Space Fence PDR Concept Development Phase

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ABSTRACT

The Space Fence, a major Air Force acquisition program, will become the dominant low-earth orbit uncued sensor in the space surveillance network (SSN). Its primary objective is to provide a 24/7 un-cued capability to find, fix, and track small objects in low earth orbit to include emerging and evolving threats, as well as the rapidly growing population of orbital debris. Composed of up to two geographically dispersed large-scale S-band phased array radars, this new system-of-systems concept will provide comprehensive Space Situational Awareness through net-centric operations and integrated decision support. Additionally, this program will facilitate cost saving force structure changes in the SSN, specifically including the decommissioning of very-high frequency VHF Air Force Space Surveillance System (AFSSS).

The Space Fence Program Office entered a Preliminary Design Review (PDR) concept development phase in January 2011 to achieve the delivery of the Initial Operational Capability (IOC) expected in FY17. Two contractors were awarded to perform preliminary system design, conduct radar performance analyses and evaluations, and develop a functional PDR radar system prototype. The key objectives for the Phase A PDR effort are to reduce Space Fence total program technical, cost, schedule, and performance risk. The overall program objective is to achieve a preliminary design that demonstrates sufficient technical and manufacturing maturity and that represents a low risk, affordable approach to meet the Space Fence Technical Requirements Document (TRD) requirements for the final development and production phase to begin in 3QFY12.

This paper provides an overview of the revised Space Fence program acquisition strategy for the Phase-A PDR phase to IOC, the overall program milestones and major technical efforts. In addition, the key system trade studies and modeling/simulation efforts undertaken during the System Design Requirement (SDR) phase to address and mitigate technical challenges of the Space Fence System will also be discussed. Examples include radar system optimization studies, modeling and simulation for system performance assessment, investigation of innovative Astrodynamics algorithms for initial orbit determination and observation correlation.

1. INTRODUCTION

Why Space Fence: The challenges of the Small

Space Situation Awareness (SSA) capability is critical for ensuring space mission capability for the U.S. and the Space Fence System (SFS) is expected to be a key pillar of the objective surveillance architecture of the space surveillance network (SSN). Space Fence will contribute to SSA by finding, fixing, tracking, and characterizing normal and small-size Resident Space Objects (RSO) and space debris. Space Fence will also contribute to other Space Control areas by providing accurate metric and characterization data.

Today, the congestion of the space environment poses a significant challenge for the U.S. to perform surveillance of all space objects and activities. This is due to the increasing amount of space debris as a consequence of increased space launch activities, breakup events and collisions. Figure 1 illustrates the key challenge that necessitates the need to accomplish uncued surveillance of small RSOs and space debris.
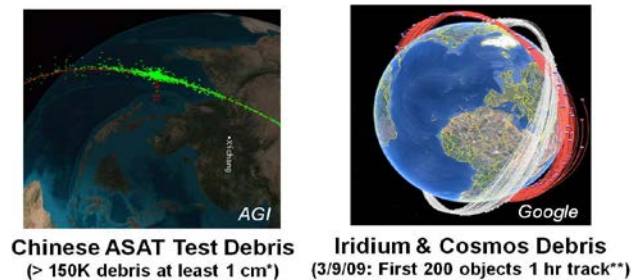

Chinese ASAT Test Debris
(> 150K debris at least 1 cm*)

Iridium & Cosmos Debris
(3/9/09: First 200 objects 1 hr track**)

Figure 1. Why Space Fence: The challenges of detecting space debris.

The large growth of the Low Earth Orbit (LEO) debris population poses significant challenges to SSA. For example, the recent Chinese ASAT test of China's Fengyun-1C weather satellite resulted in an estimated debris cloud of more than 150,000 debris pieces larger than 1 cm. Another more recent collision between a U.S. Iridium 33 communications satellite and the defunct Russian military communications satellite Cosmos 225 also created significant amount of debris. The debris generated by the collision occurred at 490 miles (790 km) above Siberia and posed a great risk to science satellites and potentially to the International Space Station (ISS).

To achieve catalog completeness of all small space debris in LEO orbits, the Space Fence must be able to perform wide area search and uncued detection of small debris. The wide area search function is best performed at microwave frequency such as S-band, i.e., 3 GHz, due to the resonant scattering characteristics of small objects at the wavelength of this electromagnetic spectrum. Besides discovering the small debris, the sensor must also have the ability to track each newly discovered object with sufficient accuracy for generating an acceptable estimate of its orbital characteristics for catalog maintenance purpose.

