Space Fence: A Cost Analysis Success Story

Rick Garcia (rgarcia@spa.com)

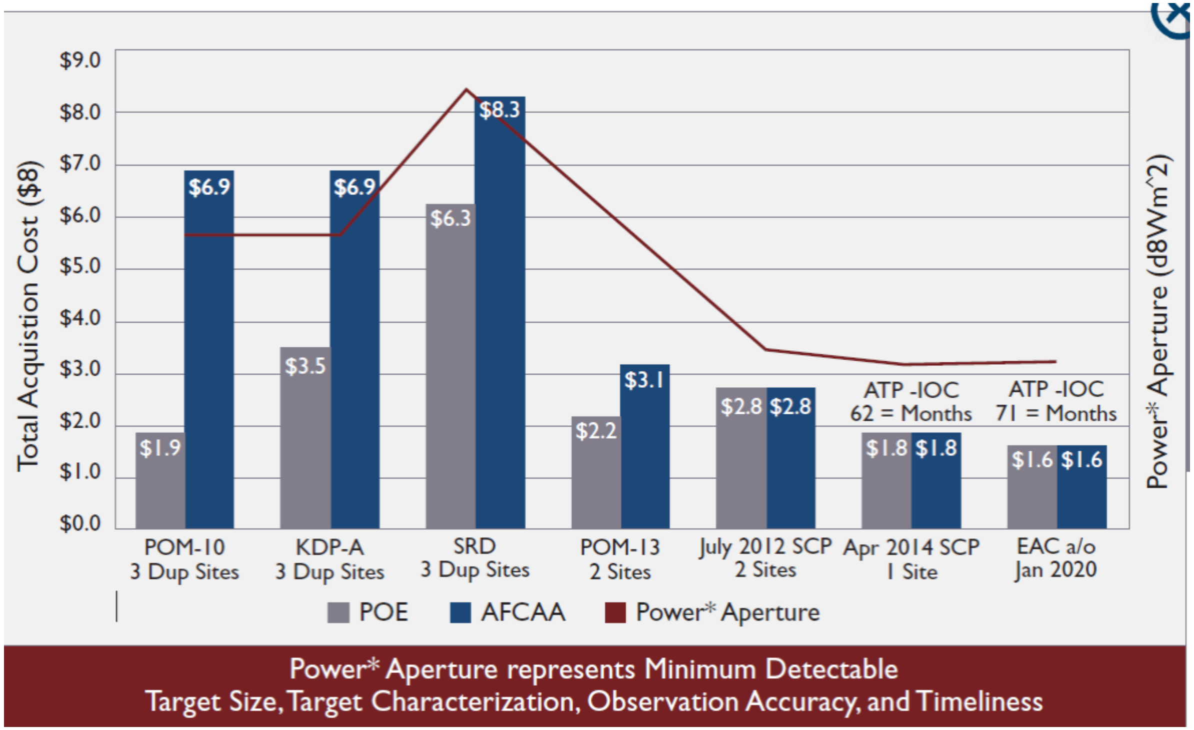
Fellow for Cost Estimating and Analysis

14 May 2024

Agenda

- 2020 SAF-FM Newsletter Space Fence Article
- Space Fence Overview
- Programmatic Overview/Timeline
- Challenges
- Solutions
- Results
- Conclusion

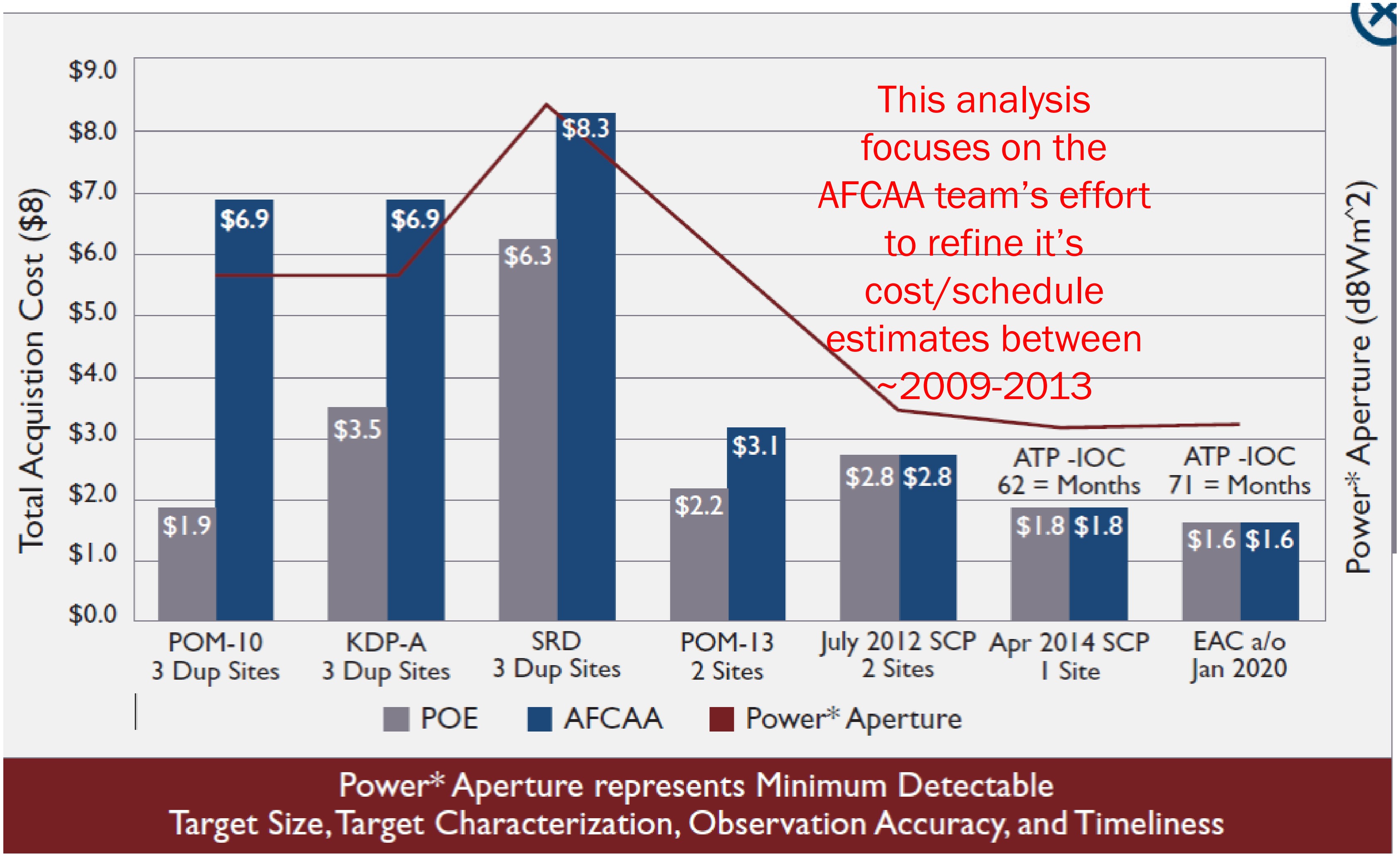
2020 SAF-FM Newsletter Space Fence Article – Authored by AFCAA



