SPACE FENCE SYSTEM OVERVIEW[1]

Joseph A. Haimerl
Lockheed Martin, Mission Systems and Training, Moorestown, NJ
Gregory P. Fonder
Lockheed Martin, Mission Systems and Training, Moorestown, NJ

1. ABSTRACT

Space is no longer a vast, empty void. Unprecedented quantities of new satellites, derelict satellites, and debris litter the skies, posing an imminent threat to America's space assets.

The Space Fence System is a ground-based system of S-band radars designed to greatly enhance the Air Force Space Surveillance Network. Space Fence provides unprecedented sensitivity, coverage and tracking accuracy, and contributes to key mission threads with the ability to detect, track and catalog small objects in Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO). Space Fence capabilities will revolutionize space situational awareness.

Space Fence includes up to two minimally-manned radar sites and the Space Fence Operations Center. Each radar site features a design with closely-spaced, but separate, Transmit and Receive Arrays that are mission-optimized for high availability and low lifetime support costs, including prime power. The radar architecture is based on Digital Beam-forming. This capability permits tremendous user-defined flexibility to customize volume surveillance and track sectors instantaneously without impacting routine surveillance functions.

Space Fence offers assured surveillance coverage for improved custody and features the capability to develop long arc tracks for accurate orbit determination, while simultaneously maintaining a persistent surveillance volume. Space Fence allows operators to reconstruct recent events—such as collisions or satellite break-ups—and accurately predict future events. For high-interest objects, a "micro fence" can be electronically constructed to gather more track data, focusing radar resources specifically on that object, providing more timely and accurate information.

The Space Fence System is net-centric and will seamlessly integrate into the existing Space Surveillance Network, providing services to external users—such as the Joint Space Operations Center (JSpOC)—and coordinating handoffs to other SSN sites. Space Fence is a robust, flexible, advanced end-to-end system that will meet the warfighter's operational needs and revolutionize Space Situational Awareness.

2. INTRODUCTION

The space in Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) is no longer a vast, empty void. Unprecedented quantities of new satellites, derelict satellites, and debris pose an imminent threat to space operations and America's space assets. The number of countries launching satellites continues to increase. With each satellite launch, additional debris such as rocket bodies, bolts, or dust from solid rocket motors reaches orbit in addition to the intended payload. Fig. 1 Illustrates NASA's "Satellite Box Score" and "Monthly Number of Objects in Earth Orbit by Object Type" that are published in the Orbital Debris Quarterly News Publication [1]. As of January 2014, there were 3,715 cataloged active payloads and over 12,940 cataloged rocket bodies and debris in orbit. Although objects occasionally deorbit, the total number of cataloged objects has continued to grow since Sputnik was launched in 1957 to close to 16,655 objects as of January 2014.

Fig. 1 shows two distinct events in 2007 and 2009 that dramatically increased the number of debris objects. In 2007, the Chinese demonstrated an Anti-Satellite Weapon (ASAT) and destroyed the Fengyun-1C weather satellite. Over 3,000 cataloged objects from the event are still in track, with even more small debris estimated to have been created in the event (Fig. 2 and [2]). In 2009, a significant collision occurred between a U.S. Iridium 33 communications satellite and a defunct Russian military communications satellite Cosmos 225, creating over 700 additional pieces of cataloged debris. (Fig. 3 and [3]).

---

1 Distribution Statement A - Cleared for public release by 66ABG PA, Case Number: 66ABG-2015-0135

SATELLITE BOX SCORE
(as of 1 January 2014, cataloged by the U.S. SPACE SURVEILLANCE NETWORK)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	155	3609	3764
CIS	1439	4737	6176
ESA	46	45	91
FRANCE	58	442	500
INDIA	53	119	172
JAPAN	124	82	206
USA	1174	3787	4961
OTHER	666	119	785
TOTAL	3715	12940	16655

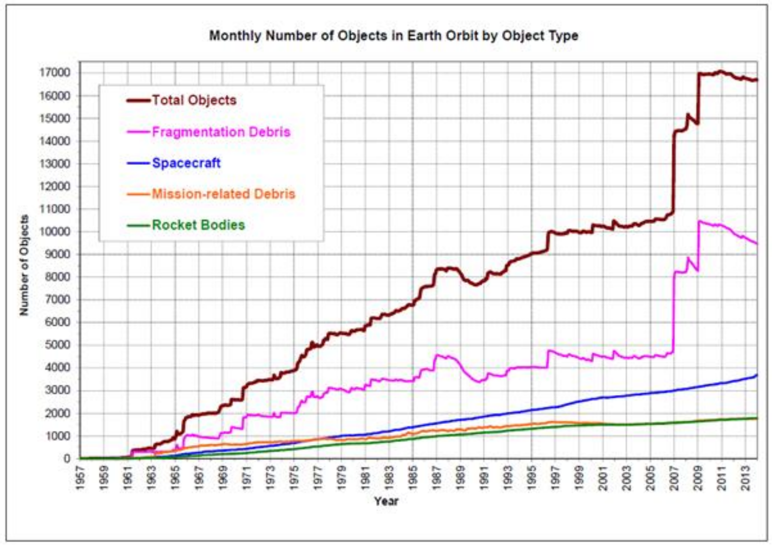


Fig. 1. Number of Countries in Space and Number of Objects in Orbit Continue to Grow [1]