LEO Payload and Space Debris Distribution

The current SSN catalog contains about 20,000 objects and the distribution of the LEO payload as a function of altitude is relatively well defined, with the majority of the payload concentrating in orbits below 2000 km. The distribution is shown by the bimodal shape of the SSN payload versus perigee in Figure 2. In comparison, the number of objects in the NASA 2030 debris catalog, with at least 100K objects, is nearly an order of magnitude larger than that of the current catalog. Likewise, a significant number of debris much smaller than 30 cm is in the NASA 2030 catalog, with the distribution of space debris located within the 500-3,000 km orbit regimes. As a consequence, Space Fence System Design Requirement (SDR) trade studies on system performance and cost trades are motivated by the information on the debris size and their orbit regimes.
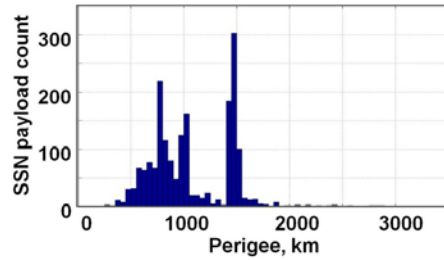
Figure 2. Space Objects versus SSN payloads: Distribution of LEO payload in LEO
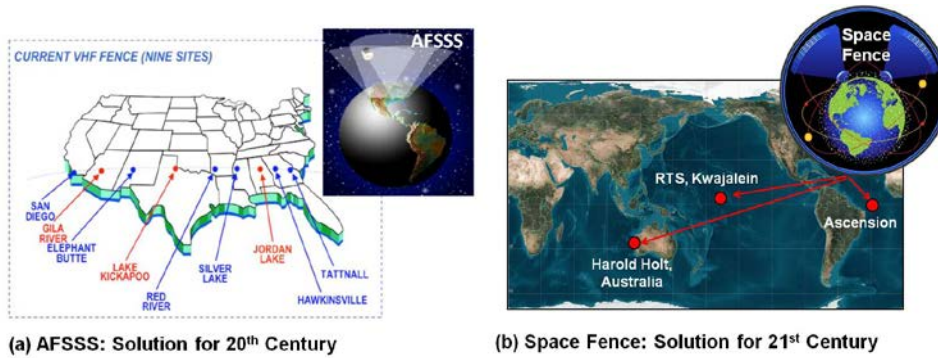
Space Fence System Evolution

Figure 3. Space Fence Evolution: (a) Air Force Space Surveillance System (AFSSS) (b) Space Fence.

The Space Fence program will provide a multi-site radar system operating in the S-band frequency range to replace the existing AFSSS Very High Frequency (VHF) radar. AFSSS is the current Air Force radar fence performing detection of orbiting space objects. As depicted in Figure 3(a), the AFSSS is comprised of three transmitter and six receiver sites located in the continental United States (CONUS). Operating for over 40 years, the existing AFSSS radar is becoming obsolete. As the system employs continuous-wave (CW) illumination, the AFSSS can only track in angles, but not in range. The system can detect targets up to Medium Earth orbit (MEO) altitudes (22,000 km), but it is limited to detect relatively large target, about (1 m^2 target size), due to the long wavelength at VHF. The lack of high precision tracking capability restricts the ability of the system to perform initial orbit determination (IOD) for effective discovery and maintenance of small space debris.

In comparison, the new Space Fence is composed of two phased array radars globally dispersed outside CONUS (OCONUS), as shown in Figure 3(b). Currently, the two candidate locations are Harold Holt, Australia, and Reagan Test Site, Kwajalein Atolls. Unlike the AFSSS, Space Fence is designed to be able to discover new small space debris to provide catalog completeness for LEO orbit regimes. To achieve this capability, it will be a pulsed radar system at S-band, capable of detecting and tracking targets in both range and angle. With a much smaller wavelength, the system will have the sensitivity to see small space objects and debris at the LEO regime but with enough design flexibility to also provide the coverage to the MEO regime. More importantly, since the system can track both in angle and range, it can perform IOD on newly discovered object with accurate metric data to support full catalog maintenance.

