A Model-Based Systems Engineering (MBSE) Approach to the Design & Optimization of Phased Array Antenna Systems

Northrop Grumman
Baltimore, MD

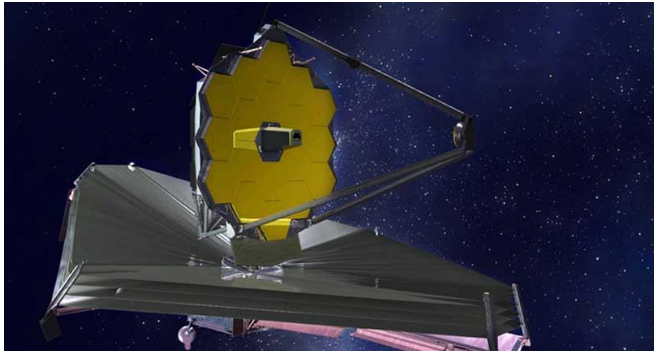
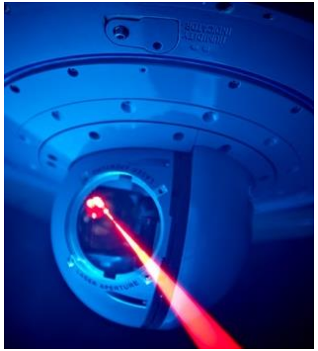
Phoenix Integration Webinar

John Hodge
Senior Principal RF Engineer

11/18/20

Northrop Grumman Today







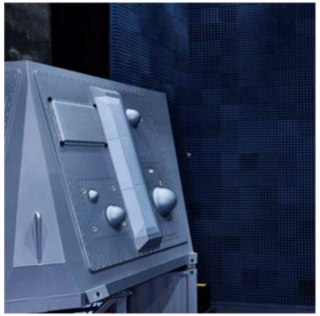




Motivation

- Increase Customer Satisfaction
- Improve Stakeholder Communication
- Increase Performance Capabilities
- More Efficient System Architectures
- Enhance Workflow Automation
- Manage System Complexity
- Reduce Cost & Schedule Inefficiencies



<u>Challenge</u>: Can we use a model-based Digital Engineering (DE) approach to enhance phased array antenna design & development?

NORTHROP GRUMMAN

Motivation (Cont.)

Legacy Solutions:

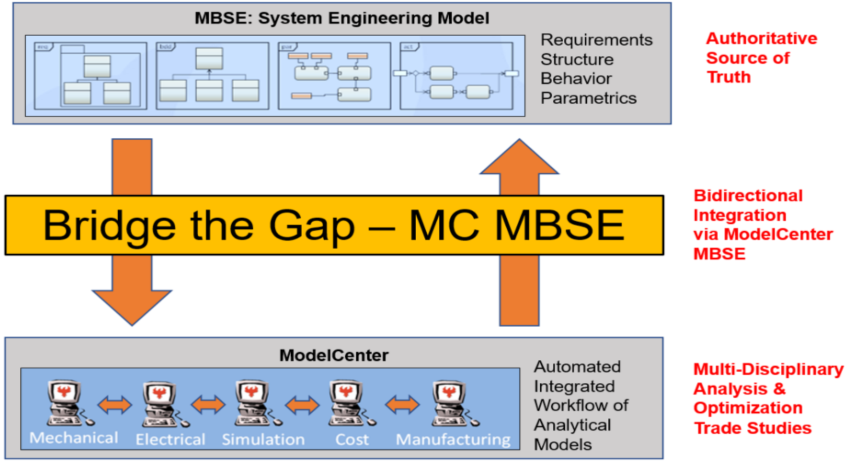
- ➢ Phased array antenna sensor systems used for wireless communications, radar, and electronic warfare
- ➢ SysML descriptive architecture models
- ➢ Disparate engineering domain analytical models

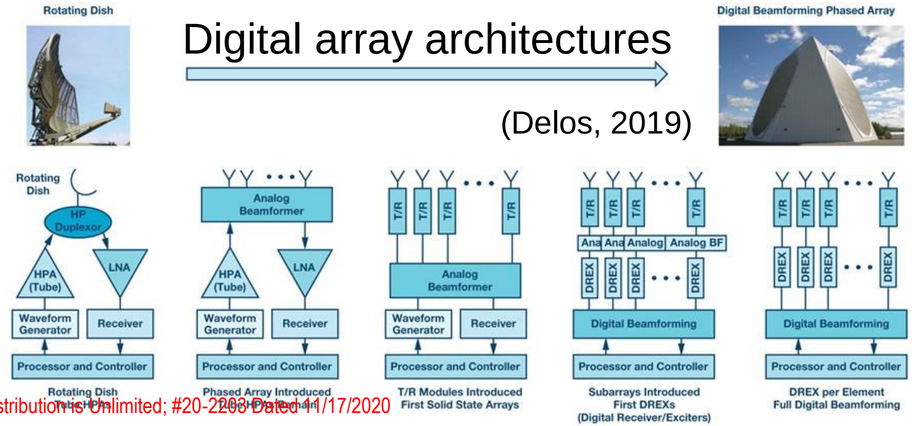
Challenges:

- ➢ Meet specified performance within size, weight, power, cooling (SWaP-C), and cost constraints
- ➢ Increasing system complexity as phased array antennas become increasing digital and multifunction
- ➢ Disparate set of engineering modeling & simulation tools across domains and disciplines

Our Solution: An integrated MBSE approach to the design & optimization of phased arrays

- ➢ SysML model captures system arch & reqs
- ➢ Multi-domain, physics-based performance analysis
- ➢ Digital twin for a model-based enterprise



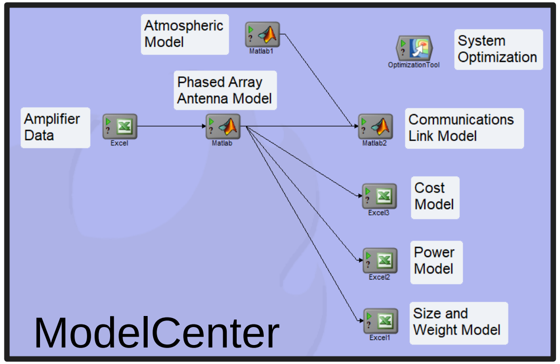


(Delos, 2019)

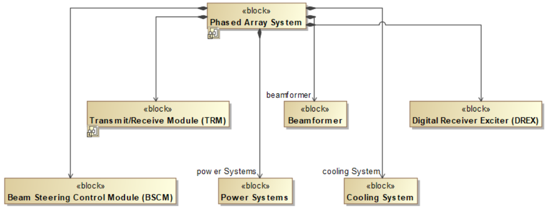
Outline

- Introduction
- Integrated Modeling Framework
- Phased Array Antenna Systems
- System Design & Optimization
- Summary & Path Forward

Integrated Analytical Models



SysML Architecture Model



Distribution Statement A: Approved for Public Release; Distribution is Unlimited; #20-2203 Dated 11/17/2020

Digital Transformation

Legacy Engineering Processes

- Document-Based
- Lack of digital integration
- Spreadsheet performance rollups
- Clean sheet designs

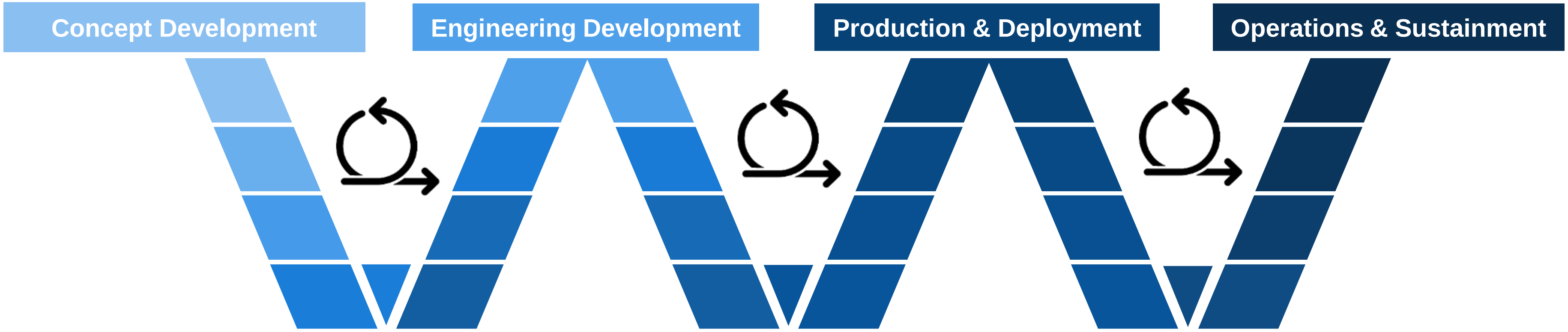
Digital Engineering Processes

- Model-Based
- Digital Twin & Digital Thread
- MDAO system analysis
- Reference architectures

**Multidisciplinary Design, Analysis, and Optimization (MDAO)*

NORTHROP GRUMMAN

Engineering Workflow Accelerated by MBSE

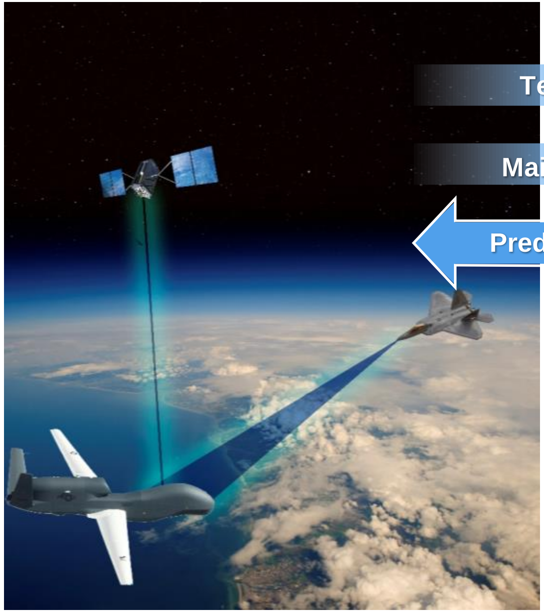


Model Based Engineering is the part of Digital Transformation by which optimizations are resultant of models and simulation applications.