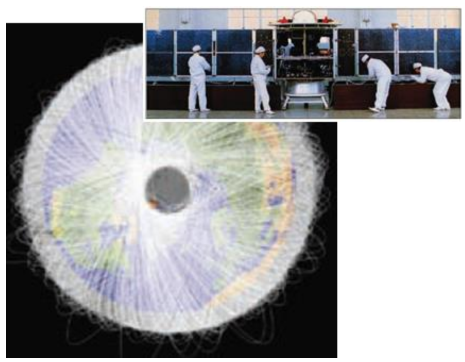


Fig. 2. Over 3,000 Cataloged Pieces of Debris from the Chinese 2007 Fengyun-1C Anti-Satellite Weapon Test Continue to Threaten Space Operations. *(Lower image shows debris map as of 2014. Upper image shows Fengyun-1C prior to launch*) [2]

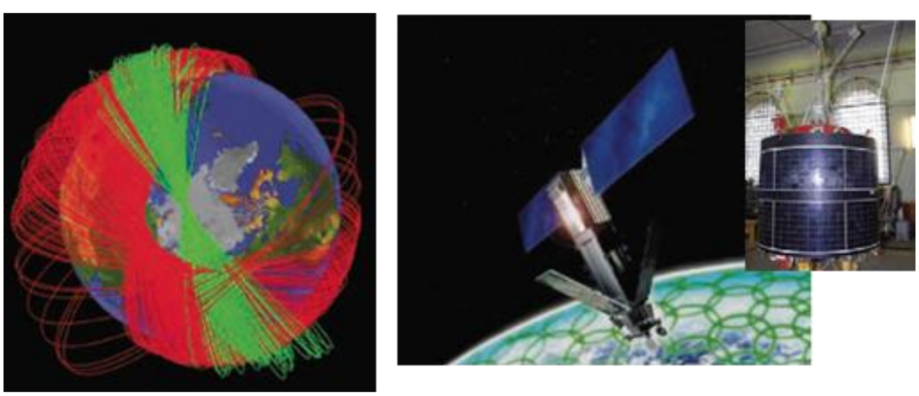


Fig. 3. 2009 IRIDIUM 33 / Cosmos 2251 Collision Created Over 700 Cataloged Objects which Continue to Threaten Space Operations *(left image: predicted debris cloud after 6mo. center image: IRIDIUM. right image: Cosmos)* [3]

Speeds on the order of 8 km/s in LEO make any collision potentially catastrophic. Even small debris objects on the order of 1mm can cause damage to operational satellites, as illustrated by window damage to the space shuttle Endeavour during STS-126 (Fig 4. and [4]). The 2009 Iridium 33 / Cosmos 2251 collision clearly demonstrated that with the growing number of satellites we can no longer rely on the 'Big Sky' theory in earth orbit to ensure safety of orbits. Since 1999, the International Space Station (ISS) has been maneuvered over twenty times to avoid debris. There were five maneuvers alone in 2014.

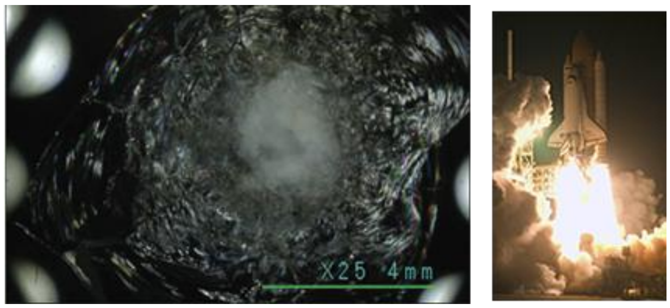


Fig. 4. Example of STS-126 Window Damage from Micro-meteroid or Orbital Debris Particle Estimated to be only 0.15mm in Diameter *(left image: window damage. right image: STS-126 launch)* [4]

