Utilizing Cubesatellites for Characterization of the AN/FSY-3 Space Fence System and Other Sensors

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ABSTRACT

In 2018, a ground-based S-band radar system named Space Fence will undergo operational testing. This radar is designed to discover and frequently track tens of thousands of satellites and debris objects in orbit around Earth. It is challenging to calibrate and test a system meant for discovering small objects, because the only calibration objects in orbit are large. To alleviate this, the Air Force Operational Testing and Evaluation Center is working with the US Air Force Academy and the Space Fence System Program Office to develop a cubesatellite to characterize the radar's ability to expand the space object catalog's fidelity. The cubesatellite will eject two small calibration spheres in low Earth orbit to be tracked by the Space Fence System and other sensors. The radar cross sections of the spheres are precisely measured to support calibration of sensors that will track them in orbit. This paper discusses the cubesatellite's design and on-orbit mission.

The cubesatellite will also benefit optical sensors. The larger sphere will have an optically-measured iridite coating, and the cubesatellite bus will contain LEDs in frequencies that support testing of selected optical sensors. This cubesatellite's design can be further adapted for use with other new sensor acquisitions and their individual capabilities. Different sized objects could be released at various speeds in any point in the cubesatellite's orbit to cater to the test requirements. This cubesatellite platform has the ability to provide real-world on-orbit characterization of billion-dollar assets built to protect the USA and its allies, as well as to expand space situational awareness.

1. INTRODUCTION – SPACE DEBRIS PROBLEM

This year marks the sixtieth anniversary of humanity sending objects in orbit, starting with the launch of Sputnik on October 4th 1957. In this time, over 42,000 space objects consisting of functioning satellites, nonfunctional satellites, rocket bodies, fairings, and debris have been cataloged by the Space Surveillance Network (SSN). It was generally regarded that space was far too vast to worry much about collisions until 2009 when the Iridium/Cosmos collision occurred [1]. This conjunction produced 3273 pieces of debris larger than 10 cm and estimates say that over 200,000 pieces of un-trackable debris as small as 1 cm were also produced. Coupling this fact with the 2087 pieces of trackable debris and over 35,000 un-trackable objects created by the 2007 Chinese anti-satellite test, it is no surprise that the world woke up on May 12th 2016 to a picture of a chipped window on the International Space Station caused by a piece of space debris. This window was one of the main viewing ports used to take pictures of Earth from the cabin, highlighting the fact that space debris and conjunctions are a significant concern.

While very low Earth orbiting objects are deorbited and disintegrated by the atmosphere, the space debris problem is continually growing as old rocket bodies explode, debris collisions occur, and payload launches shed components. Many of these debris-forming events occur at higher orbits where orbital lifetimes are significantly longer. Additionally, there has been an increasing trend of launching non-maneuverable cubesatellites; where in February of 2017, India launched a record-shattering 104 cubesatellites in a single launch [2]. Companies have been seeking FCC approval to create Low Earth Orbit (LEO) mega constellations on the magnitude of thousands of satellites. Currently, there are less than 2000 functioning satellites in orbit and with these trends, the space community could see these numbers more than double in the very near future. This means that the need for discovery and frequent tracking of small debris is becoming more apparent than ever.

2. SPACE FENCE SYSTEM

To address the need to find and track small objects, the United States Air Force started the acquisition of a $1B S-band phased-array radar system called Space Fence, built by Lockheed Martin. It is designed to increase the fidelity of the SSN and to provide more frequent tracks on resident space objects already in the space object catalog. Space Fence has two main tracking modes: un-cued surveillance and tasked tracking. To achieve its mission of 24/7 un-cued surveillance, the array maintains an East-West fence of energy to detect objects that pass through it, which initiates tracks on those space objects. The face of the phased-array is oriented radially from the surface of the Earth which enables the system to have a wide field of regard (FOR) for tasked tracking. Located near the equator on Kwajalein Atoll in the Marshall Islands, the radar sits in an opportune location to both discover and maintain daily custody over resident space objects (RSOs) across a wide range of inclinations. An analysis in 2016, based on the 2030 NASA Orbital Debris Program Office's space debris catalog, showed that Space Fence will discover and maintain tracks on roughly 50,000 new objects within the first five days after Initial Operational Capability (IOC) is declared [3]. Fig 1 below shows the stark difference that was estimated by this study between the current and projected RSO catalog once Space Fence comes online in early 2019. This radar will greatly increase our knowledge of the actual space object environment, leading to more efficient conjunction analysis and safer space flight.