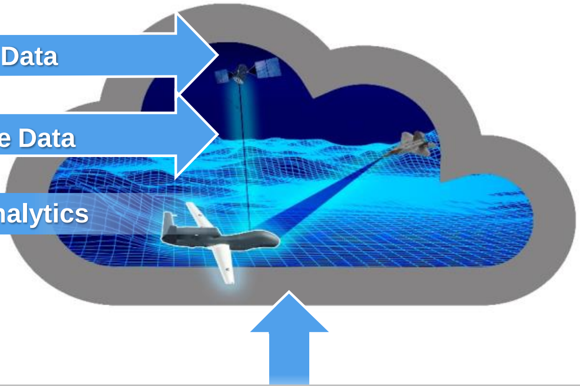
Digital Twin

Physical Asset	Digital Twin	Digital Twin Benefits

Physical Asset



Digital Twin



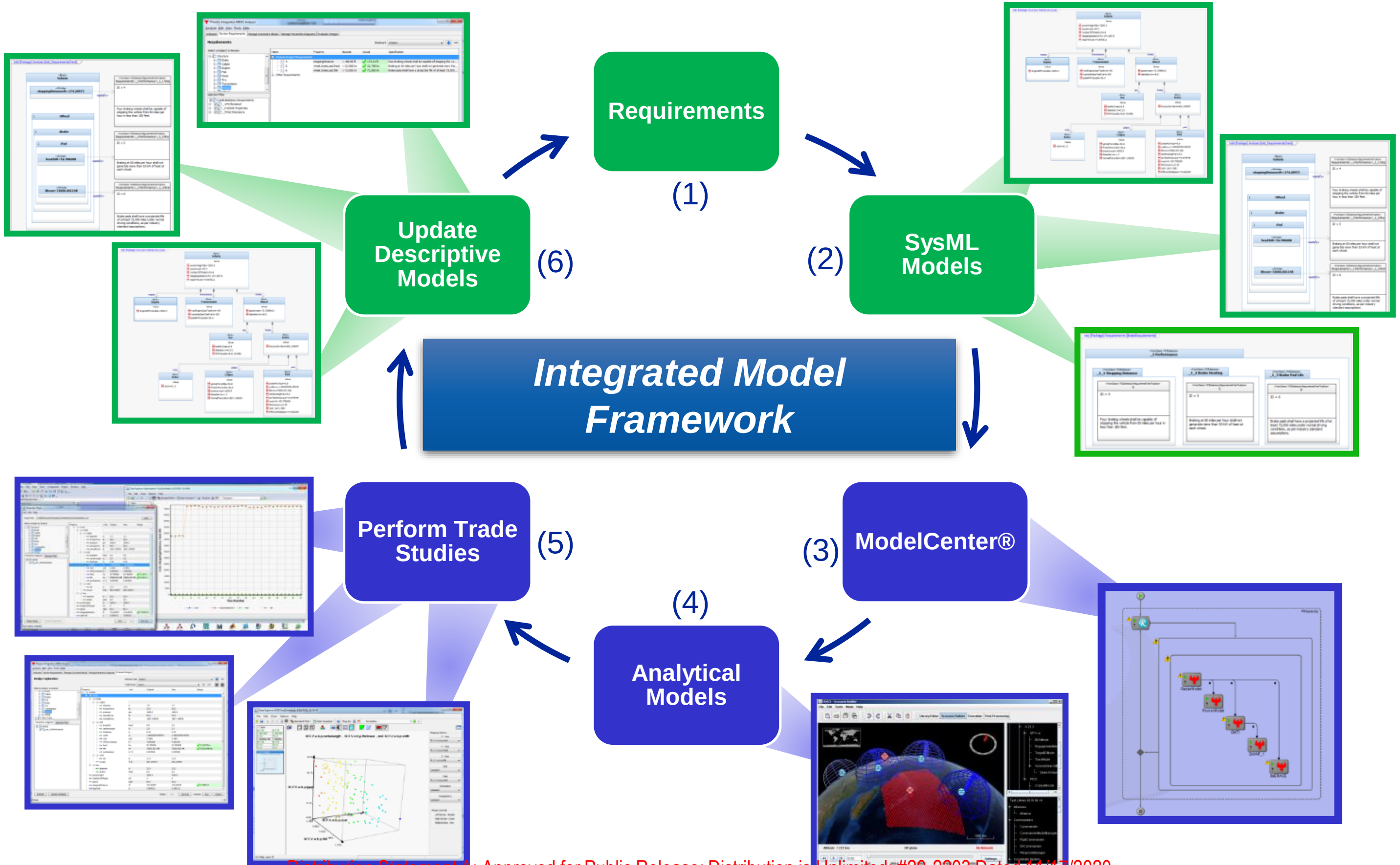
- Requirements Model
- Architectural Models
- Performance Models
- Threat Models
- Environmental Models
- Cost Models
- HW Emulators
- CAD Models
- Mission Simulation
- Operational Software

Digital Twin Benefits

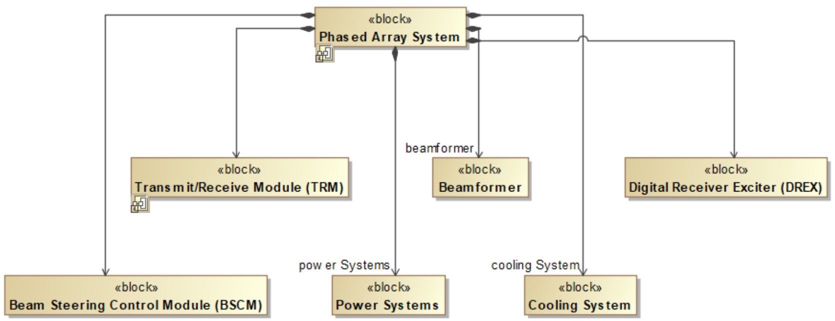
- Facilitates early discovery of performance issues
- Enables product optimization
- Supports personnel efficiency
- Rapidly evaluates system performance in ever-changing environments
- Helps to identify future business opportunities

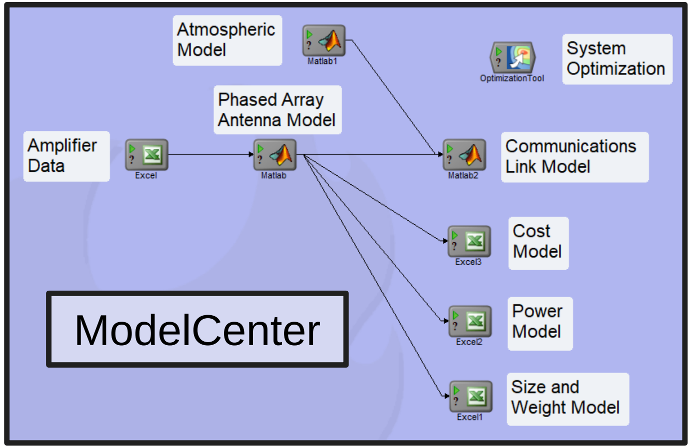
MBSE and ModelCenter enable digital twin development through modeling and simulation applications

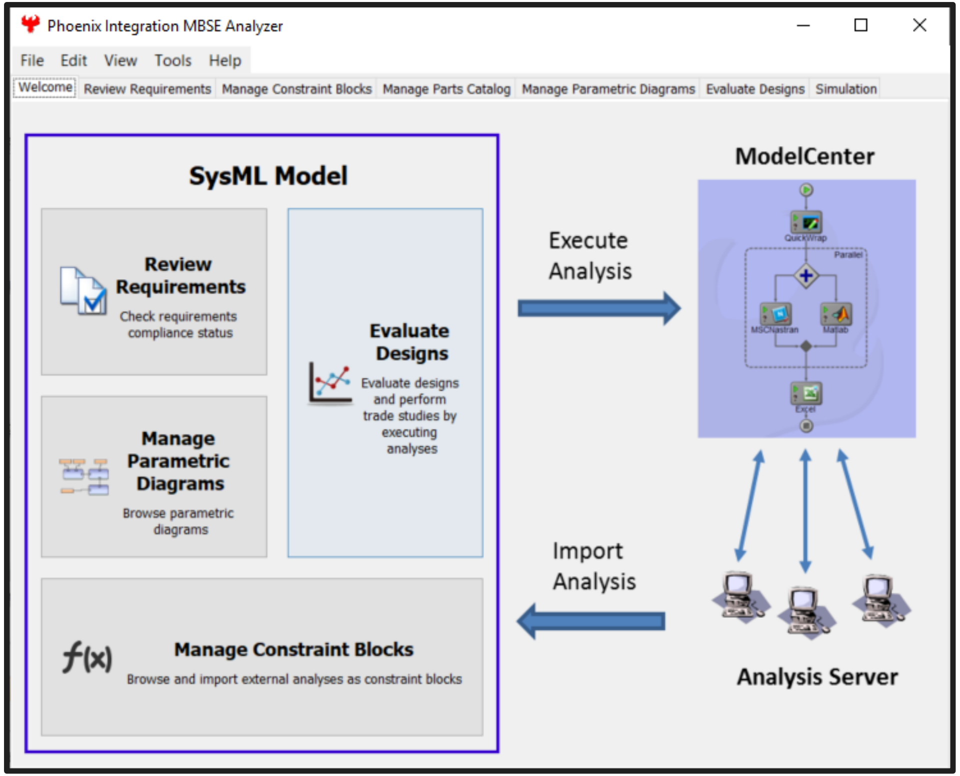
Integrated Model Framework



ModelCenter MBSE Analyzer Links SysML Descriptive Models to Analytical Models

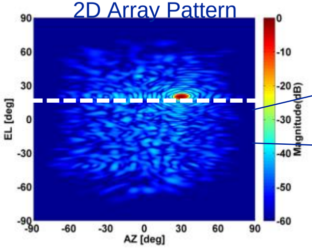


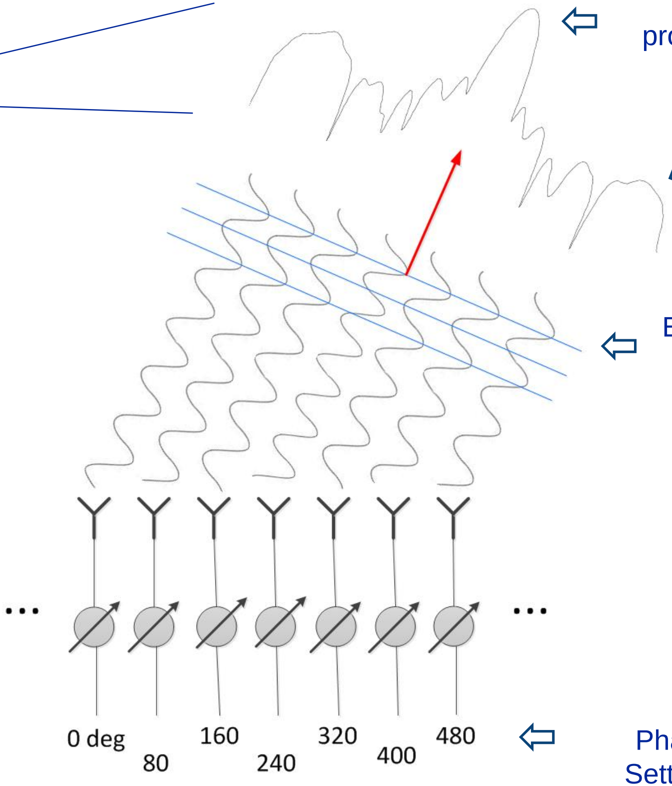




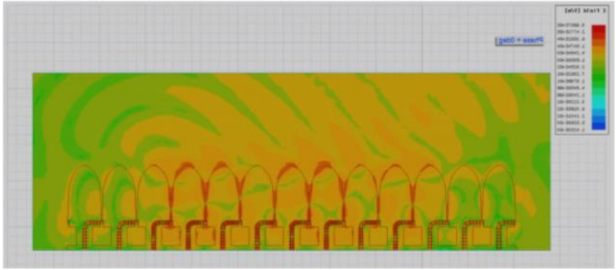
Phased Array Antenna Systems

Dynamic Array Beam Steering Achieved Via Controlling Phase At Each Radiating Site