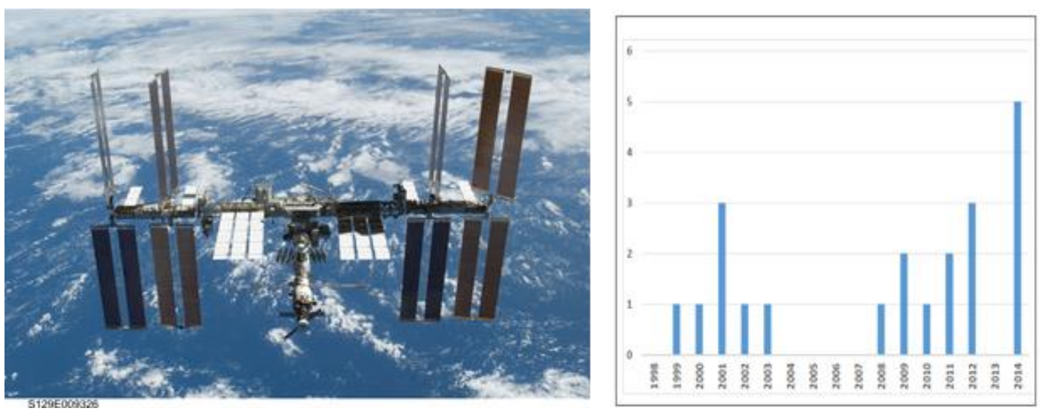
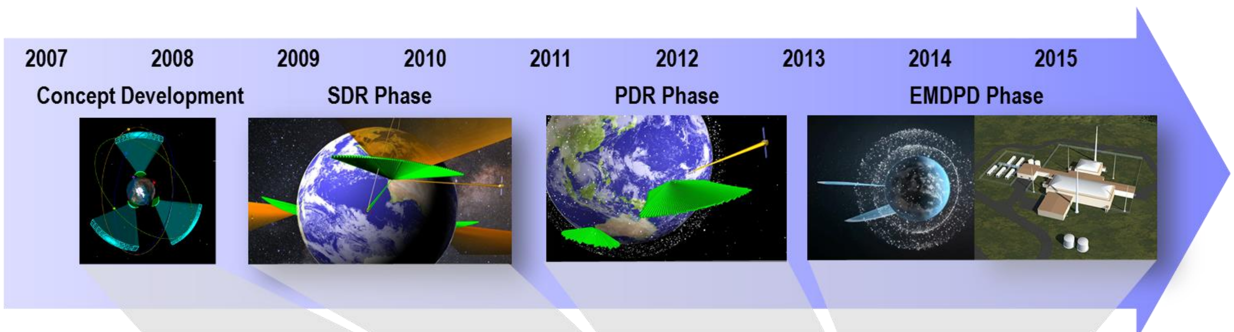


Fig. 5. ISS Makes Five Debris Avoidance Maneuvers in 2014. *(left image: ISS. right image: number of maneuvers per year)* [5]

In order to ensure safety of satellites in orbit it is essential to know their precise orbits as well as the orbits of debris that could cause damage. This information is also essential for the U.S. to maintain a Space Situation Awareness (SSA) capability to protect its space assets from potential hostile actions. The U.S. Air Force is developing the Space Fence System as part of its Space Surveillance Network (SSN) to provide unprecedented detection sensitivity, coverage and tracking accuracy. The Space Fence Program was initiated by the Air Force in 2005 to develop a system of geographically dispersed S-Band phased array radars which provide 24/7 un-cued capability to find, fix, and track small objects in LEO. The system was to replace (and greatly enhance the capability of) the now decommissioned very-high frequency VHF Air Force Space Surveillance System (AFSSS). The Air Force engaged industry with risk reduction contracts in 2006. System Design Review (SDR) Concept Development Phase contracts were awarded to 3 industry teams in June 2009 and Preliminary Design Review (PDR) Phase contracts were awarded to two industry teams in January 2011 [6]. In June 2014, the Lockheed Martin industry team was awarded the contract for the Engineering, Manufacturing, Development, Production and Deployment (EMDPD) of the Space Fence System.

3. SPACE FENCE SOLUTION

Lockheed Martin's Space Fence System solution is a result of extensive trade studies throughout the Risk Reduction, SDR Phase, PDR Phase and current EMDPD Phase, as summarized in Fig. 6. Initially, during the concept development efforts (Risk Reduction contract and self-funded studies), the requirements called for three identical Sensor Sites (SS) to be geographically dispersed around the globe and controlled by the Space Fence Operation Center (SOC). Array size at each site was driven by un-cued Medium Earth Orbit (MEO) coverage and coverage was defined by fixed angular extents (e.g., ±60º for LEO and for ±30º MEO). Since array size is directly proportional to cost, our solution attempted to minimize it through use of digital array technology and separate Transmit (Tx) and Receive (Rx) phased arrays. Digital arrays, particularly those that use element-level digital beamforming, are capable of many independent beams to support simultaneous functions, reducing required array size relative to doing the functions sequentially. These functions are performed simultaneously at different frequencies within the operating band (see Fig. 7). Use of separate Tx and Rx arrays minimizes losses during transmit and receive, which also reduces required size. Our solution also employed Gallium Nitride (GaN) high power amplifier technology for use in the Tx array to provide high power, long pulses needed for long range operations, and high efficiency for low operating costs. Even with these key affordability trades considered, the requirements still drove the Tx array sizes excessively large (78K radiating elements and Rx array size to 300K radiating elements, about three times as large as the final SS).