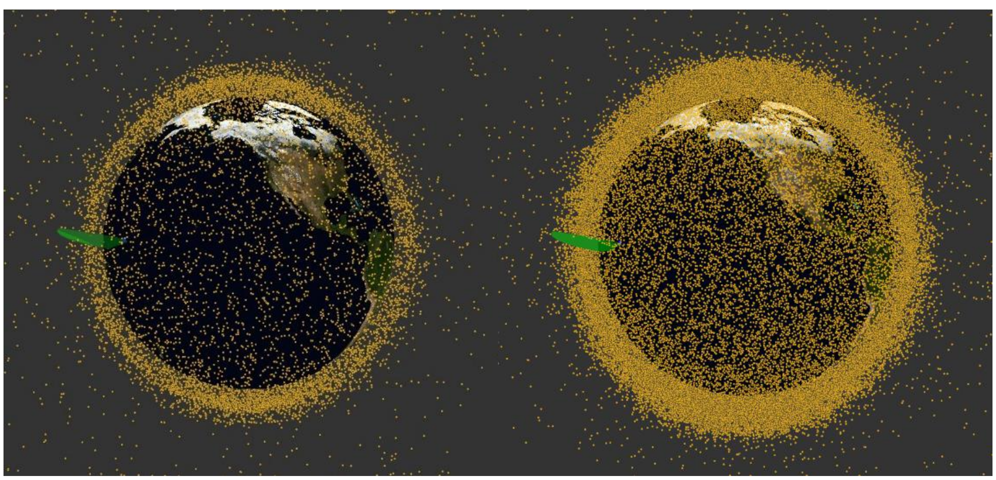


Fig. 1. Current RSOs frequently tracked in LEO (left); predicted RSOs tracked within 5 days of SF IOC (right)

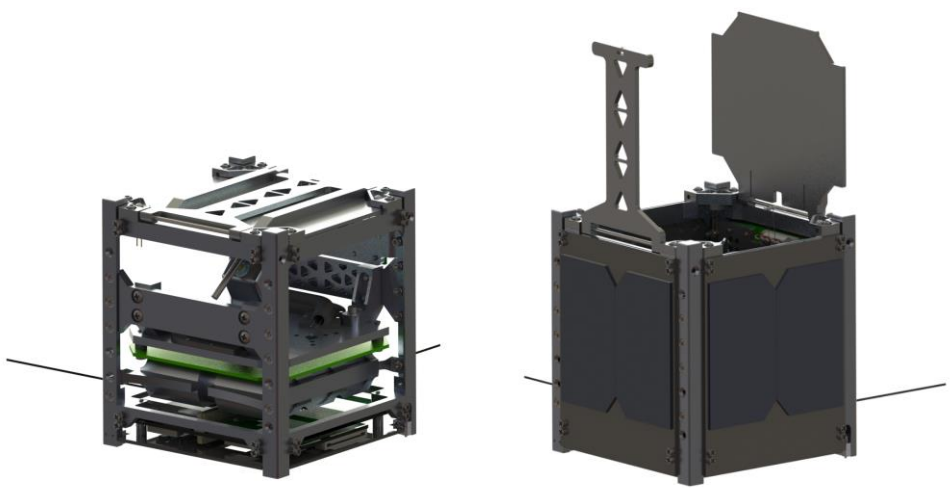
3. OPERATIONAL TESTING PROJECT

An ongoing effort in the space community to reduce the size, mass, and power requirements of modern spacecraft has led to an increased interest in small satellite programs by government agencies, private industry, and academic institutions. The trend toward developing smaller spacecraft has been made feasible by continued advances in micromachining and the development of microelectromechanical systems. The term cubesat refers to a cube shaped satellite with internal dimensions of 10×10×10 cm and having a mass typically no greater than 1.33 kg [4]. The cubesat class of spacecraft has been predominantly a university driven program, where small research groups have developed innovative methods of utilizing commercial off –the-shelf (COTS) components to build satellites capable of performing relevant scientific missions.

University based cubesat missions were traditionally limited to 1U (10×10×10 cm) size systems, but have recently began to trend towards 3U (10×10×30 cm) size systems, due to the increased capabilities and enhanced performance of the larger class. The improvements are mainly attributed to the decrease in volume and mass constraints, allowing for the 3U class of cubesats to have large and more robust components in terms of power, communications, and pointing capacity. The benefits of using 3U size cubesats allows for more sophisticated payloads, which is evident in the increase in technology and science missions over the last several years [5].

With the ever-growing problem of space debris and the need to understand what Space Fence is able to detect and track, Bruce Bishop, the Test Director for Space Fence in Detachment 4 of the Air Force Operational Test and Evaluation Center, created the Space Fence Evaluation of Radar EffectivenessS (SFERES) project. The project's mission is to release small radar cross section (RCS) calibrated stainless steel spheres in orbit to be tracked by the radar in support of operational testing in the second half of 2018. Currently, the main calibration spheres in orbit are Lincoln Calibration Sphere-1 (LCS) and LCS-4 which are meter-sized metal spheres with perigees and apogees of 2704/2869 km and 795/913 km respectively. The project will be able to provide the warfighter an on-orbit test of the system with cubesatellite-sized spheres in a nearly circular low orbit of ~400 km.

The SFERES cubesat is a 1U satellite consisting of predominantly COTS components to allow for rapid bus development and risk mitigation. The avionics, radio, battery pack, and solar panels were obtained from the California Polytechnic State University cubesat group, PolySat, based on the group's previous flight heritage and expertise in the field of nanosatellite technologies. The use of COTS components allows for the rapid design, manufacture, testing, and deployment of highly customizable payloads such as the calibration spheres that will be used to test the Space Fence. One of the constant challenges in cubesat design is the volume, mass, and power limitations; however these issues can be mitigated through the implementation of additional cube units, where cubesat designs can include two, three, or six 10-centimeter units. In the case of SFERES, there was a desire to test the radar acquisition of a 1U cubesat in addition to the payload consisting of two calibration spheres. The design is shown below in Fig. 2 (a) and (b).