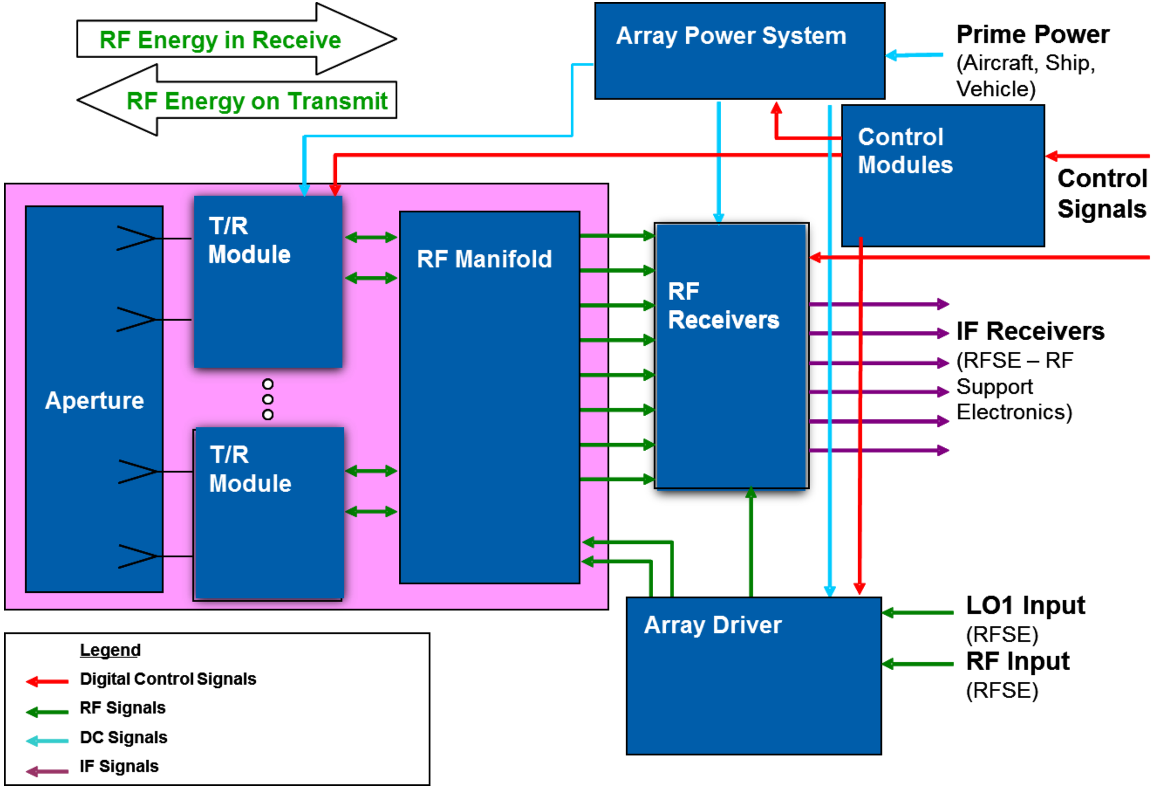


Simulated E-fields



NORTHROP GRUMMAN

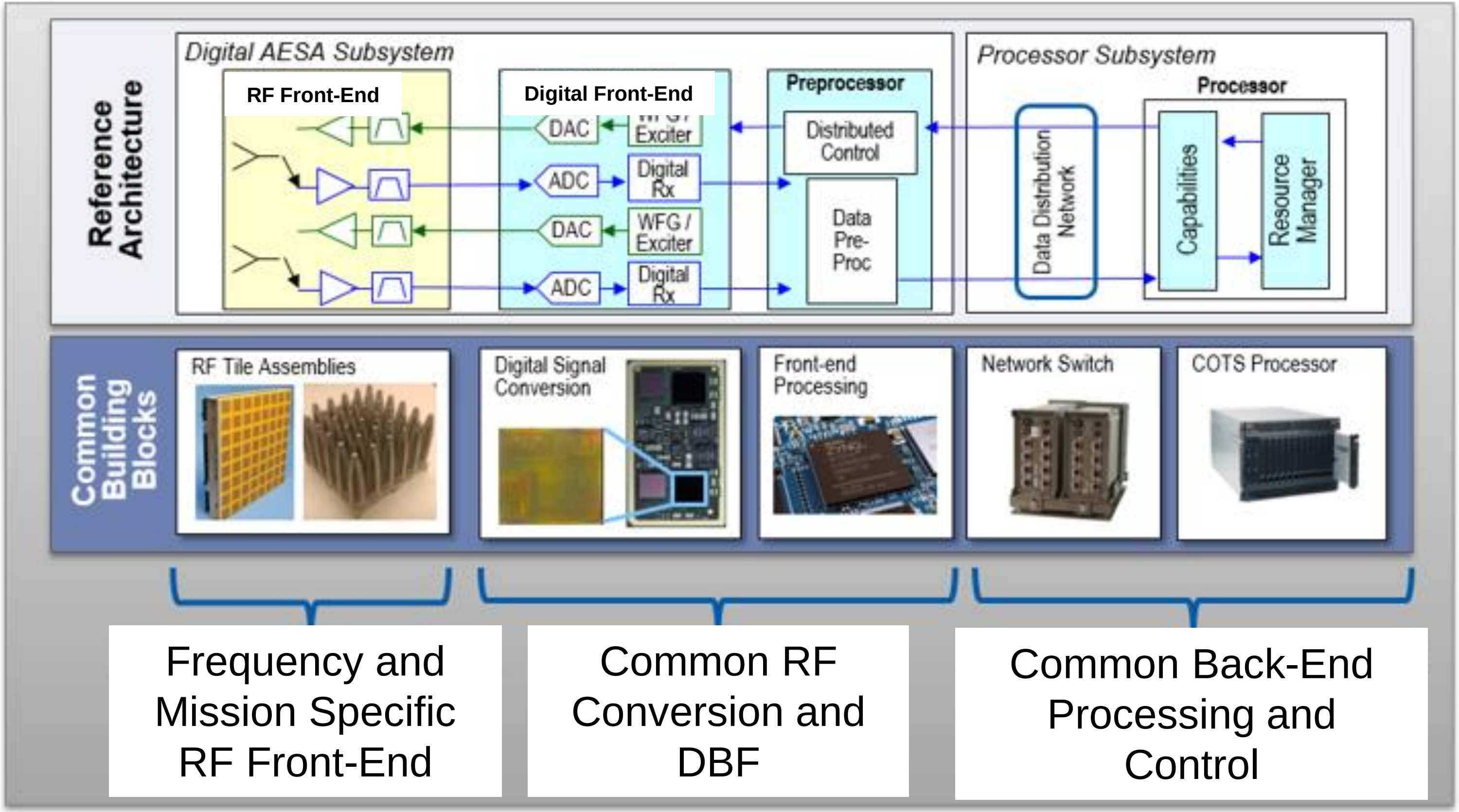
Phased Array Antenna System Block Diagram



Each component has a size, weight, power, and cooling (SWaP-C) contribution

Complex system with many subsystem and component interactions

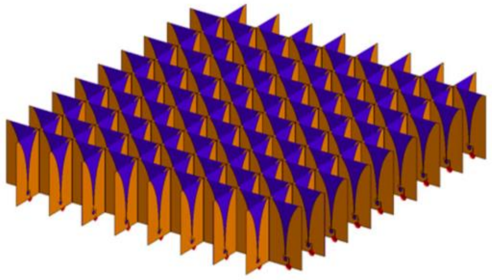
Scalable Digital AESA Architecture

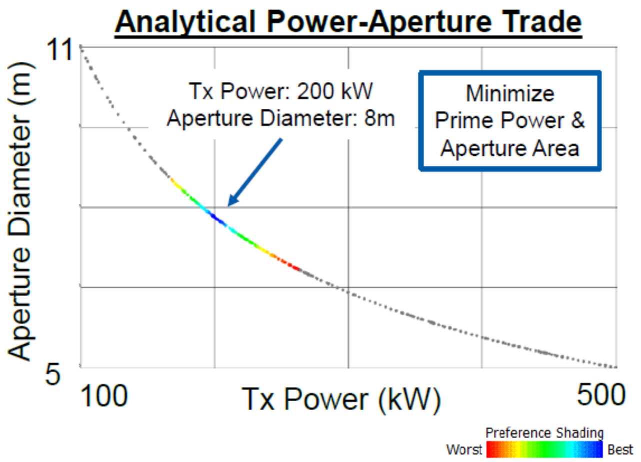


Typical Phased Array Antenna Requirements

Performance	Constraints

• Frequency Bandwidth (BW)
  • Operational
  • Instantaneous (IBW)
• Effective Isotropic Radiated Power (EIRP)
  • Aperture Gain
  • Side-lobe levels
  • Transmit Power
• Receive Sensitivity or G/T
  • Noise Figure
  • Linearity
• Aperture Efficiency
• Polarization
• Scan Volume
  • Scan Loss
• Beamwidth (Az/El)
• Scan Rate
• # of Simultaneous Tx/Rx Beams
	• Size
	  • Height
	  • Area
	• Weight
	• Power
	  • Average
	  • Peak
	• Thermal
	• Environmental
	  • Shock
	  • Vibration
	  • Radiation
	  • Etc.

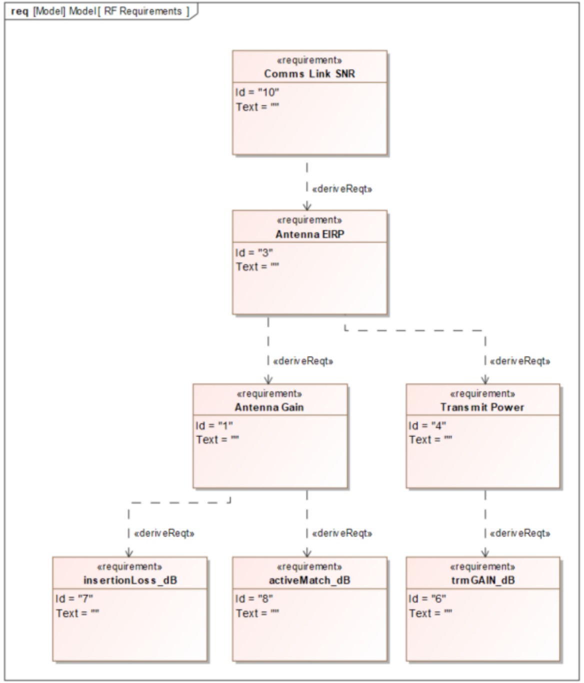


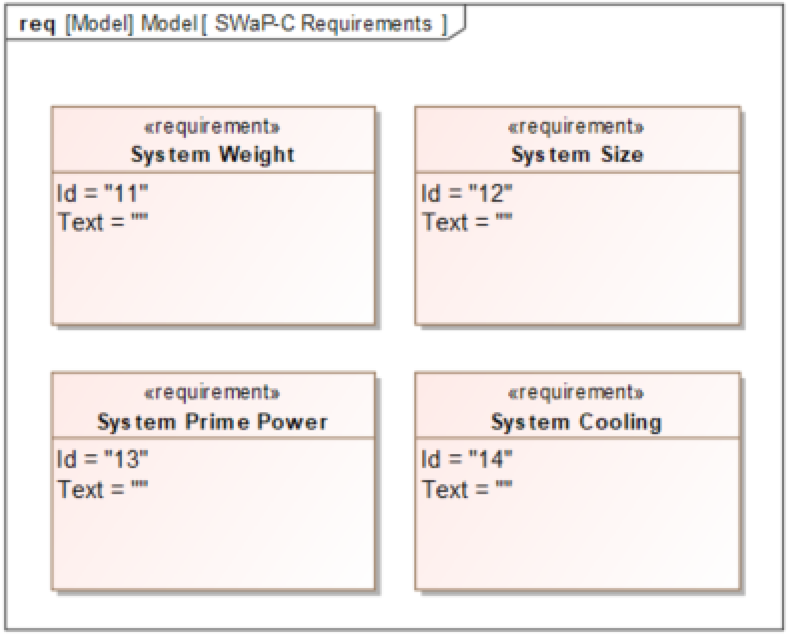


Power-aperture trade to meet EIRP or sensitivity drives array architecture

Capture Performance and SWaP-C Requirements in SysML

*Hypothetical System





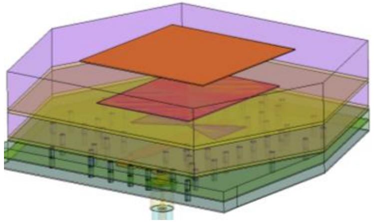
Requirements linked to provide traceability;
Verified using integrated analytical models

Requirements Drive RF Front-End Architecture

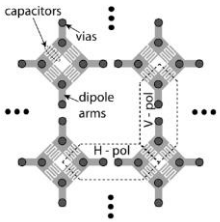
Frequency Bandwidth

Power Handling

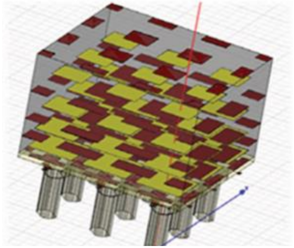
Patch / Stacked Patch



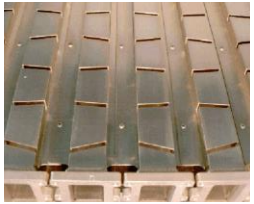
PUMA [1]