	Concept Development	SDR Phase	PDR Phase	EMDPD Phase
System Configuration	• SOC plus 3 SS	• SOC plus 3 SS	• SOC plus 2 SS	• SOC plus 2 SS
Array Size	• All SS identical • 78K Tx / 300K Rx Elements	• All SS identical • 65K Tx / 217K Rx Elements	Elements: • SS1 36K Tx / 100K Rx • SS2 18K Tx / 51K Rx	Elements: • SS1 36K Tx / 86K Rx • SS2 17K Tx / 86K Rx
Studies & Reviews	• Architecture selection: digital array, separate Tx & Rx	• Incorporated initial prototyping results • SRR • SDR	• Cost / performance trades used to refine driving requirements • PDR	• CDR • 100% Facility Design
Affordability	• Affordability and maintenance concepts development	• Matured LCCE model	• Affordability and assumption challenges	• Opportunity realizations based on CDR prototype measurements

Fig. 6. Space Fence Solution Evolution and Trades

Throughout the SDR Phase, detailed hardware prototyping of our array technology building blocks refined our performance and cost models. This led to a downsizing of our arrays to 65K Tx and 217K Rx elements for affordability. As our effort entered the PDR phase, cost models were used by the USAF to adjust requirements and remove drivers such as the continuous MEO mission sensitivity over such a large uncued volume. Updated requirements focused on un-cued LEO as the driver for radar sensitivity, with MEO as a tasked function that did not drive larger array sizes. This simplification and additional detailed performance modeling allowed further reduction of array sizes. The new requirements also reduced the number of sensor sites to 2 and adjusted the coverage to optimized contours to provide 'assured coverage', as shown in Fig. 8. Assured coverage provides optimized fence angular width as a function of altitude to guarantee one detection opportunity per pass (where the fence intersects the orbital plane) for circular orbits. Assured Coverage contours were also traded off with sensor site locations (Kwajalein Atoll and Australia, vs. antipodal sites such as Kwajalein and Ascension Island) [6].

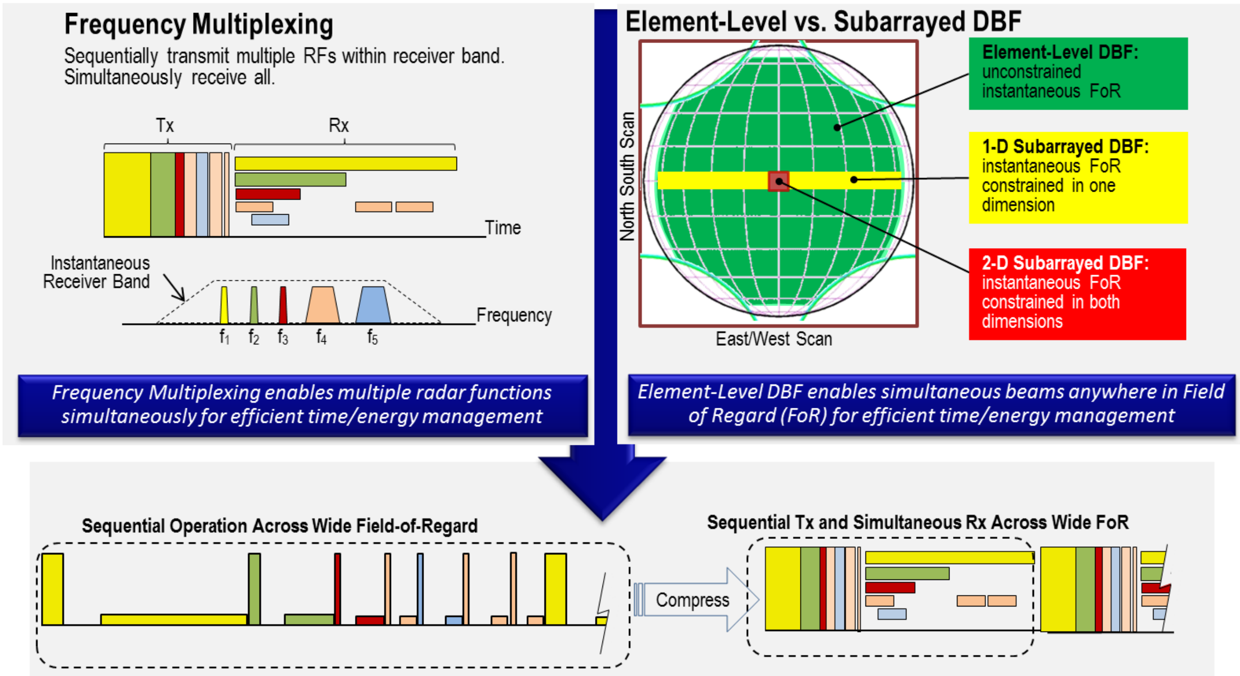


Fig. 7. Benefits of Element-Level Digital Beam Forming (DBF)

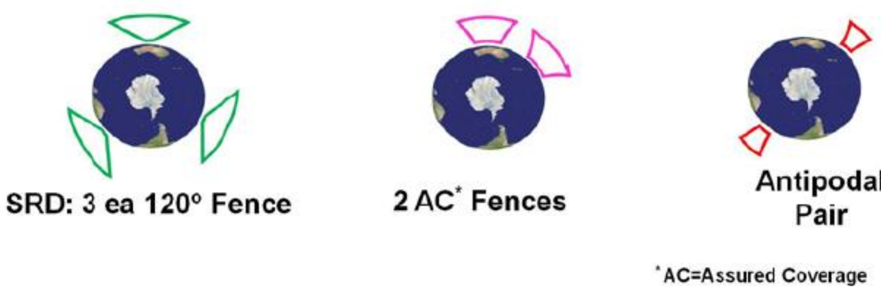


Fig. 8. Space Fence Coverage Evolution from Fixed Angular Coverage to Assured Coverage [6]