(a) (b)

Fig. 2. CAD drawings of the 1U SFERES cubesatellite bus in a) stowed and b) deployed configurations

The satellite structure, avionics, battery pack, and attitude, dynamics, and control system (ADCS) can be seen in Fig. 2 (a) with the payload door in the stowed position. The solar panels and satellite in the deployed configuration can be seen in Fig. 2 (b). To further minimize the risk involved in deploying the calibration spheres, a well-tested and characterized door mechanism was utilized from a previous cubesat mission, Falconsat-7 [6]. This cubesat payload door has been successfully tested in micro-g, thermal vacuum, and vibrational loading environments.

4. ON-ORBIT CONCEPT OF OPERATIONS

The main task to accomplish the project's mission is to know where the cubesatellite is and where the released spheres are. To do this, the cubesatellite will release the spheres individually, days to weeks apart, within coverage of Massachusetts Institute of Technology's (MIT's) Haystack Radar (HAX). This radar operates in the X-band frequency range which will have a high enough resolution to watch the sphere separate from the cubesatellite. HAX will create a high-precision element set which will then be sent to Space Fence for tasked tracking. Below, Fig. 3 shows the ideal orbital path that the cubesatellite/sphere pair will follow starting with release on the left. The cubesat and sphere will then pass over Space Fence in the Pacific.

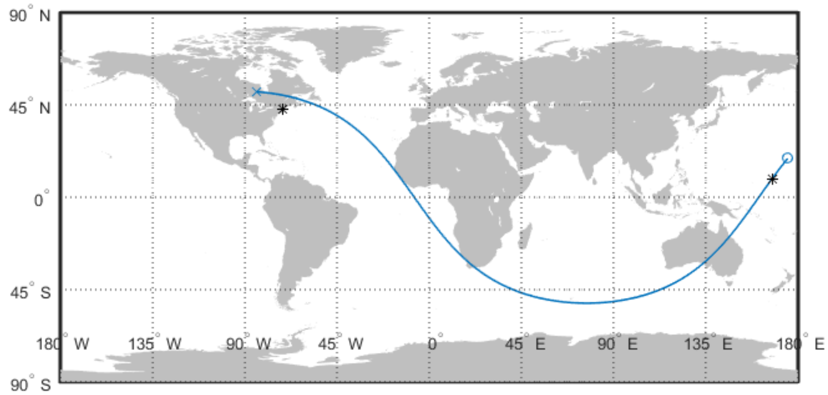


Fig. 3. Ground track of the pair's orbital path

There will be roughly a 70 minute delay between when the sphere is released and when the pair first passes over boresight of Space Fence. This gives the pairs adequate time to separate to be resolved by Space Fence as two separate objects. The ejection speed of the sphere provides a balance for detectability by both radar systems. HAX has a focused field of view (FOV), therefore the object pair must stay close to each other within the field of view to be simultaneously tracked by the mechanical radar. Space Fence creates wider beams where the two objects must be in separate beams to be detected. Therefore, the two objects must be adequately separated to be tracked by the radar; if they are too close to each other the return from one object will mask the other and the radar will only detect one object. It is planned that Space Fence will resolve the two objects separately in range. The range separation profile is affected by ejection speed, sphere/cubesatellite masses, ejection timing, and ejection direction. With the ejection speed and masses determined early in the program, CONOPS analysis was focused on optimizing ejection timing and characterizing the effects of ejection direction which are discussed later in this paper.

There are ten unique steps planned for the cubesatellite to complete its mission in orbit to characterize Space Fence before it initiates its optical tests on step twelve. These steps ensure ample time is available between each step for the satellite operators to verify the mission is proceeding correctly.

1. Deploy via NanoRacks cubesatellite deployer on the International Space Station (ISS)
2. Initiate system start-up and acquire element set of the cubesatellite from current SSN assets
3. Deploy antennas
4. Establish communications with ultra-high frequency (UHF) ground station at USAFA
5. Allow the cubesatellite to orbit through Space Fence's FOR over a period of time
6. Open payload compartment
7. Verify the door is open on a pass through Haystack's FOR
8. Command release of a sphere within Haystack's FOR at optimal time
9. Acquire element sets of sphere and cubesatellite
10. Task objects for tracking by Space Fence
11. Repeat steps 8-10 for second sphere
12. Turn on LEDs for optical sensors

Once the cubesatellite is deployed from the ISS and known to be functional, it will maintain its closed configuration and will orbit unchanged until the tests are ready to be scheduled, staffed, and executed. During this time, the cubesatellite will be passing through Space Fence's un-cued surveillance fence which will demonstrate the radar's ability to track cubesatellites. Once the payload compartment is opened with the spheres retained, the RCS of the cubesatellite will increase because the apparent area of conductive material will increase with the retaining bar extended on one side and the door on the opposite side. Tracking by HAX will be able to show that the profile increased and tracking by Space Fence should show an increase in the RCS, given that the orientation of the cubesatellite with respect to the ground sites does not mask the door's returns.