2. SPACE FENCE PROGRAM OVERVIEW

Space Fence System Concept

The overall Space Fence System concept is shown in Figure 4. It will be made up of a suite of electronically scanned array radars optimized for uncued surveillance but able to perform tracking for tasked and high priority objects. Each radar sensor will be configurable to support variable surveillance fences for LEO, as the primary surveillance region, and for the MEO regime with no increase in radar power aperture. To support 24/7 operations with high availability, the overall system will have a consolidated Space Fence operations center (SOC) with a single operations crew and minimal maintenance crew at each site. The overall system, including the SOC

and radar sensors, will be net-centric for connecting to the Global Information Grid (GIG) and will be designed with an Open Architecture technology common to SSA, SSN & Space C2 enterprise architectures.
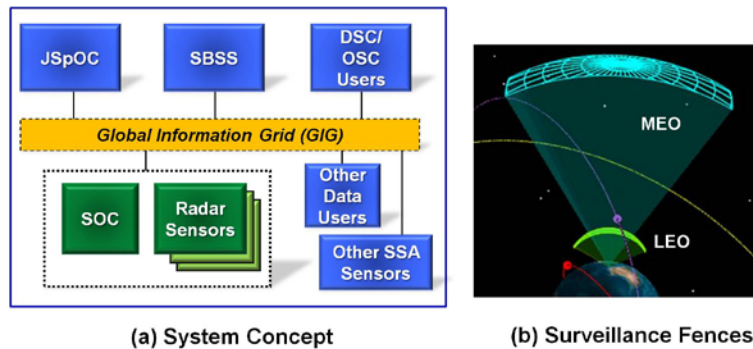

Figure 4. Space Fence System: (a) system concept (b) configurable surveillance fence.

Figure 5(a) depicts the dual-aperture concept design of the Space Fence radar in which the transmit aperture is separated from the receiving aperture. The transmitter aperture is designed to have a wide beamdwith in the Azimuth direction but highly focused in the Elevation direction. As such, it radiates energy in a fan-like beam to cover a broad angular sector in the Azimuth direction with a narrow width for detecting objects whose orbit cuts through the surveillance fence. The width of the radiated fence is narrow in the Elevation plane to minimize the required radiated power for effective wide area surveillance. The receive aperture generates a large number of receive beams to simultaneously cover the illuminated region for detecting crossing target(s) orthogonal to the Azimuth fan beam. The design of the radar surveillance fence will include both detection beams and tracking beams in order to meet both discovery (detect and track for IOD) and catalog maintenance (track for observation collect).
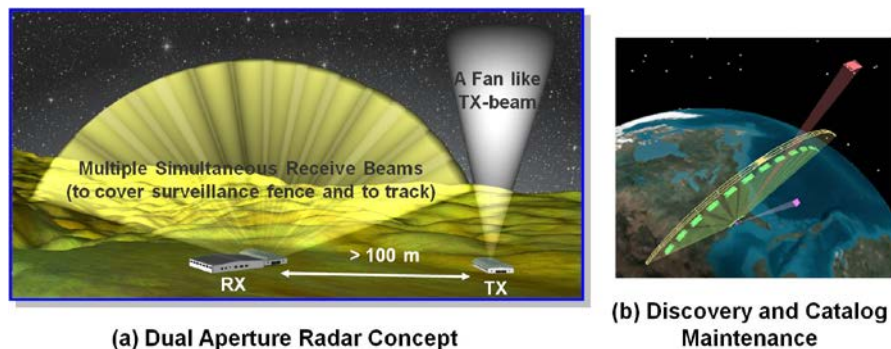

Figure 5. Space Fence radar concept: (a) Dual-aperture radar concept (b) Primary radar capability for the discovery and catalog maintenance of space objects.