Detailed prototyping continued throughout the PDR phase into the EMDPD phase and refined performance and cost models. Based on these prototyping efforts, the final design at Critical Design Review (CDR) incorporated numerous opportunity realizations focused on affordability and producibility. The final Space Fence design includes two minimally-manned radar sites with complementary coverage and the Space Fence Operations Center (see Fig. 9). Each radar site features closely-spaced, but separate, Transmit and Receive Arrays that are mission-optimized for high availability and low lifetime support costs, including prime power. Coverage is optimized to provide assured coverage at IOC down to 800 km altitude with the Kwajalein Atoll site and improved lower altitude assured coverage to 550 km at FOC with the addition of the Australian site. Both sites support cued tasking support to all altitudes including GEO. The Space Fence System is net-centric (interconnected by the Global Information Grid, more recently referred to as the Department of Defense Information Network) and will seamlessly integrate into the existing SSN, providing services to external users—such as the Joint Space Operations Center (JSpOC)—and coordinating handoffs to other SSN sites.

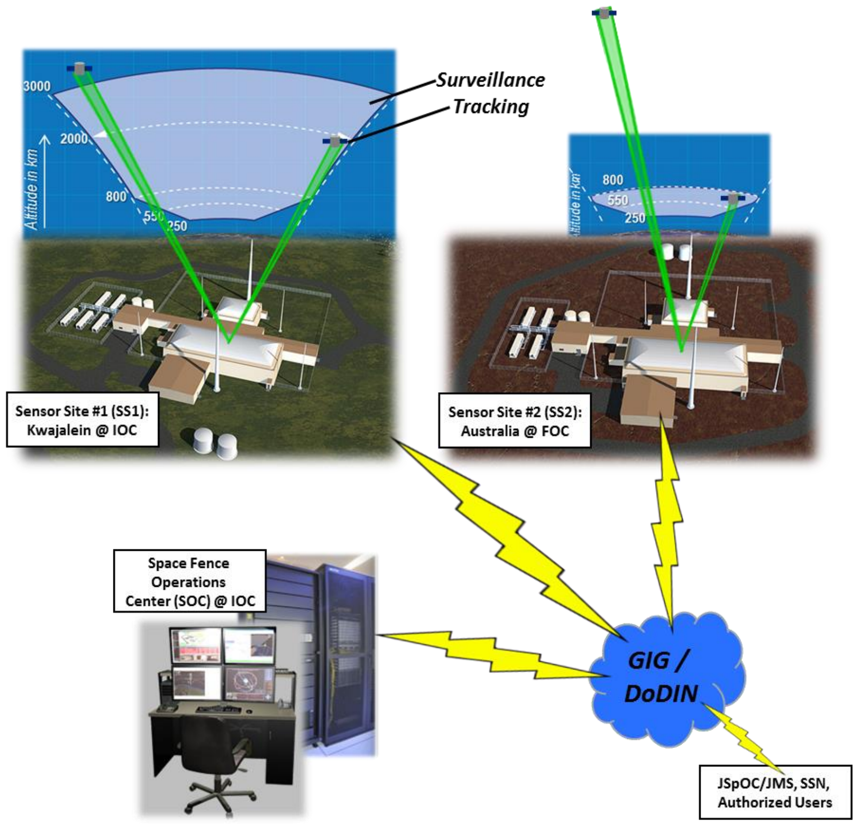


Fig. 9. Space Fence System Architecture and Coverage

The layout of a sensor site is depicted in Fig. 10. The radar architecture incorporates GaN and element-level Digital Beam-forming as previously described. These capabilities permit tremendous user-defined flexibility to customize volume surveillance and track sectors instantaneously without impacting routine surveillance functions. Arrays are built with scalable building block sections and Line Replaceable Units (LRUs) as shown in Fig. 11 and Fig. 12. Each array looks through a very low loss electronically transparent facility Kevlar radome that is air supported. Array electronics can be serviced from beneath while arrays are operational, permitting high system availability. Liquid cooling enables high performance and reliability. Radar control, signal and data processing, and mission processing are hosted on Commercial Off-the-Shelf (COTS) processing within the operations building.