Once the payload compartment is confirmed to be open, the satellite operators will analyze when the cubesatellite will be in the optimal location and orbit revolution to release the larger sphere. This will happen rapidly due to the concerns of additional drag from the higher incident area to the atmosphere. The longer the spheres stay inside the cubesatellite and are dragged down along with it, the shorter the orbital lifetimes will be of these LEO calibration spheres. The satellite operators will utilize the mission planning software described later in this paper to coordinate the sensor sites' and the ground control's manning for the release. This release will be timed so it occurs just as the cubesatellite is entering HAX's field of regard, so that it can watch the entire separation to both confirm success and to acquire element sets to send to Space Fence for cued tracking. The sphere/cubesatellite pair will separate as they continue their revolution around earth and will pass heading northwards to pass over boresight of the radar, thus providing the longest time in view with the best resolution possible. The objects will continue to be tracked by Space Fence on subsequent passes as they separate over time and their orbital paths diverge further. The larger sphere release planning and tracking will not only be a characterization of the radar, it will serve as a dry-run for the release of the smaller sphere which will require more power from the radar to detect it. The second sphere will be released and tracked in the same manner as the first. After the payloads have all been released and tracked, the cubesatellite will begin its additional mission of supporting optical sites. It will illuminate its LEDs tuned to varying frequencies for optical sites.

One primary risk that was mitigated centers around the frequent issues cubesatellites have with deploying their antennas. The cubesatellite may be functioning entirely correctly otherwise, however it may not be able to send telemetry nor receive commands. To mitigate this risk, a fail-safe measure will be loaded onto the cubesatellite before launch that will command the cubesatellite to open its door and release the spheres individually after a certain amount of time. This fail-safe will ensure that if the cubesatellite is functional, but has no connection to the ground station at the US Air Force Academy, then it will still deploy the spheres in orbit and the SSN can try to find the spheres. This measure will be overwritten if the cubesatellite successfully communicates with the ground station.

5. RELEASE ANALYSIS

To ensure that the release of the payload would provide adequate separation when viewed by Space Fence, the release was analyzed at the system level. The cubesatellite was required by Bruce Bishop to fit within a 1U form-factor, levied within the requirements document provided to the SPARC lab. This volumetric constraint led to the attitude and determination control system (ADCS) to be maintained by a magnetorquer. While the component is designed to provide reasonable pointing accuracy, there will be some uncertainty in the exact orientation of the cubesatellite when the spheres are released.

The optimal release would have the sphere ejected directly opposite the instantaneous velocity vector, providing the greatest separation when passing overhead of Space Fence. However, the pointing inaccuracy is estimated to be up to 30° off nominal in pitch and yaw. This represents a part of a hemisphere of possible release directions, up to and including 30° off-center. Of all the infinite possible release directions within that inaccuracy, four principle directions were assessed: above the orbital plane (alternatively, North due to the prograde orbit), below the orbital plane, towards Earth, and away from Earth. These release directions would have the greatest effect on the orbital path of the objects; a combination of these principle directions for example, somewhat above the orbital plane and somewhat away from Earth would show a lesser impact than one of those principle directions. Fig. 4 below visualizes these principle release directions. The center of mass of the system is represented by the yellow line showing the mean orbital path. For each sphere release direction, the cubesatellite recoils in the opposite direction similar to a satellite conducting an impulse burn.

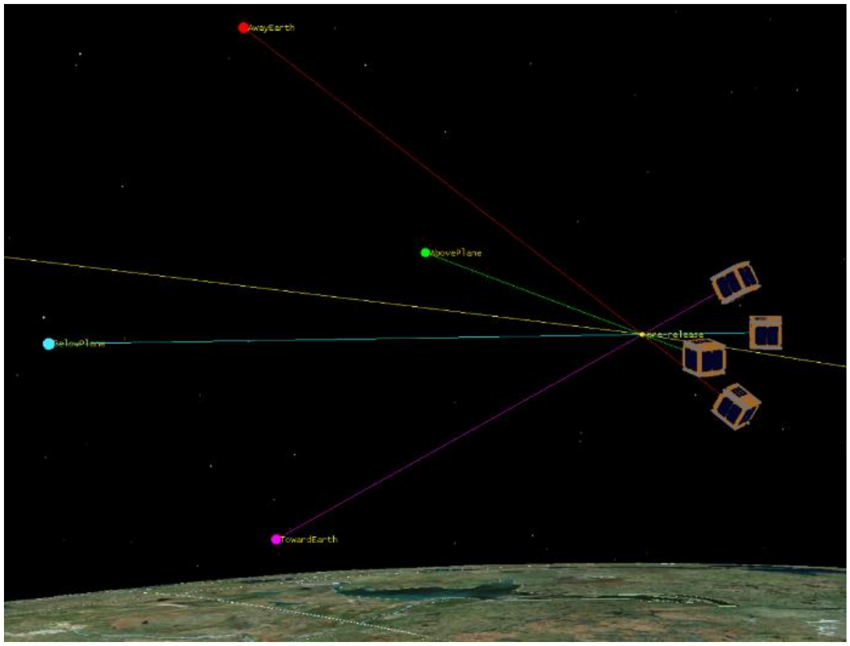


Fig. 4. Principle release directions, photo courtesy of STK by AGI

The first step to analyzing the release pattern was to understand the separation speed profile after release. Fig. 5 below shows the dynamically changing separation speed of an example two objects. For roughly the first ten minutes, the separation speed is essentially equal to the ejection velocity. About halfway through the ~90 minute orbit, the object separation speed starts to decrease as the objects pass apogee or perigee and the orbits start to converge again. As time goes on, the separation distance between the two objects grows as the phase shifts and one object approaches perigee and the other approaches apogee.