Space Fence Acquisition Schedule

The Space Fence concept studies phase of the program was conducted in FYs 05-08 and included industry risk reduction contracts that were performed in FY06. Figure 6 shows the overall updated Space Fence Acquisition Schedule. Key Decision Point A was conducted in March 2009 with the Phase A SDR concept development contract awarded in June 2009. The Phase A Preliminary Design Review (PDR) concept development contract was awarded in January 2011 to two competing contractors. Following Milestone B approval, anticipated to occur in 3Q FY12, delivery of Space Fence capabilities will occur in increments that are to be defined by the Government. Initial Operational Capability (IOC) is planned for FY17 with Full Operational Capability (FOC) planned for FY20. By FOC, Space Fence will provide significantly improved space surveillance capability through geographically-dispersed sites with 24/7 radar sensor operations.
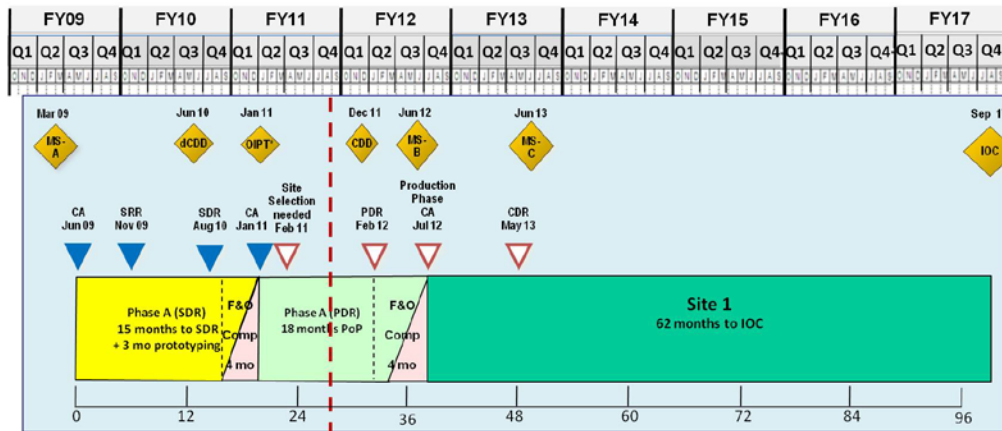
Figure 6. Space Fence Acquisition Schedule from Phase A SDR to IOC in FY17.

The key objectives for the Phase A PDR effort are to reduce Space Fence total program technical, cost, schedule, and performance risk. This will be achieved through the development of an allocated baseline that meets or exceeds Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) 6, the ability to price the next phase at reasonable risk, and the accommodation of a Technical Requirement Document (TRD) update based on a Joint Requirements Oversight Council (JROC) approved Capability Development Document (CDD), without affecting cost or schedule.

3.   SPACE FENCE SDR PHASE STUDIES AND ANALYSIS

During the Phase A SDR phase, the Program Office also funded FFRDCs to conduct numerous architecture trades and analysis of advanced astrodynamic algorithms. In particular, recognizing early on that the major challenge was IOD and correlation, MIT Lincoln Laboratory (MIT/LL) was funded to perform extensive trade studies to assess and optimize radar and mission performance requirements for achieving assured coverage, IOD and target correlation. The following provides a summary of these studies.

Guaranteed/Assured Coverage Study

The first important study seeks to investigate if alternative fence configurations, instead of the SDR 60° fan beam, could make better use of both hardware and operational resources to address object coverage from a rational orbit-determination perspective. Figure 7(a) shows the two locations of an SRD fence (120° fan) over the course of one orbit accounting for Earth's rotation. A satellite that just misses the fence on the right or left side may also miss the fence on the next pass. If the satellite completely misses crossing the left hand side of the would-be fence on the successive orbit, the fence will have missed its chance to see the object on that pass and will have to wait 12 hours when the fence passes by the orbit plane again. This can happen for satellites with circular orbits at low altitude. Also illustrated in Figure 7(a) is excess coverage at high altitudes. A high altitude satellite will cut through the large 120° fan every time it orbits the earth while a low altitude satellite will not be detected again by the fence in a 12 hour gap time. Because the fence is a phased-array radar with tremendous mission flexibility meant to detect LEO objects whose altitudes range from approximately 250 km to 3000 km, it would be advantageous to reshape the transmit beam by distributing the excess energy at higher altitude regimes to the lower altitude regimes. The resulting assured coverage fan beam is shown in Figure 7(b) where the transmitter must scan beyond +/-60° to reach out further at the lowest altitudes but reduce the surveillance width at higher altitude.
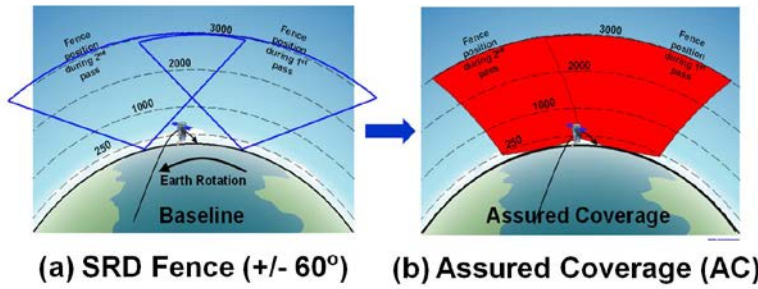
Figure 7. Guaranteed/Assured Coverage for leak proof surveillance of LEO regime.

