INTELLECTUAL PROPERTY
(This section must be signed and returned to Carole.Hedden@AviationWeek.com)

Individuals **outside your company**, including the companies listed above and other third parties, potentially including your competitors and others in your industry, may receive and/or review award submissions. All information submitted should address the program's management, leadership, and processes in a manner that you are comfortable sharing with third parties freely and without restriction, and may not include any classified or proprietary information or materials. Do not include any materials marked Confidential or Proprietary or bearing any similar legend. All responses and other submissions, whether in whole or in part ("Submissions"), shall be deemed not to be confidential, proprietary, and/or nonpublic information of any sort for any purpose.

Without limiting the foregoing, you hereby grant to Aviation Week Network, an Informa business, a perpetual, irrevocable, royalty-free, full paid-up, worldwide license to copy, reproduce, distribute, display, publicly perform, publish, republish, post, transmit, disseminate, edit, modify, and create compilations and/or derivative works of the Submissions (or any portion or excerpt thereof) in connection with its or any of its affiliates' business(es). Aviation Week Network agrees not to edit the Submissions in any way that materially alters their overall substantive meaning. Aviation Week Network may freely assign, license, transfer, and/or otherwise convey any or all of the rights and licenses granted hereunder.

Thank you for participating,

Gregory Hamilton
President
Aviation Week Network

Acknowledged, agreed, and submitted by

Robert Condren

Nominee's Signature — 23 June 2020 Date

Nominee's Name**: Robert Condren**

Title: **Space Fence Program Manager**

Company: **Lockheed Martin RMS**

AVIATION WEEK NETWORK 2020 Program Excellence Awards

NOMINATION FORM

Name of Program: **Space Fence**

Program Leader: **Robert Condren**

Phone Number: **609 760-2876**

Email: **robert.condren@lmco.com**

Postal Address: **Lockheed Martin, 199 Borton Landing Road, Moorestown, NJ 08053**

☒ Customer Approved

- Date: 22 June 2020
- Contact (name/title/organization/phone): Elaine Doyle/Space Fence Program Manager/USAF/617-233-0389

☐ Supplier Approved (if named in this nomination form)

- Date: ____
- Contact (name/title/organization/phone): ____

CATEGORY ENTERED

Refer to definitions in the document "2020 Program Excellence Directions." You must choose one category that most accurately reflects the work described in this application**. The Evaluation Team reserves the right to move this program to a different category if your program better fits a different category.**

Check one

☐ Special Projects

☒ OEM/Prime Contractor Systems Design and Development

☐ OEM/Prime Contractor Production

☐ OEM/Prime Contractor Sustainment

☐ Supplier System Design and Development

☐ Supplier System Production

☐ Supplier System Sustainment

Abstract
Space Fence is nominated in the Program Excellence category to recognize a truly exemplary system design and development effort by a great government and industry team that worked in close partnership to deliver a tremendous radar capability to U.S. Space Force.

As Prime Contractor, Lockheed Martin successfully executed this challenging fixed-price development contract through technical innovation, strong engineering discipline, rigorous program management, extensive supply chain engagement, and outstanding risk/opportunity management. Other key attributes include relentless focus on driving teamwork, communications, and rapid problem-solving during design, facility construction, production, radar installation and integration/test.

In a 27 March 2020 news release, Gen. Raymond, Commander, U.S. Space Command, said "*Space Fence is revolutionizing the way we view space by providing timely, precise orbital data on objects that threaten both manned and unmanned military and commercial space assets*." Space Fence is the next evolution in America's efforts to maintain space superiority.

Purpose
Space Fence, an advanced space surveillance system, was developed to detect, track, and identify satellites and debris in all orbital regimes. Lockheed Martin implemented a flexible element-level digital beam forming radar.

After a challenging construction effort in the remote Marshall Islands, the state-of-the-art radar completed extensive government test and trials. In a 2019 interview, General John Hyten, then U.S Strategic Command commander said of Space Fence: "*I've been out there, and the data is eye watering. It's better than we even thought it would be*."

The world's newest radar is now tracking satellites and discovering objects as small as a marble in low earth orbit. Initial Operational Acceptance was declared in March 2020, initiating a new era of enhanced surveillance with the radar becoming a key contributor to U.S. Space Force's Space Domain Awareness.

Executive Summary: Make the Case for Excellence
Program Vision
The Space Fence program provided the U.S. Space Force Space Surveillance Network (SSN) with a new ground-based radar in the remote Marshall Islands. This game-changing radar, with large hemispherical coverage and enormous simultaneous beam coverage, is a leap-ahead in capability from existing SSN radars with narrow field-of-view. It has been said that the old SSN was like "using a pencil beam flashlight to search a dark attic, while Space Fence will light up the entire room".

Space Fence enables our nation and allies to safely launch/operate satellites by detecting, tracking and cataloging Resident Space Objects (RSOs) including active satellites, derelict satellites, rocket bodies, debris and other threats. It provides satellite catalog completeness, accuracy and timeliness with much enhanced performance in Low Earth Orbit (LEO) and coverage to Geosynchronous Earth Orbit (GEO).

With improved surveillance coverage, sensitivity and timeliness, the system aids in protecting space assets against potential collisions that can intensify the debris problem in space. This benefits military satellites, manned space operations, and, government, allies and partners space-based technologies that have become an integral part of daily life around the globe - such as weather forecasting, banking, global communications and Global Positioning System (GPS) navigation.

