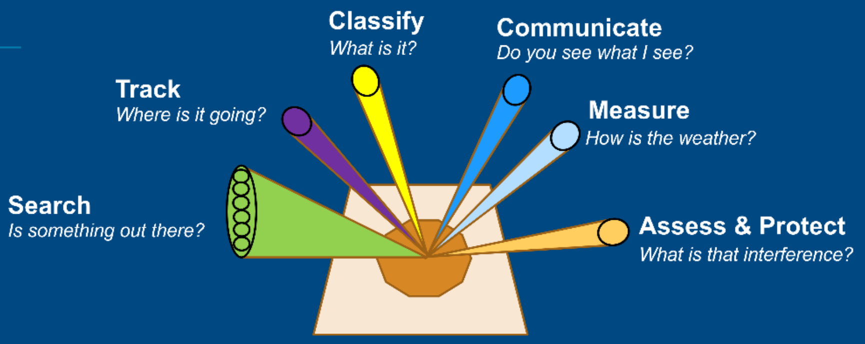
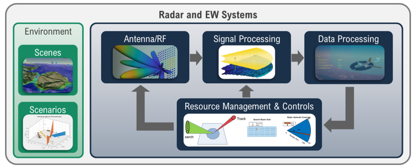
Building Datasets for AI-Enabled Radar, Communications, and EW Systems



Outline

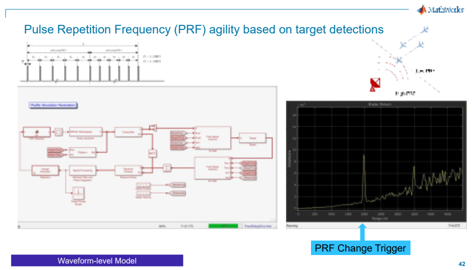
- How **Digital Engineering** helps teams collaborate
- **Modeling and Simulation** at multiple abstraction levels
- **Multifunction** RF Mode-Agility Examples
- **AI Workflow** Overview and Example