The conclusions of the Assured Coverage study were:

- Low altitude satellites in circular orbits are detectable when the fence cuts through those orbits.
- Low altitude satellites can be missed by a 120 degree fan-shaped fence
- Guaranteeing one detection per pass (where the fence intersects the orbit plane) for circular orbits yields a fence shape that requires less power at higher altitudes.
- Narrowed beam at maximum altitudes reduces radar resource requirements while still providing needed coverage.
- An "Assured Coverage" fence beam will provide more effective LEO surveillance per radar site than a 120º fence.

Single Sensor Initial Orbit Determination Study

Given an Assured Coverage design, there was still a strong need to investigate   initial orbit determination (IOD) methods to successfully correlate previously uncorrelated targets (UCTs) with high probability. The second study investigated suitable orbit determination algorithms and error covariance representation method(s) to enable single sensor or single pass IOD [1]. Figure 8 depicts how multiple objects can be discovered and associated according to ability of the sensor to correlate new tracks to existing objects as their error covariance grows in time.
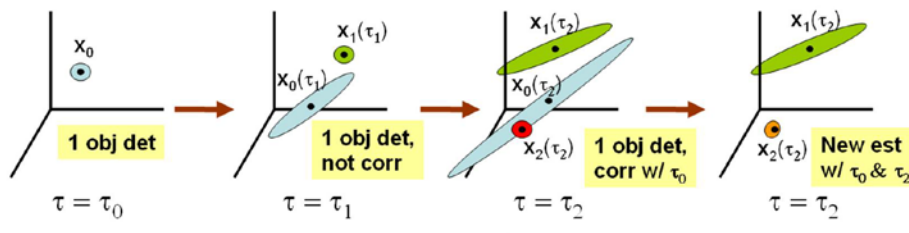

Figure 8. Initial Orbit Determination for target correlation to enable small satellite debris discovery and catalog maintenance.

A surveillance fence sensor detects, tracks, and captures observations of a target passing through its field of regard. This set of observations is then processed using an estimation scheme into a likelihood distribution centered on a state vector, located at x_o at time τ_o. The likelihood distribution associated with those observations is represented by a small (blue) confidence volume. Tasks as fundamental to SSA as RSO catalog maintenance and IOD, object correlation, space event detection and conjunction analysis all depend on a quantitative understanding of how well observations of a particular satellite translate into an accurate picture of where that satellite is and where it will be in the future. A sensor initially tracks an object and forms a state which is then inserted into a catalog. The newly established state must be correlated with the initial state whose uncertainty grows with time in a prescribed

manner. Eventually, as time evolves, observations of another object will be consistent with that of the initial object. Once a criterion is established, the observations are associated and a new combined state is formed. The process repeats as the catalog states are refined and converge to a set of stable states. For example, as shown in Figure 8, the new observation $x_2(\tau_2)$ at time τ_2 falls within the evolved confidence volume at τ_2 of the original state $x_o(\tau_2)$. This observation is combined into a new and refined estimate $x_2(\tau_2)$ with an improved confidence volume.