The government required Lockheed Martin to deliver a 100% turnkey solution covering:

- Radar Sensor to perform 24x7 hemispherical coverage, surveillance, tracking, tasking, closely spaced object resolution, Radar Cross-Section (RCS) estimation
- Mission Processing for sensor control, tracking, orbit determination, RSO cataloging, net-centric communications, operator controls and displays, event determination - breakup or maneuver
- Facilities Design and Construction including Radar Sensor Site and Power Plant Annex
- Space Fence Operations Center (SOC) in Huntsville, AL.

The radar site was specified on Kwajalein Island (total area of 1.2 square miles) in the Republic of the Marshall Islands (RMI). Kwajalein is 2,100 miles southwest of Hawaii. The site selected to be near the equator and close to the Indo-Pacific region for better visibility into orbiting satellites and coverage of new launches. It is home to approximately 1,000 residents which include military personnel, Army civilians, contractor employees, and family members. The U.S Army Garrison-Kwajalein Atoll (USAG-KA) operates the island as part of the Ronald Reagan Ballistic Missile Defense Test Site. The use of Kwajalein Atoll as a U.S. military facility is made possible through a government agreement with the RMI.

Space Fence is a large and complex radar system with a receive array structure roughly the size of a basketball court and a transmit array structure about the size of a tennis court. The system requires very high hardware reliability/availability and intuitive system controls and displays to support operation.

Space Fence began as a U.S. Air Force acquisition. With the 2020 National Defense Authorization Act and the establishment of the U.S. Space Force as the sixth branch of the armed forces, Space Fence was formally transferred to U.S. Space Force on 20 December 2019. The system is now a key contributor to the U.S. Space Force's Space Domain Awareness enterprise.

Program Unique Characteristics and Properties

The program vision was, by its very nature, extremely challenging. Lockheed Martin chose a bold path by adopting a radar architecture that was a leap ahead in digital control. While inherently high risk, it promised to deliver vastly superior flexibility and coverage. The questions were: Could we make it work and make it affordable? Could we stand up this massive capability on a tiny island in the middle of the Pacific Ocean with an aggressive schedule under a Fixed Price contract?

Lockheed Martin was awarded the Engineering, Manufacturing, Development, Production and Deployment (EMDPD) of the first Space Fence system (officially designated AN/FSY-3) in June 2014. The competitive acquisition mandated challenging Fixed Price Incentive (FPI) type contract terms.

The EMDPD award was the culmination of a competitive prototyping acquisition strategy that included study contracts in 2009-2012 which involved early cost-versus-performance trade studies to shape system concepts, program requirements, life cycle cost estimates and sensor site location. Technology was matured to reduce risk via Modeling & Simulation (M&S) and prototyping. The scale of the system was beyond Department of Defense (DoD) cost models and drove significant interaction with the DoD Cost Analysis organizations to convince government decision makers on the viability of the program. Space

Fence successfully earned the confidence of senior leaders who awarded the competitive development contract in June 2014 despite sequestration challenges and a very resource constrained environment.

Lockheed Martin decided to take the long view on maturing technology. M&S used tactical code vs. abstract mathematical models to predict system behavior. This entailed longer development time that delayed initial results but was more representative of actual system performance and was later iterated through software development and system integration and test. Prototype hardware was built using standard manufacturing production-line processes to ensure a low risk start for the final production build.

Our early demonstration test bed facility in Moorestown, NJ was constructed with a large internal investment and established its first track of a space object in December 2011, initially operating as a 40 element receive (Rx) array and 960 element transmit (Tx) array. We demonstrated scalability and modularity concepts by expanding the array until the prototype system had grown to 1,536 elements in both Rx and Tx in 2012. Representative hardware was in every portion of the end-to-end system including antenna, signal processor, mission processor, facilities array structure, cooling, monitoring, and radome. The full-scale EMDPD radar was massive compared to the first prototype and included very large-scale Rx and Tx arrays.

Moorestown Test Bed – February 2012

The digital radar concept required advanced design features to cost-effectively achieve detection and tracking with thousands of simultaneous radar beams from a single digital array system. Element-level digital beamforming controlled each of the individual dual-polarized Rx elements and Tx elements.

The Rx elements are digitized before creating any beam patterns pointed in a specific direction. Beamforming is a mathematic exercise executed by software on the array to look in as many directions as desired during one single radar-return time period; i.e. we form thousands of simultaneous beams in multiple directions. Instead of spending time to perform dozens of radar operations serially, it can now be compressed into one radar receive time interval. This approach results in a reduced antenna aperture size over other beam forming architectures while supporting rapid timeliness due to simultaneous operations.

The software-defined antenna architecture was unique and represents a huge computing machine. The Rx array is comprised of many thousands of Field Programmable Gate Array devices and ranks among the world's large super computers with processing above the Peta Operations/second level. The Rx elements were supported by low-cost high-density dual-polarized Radio Frequency Integrated Circuit (RFIC) based receivers. The on-array receivers and beamforming approach reduced cabling and off-array processing.

Disciplined systems engineering and trade studies were key to ensuring an effective and affordable solution. A major focus was reducing power-aperture (size and thus cost of radar) since at the scale of Space Fence, an extra decibel (dB) of radar power-aperture can result in $10M of acquisition costs and an extra megawatt of power consumption. To reduce system losses, the separate Tx and Rx antennas were adopted to permit independent optimization of Tx and Rx circuit paths. Low receiver noise figure was achieved by reducing Rx array temperature by physical isolation from hot Tx electronics. Array shapes were complementary and optimized for low sidelobe levels with reduced aperture weighting losses. Simultaneous reception of primary and orthogonal polarizations improved radar detection and the complementary polarizations reduces track fades on complex tumbling objects in orbit.