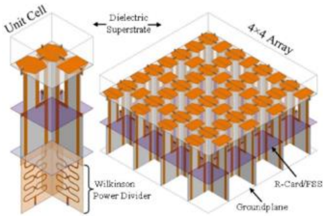
Planar-Fed Folded Notch (PFFN)



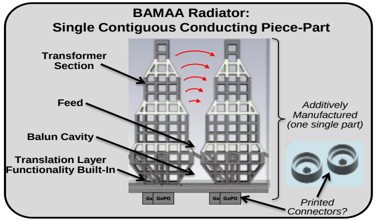
Waveguide / Slot



TCDA [2]



Stepped Notch / Vivaldi

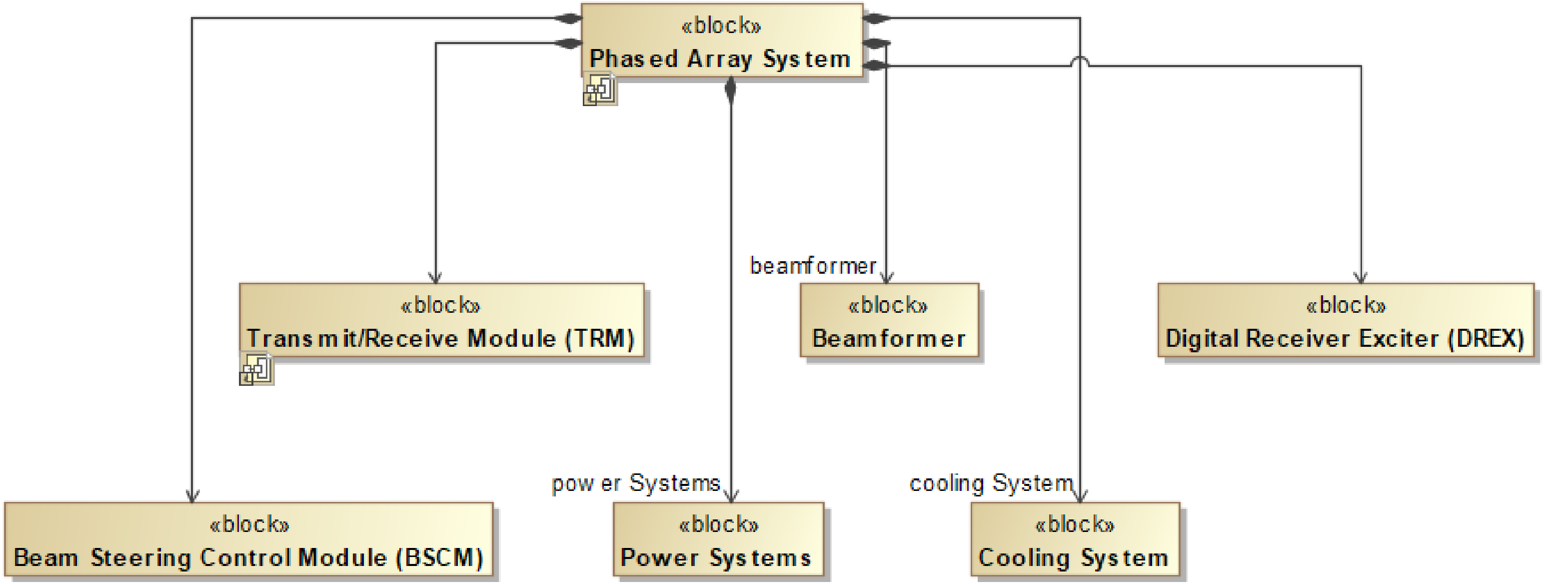


Scalable tile-based building blocks: Choose radiating element architecture based on bandwidth, scan, power handling, and height requirements

[1] PUMA: Planar Ultrawideband Modular Array (Holland, 2012); [2] TCDA: Tight Coupled Dipole Array (Papantonis, 2016)

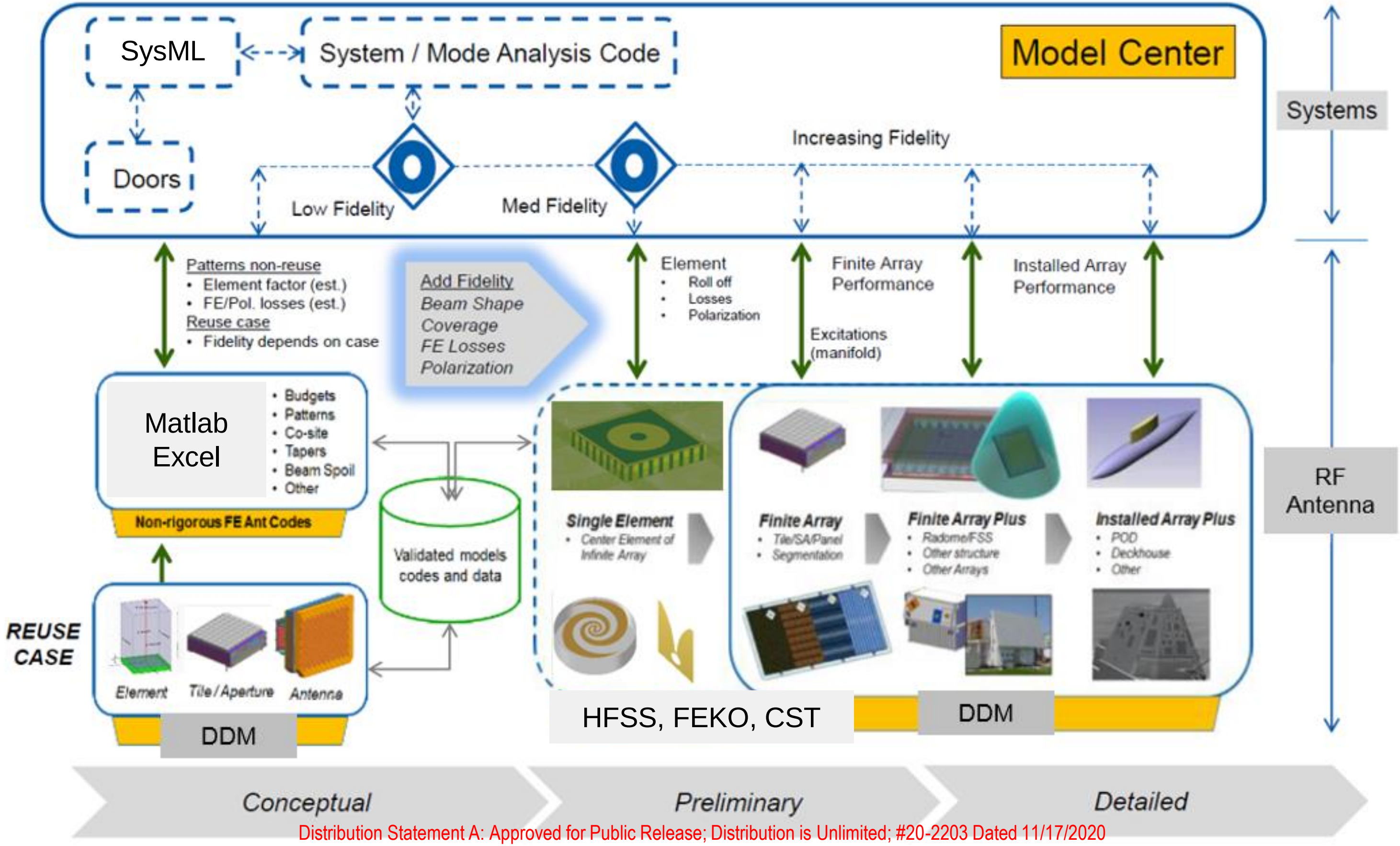
Capture Phased Array Architecture Using SysML Block Definition Diagram (BDD)

**Hypothetical System*



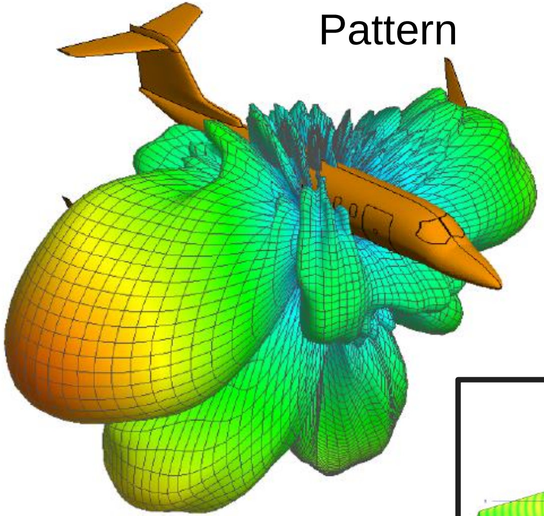
Each descriptive block capture interfaces and internal components for each subsystem; Reference architecture customized to mission needs

Increasing Levels of Fidelity Through the Antenna Design Process

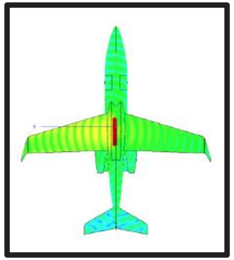


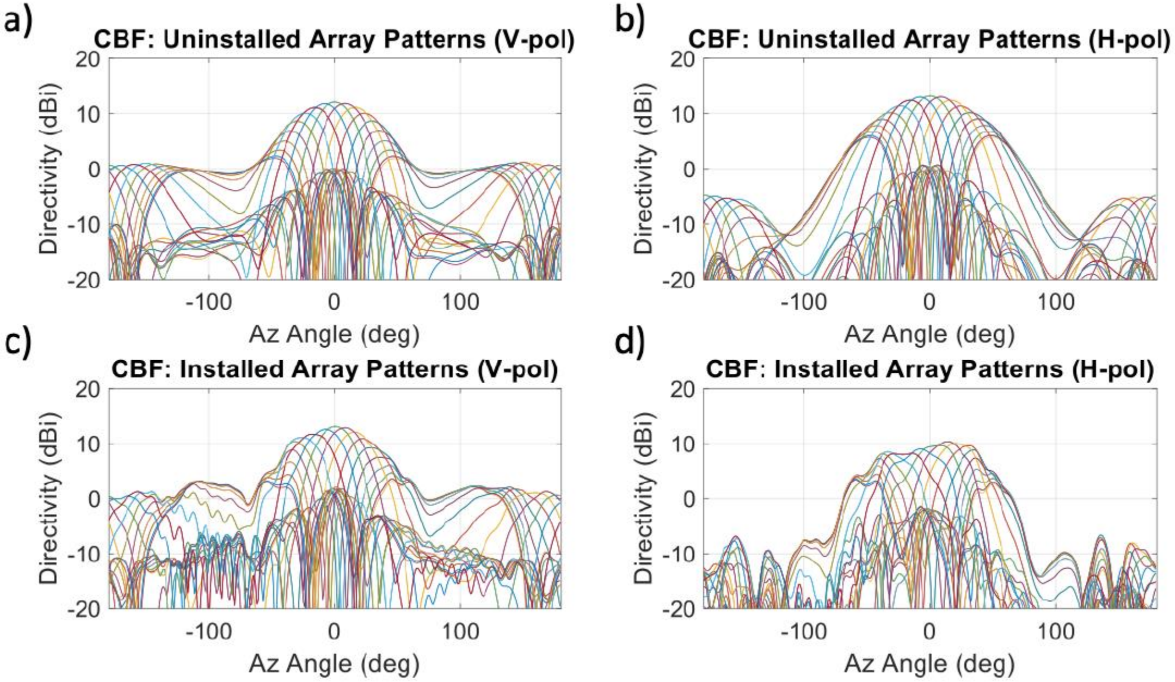
Installed Array Performance Using FEKO EM Solver

Installed Radiation Pattern



Surface Currents





Predict High-Fidelity Installed Antenna Radiation Patterns Using Full-Wave EM Solver to Inform System Design Decisions