IOD Accuracy & Sensor Design Trade Study

The scheme devised in the last trade study is confounded if the space environment is too dense such that there are many confusing objects present in an evolved covariance of some UCTs' initial state and covariance. In this trade study, we ascertain which fence requirements are needed to minimize the number of confusing objects so that the correlation algorithm can be successful [1]. Given an RSO density distribution versus altitude, the number of confusing objects expected to be present, on average, in the correlation volume depends on the angle error and velocity uncertainty of the observations. Figure 9 shows the estimated number of confusers within the correlation volume at the peak density altitude of the NASA 2030 catalog. Correlation is most successful when the average number of confusers is much less than one within the correlation volume, i.e., the green and blue zones. The correlation scheme is still viable in the yellow region, but is degraded and takes more time for acquisition. Above that threshold, the correlation would be much more difficult due to the large number of confusers, i.e., the brown or red region.
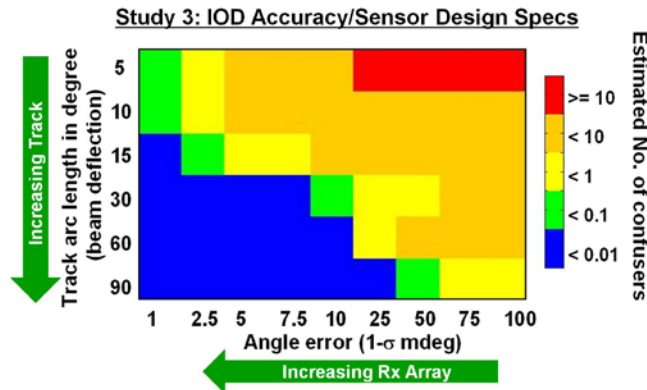

Figure 9. IOD accuracy requirements for achieving correlation in a dense space environment as a function of sensor performance capabilities.

By containing the initial along-track velocity uncertainty, one can restrict the growth of the spatial uncertainty volume. Dramatic reductions in spatial uncertainty volume can be realized with:

- Improving angular accuracy, or reducing radar angular error, by increasing the size of the receiving array.
- Increasing the number of independent observations per track (increasing the number of observations per track is effectively equivalent to improving the angular accuracy).
- Increasing tracking extent to improve the velocity estimate when performing IOD.
- Reducing the growth of the spatial uncertainty volume by shortening the time between tracks (i.e., reacquisition time) which is correlated with number of guaranteed-coverage fences.

4. SPACE FENCE RADAR SYSTEM ARCHITECTURE TRADES

During the SDR phase, there was a critical need to obtain an accurate cost model of the Space Fence radar in order to evaluate contractors' design performance and cost models. The Program funded MIT/LL and MITRE to create an independent government reference radar design (GRRD) based on an achievable bottoms-up radar design. Based on the GRRD efforts, additional Space Fence radar architecture excursions were performed to understand the tradeoff between the total cost of the system (acquisition + life cycle cost estimate) and the altitude/surveillance fence extent [2]. In the first excursion on surveillance fence trades, we consider the cost implication associated with the size of the surveillance fence and the altitude requirements for the minimum detectable target (MDT), as shown in Figure 10. Smaller fence coverage volumes and decreased maximum altitudes reduce radar power aperture requirements. The Assured Coverage design can be used in place of the SRD solution to improve low altitude

coverage while preserving all LEO requirements for MDT. For the antipodal radar pair solution, the surveillance fence of each radar can be reduced while keeping the track field of view (FOV) unchanged. This reduces the power aperture potentially by half.
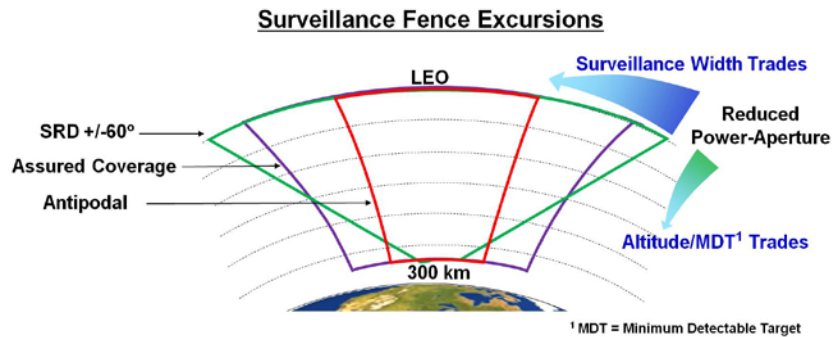

Figure 10. Radar surveillance fence and radar power aperture excursion trades.