Numerous mechanical and environmental challenges were addressed. Antenna arrays required very tight mechanical level and flatness tolerances across the two very large Tx and Rx arrays. Air-supported radomes over each array significantly reduced signal losses over an alternate rigid radome design.

As with any new system development, life cycle cost was a major focus and a robust Design to Cost effort was executed to ensure affordability. Careful trade study and affordability initiatives reduced the costs of acquisition as well as the Operations and Maintenance (O&M) costs of the radar. The optimization of the separate Tx and Rx arrays considered both acquisition and O&M costs in the analysis. A novel power architecture with efficient solid state transmit modules and a unique capacitor-based system with enormous energy storage capacity supports very long transmit pulse widths at high duty. Single stage AC/DC power conversion avoided multi-stage DC-DC conversion loss for high efficiency.

A simple maintenance concept was vital to minimize manning and long-term support cost. The extremely large radar and complex facility required easily assessed performance, rapid identification and isolation of failures, and redundancy in all system elements to avoid single points of failure. Trained operators maintain the system without on-site engineering experts.

Producibility of the radar was a risk since it involved a huge production volume in a very short time interval. In small quantities, Lockheed Martin completed initial "Proof of Design" and "Proof of Manufacturing" builds before release of the full rate production. These incremental builds validated the final design and manufacturing processes and helped avoid latent defects later in the production flow. It reduced the chance of costly rework and schedule impacts from late discovery of producibility issues.

Massive buildings were purpose-built to meet radar mechanical and environmental requirements in tropical temperature/humidity and the stringent "Pacific Ring of Fire" seismic environment. There were tough working conditions and weather challenges with heavy trade winds, tropical windy season and heavy annual rainfall of 100 inches which is extreme when compared to Seattle at a mere 38 inches.

Logistics planning was critical to ensure material was on hand… "*if you didn't bring it with you or ship it ahead of time, you won't have it!*". Executing a U.S. Air Force program on a U.S. Army base also added an extra layer of rules and decision-making outside of Lockheed Martin's direct control. There was no available labor pool on site and all personnel entry needed to be approved via an Army process. Lockheed Martin had to manage housing and dining on Kwajalein and employee care and well-being were critical. Groundbreaking and excavation periodically were interrupted after discovery of artifacts from World War 2 including human remains and unexploded ordnance. The radar site was also near the Kwajalein aircraft landing strip which complicated construction and system integration and test activities.

In summary, Space Fence was an enormous effort encompassing the design, development, production and fielding of a very large and complex system. Construction on a remote island was a giant undertaking and Lockheed Martin needed to ensure the facility and radar would perform as predicted when scaled to full size. After the Lockheed Martin Contractor Test period, the customer completed a successful government Developmental Test (DT) performed by the 45th Test Squadron and an Operational Test (OT) performed by Air Force Operational Test and Evaluation Center (AFOTEC). A successful four-month Trial Period with Space Command was subsequently completed with the operational community. The IOC declaration is the culmination of a major engineering feat that will benefit the international space community and global economy. Space Fence enhances Space Domain Awareness and supports future Space Traffic Management. Longer term, it will assist the proliferation of new mega-constellations as space-based activities rapidly expand to support global prosperity and security around the world.

VALUE CREATION

Program Value to Corporation Beyond Profit and Revenue

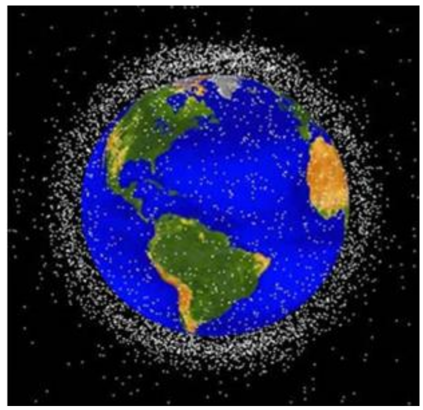
Space Fence was an important customer priority in the solid-state radar market. It became a national concern as space continued to grow more congested and contested. It also represented an opportunity to apply advanced concepts and leap-ahead technologies into a fielded product of major significance – the essence of a technology company executing a forward leaning vision to support customer needs.

Space Fence is the next major step in the evolution of Lockheed Martin's radar technology roadmap. It utilizes Radio Frequency Integrated Circuits (RFICs) in the receiver chain, eliminating hundreds of thousands of discrete parts, reducing cost and complexity while improving performance and reliability. Space Fence technology is now feeding back to other Lockheed Martin antenna programs. The construction effort also enhanced our expertise and credibility building large special-use facilities at austere sites, which benefit other Lockheed Martin ground-based projects in remote areas.

The complex program was an opportunity to leverage expertise across the corporation to deliver a much-needed sensor capability to the nation and global space community. It is a major point of corporate pride.

Program Value to the United States Air Force (USAF) / Space Force (USSF)

With the congested, contested and complex environment in space, new capabilities were vital to maintain current operations and address emerging requirements beyond the existing capabilities of the SSN.



"*Space Fence is revolutionizing the way we view space by providing timely, precise orbital data on objects that threaten both manned and unmanned military and commercial space assets*," said Gen. Jay Raymond, Commander, U.S. Space Command, in a Space Force news release. "*Our space capabilities are critical to our national defense and way of life, which is why Space Fence is so important to enhance our ability to identify, characterize and track threats to those systems*."

According to Space Force, the system is the most sensitive search radar in the SSN, capable of detecting objects in orbit as small as a marble in LEO. The new radar is now providing a key tactical advantage to our warfighters in the space domain by improving the quantity and quality of orbital information to support our national security interests in space.