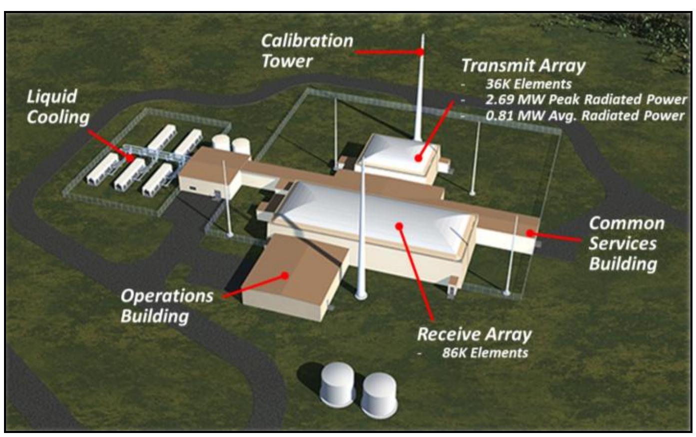


Fig. 10. Space Fence Sensor Site Overview

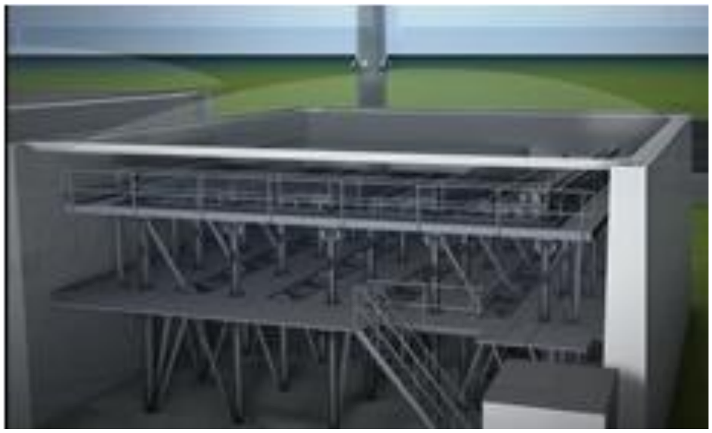


Fig. 11. Scalable Aperture Design

Fig. 12. Array Electronics Serviceable From Beneath Array While Operating for High Availability

Use of element-level DBF allows Space Fence to maintain persistent surveillance while performing tracks on hundreds of simultaneous objects detected in the fence (Fig. 13). The system automatically manages resources by performing long-arc tracks on Uncorrelated Targets (UCTs) to support accurate initial orbit determination. For high-interest objects, a "micro fence" can be electronically constructed to gather more track data, focusing radar resources specifically on that object, providing more timely and accurate information, as depicted in Fig. 14. Use of element-level DBF allows Space Fence to support these cued tasks without interrupting un-cued surveillance. System resource control automatically adjusts the number of beams and range extents to cover the required volume of the micro fence.

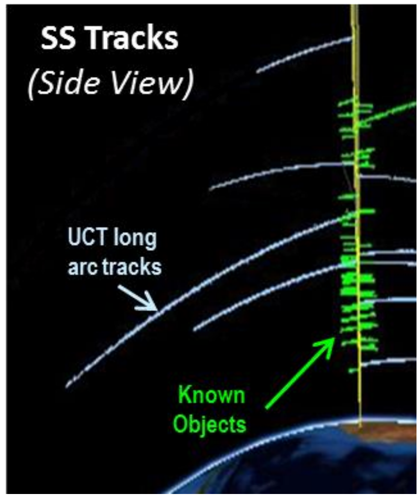


Fig. 13. Element-Level DBF Enables Long Arc Tracking Simultaneously With Un-cued Surveillance

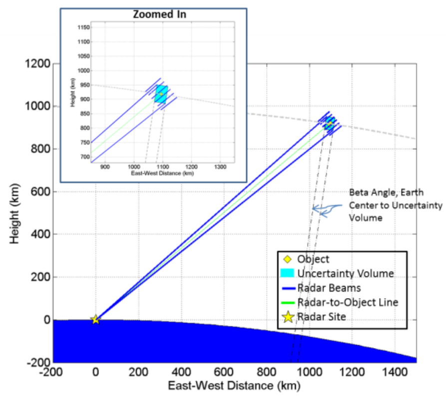


Fig. 14. Micro-Fence (Cued Search) for High Interest Objects Performed Simultaneously with Un-Cued Surveillance

Space Fence is being developed with significant flexible coverage capabilities. For events and objects where orbit information is known, the micro fence capability can be used to put up a persistent volume without impact LEO performance. An example from high fidelity modeling and simulation is shown in Fig 14, a micro fence was used to keep a persistent volume along the ephemeris of a suspected breakup. Nearly 1000 new objects were detected and tracked as the micro fence and resources are automatically adjusted by the system to provide contiguous coverage of the suspected breakup. Micro fences can be erected anywhere in LEO, MEO or GEO coverage. When little is known about the objects of interest, another method of flexible coverage is to reallocate the un-cued surveillance resources to another altitude regime such as MEO or GEO. Fig. 14 also illustrates an example of un-cued MEO surveillance; sized for a particular target size (available coverage will depend upon resources needed to detect the sensitivity of the objects of interest). Note during the M&S scenario for this flexible coverage case that the larger 'future' LEO catalog was still maintained automatically by the sensor site using micro fences and less than 1/3 of the radar resources.