Excerpt from SAF-FM Online Newsletter, June 2020, Volume 16, Issue 5

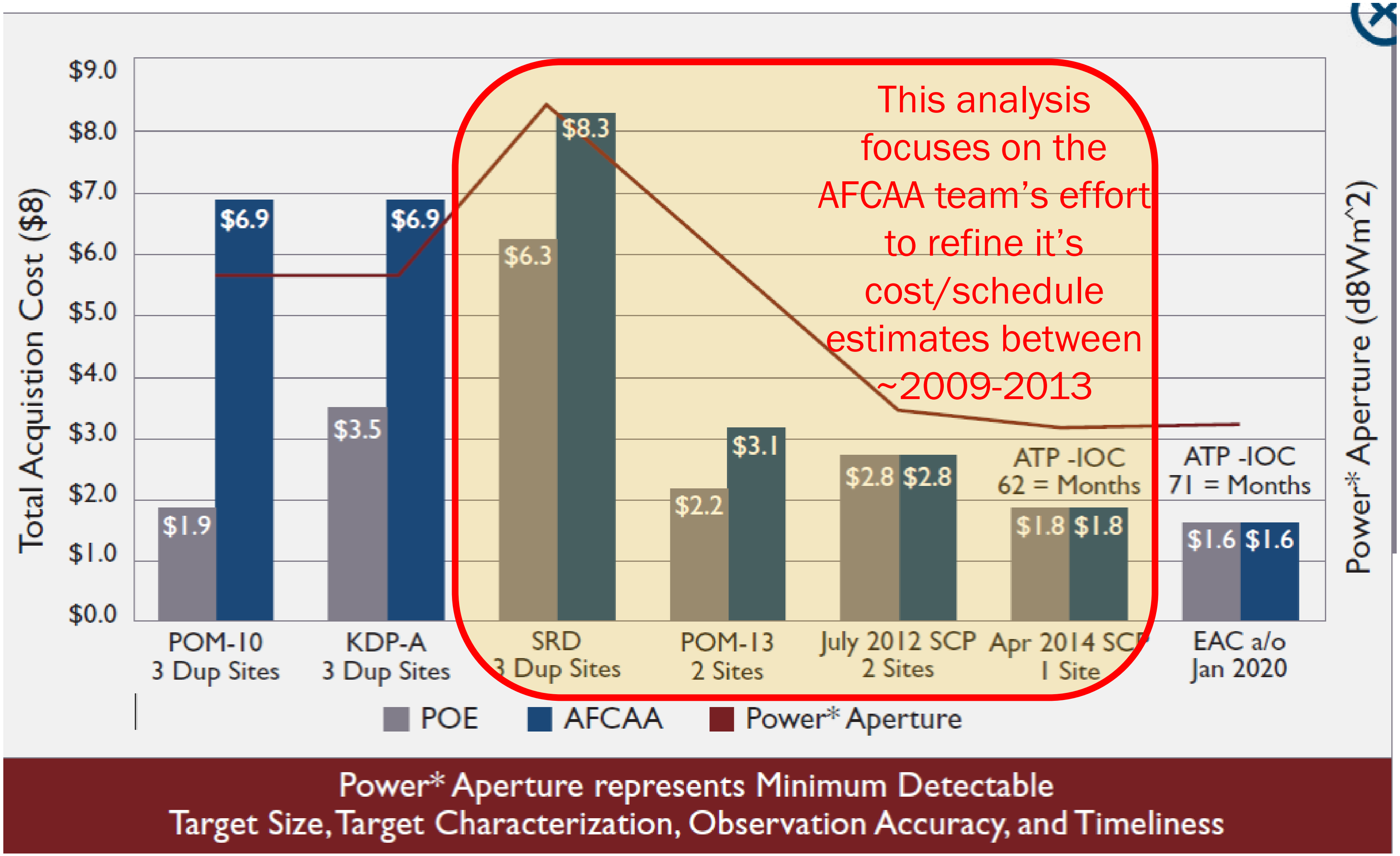
- “The program came in approximately $200 million under the 2014 Service Cost Position (SCP) projected $1.8 billion total acquisition cost.”
- “…AFCAA early estimates led to extensive affordability trades prior to the April 2014 decision to proceed with the program…”
- “Without AFCAA’s non-advocate assessments, the program could have easily fallen prey to the optimistic cost, schedule, and requirements projections”

2020 SAF-FM Newsletter Space Fence Article – Authored by AFCAA



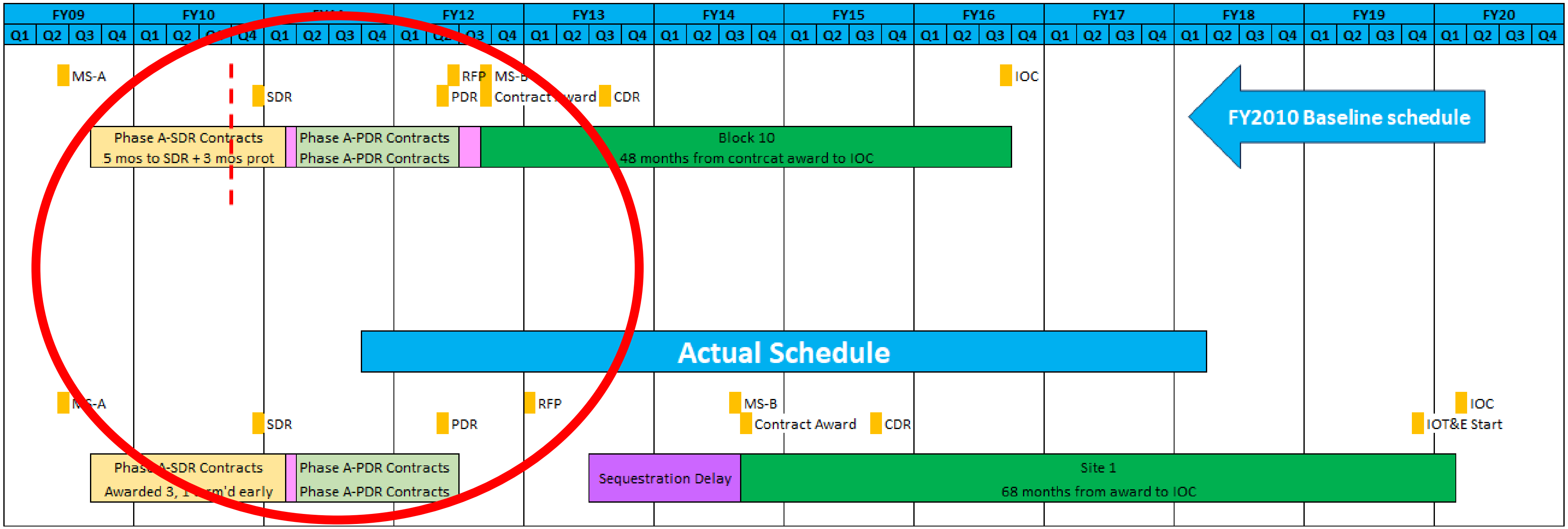
Excerpt from SAF-FM Online Newsletter, June 2020, Volume 16, Issue 5

2020 SAF-FM Newsletter Space Fence Article – Authored by AFCAA



Excerpt from SAF-FM Online Newsletter, June 2020, Volume 16, Issue 5

Original Program Baseline VS Actuals



- AFCAA's input from 2009 to 2014 resulted in reduced requirements that dramatically changed the Space Fence tech baseline to fit within Air Force Affordability
- From 2009 to 2012, the author was part of the AFCAA team that championed Space Fence affordability discussions and challenged optimistic Program Office (PO) and Contractor assumptions to be better supported and/or explained
- This discussion will summarize AFCAA's collaboration with the Program Office and Industry as it helped inform credible cost and schedule estimates

AFCAA's Space Fence Team

- AFCAA
- MCR (now SPA, Inc) (cost estimating, data analysis, engineering)
  - Amanda Feather (now AFCAA)
  - Rick Garcia
- Technomics (radar cost/schedule data, engineering)
  - John Horak
- Georgia Tech Research Institute (radar and technical expertise)
  - Mike Harris
  - Sam Piper
  - Molly Gary
- Space Fence Program Office (program and technical expertise)
  - David Becker
  - Dr. Phillip Phu