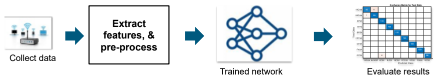


Power-level Model

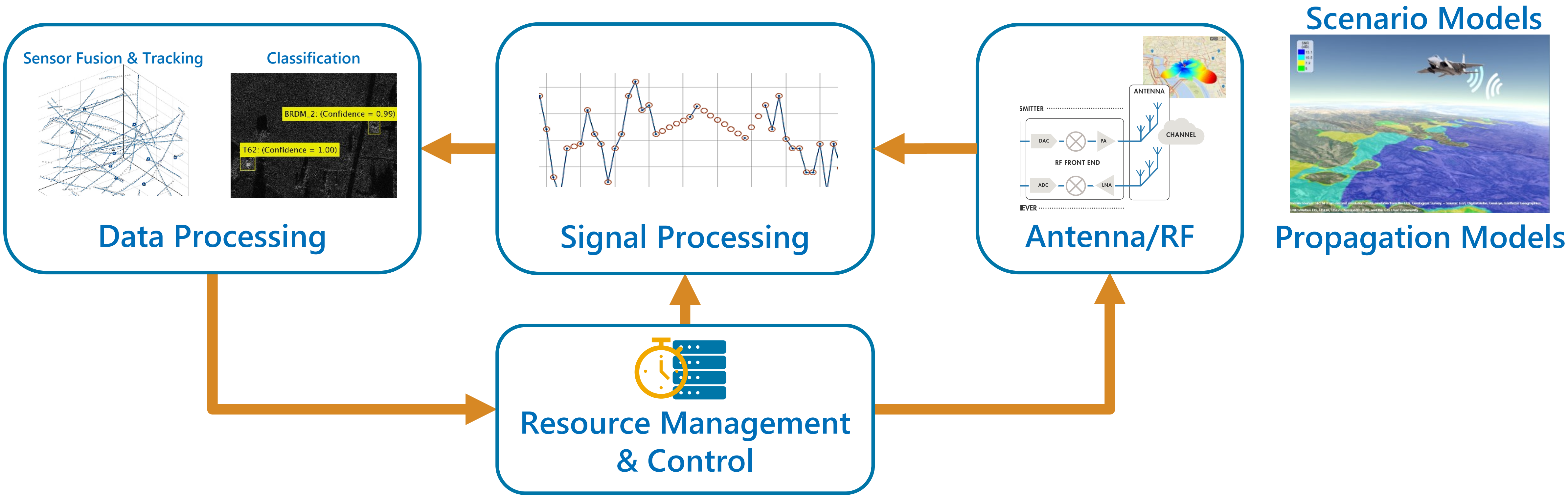
Measurement-level Model

Signal-level Model

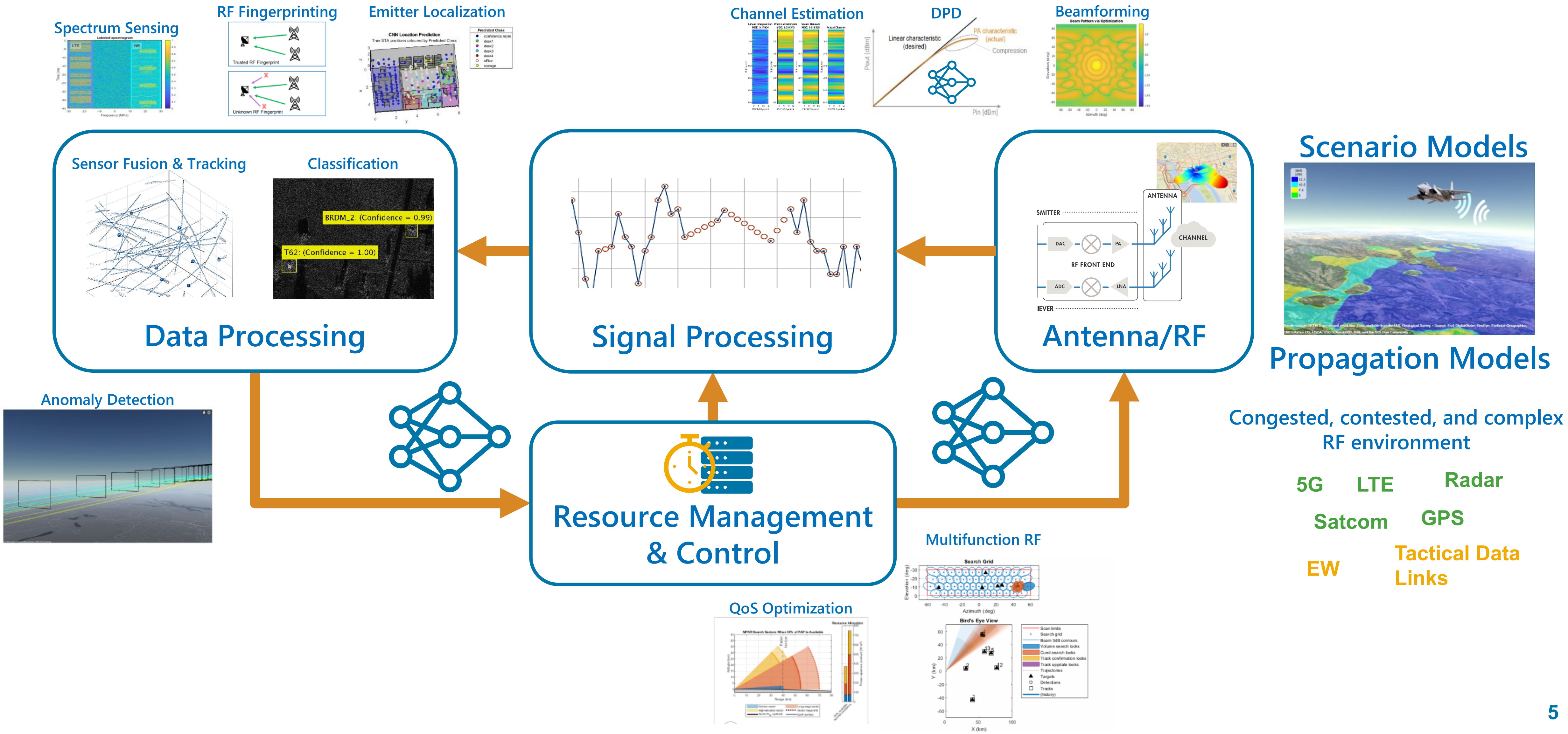




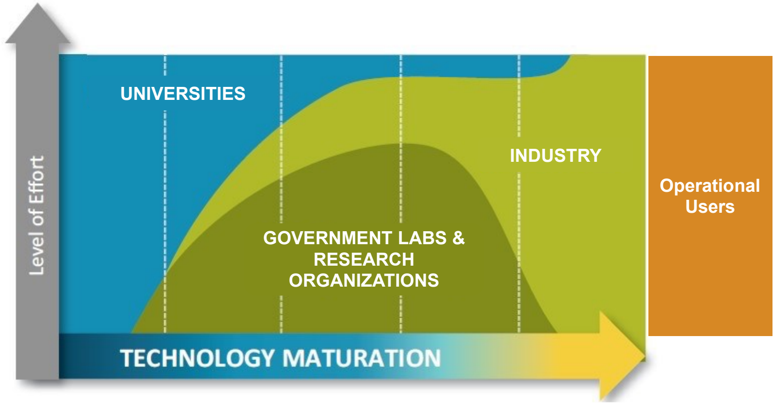
Electromagnetic Spectrum Operations (EMSO) span multiple domains