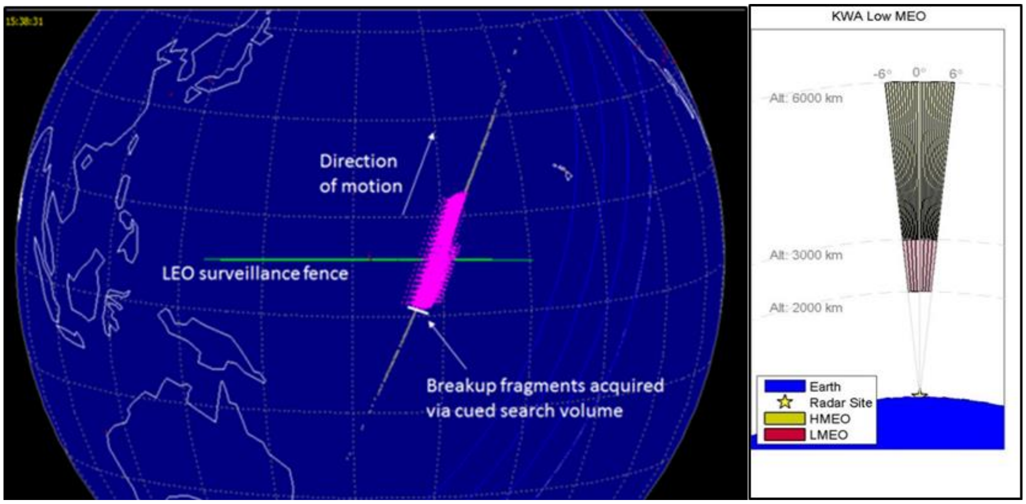


Fig. 15. Flexible Coverage Examples *(left: example of a micro fence to detect nearly 1000 new objects after a suspected breakup event while leaving un-cued LEO unaffected. right: example of reallocating un-cued LEO resources to un-cued MEO surveillance while maintaining the LEO catalog with automatically generated micro fences)*

4. PROGRAM STATUS

The overall program schedule is depicted in Fig. 16. Recently the Critical Design Review (CDR) and 100% Facility Design Review were successfully completed. These events not only reviewed the design, but also assessed the Technology Readiness Level (TRL) as level 7 and the Manufacturing Readiness Level (MRL) as level 7. During the CDR event an extensive end-to-end prototype demonstration of the system was successfully conducted (Fig. 17). This prototype has been previously described in [7] as part of a multi-sensor (radar, laser, telescope) net-centric test bed. Ground breaking for sensor site 1 took place on Kwajalein Atoll in February 2015, as illustrated in Fig. 18. The sensor site consists of the radar as well as a power plant annex to bolster the generation capabilities of Kwajalein. The Space Fence Program is on-track for Initial Operational Capability (IOC) in 2018. The second sensor site is planned for 2021.