Space Fence Overview

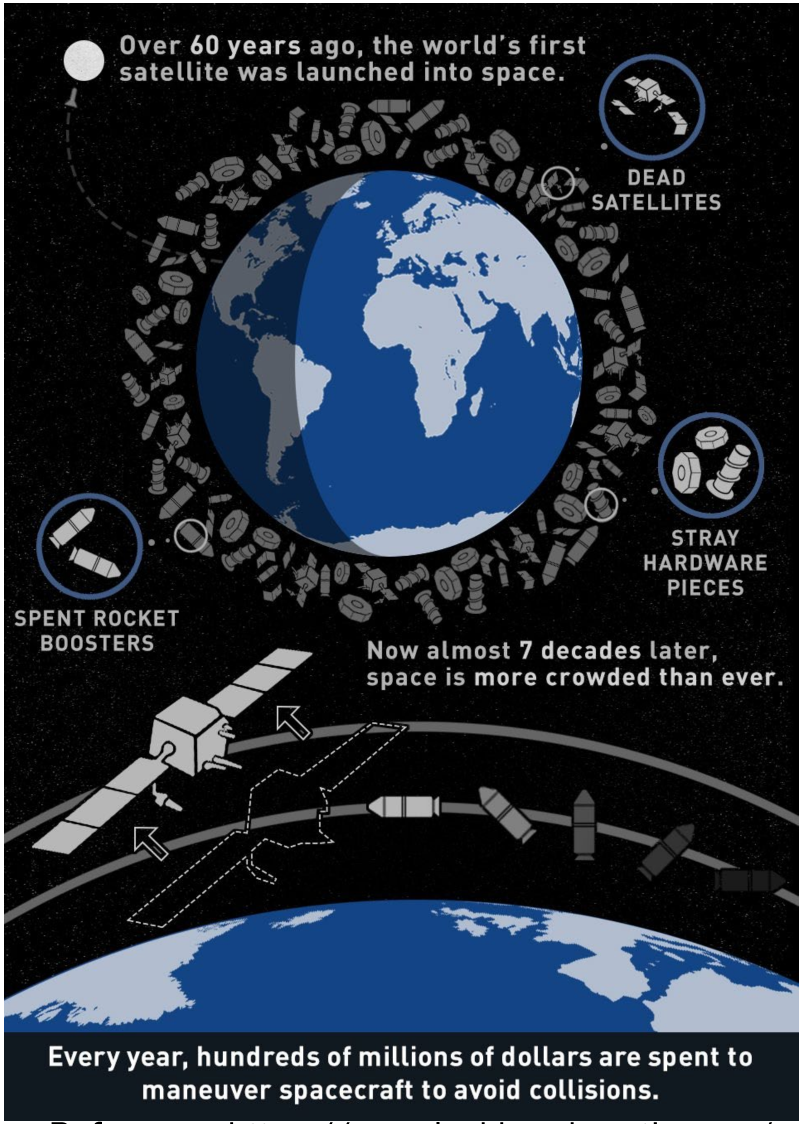
- The Air Force Space Surveillance System S-Band Radar (Space Fence) is solid state, upward facing radar, built by Lockheed Martin between 2014-2019
  - Significant prototyping and risk reduction occurred between 2007-2014
- Space Fence operates in S-Band (2 - 4 Ghz) and can track commercial and military satellites, empty rocket boosters, and space debris in low, medium and geosynchronous orbits
- Space Fence consists of one site with separate transmit and receive apertures
  - Transmit array structure ~2,400 sq ft (about the size of a tennis court)
  - Receive array structure ~4,700 sq ft (roughly the size of a basketball court)
- Space Fence can detect objects under 4 inches at Low Earth Orbit (LEO)
- Replaced the AN/FPS-133 radar

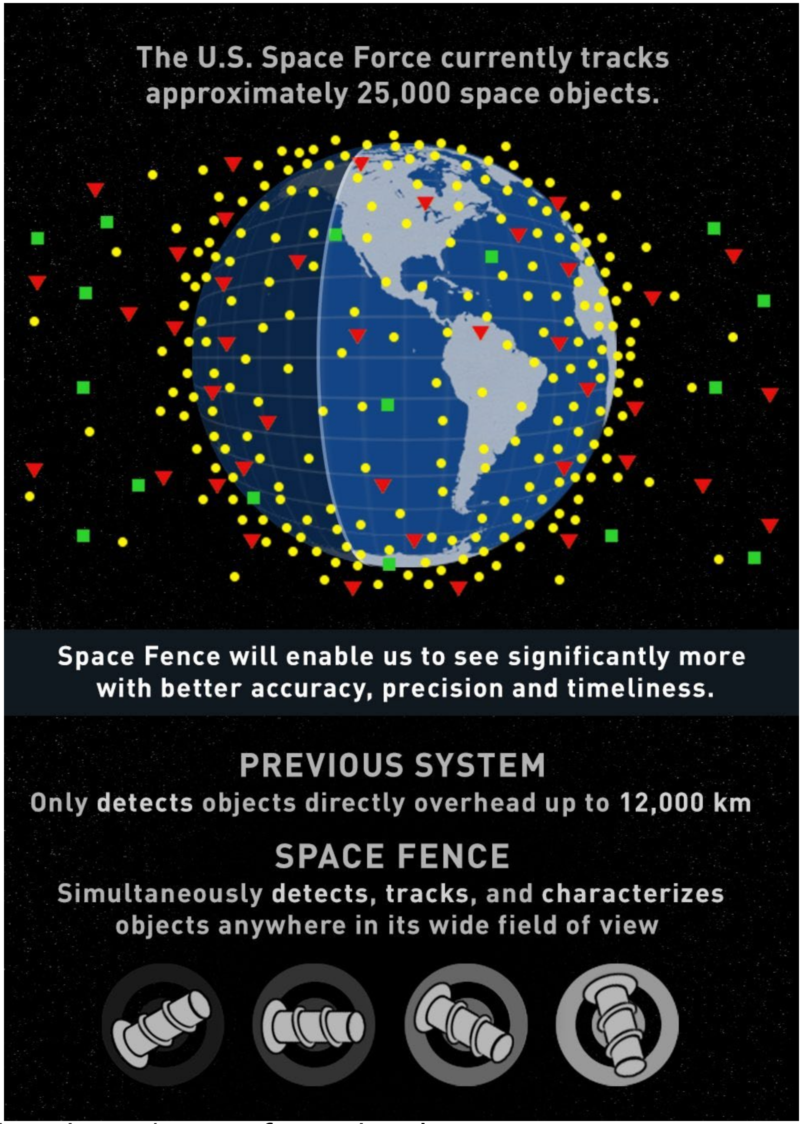
Space Fence Overview (continued)

- AN/FPS-133 radar (1961 - 2013)
- AN/FPS-133, also known as the Air Force Space Surveillance System (AFSSS) operated in the Very High Frequency range (~217 MHz)
- AN/FPS-133 consisted of 9 sites; 3 transmitter and 6 receives sites across the Southern US, from California to Georgia
  - The largest of the 3 transmit antenna was almost 2 miles long had an average power output of 766 kW
  - Total power output averaged ~850 kW
- AFSSS VHF "Fence" radar was built to detect objects down to 30 inches at heights up 19,000 miles

Reference: https://en.wikipedia.org/wiki/Air_Force_Space_Surveillance_System

Space Fence Overview (continued) [B]





- Reference: https://www.lockheedmartin.com/en-us/products/space-fence.html

Space Fence Cost Estimating Challenges

1. The estimates were not anchored to cost and schedule data from analogous military or commercial radar systems Existing estimates were primarily based on
   - Request for Information (RFI) responses
   - Other program estimates, and
   - Outdated ground radar proposals
2. Available Radar methodologies did not reflect current radar design and manufacturing processes
3. A data-driven Ground Radar schedule estimating methodology did not exist
4. A commodity specific expenditure and obligation phasing model did not exist

Space Fence Cost Estimating Solutions

1. Identify and Collect: analogous radar system data needed to produce a comprehensive multi-Service radar database including the cost, schedule, and technical parameters of 14 phased array and planar array radars.
2. Understand: current radar design and manufacturing processes and Develop methodologies and/or adjustments, if needed
3. Build: a data-driven Ground Radar schedule estimating methodology
4. Build: a commodity specific expenditure and obligation phasing model