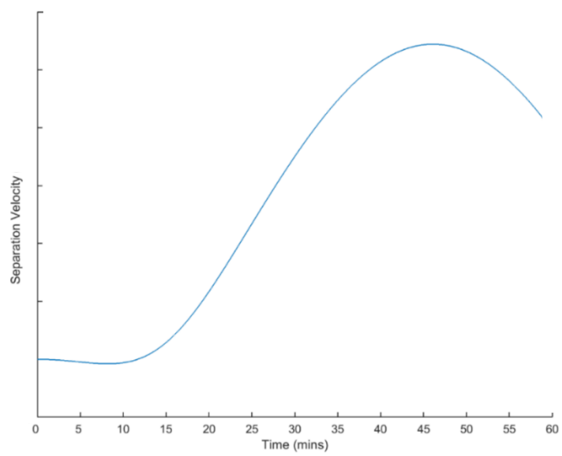


Fig. 5. Separation velocity profile

The calibration spheres are placed within the payload area of the cubesat and are held within a cylindrical deployment tube using a pull-pin designed using nitinol, which upon application of electrical current will retract allowing a compressed spring to eject the calibration sphere. The spring constant has been selected to produce a low separation velocity reliably. The sphere deployment was modeled along the velocity and anti-velocity vector using the System Tool Kit (STK) software. A schematic of an anti-velocity vector deployment is shown below in Fig. 6. In this case, the momentum transfer between the cubesat and deployed calibration sphere will cause the spacecraft velocity to increase thereby slightly raising the orbit of the cubesat.

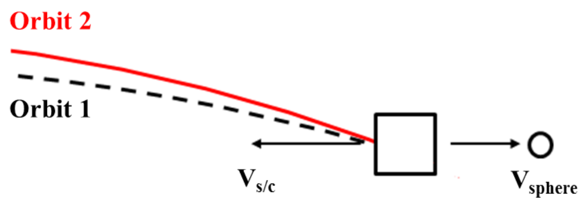


Fig. 6. Schematic of the anti-velocity vector deployment

To bound the maximum and minimum separation distances as a function of time, the ejection scenarios were initially modelled only in the velocity and anti-velocity vectors. To increase the fidelity of the simulations the effects due to spacecraft drag were implemented using the MSISE-00 neutral density model. The results for separation distance as a function of time and incorporating atmospheric drag are shown below in Fig. 7Fig. . The deployment scenarios that neglect the effects of aerodynamic drag return equal separation distances as a function of time; however, when drag is applied to the cubesat and calibration sphere the separation distance is observed to vary significantly based on the deployment angle. When deployed along the spacecraft velocity vector there is a significant reduction in the magnitude of the separation distance after a period of time due to the difference in drag between the cubesat and sphere, which can potentially lead to secondary tests of the Space Fence radar system.

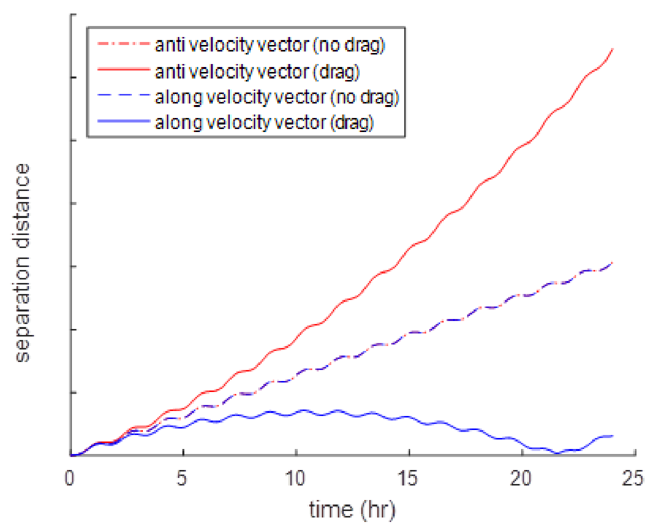


Fig. 7. The effects of drag on separation distance as a function of time

The separation distance as a function of ejection velocity was additionally modelled using STK. An example profile is shown below in Fig. 8. The difference in separation distance as a function of ejection velocity is fairly intuitive, i.e. faster ejection velocities will result in larger separation distances as a function of time. This showed that the absolute separation distance between the objects was non-linear over time, but showed an apparent linear growth when the release speed increased at the hour mark.