With ruthless focus on cost, the program executed well below the initial cost estimates. According to the most recent General Accounting Office (GAO) Weapon Systems Annual Assessments, Space Fence program cost performance consistently executed below the June 2014 starting estimate. The government program office returned significant budget based on positive program performance and ended well below the original estimates from the Department of Defense Cost Assessment and Program Evaluation (CAPE) organization. As reported to Congress, in the Selected Acquisition Report (SAR) dated Dec 2019:

SAR December 2019	Base Year	Then Year
CAPE estimate ($M)	$1,567.7	$1,594.2
Current program ($M)	$1,437.6	$1,446.3
	8.3% below	9.3% below

Program Value to Members of the Lockheed Martin Team

Space Fence was a highly sought-after assignment with diverse engineering challenges, a clear need for the capability and great meaning to our country. The broad scope of the program and technological challenges ranged widely across many engineering disciplines. The program included many technology "firsts" including a leading-edge radar architecture with element level Digital Beam Forming (DBF). The array digital processing ranks among the world's largest super computers with processing above the Peta Operations/second level. Analysis of satellite behaviors across all orbital regimes supported tracking of known objects and discovery of interesting new objects with complex inclinations and eccentricities.

It was also an exciting once-in-a-lifetime opportunity to work at a remote Pacific site and deliver the state-of-the-art phased array radar to the warfighter. The team was attracted to the appeal of an interesting work/life experience in a tropical location in the middle of the Pacific Ocean with access to water sports, sailing, fishing and a welcoming island community on a strategic U.S. military installation.

Program Contribution to the Greater Good

Life on earth is intricately connected to operations in space, from the mundane day-to-day activity (voice communication, social media, and entertainment) to the critical backbone of society such as finances, navigation, and emergency communications. Space Fence will aid in safer satellite operations amid the growing amounts of objects and space debris orbiting the Earth.

In the early days of the space era, most countries felt safe launching rockets and operating satellites under the "big sky" concept. According to the theory, space was so vast that one more satellite in orbit had little or no chance of colliding with another. Today, many countries operate in space and the environment is increasingly crowded with active satellites as well as enormous quantities of debris. According to a recent NASA Orbital Debris Quarterly News, NASA calculates about 17.6 million pounds of objects are in earth's orbit and increasing with more commercial constellations and small satellites. Major events in the news included the 2009 Iridium/Cosmos collision and Chinese/India antisatellite events which created large debris fields in orbit and underscore the growing challenges in space. Traveling at speeds upwards of 15,000 mph, debris threatens not only commercial satellites, but also military assets that help monitor and protect nations around the world. Debris add risk to future plans for large satellite constellations such as the commercial SpaceX Starlink mega-constellation and future elements of the space defense layer.

METRICS

Program Metrics

Wide ranging metrics played a critical role in program success and spanned across program activities to facilitate informed decision-making and identify key opportunities to improve outcomes.

Space Fence maintained a comprehensive metrics program for planning, controlling, and executing the contract. The process was compliant with Capability Maturity Model Integration (CMMI) Level 5 and Lockheed Martin Command Media. CMMI Level 5 drive process consistency and affordability, with quantitative measures that allow insight into system development, integration and test. Measurement activities supported government needs, program control, and organizational business goals.

Space Fence established and tracked goals on program metrics. Quality and Process Performance Objectives (Q&PPOs) were established for product quality, service quality, and process performance. Q&PPOs were derived from various input sources in conjunction with relevant stakeholders and organizations. Program measures included customer required metrics such as software quality, defect open/closure rates and productivity as well as internal "Lockheed Martin Headlight" metrics.

The Headlight metrics are leading indicators in key areas that can be utilized to forecast future performance based upon current and past performance. They included items such as staffing measures, Management Reserve (MR), requirements stability and To Be Determined (TBD) requirements. MR was controlled at the overall program level and distributed to fund high priority needs and ensure resources were applied to vital risk-mitigation and key opportunity-capture efforts. Our strategic distribution of MR was representative of a meaningful commitment to the success of Lean and Six Sigma initiatives.

Disciplined Performance Management focused on schedule, Critical Path analysis (first, second and third critical paths), and included robust monthly Schedule Risk Assessments (SRAs). The Monte Carlo based SRA utilized a schedule risk assessment on each task. The "Risk Factor" assigned was based on a decision tree designed around the major types of schedule duration risk:

- Task types were assessed (deterministic, routine or developmental)
- Past experience was categorized (experienced or inexperienced)
- Technical difficulty was assessed (low, moderate or extreme)
- Resource supply was also considered (abundant, limited or dependent)
- Likelihood of resource conflicts was also assessed

SRA assessments by tasks were made by the individual Control Account Managers on the durational risk. Multipliers in the SRA model were drawn from company experience and the SRA tool determined Minimum, Most Likely, and Maximum durations (optimistic, natural, pessimistic). The SRA provided leadership with analysis to support informed decision making, improve forecasts and support decisions to add labor resources on high risk tasks or use expensive charter air flights to expedite vital material.

SRA results were openly shared with the government throughout the lifecycle of the program. Col. Stephen Purdy, then Director, Space Superiority Systems Directorate (SMC/SY) at Los Angeles Air Force Base commended the rigor and application of the SRA process to manage risk and improve schedule forecasting. As a result, our 2018 Contractor Performance Assessment Report noted that "*The LM Schedule Risk Assessment (SRA) process was recognized as a best practice by SMC/SY*".