1. Radar Systems Database

Identify and Collect Analogous Radar System Data

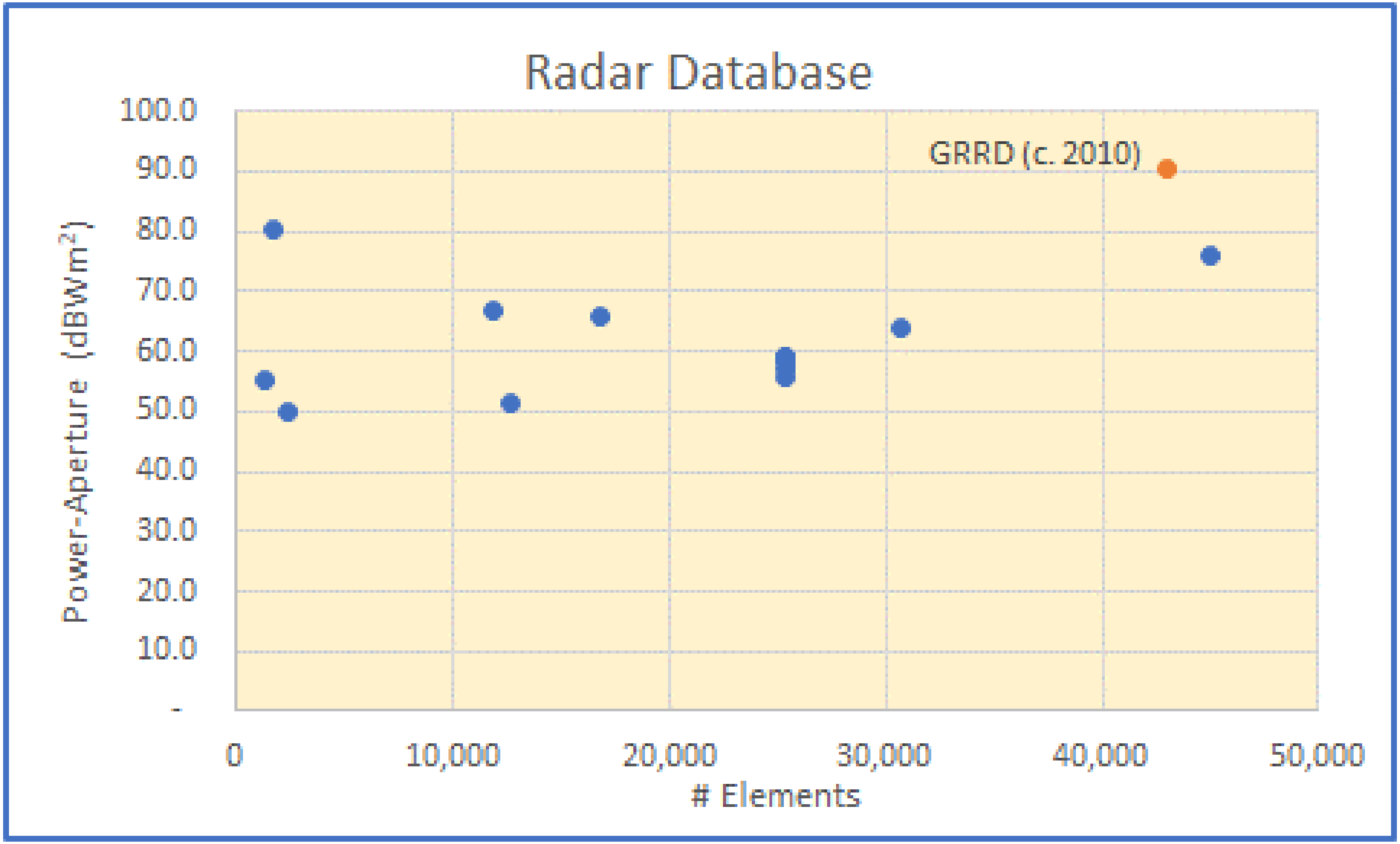
- In 2009, AFCAA commissioned Technomics to develop the AFCAA Ground-Based Radar Cost Model and Database
- Database collected data for 14 ground- fixed, ground-mobile, and ship-based radar programs
- WBS will also serve as basis for estimate comparisons across designs

- Total Radar Development
  - Prime Mission Equipment - Rec Hdw Total (First Radar)
    - Antenna(s)
      - Array (Transmit)
      - Cooling Unit/Power Distribution (Transmit Array)
      - Array (Receive)
      - Cooling Unit/Power Distribution (Receive Antenna)
    - RF Electronics
      - Exciters
      - Receivers
      - Xmtr/Rcvr Data & Time Distribution
      - Frequency Time Standard
    - Back-End Group
      - Signal Processors
      - Data Processors
      - Recorder
      - Controls & Displays
    - Communications Equipment
    - Hdw Subtotal Cost
    - Integ & Assy
  - PME NRE (First Radar)
    - Hardware NRE
      - Antennas
        - Transmit Array
        - Receive Areray
      - RF Electronics
      - Back-end Group
      - Communications
      - Integ & Assy
    - Software Development
  - Development Support (First Radar)
    - System Engr/Pgmt Mgmt
      - System Engr
      - Pgm Mgmt
    - System Test & Evaluation
    - Training
    - Data
    - Peculiar Support Equipment
    - Operational/Site Activation
    - Initial Spares & Repair Parts

- Array (Transmit)
  - Array (Structural)
  - Feed
    - Column Assys
    - Exciters-to-Column Assys
  - Transmit LRUs
  - Power Supplies
  - Beam Steering Computer
- Cooling Unit/Power Distribution (Transmit Array)
- Array (Receive)
  - Array (Structure)
  - Feed
    - Column Assys
    - Receive Networks
    - Combiner Assys
  - Receiver LRUs
  - Power Supplies
  - Beam Steering Computer
- Cooling Unit/Power Distribution (Receive Antenna)

Program Name
THAAD D&V
THAAD D&V and UOES
THAAD SDD (Unit1)
THAAD SDD (2 Units)
FBX (Unit1)
FBX (Units 1-4)
GBR-P
SBX Hdw
Cobra Judy X-band
Cobra Judy S-band
TPQ-47 Dev
TPS-59 Dev
PAVE PAWS

Identify and Collect Analogous Radar System Data



2. Understand current radar design and manufacturing processes and develop methodologies and/or adjustments

Key Differences/Improvements (from previous radars)

- Used advanced solid-state S-band radar technology
- Element level digital beamforming
- Gallium Nitride (vs Gallium Arsenide)
- Software defined programmability
- Optimized Sizes of Large, Separate Tx and Rx Arrays
- Increased Integration of LRUs and System-on-Chip RFIC Technology
- Designed for Automated Commercial Manufacturing and Low-Touch Labor

Antenna Differences/Improvements

BEFORE

- Low Levels of Functional Integration
- 18,000 RF Cables (Supports Overlapped Subarray Beamforming)
- On and Off-Array Analog Beamformers
- Cabled Power and Digital Distribution
- Touch Labor Intensive
- Tactical/Mobile Environment
- Mil Packaging
- Complex Machined Structures/Coldplates
- Custom Power Converters

NOW

- Eliminates receive back-end portion of the radar
- Total Functional Integration of Array LRUs (RADAR on a board)
- COTS Based MMIC Packaging; RFICs
- All Digital Array (No RF Beamformers or Cables due to Element Level DBF)
- Fixed, Benign Environment
- Commercial Packaging (standard surface mount processes)
- Extreme Touch Labor Reduction
- COTS Based Power System

Digital Array Architecture Greatly Reduced Packaging Complexity and Cost
Examples:
New Tx module costs approx. 25% of previous Rx/Tx modules
New Rx module costs approx. 20% of previous Rx/Tx modules

Space Fence Cost Estimating Solutions

- Independent Technical Analysis
  - GTRI works on a wide range of radar R&D / Production programs
  - GTRI assessed the different designs and deemed they would all meet the Govt performance requirements
  - Technical parameters independently validated:
    - HW analogies
    - Array Sizing
    - Performance Analysis
- Radar Database / Methods Development
  - Technomics provided radar systems cost research and analysis
    - Completed AFCAA Ground Based Radar Database which represents 12 major programs and components of multiple other radar programs
    - Developed estimating methods for Space Fence

Space Fence Cost Estimating Solutions (continued)

- Conducted contractor visits
  - Latest contractor Phase A efforts (prototype HW, analysis, etc.)
  - Detailed Q&A with contractor teams
- Normalize inputs with GTRI and Program Office
  - Effects of design changes analyzed and methodologies updated
  - AFCAA Radar Database technically adjusted to account for power differences, functionality and additional RF component parts
- Investigate and quantify impact of T/R module separation
  - Incorporate both GTRI experience in manufacturing and Technomics experience in radar engineering
  - Identified detailed component-based methodology
  - AFCAA Radar Database adjusted for separate transmit and receive elements
- Incorporate Scenario Based Risk Assessment
  - Current contractor architectures bound the range of likely outcomes; driven primarily by the number of transmit and receive elements

Early and Continued Insight into Contractor Actuals to Date and ETCs

- During the Phase A Cost IPTs (FY 2010 – FY2012) contractor visits and presentation were followed by specific action items driven by Program Office's and AFCAA's inquiries
- One particular, recurring focus area was Software
- The contractors each provided a data matrix detailing
  - The different categories of code (developed, modified, re-use, etc.) broken out by percent complete by major milestone and associated cost
  - A list of the programs that any re-use code was leveraged from
  - Identifying the number of SLOCs leveraged
- Major portions of the total SW effort were being completed and tested during the PDR contract phase

Early and Continued Insight into Contractor Actuals to Date and ETCs

- Q2 FY 2012
  - Just prior to the close of the PDR phase of the contracts
  - One full year prior to planned RFP release