System Design & Optimization

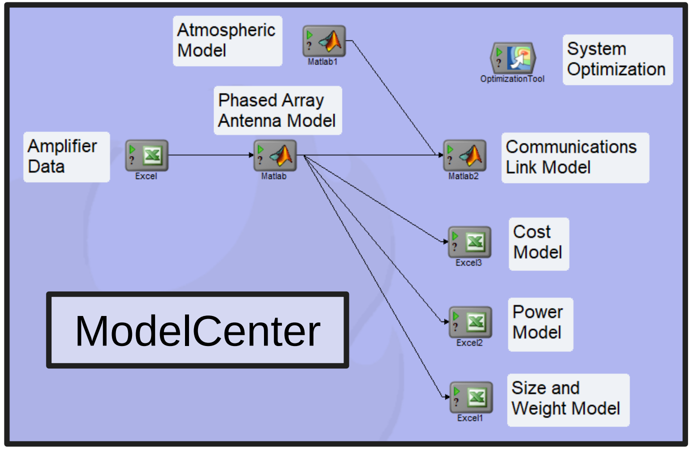
Use ModelCenter to Perform Parametric Performance vs. SWaP-C Trade Study Analysis

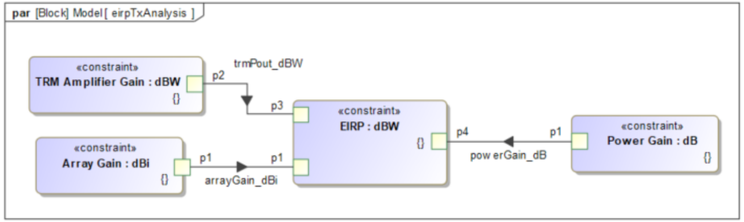
NORTHROP GRUMMAN

Objective: Discover best system design and phased array architecture for a wireless communication system to achieve required signal-to-ratio (SNR) at receiver

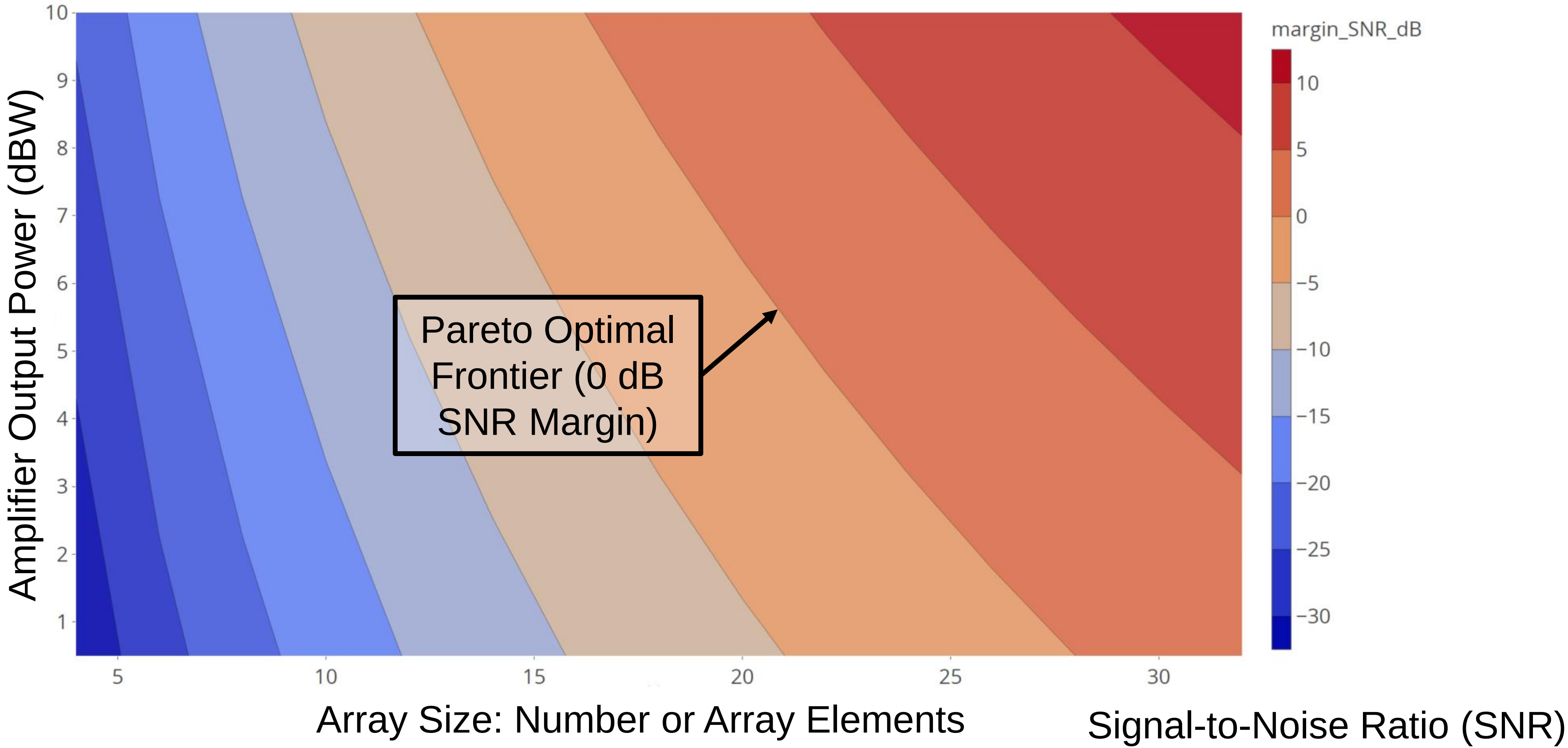
Inputs:
- Frequency
- Bandwidth
- Array Grid
- Amplifier Power Per Element
- Antenna Scan Angle
- # of Tx Beams
- Required SNR

Outputs:
- SNR at Receiver
- Link Margin
- Antenna EIRP
- Az/El Beamwidth
- Size
- Weight
- Prime Power
- Power Density
- Cost

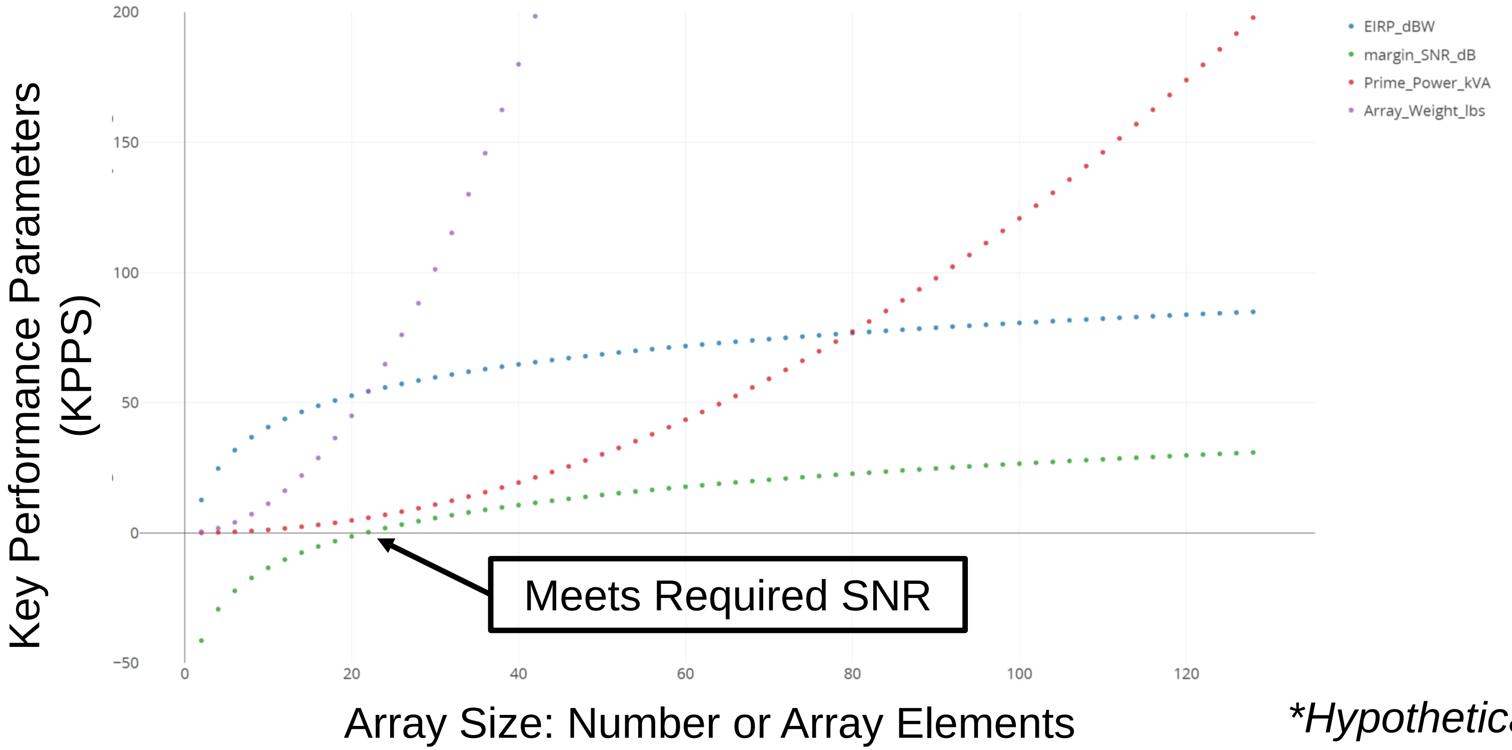




Power-Aperture Trade Study to Satisfy Required Communications Link SNR Margin using ModelCenter



Understand how increasing array size drives EIRP, prime power, weight, and SNR link margin using ModelCenter