The overall system performance model was tracked every step of the way as elements of the system were produced in initial quantities and tested to validate performance models. System performance margin was held at the top level and managed along the way as the team completed individual component design, subsystem development, test and verification. Engineers were directed to design elements with essentially zero margin, with the understanding that margin was held at the system level and would be distributed if required during system integration. This avoided the compounding costs of overly conservative design stack-up. An early success was the challenge to reduce the Rx array from 100,000 elements in the proposal baseline to 86,016 elements, which captured $15M in MR.

Rigorous material and Line of Balance tracking along with extensive production metrics were utilized as the program managed more than 450 suppliers and the radar manufacturing spread across five major Lockheed Martin factories. The Production Operations team maintained a technical performance measure dashboard for the key strategic hardware elements. With its continuous update, subject matter experts could review data daily to understand trends and update radar performance models.

Constant updates were also made to the Life Cycle Cost (LCC) model as the performance prediction was validated incrementally. The final Tx/Rx antenna scaling was optimized, and a very low radar power consumption was achieved. This configuration provided the required radar sensitivity with the least power draw while still maintaining a small margin. In the end, the system used <80% of the input power requirement which provides a huge LCC benefit.

DEALING WITH PROGRAM CHALLENGES (VOLATILITY, UNCERTAINTY, COMPLEXITY, AMBIGUITY, OR VUCA)

Program Challenges: Overall VUCA Faced by the Program

As prime contractor, Lockheed Martin faced many degrees of volatility, uncertainty, complexity and ambiguity (VUCA) to complete system design, facility construction, hardware production, radar installation, software development and system integration and test in the middle of the Pacific Ocean.

The overall system requirements drove a complex solution to provide assured radar coverage for LEO and flexible coverage for all orbital regimes up to GEO. This required radar operation with thousands of simultaneous beams for detection, tracking and tasking from a single array, complex Mission Processing software for near-real time control of the radar, as well as scaling of legacy government astro-dynamics standards and libraries to very large catalog sizes.

The radar solution was highly innovative, eye-watering technology but involved great technical development risk. Element-level digital beamforming provided full hemispheric coverage and long arc tracking to determine accurate orbits. Early company investment matured key designs to Technology and Manufacturing Readiness Levels (TRL6/MRL6) but producibility and maintainability remained a risk.

Lockheed Martin held significant commercial risk while executing the fixed price contract. As prime contractor, Lockheed Martin managed a very large and complex supply chain on a demanding schedule. Fortunately, the scalable architecture easily supported the building-block approach and enabled incremental system development to "*build a little, test a little and learn a lot*". An important execution strategy was established in the proposal with an Integration Test Bed (ITB) in Moorestown, NJ. This was not a firm contract requirement but a major discretionary expenditure that reduced risk with early testing in Moorestown of a 3% subscale radar version of the Kwajalein radar. The ITB test of representative end-to-end hardware identified issues early and reduced risk. The architecture also enabled a similar incremental approach at site as the radar hardware was incrementally shipped, integrated and tested.

Facility design and construction was incorporated into the prime contract with no Military Construction (MILCON) components. Construction, installation, integration, and test of a system in a remote location introduced many aspects of volatility, uncertainty, complexity and ambiguity. Long material shipment time, limited on-island logistic support and personnel travel planning was challenging due to strict U.S. Army Garrison regulations, limited commercial/military air transportation and export regulations associated with the Marshall Islands location. The U.S. Army imposed a formal process for visit approval which constrained personnel access and required careful planning. Numerous second tier and third tier subcontractors deployed to Kwajalein and the radar installation and test schedule was at great risk with every delay in facility construction and outfitting. Site schedules were also impacted by Army/Missile Defense Agency Mission Freezes, tropical weather (rain, trade winds, and windy season conditions) and Differing Site Conditions from sub-surface discoveries including human remains, unexploded ordnance, and buried materials and debris. Authorities Having Jurisdictions (AHJs) spanned from the U.S. Air Force, U.S. Army Garrison-Kwajalein Atoll, U.S. Army Corps of Engineers with unclear boundaries and limited Air Force control. The dividing lines between Prime Mission Equipment and Real Property Installed Equipment (RPIE) were complex.

Program Challenges: Specific Examples and Program Response

Numerous challenges were addressed to complete system design, facility construction, hardware production, radar installation, software development and system integration and test.

Space Fence requirements for assured coverage for LEO and flexible coverage for all orbital regimes required a complex system solution. A great team of talented designers and analysts developed the software builds incrementally in a high-fidelity Modeling & Simulation environment. Radar and mission algorithms were matured in a representative environment initially with simulation and then tactical code followed by end-to-end testing using the Moorestown ITB facility as a live radar feed with a radar that was 3% of the full system. The government's Performance Assessment Simulator provided stressing scenarios to exercise software with the ITB and then the full system on Kwajalein.

Massive amounts of radar data were analyzed to confirm system performance. The Massachusetts Institute of Technology / Lincoln Laboratory (MIT/LL) Nyx environment for real-time space object processing was netcentrically connected with the ITB. MIT/LL received ITB data and the netcentric feed facilitated data transfer with rapid analysis that was vital to algorithm refinement and continued system tuning. A close relationship was established with MIT/LL with strong communications and regular working group meetings to evaluate performance and discuss system refinements. The joint team subsequently presented many well-received papers at key radar conferences and industry events.

Lockheed Martin held significant commercial risk while executing the fixed price contract and the team worked through daily challenges with great agility. The radar design, development and production held significant risk with digital beam forming development and large hardware builds.