		CSCI	New	Modified	Reuse	Origination Prog (Reuse)	PDR Phase % Complete of IOC	PDR Phase $ (% of total)
Radar Subsystem	Radar Subsystem	Digital Signal Processor CSCI	67.9%	0.0%	32.1%	IRAD/MMSP	55	11.1%
		Radar Control Program CSCI	67%	18%	15%	IRAD/ABMD	41	6.8%
		Health & Maintenance CSCI	100%	0%	0%	None	17	0.6%
		Calibration CSCI	0%	0%	0%	None	0	0.0%
		Rx LRU Firmware CSCI	100%	0%	0%	None	59	3.5%
		Tx LRU Firmware CSCI	100%	0%	0%	None	67	11.3%
Mission Subsystem	Mission Subsystem	Common Middleware CSCI	95%	1%	5%	ISC2	16.8	4.5%
		Database/Storage CSCI	81%	0%	19%	ISC2	7	1.3%
		Mission Management CSCI	100%	0%	0%	None	2.2	0.4%
		SS Mission Processing CSCI	7%	1%	93%	CMS/OMHT	9.2	18.0%
		Space Situation Evaluator CSCI	100%	0%	0%	None	30.2	1.2%
		Orbital Mechanics Processing CSCI	9%	1%	90%	AT&T IRAD	8	18.7%
		Orbital Mechanics Services CSCI	75%	0%	25%	Astrodynamics Support Workstation	79.8	12.4%
		Simulation Software CSCI	100%	0%	0%	None	28	2.5%
		Net-Centric Communications CSCI	39%	1%	60%	Space Fence	4.5	0.5%
		Display and Control CSCI	13%	4%	83%	Space Fence	6.8	7.1%

Significant product knowledge early and throughout the program enabled high confidence in cost/schedule estimating methods and resultant cost/schedule estimates

3. SER Development

Schedule Estimating Relationship (SER) Development

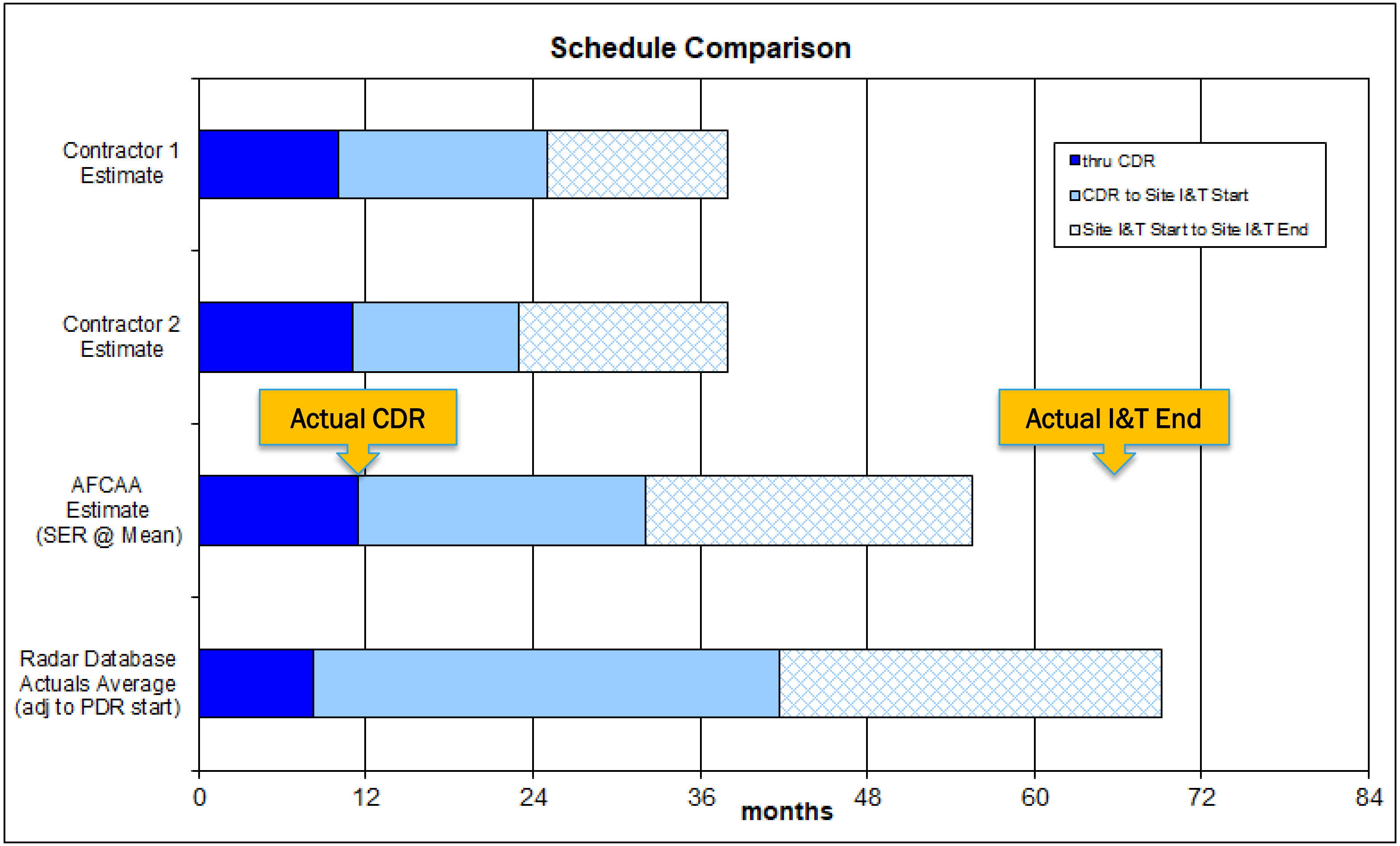
- Radar Schedule Database consisted of data collected from over 25 Ground, Ship, and Mobile Radar programs
- Over a dozen categories of technical data, coupled with several documented program milestones dates allowed us to perform several dozen excursions looking for the best regression and fit statistics
- The result was a three-part SER, with each SER driven by up to 4 parameters

Technical Parameters
XAPO (kW)
Development
Follow-on
Prod
Tx and RX Apertures (feet squared)
Frequency (GHz)
AvgProdLot
Quantity
Active Phased Array (Y/N)
Pedestal (Y/N)
Follow-on Effort
Ship (S), Ground Mobile (M), or Ground Fixed (G)
Elements
Aperture Density (# Elements / Rx Aper (sq ft))

SER Parameters	SER Phase		
	ATP to CDR	CDR to Site I&T Start	Site I&T Start to Site Test End
1st Parameter (D1)	D&V (1) or Other (0)	D&V (1) or Other (0)	D&V (1) or Other (0)
2nd Parameter (D2)	Pedestal (1) or No Pedestal(0)	Ship Based (1) or Ground/Mobile (0)	Pedestal (1) or No Pedestal(0)
3rd Parameter (x1)	Rx Aperture (sq ft)	Rx Aperture (sq ft)	Element Density (# El / Sq Ft Aper)
4th Parameter (X2)	n/a	Quantity	Quantity

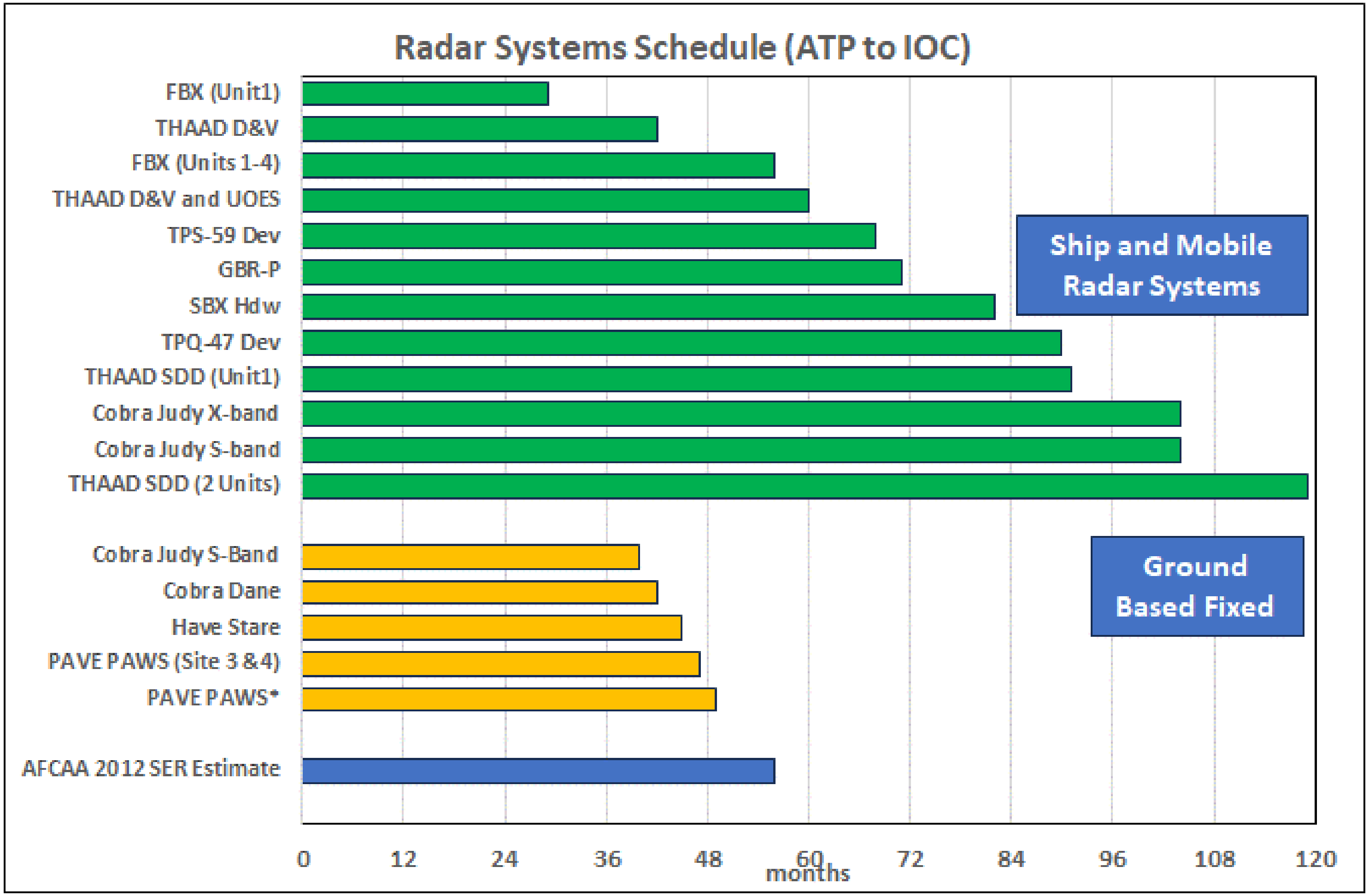
Development Schedule Dates/Durations
Total Schedule Duration (months)
SDR
PDR
CDR
Start Sensor I&T
Delivery to Test Site
Start Site I&T

