events will become critical for future space operations.

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