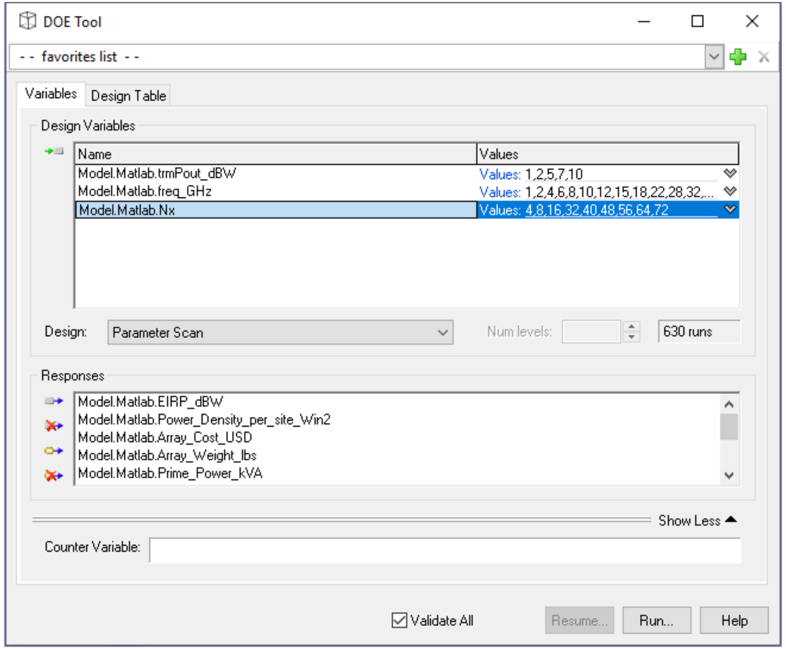


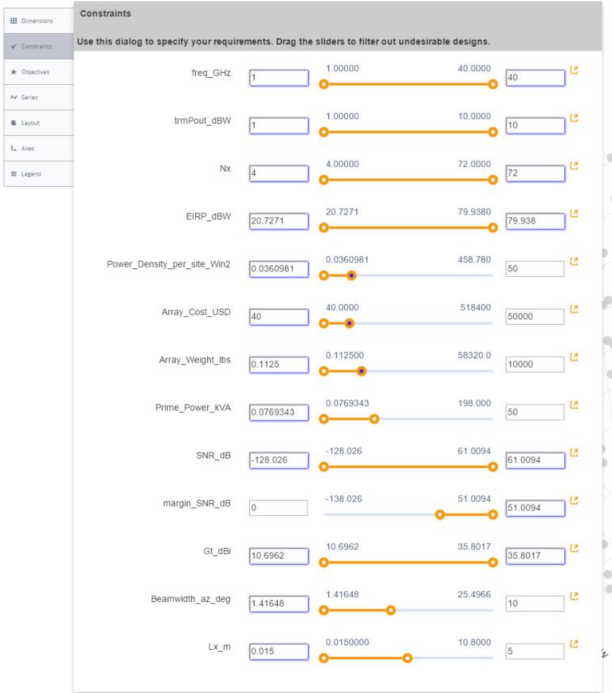
**Hypothetical System*

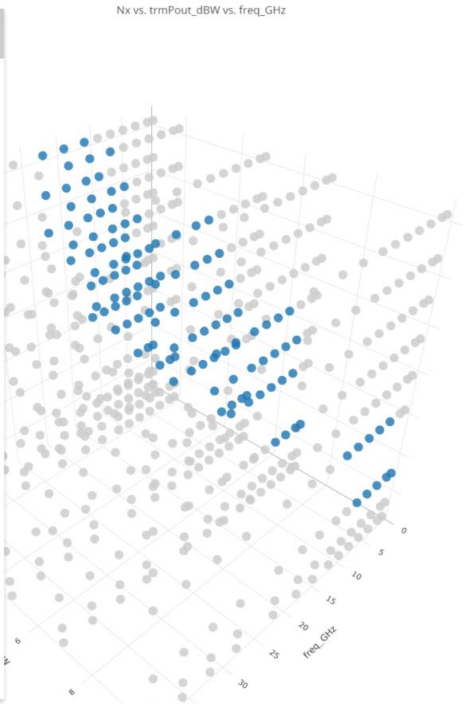
Model sensitivity of input design parameters on system KPPs and SWaP-C

Parametric trade study using design of experiment (DOE) tool simulates 630 system configurations

NORTHROP GRUMMAN

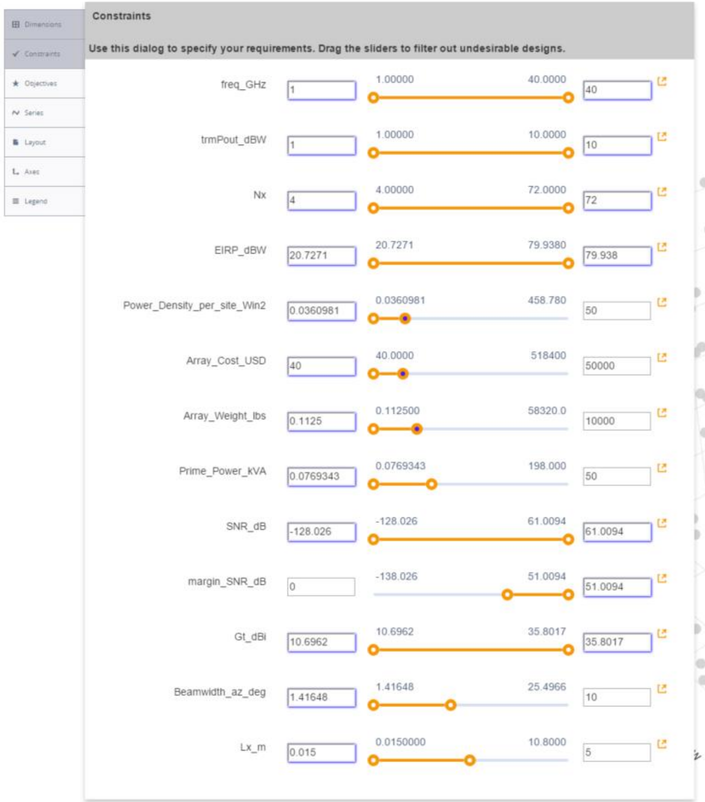


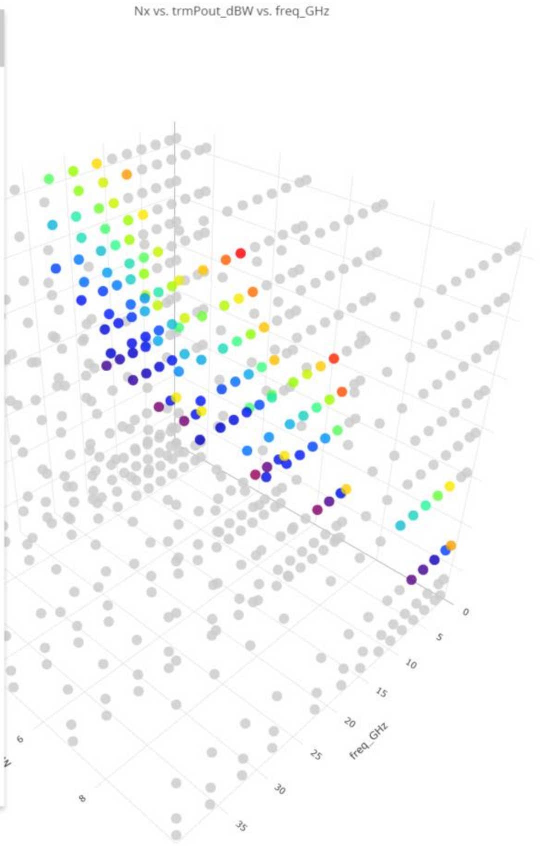




Each point is an evaluated system configuration; Gray dots shaded out because they do not meet system requirements and constraints

Color shading used to identify architecture configurations with lowest power, weight, and cost

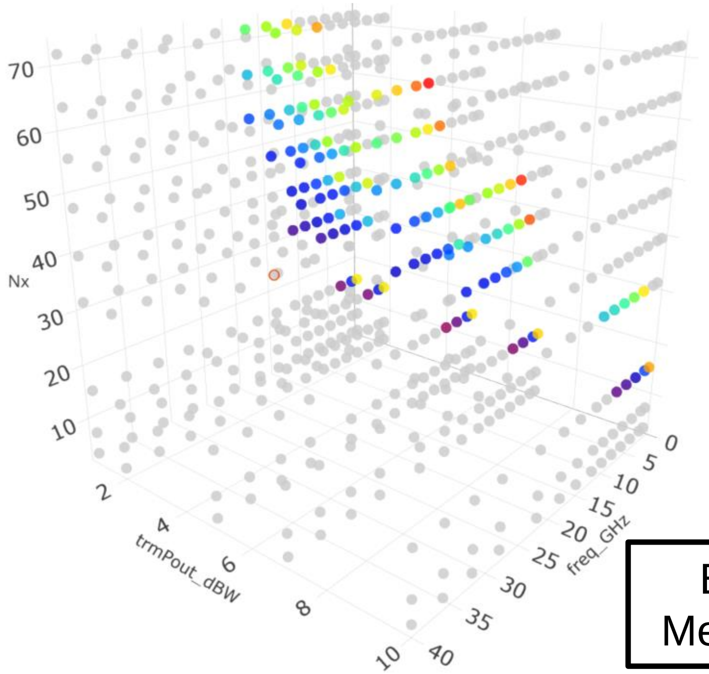


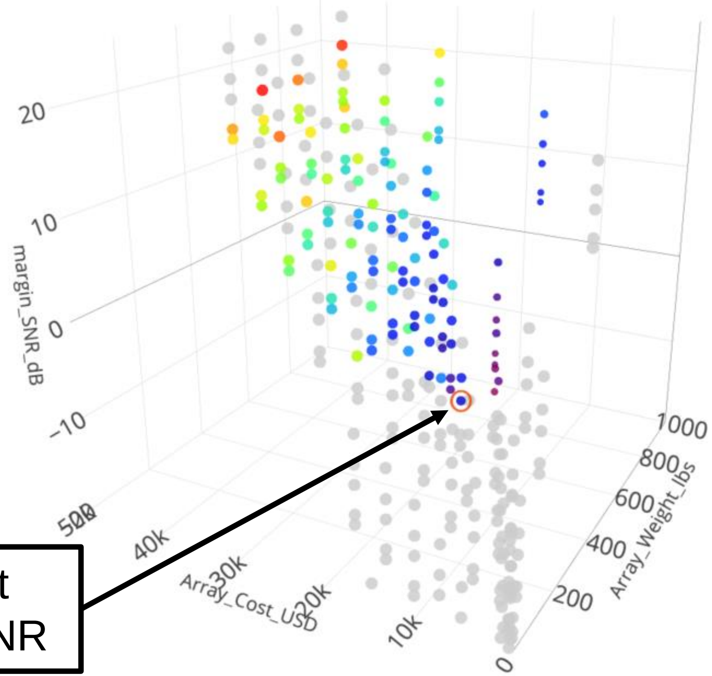


Mapping design inputs to key performance parameter (KPP) outputs to understand key relationships in data

