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

Northrop Grumman
Baltimore, MD

Phoenix Integration Webinar

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Motivation

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

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

Digital array architectures

(Delos, 2019)
Outline

• Introduction

• Integrated Modeling Framework

• Phased Array Antenna Systems

• System Design & Optimization

• Summary & Path Forward
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)
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**

- 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

1. Requirements
2. SysML Models
3. ModelCenter®
4. Analytical Models
5. Perform Trade Studies
6. Update Descriptive Models
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

2D Array Pattern

In phase energy produces a main beam

Smaller lobes produced elsewhere

Energy is in phase at an angle off array normal

Radiating Sites
Module Phase Shifters

0 deg 80 160 240 320 400 480

Phase Settings

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

Complex system with many subsystem and component interactions.
Scalable Digital AESA Architecture

Frequency and Mission Specific RF Front-End

Common RF Conversion and DBF

Common Back-End Processing and Control
**Typical Phased Array Antenna Requirements**

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

Power-aperture trade to meet EIRP or sensitivity drives array architecture.
Capture Performance and SWaP-C Requirements in SysML

Requirements linked to provide traceability; Verified using integrated analytical models

*Hypothetical System
Requirements Drive RF Front-End Architecture

Frequency Bandwidth

Power Handling

- Patch / Stacked Patch
- Waveguide / Slot
- PUMA [1]
- TCDA [2]
- Planar-Fed Folded Notch (PFFN)
- Stepped Notch / Vivaldi

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


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

SysML → System / Mode Analysis Code

Low Fidelity → Med Fidelity → Increasing Fidelity

Patterns non-reuse
- Element factor (est.)
- FE/Pol. losses (est.)
- Reuse case
- Fidelity depends on case

Add Fidelity
- Beam Shape
- Coverage
- FE Losses
- Polarization

Element
- Roll-off
- Losses
- Polarization

Finite Array
- Performance
- Excitations (manifold)

Installed Array
- Performance

Matlab Excel

Non-rigorous FE Ant Codes

Validated models, codes, and data

REUSE CASE

Element → Tile/Array → Antenna

DDM

HFSS, FEKO, CST

DDM

Conceptual → Preliminary → Detailed
Installed Array Performance Using FEKO EM Solver

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

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

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

Pareto Optimal Frontier (0 dB SNR Margin)
Understand how increasing array size drives EIRP, prime power, weight, and SNR link margin using ModelCenter.

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.

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

Shading based on system requirements to find best design

Best Design That Meets Required SNR
Scatter Matrix Visualizes Trade Study Results and Complex System Interactions

Visualize Relationship Between All Input and Output Design Variables
Built-in Optimization Tools Help Discover Best Design

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

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

(US DoD, Digital Engineering, 2018)
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
Acknowledgements

• Phoenix Integration Staff
• My NGC Mentors and Co-workers
Thank You!

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Value of Modeling Based on Defining Capabilities

Descriptive: Software or Relationship Driven Capability

- Descriptive Modeling Typically Adds More Value
- Outsource: Likely Low-Value Activity

Integrated Analytical and Descriptive Modeling Solution for Complex Sensor Systems

Analytical: Hardware or Algorithm Driven Capability

- Analytical Modeling Typically Adds More Value

This talk
Providing Virtual Integration of Systems for Earlier Verification & Validation (V&V)
Path Forward (Cont.)

Reconfigurable Intelligent Metasurfaces

Machine Learning Driven Integrated Design

Expand Domains of MBSE & MDAO for Next-Generation Applications

(Hodge, 2020)

(Hodge, 2019)
Four Operating Sectors at a Glance

**Aeronautics Systems**
- Autonomous Systems
- Aerospace Structures
- Advanced Technologies and Concepts
- Aircraft Design, Integration and Manufacturing
- Long-range Strike
- Multi-Domain Integration and Operations
- Intelligence, Surveillance and Reconnaissance
- Battle Management

**Defense Systems**
- Integrated Air & Missile Defense
- Defensive Cyber and Information Operations
- Platform Modernization and Fleet Operations Support
- Advanced Weapons
- Precision Munitions
- Software Systems Modernization and Sustainment
- Training and Simulation
- Propulsion Systems

**Mission Systems**
- Airborne Sensors and Networks
- Artificial Intelligence/Machine Learning
- Cyber and Intelligence Mission Solutions
- Navigation, Targeting and Survivability
- Maritime/Land Systems and Sensors
- Engineering & Sciences
- Emerging Concepts Development
- Multi-domain C2
- Agile/DevSecOps Systems

**Space Systems**
- Launch Vehicles
- Propulsion Systems
- Commercial Satellites
- Military and Civil Space Systems
- Science and National Security Satellites
- Human Space and Advanced Systems
- Space Components
- Missile Defense
- Space Exploration
- Space ISR Systems