SER Development (continued)



- In 2011/2012, the AFCAA assessment estimated the schedule at approximately 57 months (actual duration was ~68 months)

SER Development (continued)



- In 2011/2012, the AFCAA assessment estimated the government referenced design at around an average mobile radar schedule and higher than the fixed radar programs, due to Space Fence's large size

4. Phasing Analysis

Phasing Analysis: Challenge and Proposed Solution

- Need / Problem Statement
  - Independent Cost Estimate needed a methodology for recommending a realistic expenditure and obligation phasing in support of a POM input
  - Existing expenditure phasing models are generic to Department of Defense space or ground infrastructure programs (they are not ground radar specific)

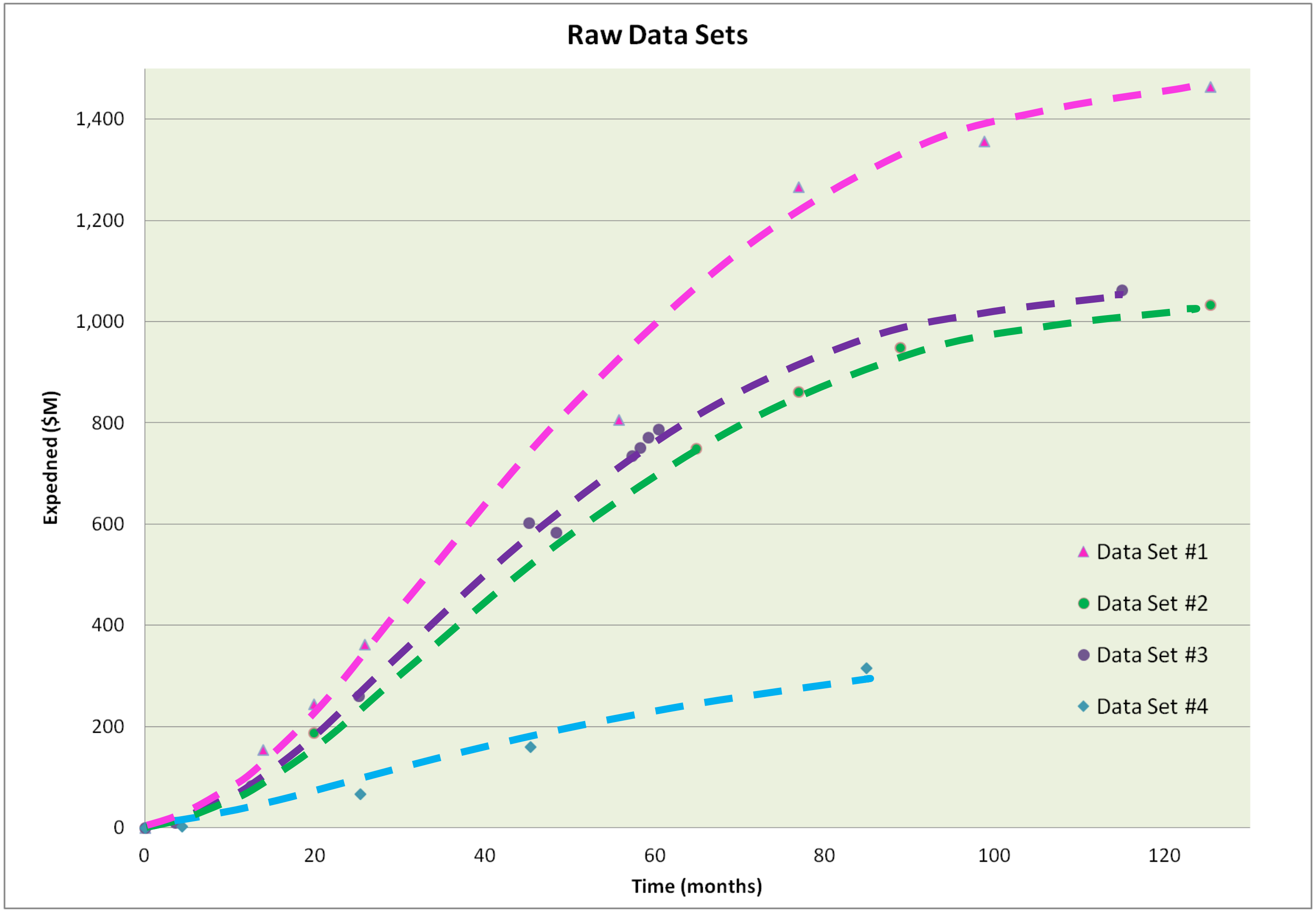
- Proposed Solution
  - Develop a Ground Radar specific expenditure phasing model based explicitly on historical ground radar program data (CPRs and CSDRs)

Phasing Analysis: Data Identification Summary

Data Sets	Data Points		Usable ? (Y/N)	Reason
	AFCAA DB	Phase		
Data Set #1	8	EMD	**Y**	EMD or D&V and time series.
Data Set #2	6	EMD	**Y**	EMD or D&V and time series.
Data Set #3	11	EMD	**Y**	EMD or D&V and time series.
Data Set #4	5	EMD	**Y**	EMD or D&V and time series.