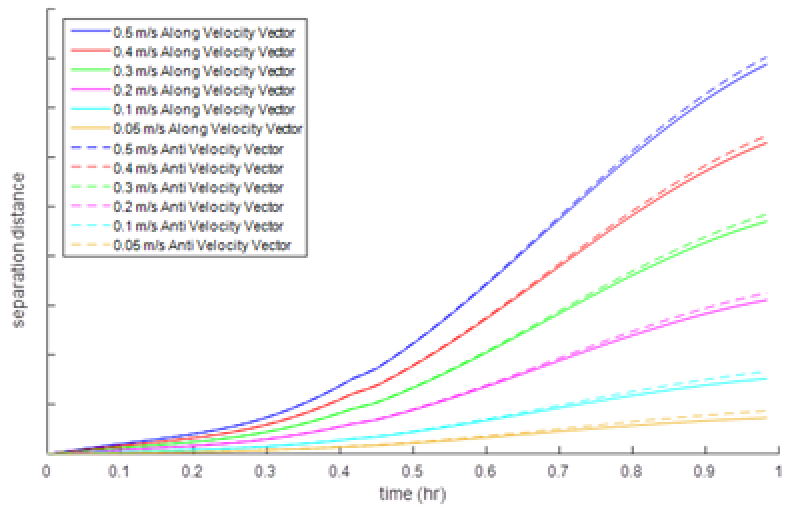


Fig. 8. Separation distance as a function of time, angle, and separation velocity

After understanding the change in absolute distance between the two objects, a study began to investigate the effects of the release direction on the range difference when viewed by Space Fence. An instantaneous velocity change was added to a state vector defining the moment after release of the two objects as they enter HAX's FOR. The velocity change was added along the principle directions to create a set of state vectors that defined each principle direction release. These state vectors were propagated forward in time as they passed overhead of Space Fence's location. The range difference between each principle release direction's object pair was calculated and plotted over time. This was repeated for a range of pointing uncertainties and compared. Fig. 9 below shows an example of the range separation over time when calculated from Space Fence's location. The larger the separation, the more likely the objects would be resolved separately. As the angle increases, the separation decreases because less of the deltaV is imparted along the velocity vector which is equivalent to Hohmann orbit transfer burns, the ideal way to adjust apogees and perigees. Due to the orbital dynamics and time in the revolution that the release occurs, a release towards Earth affects the initial range separation the most then a release away from Earth affects the interim range separation the most. By taking the average of these principle directions, it is readily apparent that the greater the release angle is off nominal, the smaller the range difference will be overhead Space Fence in the first revolution post-release. Thus, a large amount of work went into optimizing the performance of the ADCS and extracting as much performance from it as possible to release as close to the ideal direction as possible.

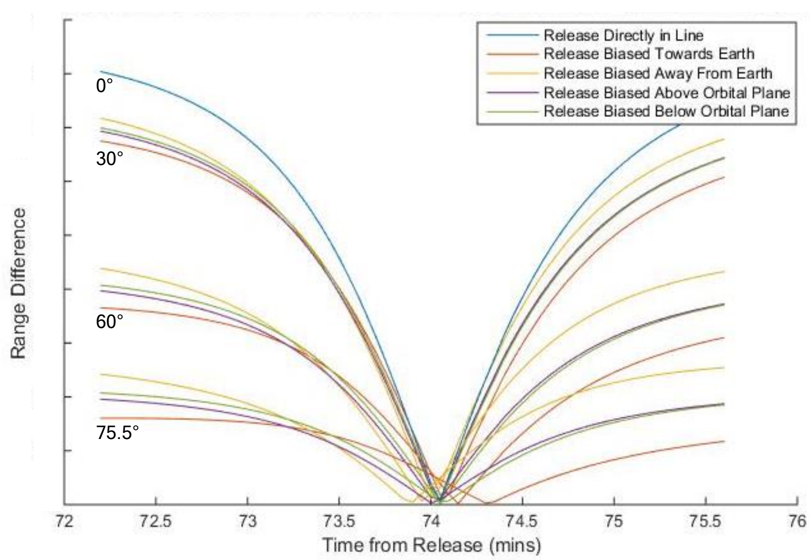


Fig. 9. Range difference between cubesatellite and a sphere when viewed by Space Fence

6. MISSION PLANNING SOFTWARE

Once the cubesatellite is in orbit and the test team has decided to release the spheres soon, they will utilize a mission planning software (MPS). The MATLAB program accepts information about the release and finds the best opportunities in the future to release the sphere. It optimizes the release by selecting the revolutions that bring the cubesatellite closest overhead of the viewing sites and with the least time between viewings by the given sites. This will inform the test team when the observing radar sites need to be manned and it will define the release time that must be uploaded to the cubesatellite the next time the ground station has contact with SFERES.

The analysis needed to find the optimal release time is nontrivial when done by hand. The cubesatellite will be in a ~90 minute orbit so it will have ~16 revolutions per day which equates to 112 revolutions per week. Finding the optimal revolution from the 112 is time consuming and this software reduces this workload to seconds. Below Fig. 10 shows a scenario being built for analysis. The orbital path is calculated by selecting a NORAD two-line element set (TLE). Due to the inherent inaccuracies of the TLE and the perturbing atmospheric affects in LEO, only the most recent TLE will be used to minimize error. The MPS visualizes the orbit in the ground track, showing the current position of the satellite and its orbital path for the next revolution and it also shows the ground viewing sites. The graphic user interface tracks and lists the viewing sites with a summary of its attributes. The user defines the sequence that the satellite should enter each FOR and the priority for a long pass through the FOR. For SFERES, it is top priority that the cubesatellite will fly overhead of Space Fence and it need only spend some time in HAX's FOR to watch the release and acquire the initial orbital element set. The software defines a hemispherical FOR of each site to use for its automated separation analysis which accepts inputs from the bottom right section. It will look a given number of days in the future to find the optimal release time. The test planners will look at most seven days into the future to upload the release time, to minimize uncertainties from TLE age and SGP4 propagation.