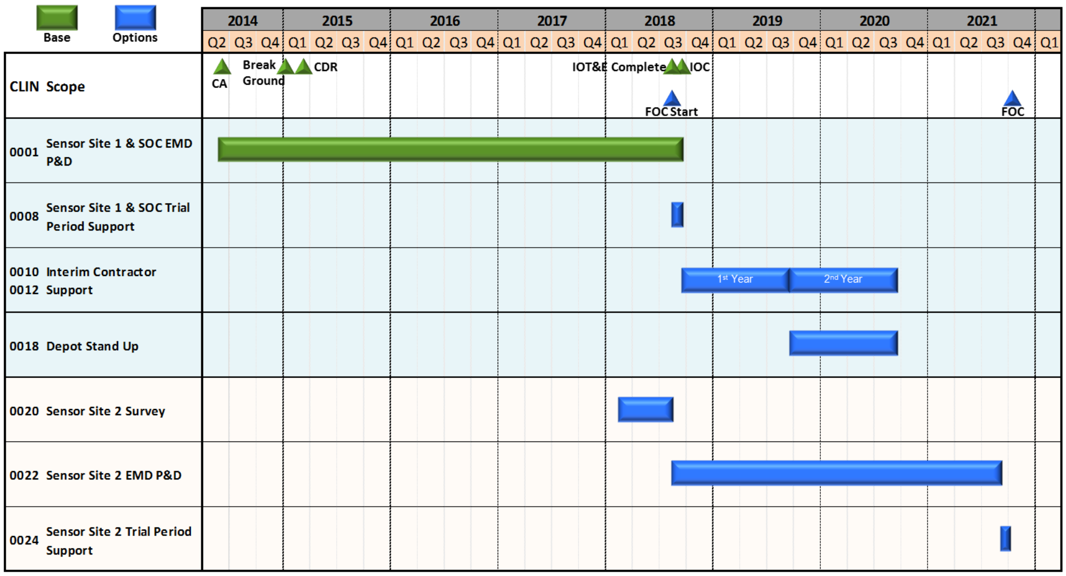


Fig. 16. High Level Overall Space Fence Program Schedule

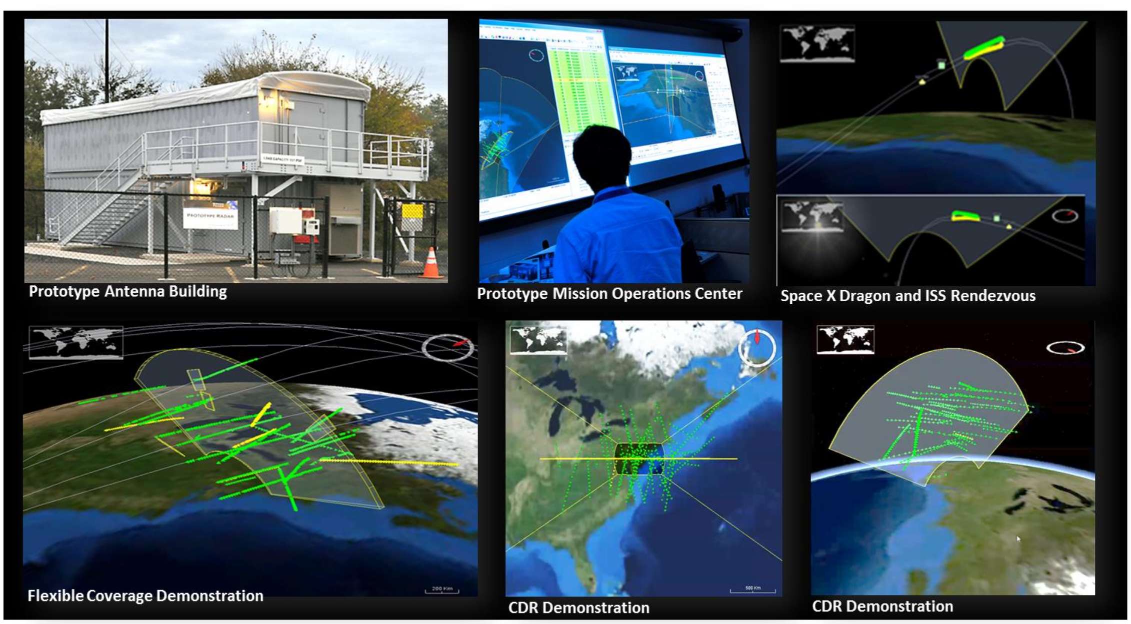


Fig. 17. A Successful End-to-End Prototype Demonstration Was Conducted at CDR in March 2015.

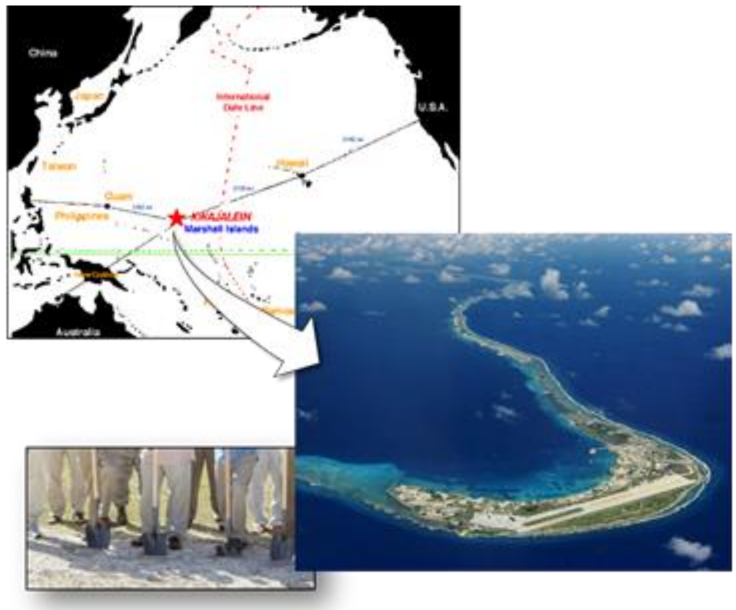


Fig 18. Ground Breaking on Kwajalein Atoll for Sensor Site 1 [8]

5. SUMMARY

Space Fence is designed to address the Space Situational Awareness challenges presented by the growing number of objects in orbit. It is an optimized, low risk and affordable solution resulting from years of trade studies, prototyping and modeling and simulation. The Space Fence solution, based on GaN and element-level DBF, not only provides a robust solution to meet the key LEO requirements, it provides tremendous flexibility for other missions as well. Space Fence is a robust, flexible, advanced end-to-end system that will meet the warfighter's operational needs and revolutionize Space Situational Awareness, starting at IOC in 2018.

6. REFERENCES

1. "Satellite Box Score" and "Monthly Number of Objects in Earth Orbit by Object Type", NASA Orbital Debris Quarterly News, Volume 18, Issue 1, 2014.
2. "Fengyun-1C Debris Cloud Remains Hazardous", NASA Orbital Debris Quarterly News, Volume 18, Issue 1, 2014.
3. "Satellite Collision Leaves Significant Debris Clouds", NASA Orbital Debris Quarterly News, Volume 13, Issue 2, 2009.
4. "STS-126 Shuttle Endeavour Window Impact Damage", NASA Orbital Debris Quarterly News, Volume 13, Issue 2, 2009.
5. "International Space Station Performs Fourth and Fifth Debris Avoidance Maneuvers of 2014", NASA Orbital Debris Quarterly News, Volume 19, Issue 1, January 2015.
6. Linda Haines and Phillip Phu, "Space Fence PDR Concept Development Phase", Advanced Maui Optical and Space Surveillance Technologies Conference Proceedings, September 2011.
7. Bill McShane, "Next Generation Space Surveillance System-of-Systems", Advanced Maui Optical and Space Surveillance Technologies Conference Proceedings, September 2014.
8. US Army Reagan Test Site Media (http://www.smdc.army.mil/RTS.html), July 10, 2015.