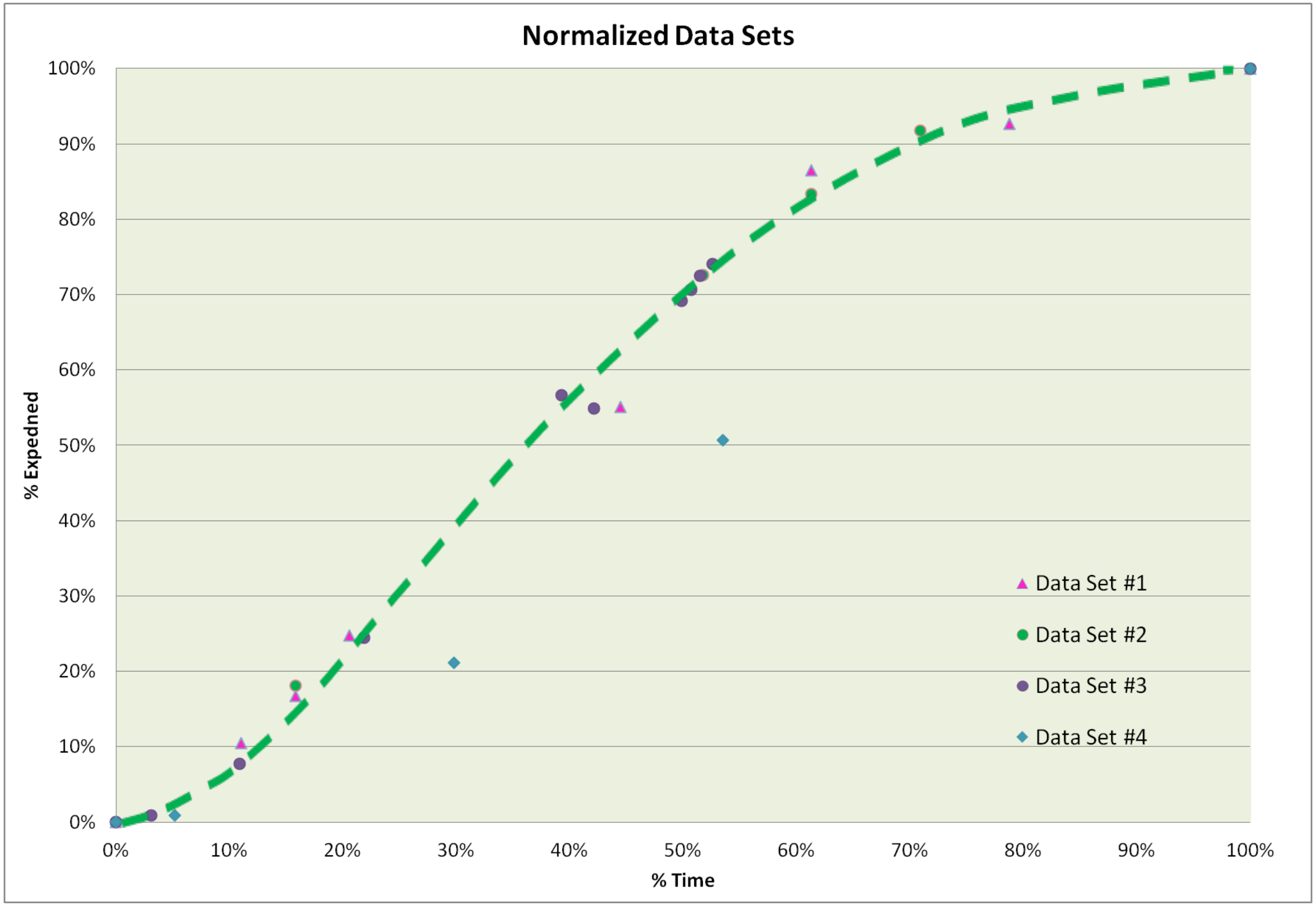
- 30 Data points (Data Sets #1-#4) from four separate sets, were deemed useful for analysis
- A fifth complete data set of 50 data points was excluded from this direct analysis
  - If used in regression, it drives regression results
  - Data Set # 5 was used to test/verify analysis

Phasing Analysis: Raw Data



- Raw Data: Time (in months), Dollars (in $M)