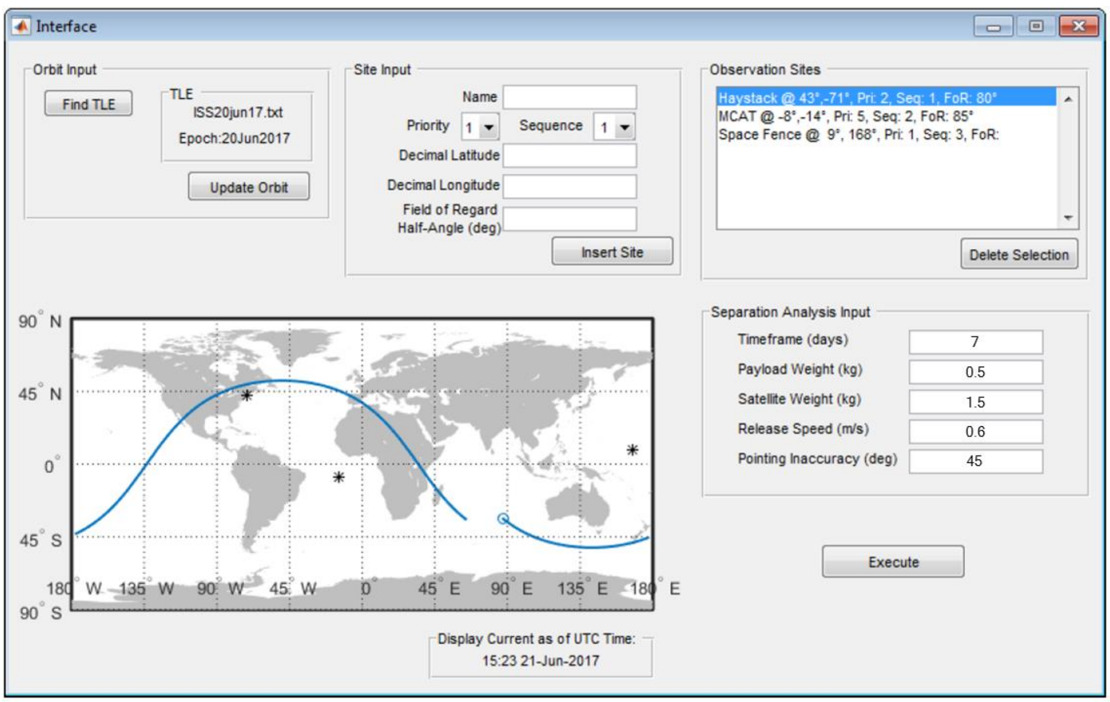


Fig. 10. Graphic user interface of the mission planning software

The MPS informs the user of the top release times over the given analysis period. The optimal path is displayed in a 3D visual of Earth, with the sites' FORs, and as a ground track of the satellite entering the first site's FOR, continuing its orbit, then exiting the last site's FOR. Additionally, it outputs the azimuth, elevation, and range difference of the satellites while in each site's FOR. The differences are shown for the release along the nominal and the four principle direction defined by the pointing inaccuracy angle, as shown in Fig. 4.

7. OPTICAL TARGETS

The larger sphere that SFERES will deploy has been coated with electrodeposited Zinc plating with yellow chromate for NASA's Meter Class Autonomous Telescope (MCAT). While this extremely thin coating will have no appreciable impact on the object's RCS, the object was calibrated after the coating was applied. This coating was specifically chosen by NASA to adjust the spectral return when compared to the sphere's polished stainless steel make-up and was characterized through optical calibration tests conducted with NASA.

After the SFERES primary sphere release objective is complete, the optical measurements of the mission will commence. These include optical tracking of the calibration spheres by MCAT located on Ascension Island along with the numerous Falcon Telescope Network (FTN) nodes shown below in Fig. 11.

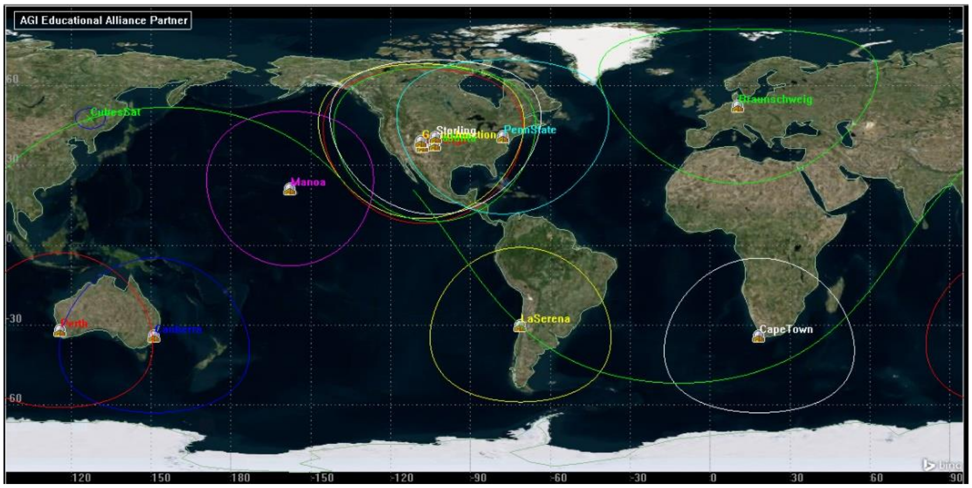


Fig. 11. FTN ground station locations

Several LEDs have been selected for the mission based on the Sloan Digital Sky Survey (SDSS) optical filters used by the Falcon Telescope Network whose visual magnitude is characterized in the Fig. 12 below. These LEDs are placed around the cubesatellite and will be used for detection characterization for the ground sites. Because the selection of LEDs have distinctly different wavelengths and locations on the cubesatellite, they will allow for the possible determination of satellite attitude as the cubesat passes out of direct sunlight.