Inputs: Array Size, Tx Power, Frequency

Outputs: Link Margin, Weight, Cost



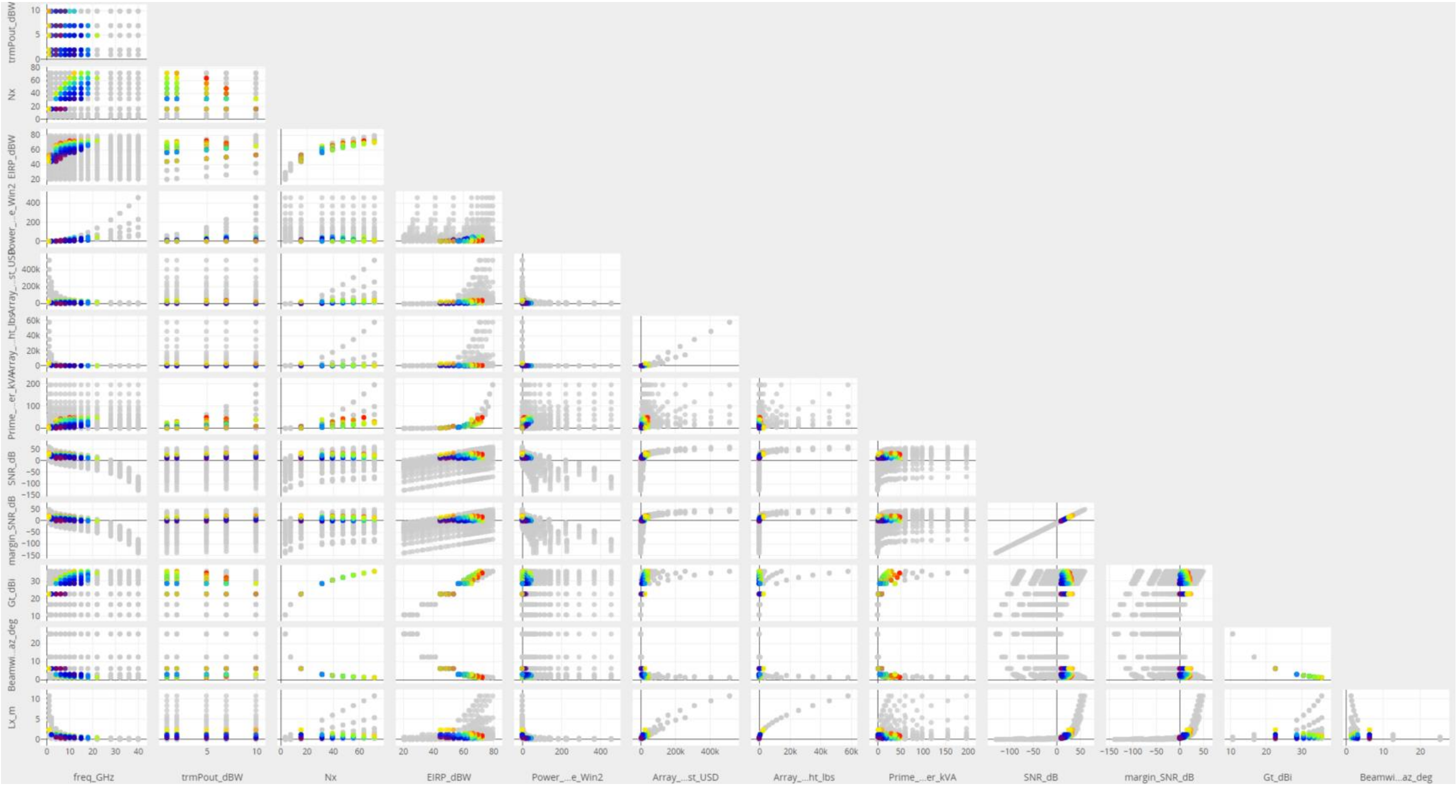


Best Design That Meets Required SNR

Shading based on system requirements to find best design

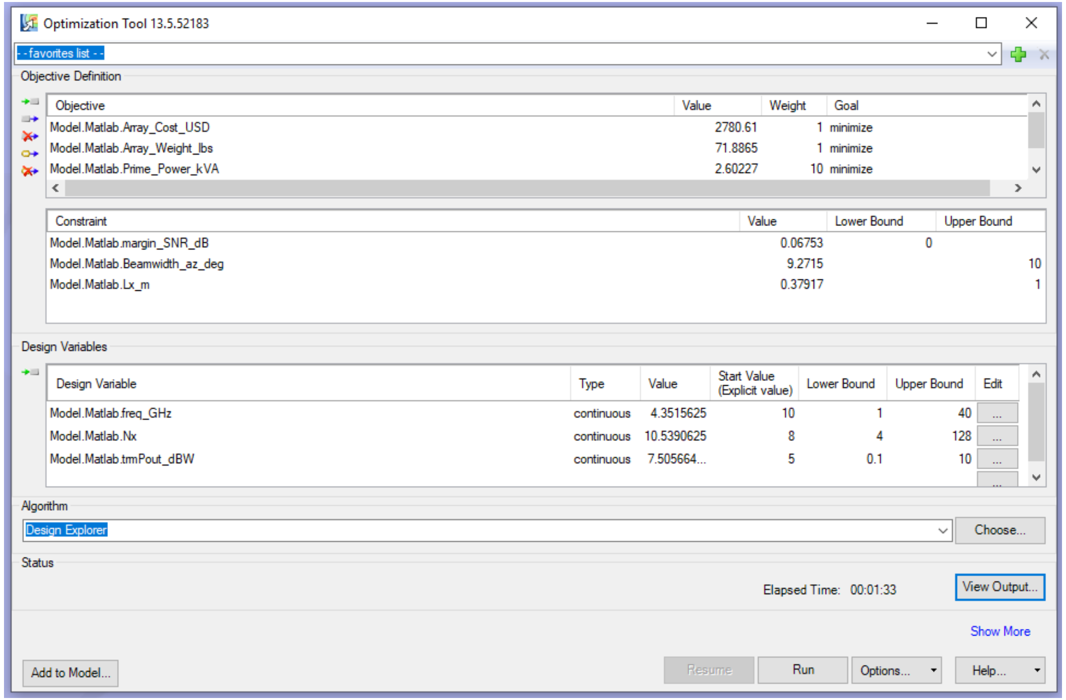
Scatter Matrix Visualizes Trade Study Results and Complex System Interactions

NORTHROP GRUMMAN



Visualize Relationship Between All Input and Output Design Variables

Built-in Optimization Tools Help Discover Best Design



Best Design

Run Number 101

Objective(s)

Name
(1 * (Model.Matlab.Array_Cost_USD)) + (1 * (Model.Matlab.Array_Weight_lbs)) + (10 * (Model

Constraint(s)

Name	Value
Model.Matlab.margin_SNR_dB	0.06753
Model.Matlab.Beamwidth_az_deg	9.2715
Model.Matlab.Lx_m	0.37917

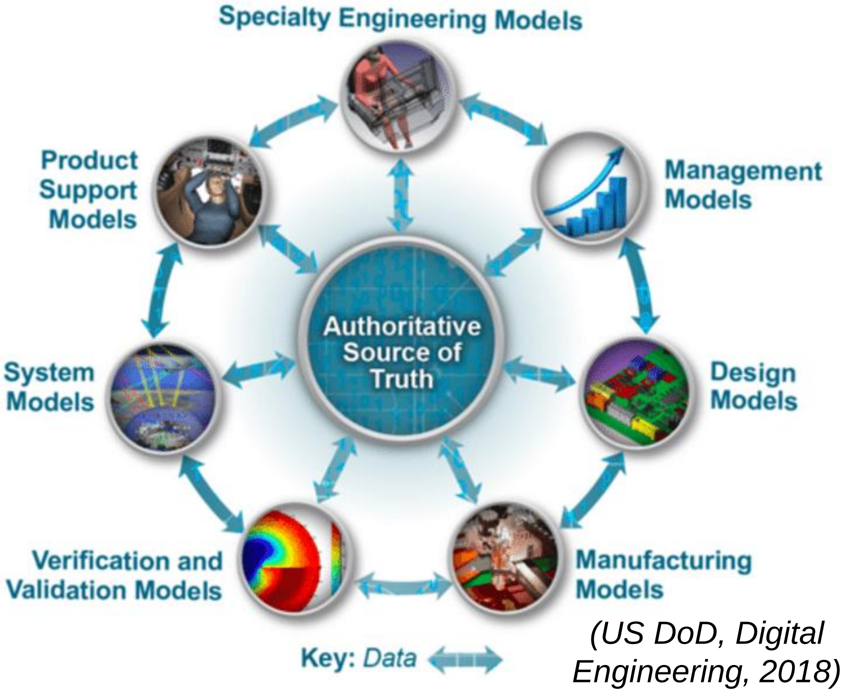
Design Variable(s)

Name	Start Value	Value
Model.Matlab.freq_GHz	10	4.35156
Model.Matlab.Nx	8	10.5391
Model.Matlab.trmPout_dBW	5	7.50566

Set to satisfy required link margin while minimizing cost, weight, and power

Path Forward

- Broaden MBSE adoption and digital engineering across the enterprise
- Continue to integrate models into unified digital twin using ModelCenter
- Directly integrate CAD models with descriptive and analytical models
- Deepen MBSE integration with product lifecycle management (PLM) systems



(US DoD, Digital Engineering, 2018)

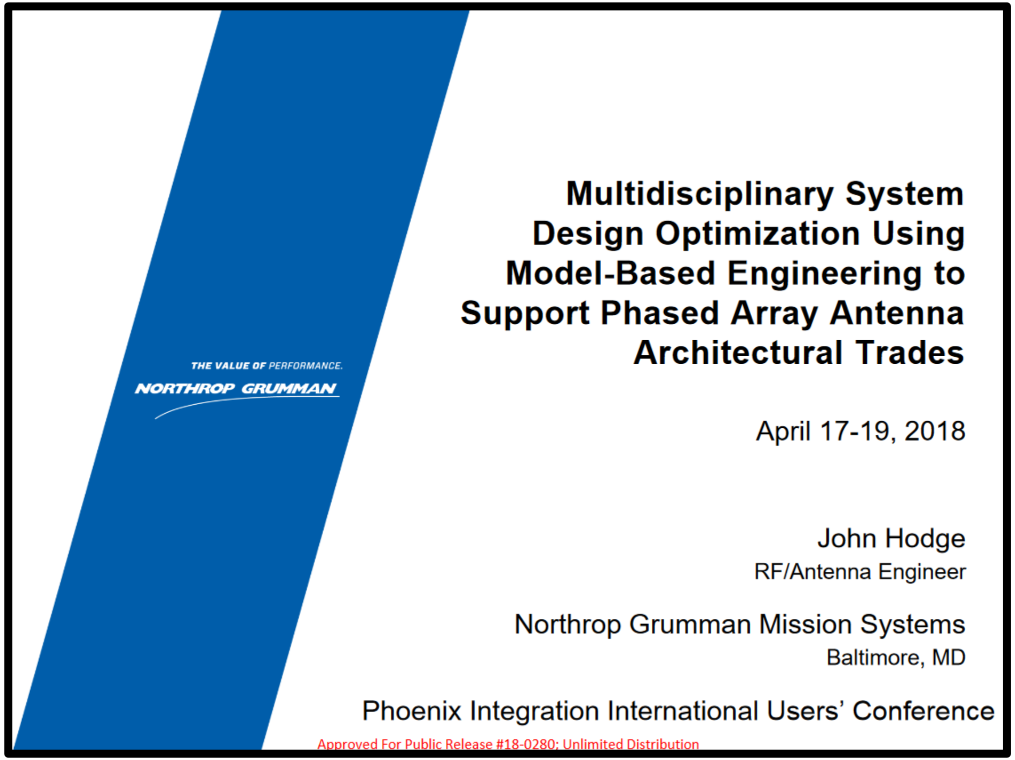
Help our customers adopt and transition to MBSE to increase system performance while reducing cost, schedule, and risk

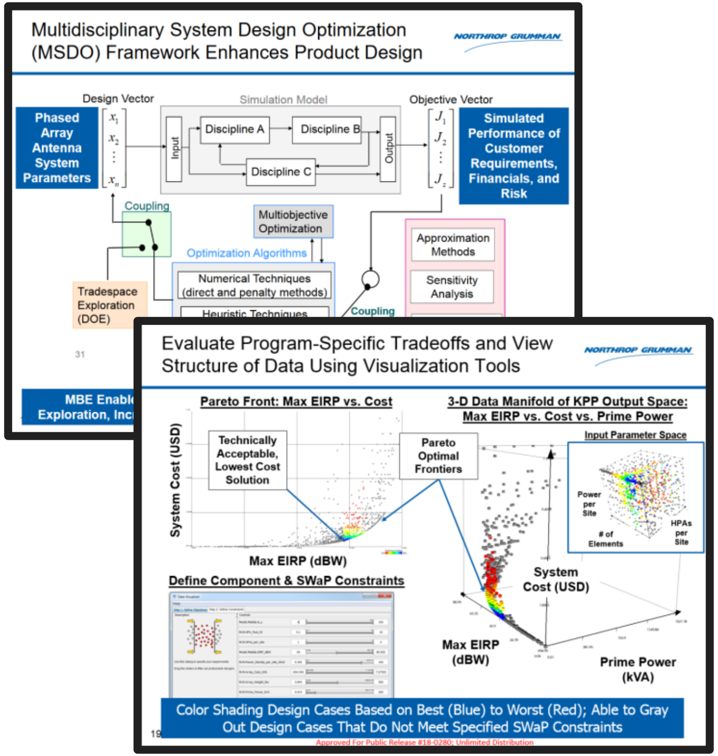
Summary

- Demonstrated a MBSE approach to the design & optimization of next-generation phased arrays
- Developed innovative integrated phased array system model to perform rapid multi-domain trades
- MBSE: Connect systems architecture models with engineering analyses
- Using ModelCenter to link descriptive SysML models to analytical performance model
- MDAO: Calculate system performance, check requirements, and perform design trade-offs

Flexible model for evaluating trade studies, performing system optimization, and system verification for phased array sensor systems