The supply chain was complex and challenging. Shortly after contract award, the radar team lost two key suppliers in the proposal baseline after IBM sold a product line to a Chinese company and a selected power supply company refused to honor contract terms. This required rapid action to quickly establish qualified alternates. High-volume production created challenges for key suppliers including antenna radiators, power components, mechanical assemblies and cabinets. The large and diverse supply base was stressed when producing simple parts such as springs or cables in very high volumes. Complicated components, such as radiating tiles and cold plates, required additional design and test before production.

The key to managing the supply chain was a strong Subcontract Management Team (SMT) approach with dedicated Program Management, Engineering and Sourcing representation to ensure management discipline, engineering process control and supplier success. Our high energy Master Black Belt engaged with Lean and Six Sigma tools to solve issues and drive program excellence in the supply chain.

Material shipments to the remote Marshall Islands were challenging. Hundreds of thousands of items for export were carefully coordinated and tracked. Shipments utilized the Port of Los Angeles as a collection point to efficiently pack containers for transport. Shipping containers included instruments to verify shock and temperature in transit. Large amounts of material including 1,600 tons of steel were shipped without major issues. A total of 55 standard forty-foot shipping containers were required for the bulk of the radar equipment. High cost air shipments were limited to vital deliveries to protect critical path.

Construction, installation, integration, and test of a system in a very remote and distant location introduced many aspects of volatility, uncertainty, complexity and ambiguity. In addition to the radar, the prime contract included the site and facility design, construction, outfitting and commissioning with a variety of AHJs. A dedicated leadership team in Moorestown and on Kwajalein worked 24/7 to drive progress and solve problems. The Facility Subcontract Management Teams (SMTs) with program management, engineering and sourcing were augmented with additional project engineers and subject matter experts on Kwajalein. Lockheed Martin senior executives also met regularly with their counterparts at major subcontractors to discuss supplier performance, issues and program priorities.

Site preparations on Kwajalein ramped up rapidly after contract award with site surveys and large shipments of equipment and materials to support site preparation. More than 100 million pounds of soil was processed on the construction sites. A batch plant was erected to process over 16,000 cubic yards of concrete. A housing camp and dining facility was also established to accommodate up to 250 workers due to lack of Army base capacity. Discovery of unknown conditions was a constant challenge during the early site preparation phase. Historic artifacts uncovered from World War 2 included human remains, weapons and Unexploded Ordnance (UXO). Our on-site team included a trained archeologist who rapidly assessed and adjudicated cultural discoveries with the U.S. Army and Republic of the Marshall Island officials. A large abandoned underground foundation was also encountered at the power plant annex site. The new PPA foundation was rapidly redesigned and additional fill material barged into Kwajalein to raise the PPA elevation and avoid disturbing the buried structures.

As prime contractor, Lockheed Martin managed over numerous second tier and third tier subcontractors who deployed to Kwajalein with varying supplier performance. As delays were experienced in one area, agility was required to work around issues up, down and across the program. Schedule was protected by overlapping construction, outfitting and commissioning of the facility/power plant with the radar hardware installation and test. Our Master Scheduler maintained an Integrated Master Schedule (IMS) and routinely worked on Kwajalein to analyze/improve the subcontractor IMS and conduct schedule risk assessments. Our Master Black Belt and Master Scheduler ran numerous on-island Structured Improvement Activities (SIAs) to mitigate risks and develop opportunity strategies. The program used the Corporate Facilities expertise to strengthen facility design/construction strategies. We also engaged Lockheed Martin Aeronautics to model and design protective wind barriers to permit successful installation of the large radomes during the very challenging tropical windy season.

As activities were coordinated with U.S Army Garrison-Kwajalein Atoll (USAG-KA), collaborative relationships developed between Space Fence and the USAG-KA operations. Joint planning was vital around mission freezes. Areas of bilateral support grew to eventually include the USAG-KA paint shop and calibration lab and Lockheed Martin heavy equipment and supplies. Temporary power from USAG-KA also allowed radar test to work around early Space Fence Power Plant Annex (PPA) issues. The Army even utilized the PPA to support the island when the USAG-KA Kwajalein Power Plant had issues. The USAG-KA Hourglass weekly community newspaper highlighted Space Fence achievements.

Collaboration was key to forward progress. Various AHJs were responsible for enforcing the requirements of codes or standards and included Air Force organizations, USAG-KA and Army Corps of Engineers with limited Air Force control and some unclear boundaries. Strong communications and many face-to-face meetings were vital to AHJ engagement and helped clarify requirements uncertainty on the demarcation between Prime Mission Equipment and Real Property Installed Equipment (RPIE).

Network communications and security required numerous government approvals and compliance to dynamic cybersecurity requirements. This required agility, patience and a badge-less approach to jointly solve problems to establish secure high-speed communication networks from the radar site on Kwajalein through the wider enterprise to the Space Fence Operations Center in Huntsville, AL. USAG-KA approval to transition into classified operations was also challenging and we protected schedule by maximizing unclassified system testing until the final authorization for classified operations at site.

A key leadership focus was the safety, health and well-being of the Space Fence team on Kwajalein. We drove a safety-minded culture with regular team training, posted signage and frequent reminders. We achieved an exemplary safety record with no fatal accidents or broken bones and only minor incidents. Food service and housing was a priority to our 250 people, and we delivered 500,000 meals at the Space Fence dining facility. The workers greatly appreciated extra effort at holidays to provide special meals and holiday cheer. Team-building events and executive visits to the island also served to boost morale.