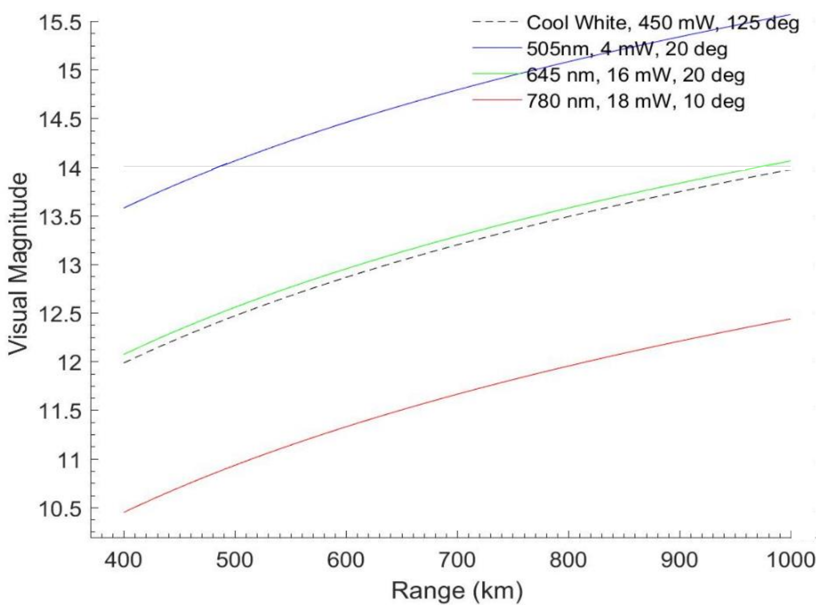


Fig. 12. LED visual magnitude as a function of range

8. ADAPTATION FOR FOLLOW-ON CUBESATELLITES

SFERES is a single cubesatellite tailored for use with Space Fence, MCAT, and FTN; however it can be adapted to a variety of missions. The payload section of the cubesatellite can be adjusted to accommodate a variety of payloads, while maintaining the bus and door configuration. SFERES's sphere release mechanism can be scaled to fit smaller or larger calibrated sphere targets, enabling the cubesatellite to carry objects tailored to the detection capability of a new space surveillance asset, be it a phased array radar, mechanically steered radar, or telescope. The deployed payload does not have to be a sphere; it could be anything such as a retroreflector or inflatable target. A small amount of gas could be placed in a compressed Mylar balloon that would be jettisoned and allowed to expand, creating a target much larger than the width of the cubesatellite.

The payload section could be elongated to make the cubesatellite anything from a 1.5U to a 3U, following the Nanoracks standard. This would provide 500 to 2500 cubic centimeters of additional space for additional payloads. Whereas SFERES is designed to release two objects within a month, the cubesatellite could hold many more calibrated payloads to be released over an extended period of time. If the cubesatellite were inserted in a higher orbit, its extended orbital lifetime would enable it to be available to release a chosen calibrated object of a given size on demand, at the request of the space community and/or acquisitions program offices entering operational test and evaluation. Additionally, the extended payload section would provide the opportunity to enhance the ADCS system. The magnetorquer system could be replaced with a three-axis stabilization gyro system to provide greater control of the cubesatellite's attitude. This would not only increase release direction precision, it would enable the operator to finely control the orientation of the cubesatellite while passing through a sensor's field of regard. The operator could then run a series of tests changing the angle between the normal of a face of the cubesatellite and the site, from directly on a corner to the flat side. This would greatly adjust the returns a radar or telescope would receive and when coupled with RCS calibration of the cubesatellite according to viewing angles.

9. SUMMARY

SFERES is a 1U cubesatellite that will release two small calibration spheres individually in orbit in the second half of 2018. It will assist operational testing of the Space Fence radar to characterize the system's ability to discover and track small space objects and debris. Extensive work and planning was invested in the test to reduce risk and to optimize its performance. The cubesatellite will also assist in characterizing optical sites with the LEDs of varying light frequencies and intensities. The design of the cubesatellite can be adapted to create a new cubesatellite to support any number of characterization missions. Any interest in collaborating with the authors as the SFERES mission is executed or for any follow-on missions can be directed to any of the authors.

10. RECOGNITION

This cubesatellite mission was funded and supported by NASA, AFOTEC, Space and Missile Systems Center, Space Test Program, and the Director of Operational Test and Evaluation's Resource Enhancement Program. Massachusetts Institute of Technology's Lincoln Labs, MITRE Corporation, and Lockheed Martin Corporation provided technical support for this project. A special thanks goes out to these organizations and the support they provided.

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