By trading off timeliness requirements of the SF system, it is possible to explore different system-of-system (SoS) options in which not all radars have to be identical. The system excursions consider the possibility of mixing different radar functionality within the system. Figure 11 shows the three fundamental radar architecture system options. Option 1 is the SRD design with 3 radars, each with 120° fences. Option 2 is made up of two large surveillance radars for catalog discovery and orbit maintenance. Option 3 is an Antipodal pair with a 50% reduction in surveillance aperture by the virtue that RTS and Ascension are nearly on opposite sides of the earth. Both systems work in tandem to provide the same assured coverage with a smaller surveillance volume. For a pair of radars with reduced power aperture, the overall O&S cost can be substantially lower as fuel cost is the largest O&S cost of a radar with 24/7 operation.
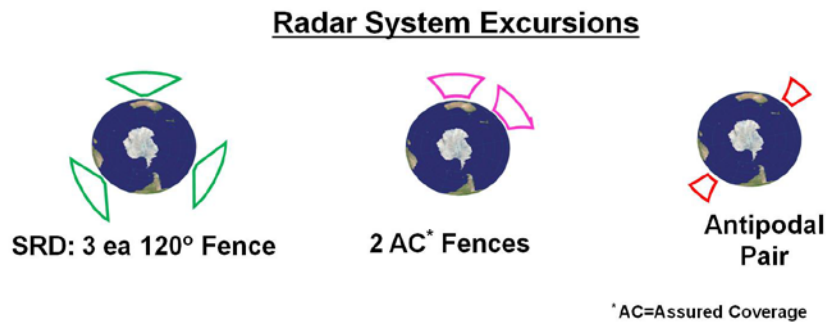

Figure 11. Radar system architecture excursion trades

5. SPACE FENCE PDR DEVELOPMENT PHASE

For the PDR phase, both competing contractors are funded to provide a preliminary design that demonstrates sufficient technical and manufacturing maturity and that represents a low risk, affordable approach for entering the Production Phase supported by a functional radar prototype [2]. The overall system, including Software (SW) and Hardware (HW) components and subcomponents, is representative of technology used in the final design intended to meet TRD requirements. The prototype and its performance demonstration shall validate that the critical technology elements (CTE's) are at technology readiness level (TRL) 6 or higher. Further, the contractor shall develop a preliminary design that meets overall system performance requirements with controlled life cycle costs.

Performance Assessment System

The Space Fence Program funded MIT/LL during the SDR phase to create the Performance Assessment System (PAS). PAS has the ability to perform high fidelity modeling and simulation for the end-to-end assessment of the contractors' proposed designs and to provide a software simulation environment to assess Space Fence system operational performance. The contractors are funded to develop a capability for providing an end-to-end simulation

of the radar system and SOC which interfaces with the Government provided satellite simulation, radar validation, and radar performance assessment service, as shown in Figure 12.
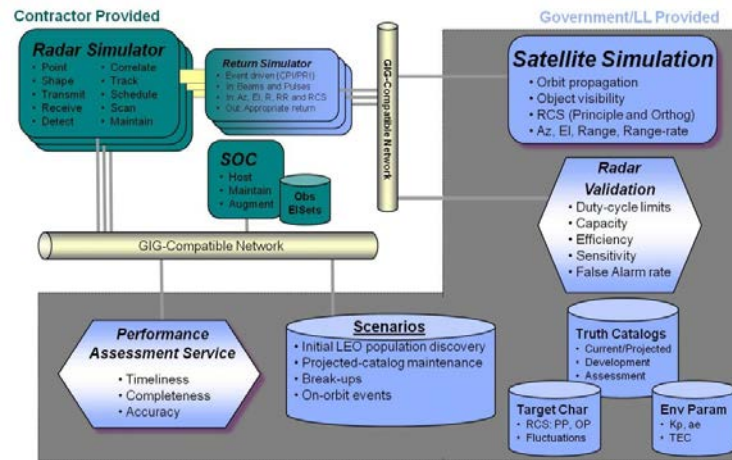

Figure 12. Space Fence Phase-A PDR Performance Assessment System for high fidelity Modeling and Simulation testing.

The major components of the PAS system are listed below:

– Satellite simulator contains the satellite catalogs and creates scenarios with the required target characteristics in the appropriate environments to simulate the time evolution of the satellite orbits.
– Radar return simulator accepts satellite position, range rate and radar cross section inputs and produces radar return outputs appropriate for the simulated beams and pulses.
– SOC simulator is a capability developed by the contractor to receive and store the initial resident space object catalog from the performance assessment simulation and to deliver observations, RCS estimates and an updated/augmented catalog. Radar performance evaluation tools provide a software simulation environment to assess Space Fence system operational performance
– Emulated net-centric SSN environment contains the Transmission Control Protocol/ Internet Protocol (TCP/IP) network communications capability to interface the radar return simulation, radar simulation, and Space Fence operations center simulation with the Government-provided performance assessment simulation in real-time or at pseudo real-time rates.