Many skilled design and test engineers with little international travel experience were needed on Kwajalein to support the test program. Informational briefings, incentives, training, indoctrination and support were provided to facilitate individual travel and family transfers to Kwajalein. This enabled the team to safely transition to site and work and thrive in a challenging environment. The skills of our long-term team of system operators were also developed. The island staff is agile and has been cross trained to perform in multiple roles. This has paid dividends since the COVID-19 travel ban was recently imposed by the Marshall Islands and we continue to operate this critical system with the team.

ORGANIZATIONAL BEST PRACTICES AND TEAM LEADERSHIP

Unique and Innovative Practices, Tools and Systems Helping to Achieve Program Excellence

Lockheed Martin's approach to program excellence on this massive fixed price development contract revolved around three pillars: 1) Relentless Focus on Affordability and Operational Excellence, 2) Disciplined Program Performance Management and 3) Strong Customer Relationships.

We maintained a Program-wide Focus on Affordability and Operational Excellence. The rigorous cost focus enabled a truly innovative technical solution. During the early phase of the program, the government commented that they were surprised that Lockheed Martin *"had the courage to propose an element-level DBF solution on this enormous scale."* This decision was enabled by a commitment to an affordability strategy by Lockheed Martin leadership and all program Integrated Product Teams (IPTs) to establish a wide structured affordability and program excellence approach. It included an Affordability Leader (Master Black Belt), Life Cycle Cost (LCC) engineering, and Corporate Engineering and Technology Office (CETO) resources to coordinate and support the effort in concert with LCC goals. A formal Affordability Management process and status meetings were key to system development.

The process applied a cycle of rigorous cost analysis, value assessment and reduction opportunities that resulted in design and process changes to achieve lowest cost with highest value. Affordability activities spanned across all areas of the program from design to production and extended into our subcontractors and teammates. Our Affordability activities included collaborative workshops that served as mechanisms for innovation, improvements, and decisions. Affordability reviews were held to document, status and drive results seamlessly into the Space Fence proposal and contract baseline. The effort reduced radar acquisition costs and drove down life cycle costs to meet challenging Design to Cost goals. This passion and commitment were carried into the program operational excellence strategy for contract execution.

Strong Program Performance Management and Process Discipline were the program standard. Space Fence embraced Capability Maturity Model Integration (CMMI) Level 5 Engineering Discipline. We used Model Based Systems Engineering (MBSE) to develop extensive architectural models in Rhapsody. The well-defined interfaces and "use cases" were developed early to set the path for detailed design to support system requirements. Traceability continued to low levels of the design. The software team also used agile methodologies and relied on Atlassian tools to deliver over one million lines of code.

Disciplined Performance Management ensured accountability, management rigor, and process discipline. There was persistent focus on a strict Earned Value Management System, Integrated Master Schedule and critical path analysis, milestone forecasting and cost performance. Robust risk and opportunity management was coupled with the Lean and Six Sigma efforts to mitigate risks and capture opportunities.

The strong business rhythm strategically managed resources. MR funding of high impact / high pay-off discretionary efforts enabled the team to mitigate risks and capture opportunity. Our high energy Master Black Belt was a key member of the leadership team and drove the team to hold SIAs and embrace Lean and Six Sigma tools and methodology. Disciplined use of Root Cause and Corrective Action (RCCA) fishbone analysis tools addressed major issues or challenges. The Master Black Belt maintained a dashboard of SIA activities and upcoming plans across all IPTs for regular leadership review to oversee progress and drive discretionary SIA events across the IPTs.

Strong customer relationships were a priority focus. The government and industry teams operated as partners and maintained strong horizontal and vertical communications. The talent in government and industry shared a common vision and were able to specify, design, build and test a superior system while demonstrating agility to work around every issue that came up. Communication was supported with scores of formal Working Groups and Technical Interchange Meetings and regular informal tag-ups. Daily meetings were held to drive progress during the most critical phases.


Site Groundbreaking – February 2015

Industry and government leadership held formal groundbreaking events at the Kwajalein Sensor Site and Moorestown ITB site. At the senior level, there were frequent executive meetings between Lockheed Martin, Department of Defense, and major subcontractors. Ribbon cutting events also celebrated the opening of the ITB and Space Fence Operations Center in Huntsville, AL.

The program conducted joint risk review boards to discuss joint risks and mitigation strategies. Key risk mitigation activities were developed for action. Lockheed Martin also arranged independent customer surveys with senior government stakeholders to solicit actionable feedback and drive program excellence.

<u>**Unique and Innovative Practices to Develop People and Transfer Knowledge**</u>

Lockheed Martin embraced full spectrum leadership strategies to engage employees and customers to effectively plan and execute Space Fence as the very large effort involved many government stakeholders and a team of more than 2000 employees across all functions (program management, business operations, engineering, logistics, and production) and numerous geographical site locations.

The program maintained a positive people-focused culture with strong communications. Program start-up included internal kickoff meetings and employee indoctrination sessions. Informal "Meet and Greet" sessions and "All Hands" meetings brought the teams together on a regular basis. In addition to the formal business rhythm, teambuilding included recognition events as well as no-host socials with the government team to strengthen relationships. Space Fence team newsletters were distributed to the employee population to provide status, priorities and best practices/lessons learned to improve efficiency.

Leadership inspired passion about the mission and grew talent. Space Fence "All-Hands" meetings were coordinated with government executive visits to Lockheed Martin facilities and key supplier sites so leaders could engage with the larger team, recognize successes, share perspectives and discuss the criticality of the mission. Mentorship/coaching initiatives were promoted. The team welcomed college engineering interns and created leadership development assignments. One very early addition was Mr. Greg Fonder who joined the program in the initial concept phase as the Lead System Analyst and his early success on cost-versus-performance trade studies and affordability led to his recognition by Aviation Week and Space Technology on their "40 under Forty" list of emerging talent in 2014.