If you enjoyed today's talk



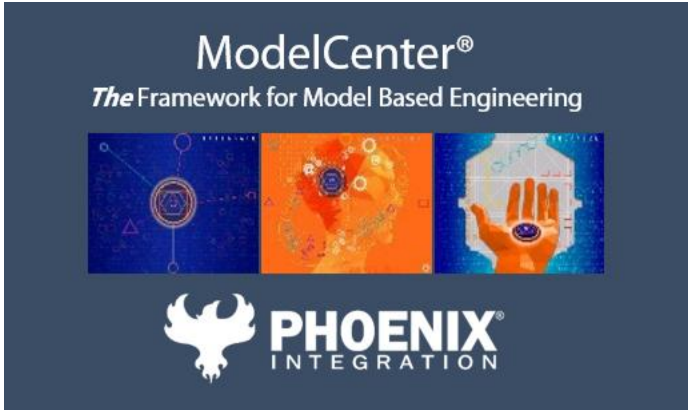


My 2018 webinar is available on the Phoenix Integration website

NORTHROP GRUMMAN

Acknowledgements

- Phoenix Integration Staff
- My NGC Mentors and Co-workers

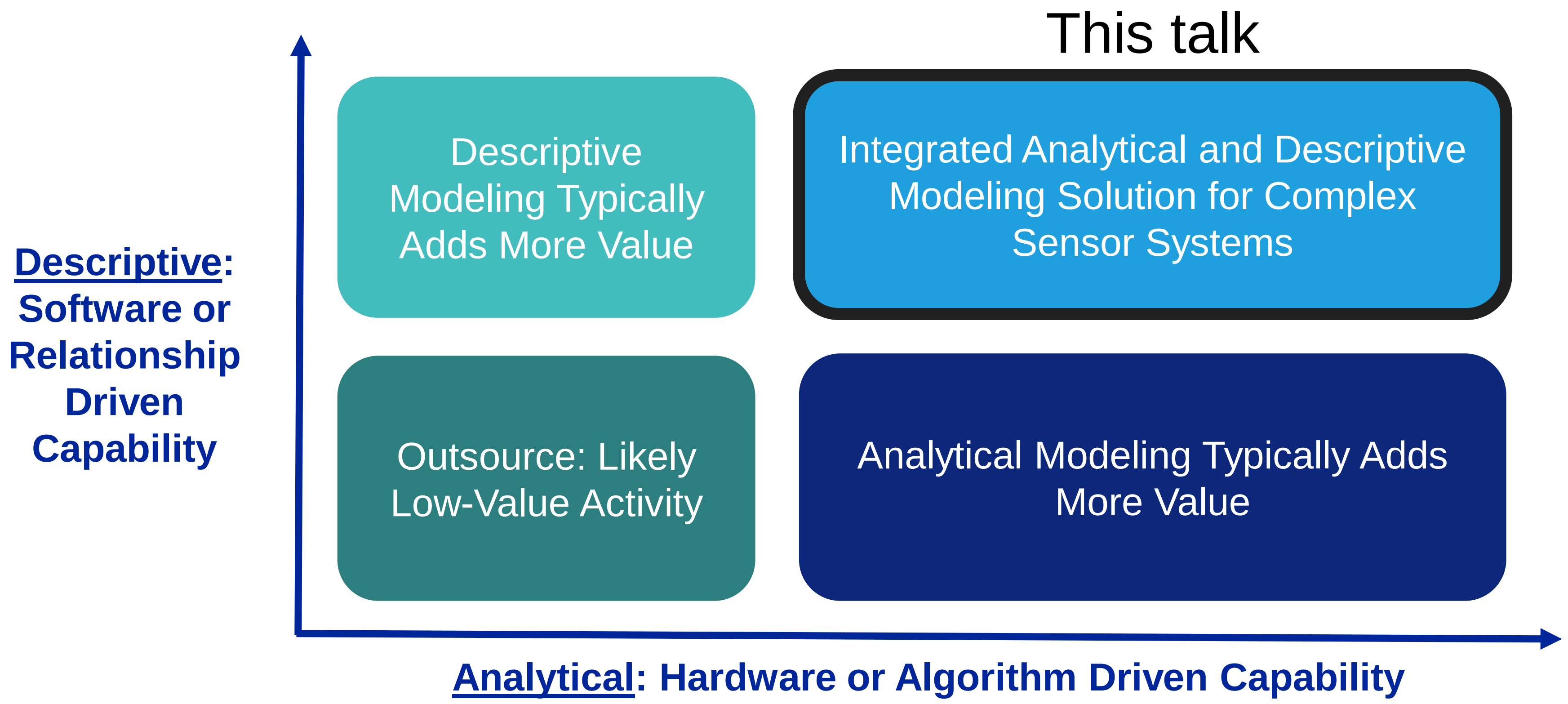


Thank You!

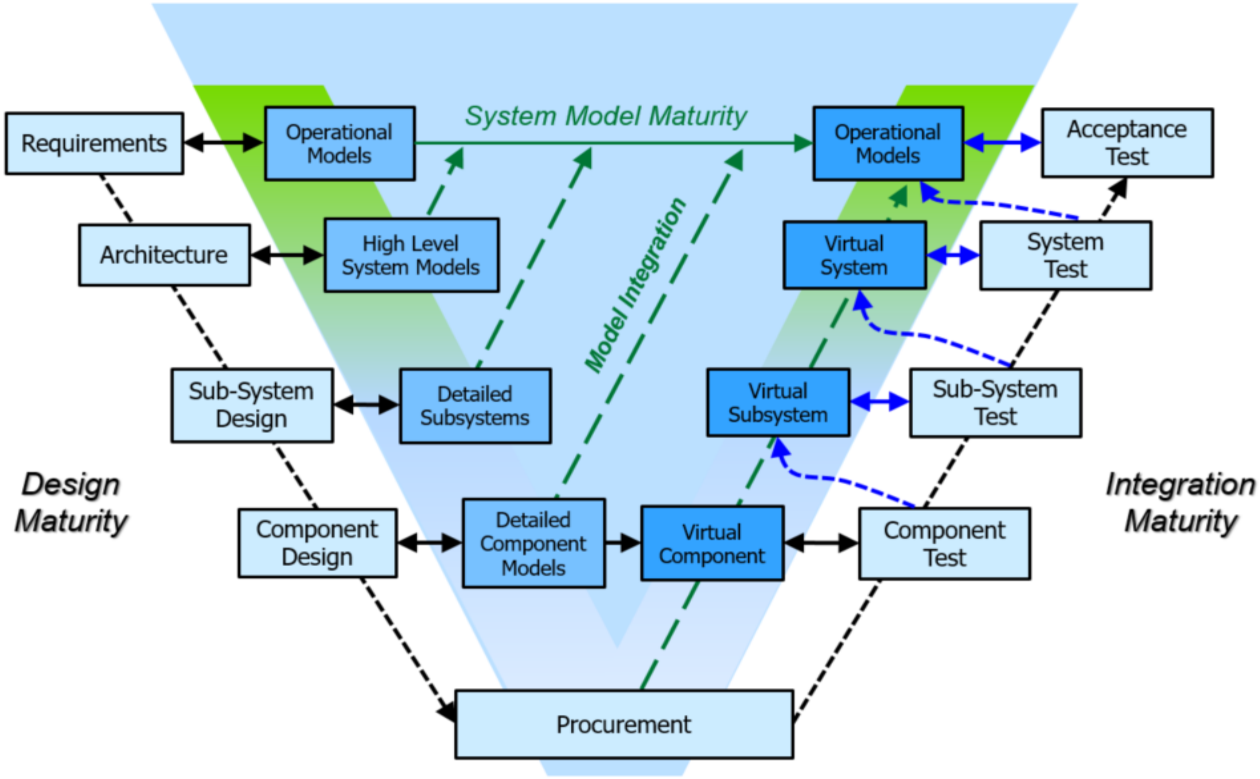
Contact: john.hodge@ngc.com

NORTHROP GRUMMAN

Value of Modeling Based on Defining Capabilities

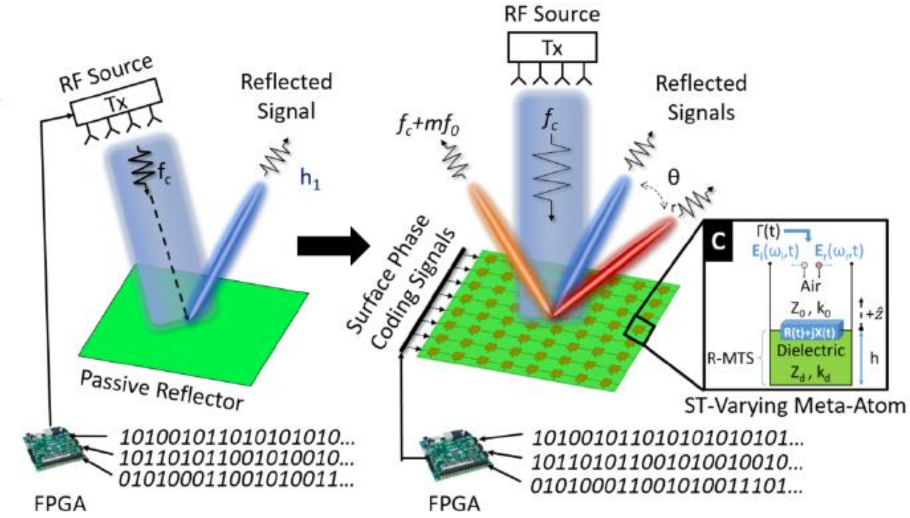


Providing Virtual Integration of Systems for Earlier Verification & Validation (V&V)



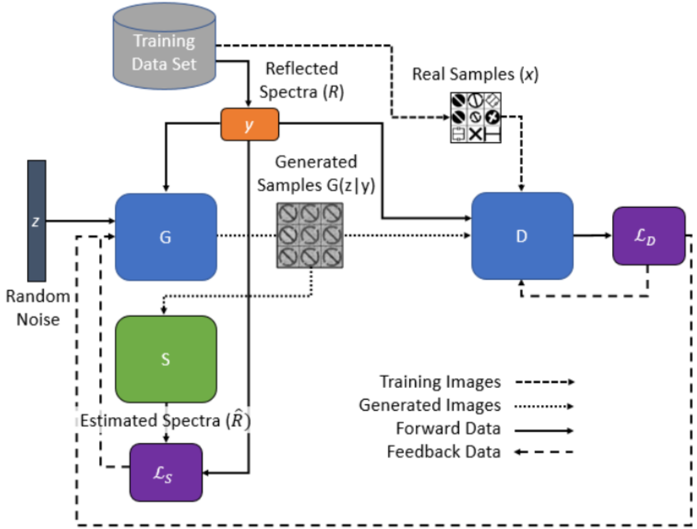
Path Forward (Cont.)

<u>Reconfigurable Intelligent Metasurfaces</u>



(Hodge, 2020)

<u>Machine Learning Driven Integrated Design</u>

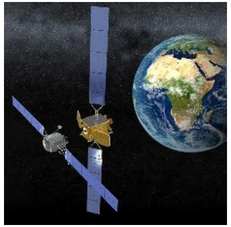


(Hodge, 2019)

Expand Domains of MBSE & MDAO for Next-Generation Applications

NORTHROP GRUMMAN

Four Operating Sectors at a Glance

Aeronautics Systems	Defense Systems	Mission Systems	Space Systems
 	 	 	 
Autonomous Systems	Integrated Air & Missile Defense	Airborne Sensors and Networks	Launch Vehicles
Aerospace Structures	Defensive Cyber and Information Operations	Artificial Intelligence/Machine Learning	Propulsion Systems
Advanced Technologies and Concepts	Platform Modernization and Fleet Operations Support	Cyber and Intelligence Mission Solutions	Commercial Satellites
Aircraft Design, Integration and Manufacturing	Advanced Weapons	Navigation, Targeting and Survivability	Military and Civil Space Systems
Long-range Strike	Precision Munitions	Maritime/Land Systems and Sensors	Science and National Security Satellites
Multi-Domain Integration and Operations	Software Systems Modernization and Sustainment	Engineering & Sciences	Human Space and Advanced Systems
Intelligence, Surveillance and Reconnaissance	Training and Simulation	Emerging Concepts Development	Space Components
Battle Management	Propulsion Systems	Multi-domain C2	Missile Defense
		Agile/DevSecOps Systems	Space Exploration
			Space ISR Systems