Phasing Analysis: Raw Data => Normalized Data



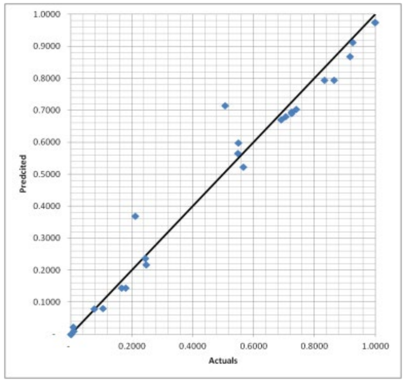
- Normalized Data: % Time, % Expended

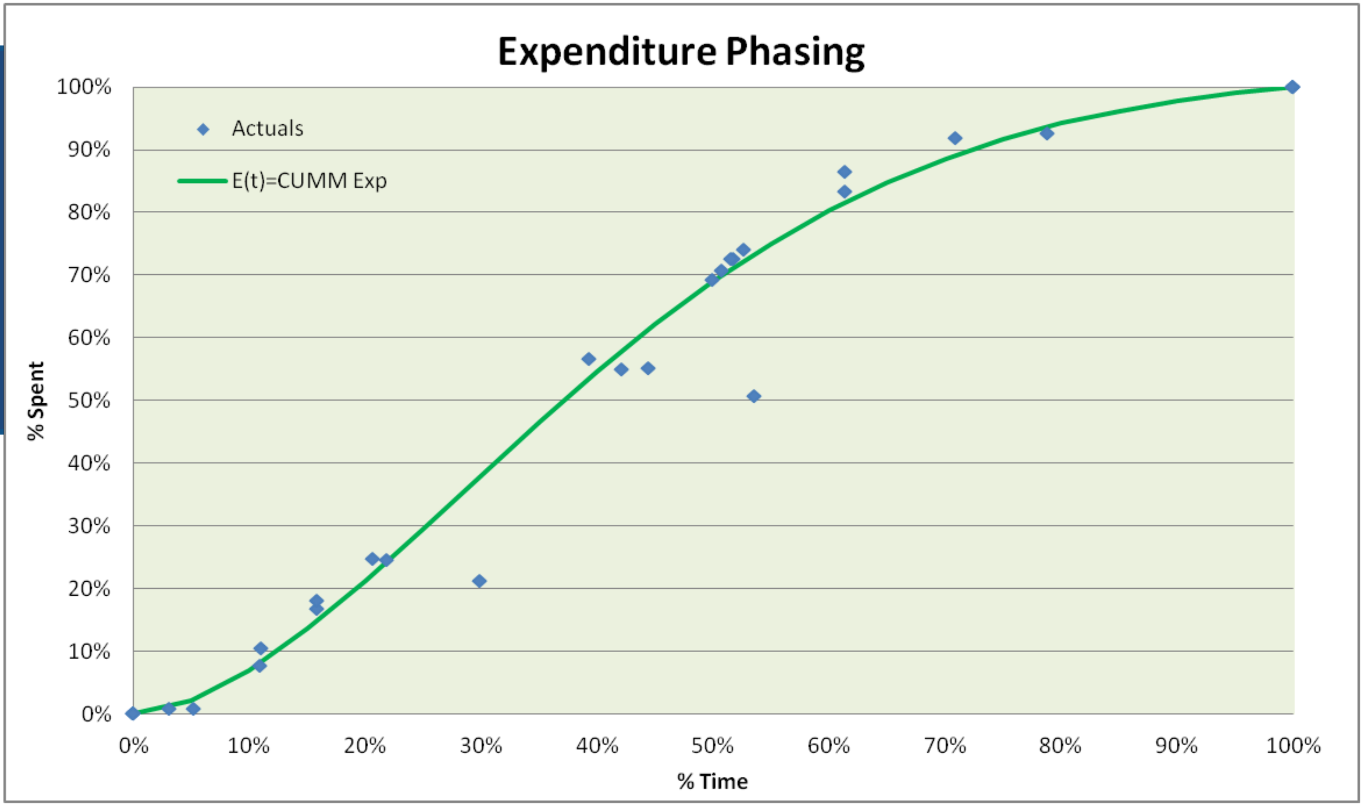
Phasing Analysis: Results

$$E(t) = (1-e^{-(\alpha t^{\beta})})$$

with β=1.7143, α=3.6586

N = 30
R^2 = 97.8%
Std Error = 17.95%
Bias = 0%



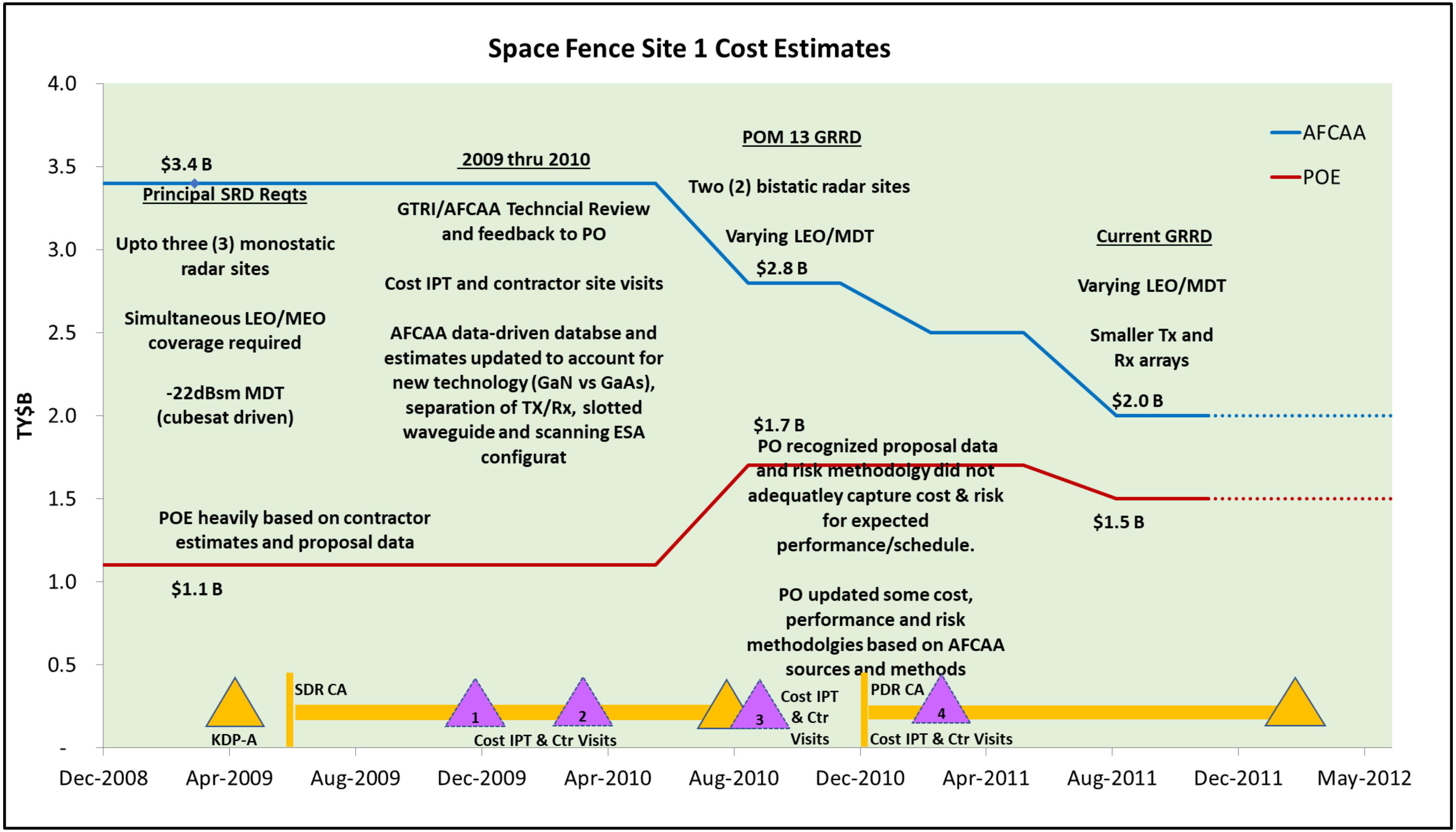


ZMPE equation based on all 30 data points (4 data sets)

- Detailed, step-by-step discussion of the development of the Ground Radar Expenditure and Obligation Phasing Model is available in the ICEAA archives
- "Ground Radar Expenditure Phasing Analysis (ICEAA – June 18, 2013), Rick Garcia
- Search the ICEAA Archives using "**2013-M204**"

Results

Results



Space Fence Site 1 Cost Estimates
TY$B
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
-
Dec-2008
Apr-2009
Aug-2009
Dec-2009
Apr-2010
Aug-2010
Dec-2010
Apr-2011
Aug-2011
Dec-2011
May-2012
AFCAA
POE
$3.4 B
Principal SRD Reqts
Upto three (3) monostatic radar sites
Simultaneous LEO/MEO coverage required
-22dBsm MDT (cubesat driven)
2009 thru 2010
GTRI/AFCAA Techncial Review and feedback to PO
Cost IPT and contractor site visits
AFCAA data-driven databse and estimates updated to account for new technology (GaN vs GaAs), separation of TX/Rx, slotted waveguide and scanning ESA configurat
POM 13 GRRD
Two (2) bistatic radar sites
Varying LEO/MDT
$2.8 B
Current GRRD
Varying LEO/MDT
Smaller Tx and Rx arrays
$2.0 B
$1.7 B
PO recognized proposal data and risk methodolgy did not adequatley capture cost & risk for expected performance/schedule.
$1.5 B
POE heavily based on contractor estimates and proposal data
$1.1 B
PO updated some cost, performance and risk methodolgies based on AFCAA sources and methods
KDP-A
SDR CA
1
2
Cost IPT & Ctr Visits
3
Cost IPT & Ctr Visits
PDR CA
4
Cost IPT & Ctr Visits

Results

SAR (Dec 2019)	TY$B
Current Program ($B)	$1.4
2014 SCP Estimate ($B)	$1.6
% Under SCP	10%

- Program cost actuals came in at approximately 10% under the AFCAA cost estimate/Service Cost Position (SCP)
- Program schedule actuals came in at 12 months longer than the 2013 AFCAA schedule estimate
  - AFCAA estimate did not anticipate months long delay due to sequestration in 2013/2014; (12 months between DAB (Defense Acquisition Board) and Acquisition Decision Memorandum (ADM))
  - Integration deficiencies and issues with interoperability testing delated IOC

Conclusion

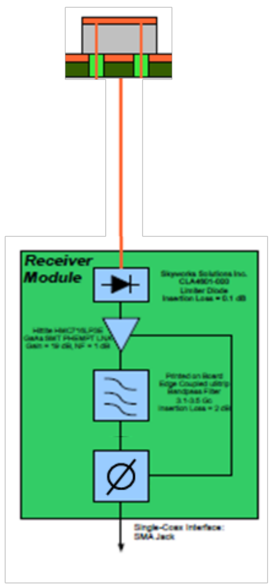
- Reliable and complete cost and schedule estimates were made possible by cooperation between Government and Industry entities
- Space Fence used advanced solid-state S-band radar technology. The technology includes element level digital beamforming, Gallium Nitride-based, software defined programmability
  - Early on in the program (~2009), the AFCAA noted that the scale of the Space Fence system was beyond the existing cost models; this drove significant interaction with the contractor to better understand current radar design and manufacturing processes and perform appropriate data collection efforts and develop new methodology, where appropriate

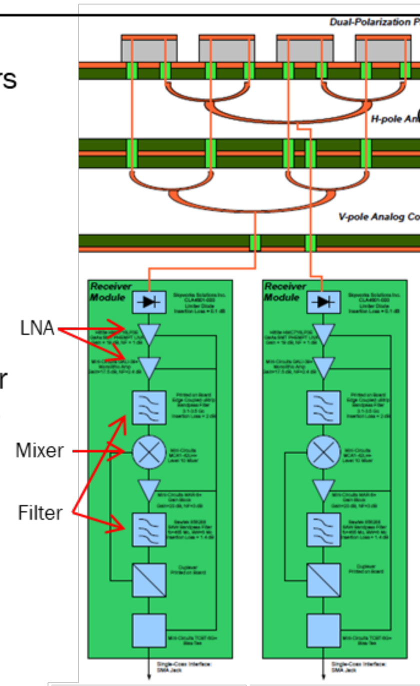
Backups

Space Fence Overview

- In March of 2020 the United States Space Force (USSF) declared operational acceptance and initial operational capability of the Space Fence radar on the Kwajalein Atoll in the Republic of the Marshall Islands.
- Space Fence, now the world's most advanced radar, provides uncued detection, tracking and accurate measurement of space objects, including satellites and orbital debris, primarily in low-earth orbit (LEO). The new radar permits the detection of much smaller microsatellites and debris than current systems. It also significantly improves the timeliness with which operators can detect space events. The flexibility and sensitivity of the system also provides coverage of objects in geosynchronous orbit while maintaining the surveillance fence.
- Before Space Fence, the Space Surveillance Network (SSN) tracked more than 20,000 objects. Now, the catalog size is expected to increase significantly over time. Space Fence also detects closely spaced objects, breakups, maneuvers and launches. According to the 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 low Earth orbit (LEO).

Receive Antenna Comparison





Historical Database (1 Component/Radiator)	GRRD Design	Added GRRD Complexity	Rx Function Adjustment	X Cost Breakout of Antenna (%)	X 4:1 Combining	X Dual Polarization	= Weighted Complexity Factor Per Radiator (%)
Radiators		Combining Network	0.25	23%	1.0	1.0	5.8%
Receiver Module		More Receiver Functionality & Complexity (added LNA, Mixer, & D/A Converter)	0.25	48%	0.25	2.0	6%
Power Supply	P.S. / P.S		0.25	7%	0.25	2.0	0.9%
Digital Control	Digital Control / Digital Control		0.25	4%	0.25	2.0	0.5%
Antenna Structure	Antenna Structure		0.25	12%	1.0	1.0	3%
Integration & Assembly	Integration & Assembly		0.25	6%	1.0	1.0	1.5%

Applied to CER → **17.6%**