Large team surveys were also conducted by Corporate Internal Audit to gauge communications and employee engagement. The results were viewed as exceptional with responses above the corporate average on all 30 standard survey questions, and one-third scored in the 90th percentile.

The Lockheed Martin ITB and software labs helped develop people and transfer knowledge. The ITB validated operation/maintenance concepts and supported modeling and simulations efforts, software development and final system end-to-end tuning. During system test on Kwajalein, the radar system engineers made numerous improvements to radar algorithms. These improvements were evaluated in MATLAB® models and run against real-world raw radar data collected from the sensor site. Once improvements operated in MATLAB®, they were implemented in software and evaluated by automated regression testing. The improvements were then verified in the ITB radar environment to ensure a high-quality product was delivered to the Sensor Site. The strong process discipline demonstrated an effective use of engineering subject matter expertise and available test assets distributed around the company to tune the system.

User Evaluation Periods (UEPs) also played a key role to transfer knowledge to system designers. Multiple stakeholder events were held in our Colorado lab to validate Graphical User Interface (GUI) concepts and refine evolving designs for system control and displays. To satisfy users, the team had the foresight to include budget on the fixed price contract to implement GUI changes requested at the UEPs.

Lockheed Martin hosted scores of government Working Groups/Technical Interchange Meetings with sessions focused on requirements, radar, facilities, software, test, and logistics. This enabled government-to-contractor dialogue and ensured common understanding of requirements and expectations from the operational community to designers. We also attended external events such as the government's Space Surveillance Network (SSN) Metrics IPT meetings to better understand and educate the SSN community.

Lockheed Martin, as Prime Contractor, also established a common collaborative environment across multiple development locations and subcontractors. Using network/web enabled tools such as SharePoint, DOORS®, and Atlassian Jira, over 100 engineers from multiple, geographically locations were able to work with a common set of requirements and collaboratively design their respective components that "plugged" into the larger system design. Government access was also provided.

Lockheed Martin production operations team drove Lean and Six Sigma. "Operations Excellence Teams" were deployed to drive a Continuous Improvement Program focus on the factory floor to reduce defects and assembly hours/unit. Production operations also launched a Yellow Belt program which was initiated in our Clearwater, FL manufacturing facility as an expansion of Lockheed Martin's Operating Excellence program. This effort expanded Lean and Six Sigma principles to the touch labor population and was recognized as an Observed Area of Excellence during a Corporate Internal Audit of Space Fence.

Unique and Innovative Practices to Engage Customers

The partnership between the government and contractors and the many talented people across the program who shared a common vision were major enablers for overall program success.

The Space Fence commitment to partnership was the foundation of the program. The Lockheed Martin and government leadership envisioned a collaborative approach to contract execution and held a two-day Acquisition Program Transition Workshop (APTW) immediately after the Post Award Conference in July 2014. The APTW process is viewed as a "Best Practice" by the Defense Acquisition

University and was enthusiastically supported by the Space Fence program. It provided a structured process to drive teamwork, collaboration, communication and trust. It helped synchronize startup activities, establish lines of communications and refine longer-term plans for execution. Facilitated by a high energy Master Black Belt from Lockheed Martin's Lean Six Sigma team, it drove alignment between government and contractor teams. The outputs included a Team Charter to foster partnership, collaboration and transparency.

Lockheed Martin engaged customer organizations and promoted partnership. The spirit of partnership was reflected in the leadership agreement to exchange draft contracts letters to highlight emerging issues or concerns. This empathetic approach avoided surprise and permitted some issues to be immediately addressed or initiated critical discussion to clarify concerns. Controversial issues were handled professionally, and emotional adversarial reactions were reduced.

Mutual trust developed as the government participated in internal radar briefings to Lockheed Martin leadership. This improved information flow about emerging issues and action plans but required a customer with enough savvy and experience to participate without overreaction. The process worked effectively, and the team benefited from government ideas and suggestions. Strong communications were maintained between software teams. Internally, the Atlassian Jira product was used for project tracking and issue management. The government was provided Jira access, and this facilitated full transparency and unprecedented insight into the software development activities, peer reviews and defects.

Mr. Frank Kendall, Under Secretary of Defense for Acquisition, Technology and Logistics (AT&L), believed this joint software development process should be heralded as a Best Practice. He recommended Space Fence as a case study at the Defense Acquisition University (DAU) since it provided unparalleled insight into the software development, well beyond what is provided by monthly metric reporting.

System Verification was structured with the government to address requirements as early as possible via an incremental approach. The modular and scalable architecture drove efficiency and lowered risk by accelerating test activities and reducing the test time required with the full end-item system. The In-Plant Contractor Test in Moorestown verified system requirements early with end-to-end software running with live satellite tracks from the ITB. The In-Plant effort addressed more than 63% of system requirements and completed ahead of the formal testing on Kwajalein to reduce the final test time. On-Site Contractor Test was also executed incrementally to drive requirements verification ahead of full system configuration being in place. This provided the test team with flexibility to successfully work through a myriad of complex issues ranging from some final radar hardware delays (late power supply shipments) and lengthy approvals of the final facility security measures by USAG-KA.

IOC declaration on 27 March 2020 was the culmination of a great system design and development effort by a dedicated government and industry team that worked in close partnership to deliver a tremendous new capability to U.S. Space Force. A Gen Raymond tweet recognized the milestone and called out the program partnership: ***Great teamwork w/our partners @Lockheed Martin and @AF_SMC and @Pete AFB to achieve this milestone...***