The contractor must develop radar model and simulations with the capability of producing beam and pulse definitions, generating and processing the simulated radar returns to produce observations. The contractor must also correlate observations to the RSO catalog and complete extended tracking for IOD.

PDR Prototype Demonstration System

In addition to gaining significant insights into the high level system performance of the space fence system based on PAS, it is vital to the program to fully understand the operational environment as it relates to the system, its subsystems and components. To achieve this objective, the contractor is required to perform prototyping to verify the design performance and the maturity levels of CTEs and Critical Manufacturing Processes (CMPs), and to support the cost basis of a system that satisfies the Space Fence TRD and Facility Requirements Document (FRD) requirements. At the conclusion of the PDR phase, the contractor will produce a scalable PDR Prototype System with the government-approved allocated baseline and B-specs. The prototype system must also be capable of detecting and tracking an RSO and demonstrate how it can be upgraded to a CONUS testbed in the next Critical Design Review (CDR) Phase.
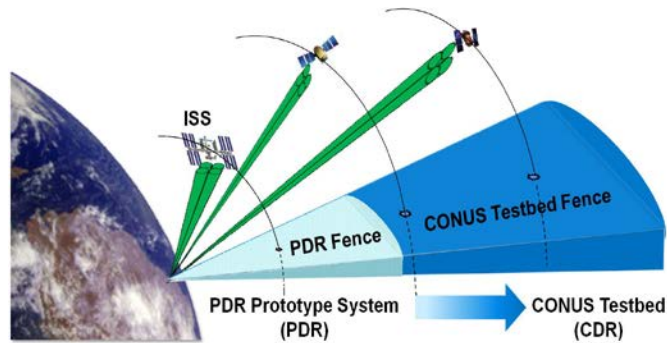
Figure 13. Scalable Space Fence Phase-A PDR prototype demonstration system with the potential for extending to the CONUS testbed for SF CDR Phase.

Figure 13 depicts a conceptual view of the PDR phase contractor prototype system to demonstrate the end-to-end radar system. Each PDR prototype system shall be capable of performing the following real-time radar functionality:

- Setup a representative transmit fence with sufficient fan width and thickness for target detection.
- Generate a sufficient number of simultaneous receive beams to cover the surveillance region. These beams shall enable the detection of RSO targets passing through the fence with sufficient sensitivity. The candidate RSO targets used for the demonstration shall be selected according to the radar sensitivity based on the power aperture of the prototype system.
- Perform real-time closed loop target tracking with the appropriate transmit and receive beam clusters .
- Collect a sufficient number of observations to demonstrate that the system can perform IOD.
- Perform real-time target correlation with an internal RSO catalog to demonstrate UCT Recognition.

6. SUMMARY

The Space Fence System will become the dominant LEO uncued sensor in the SSN. It will provide a 24/7 un-cued capability for catalog completeness and maintenance.. During the SDR phase, significant efforts on trade/analyses, new algorithm development, and modeling and simulations resulted in the development of flexible radar system architectures with a high performance modern phased array sensor. This enabled the adaptation of advanced and innovative astrodynamic approaches. Informed by bottoms-up Program Office developed cost data based on independent achievable radar design and informed by contractor cost models, different achievable and affordable Space Fence system options were developed to meet different CONOPS requirements. The current Acquisition Schedule keeps system IOC on track for FY17 by awarding and funding two independent contractors to develop independent PDR designs for the PDR phase and by ensuring the third CDR contract on schedule for the final development/production. The PDR Contractors are on track to perform continued trades and analyses that will inform CDD, TRD and life cycle cost updates and to develop the scalable end-to-end prototype system for PDR demonstration.

7. ACKNOWLEDGEMENTS

8. REFERENCES

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[2] Linda Haines and Phillip Phu, "Space Fence Technology Development Overview", 2010 Space Control Conference, MIT Lincoln Laboratory, May 4, 2010.
[3] Linda Haines and Phillip Phu, "Space Fence PDR Concept Development Phase", 2011 Space Control Conference, MIT Lincoln Laboratory, May 4, 2011.