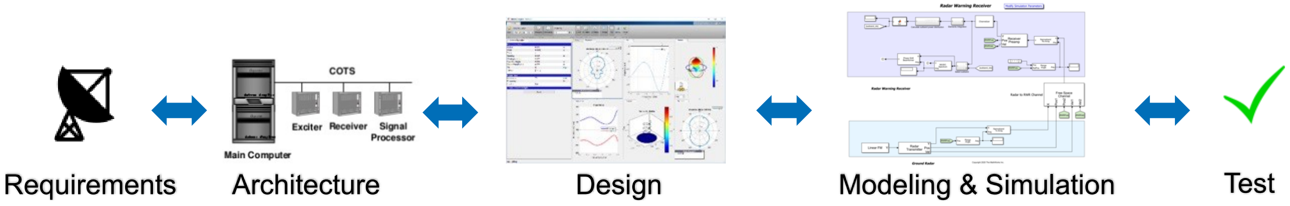
AI can be applied to many aspects of these subsystems…

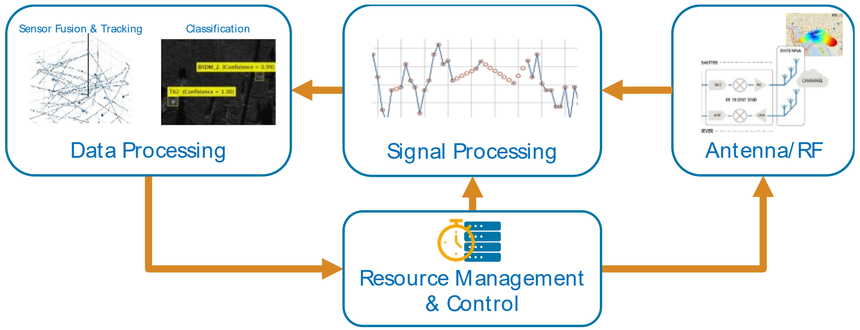


Modeling and simulation needs vary based on multiple factors

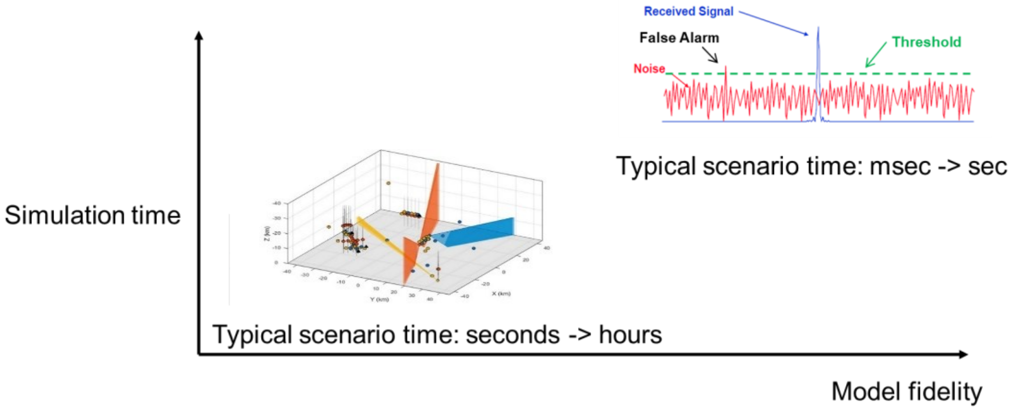


Phase of development life cycle





Area of focus

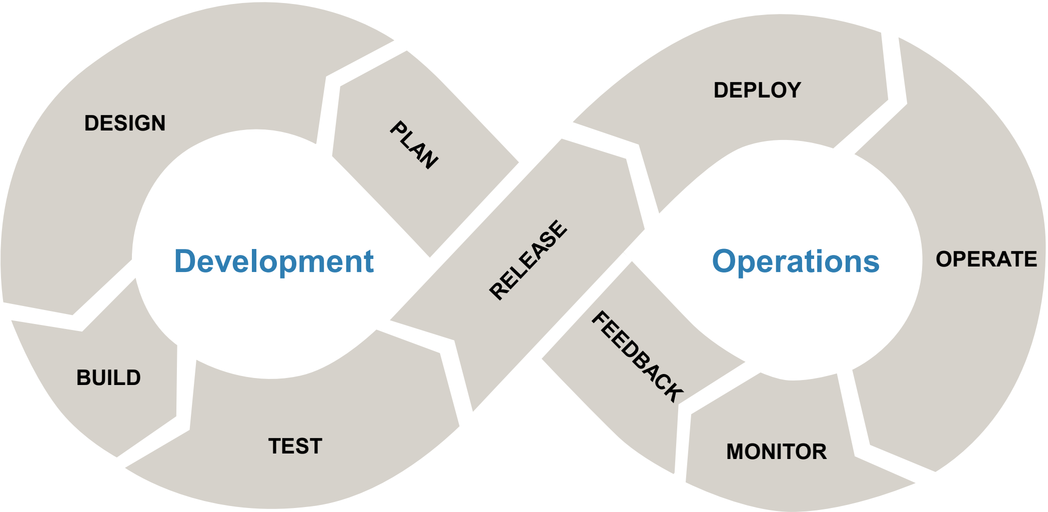


Type of scenario being simulated

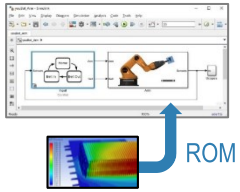
DevOps: A Set of Practices to Automate/Integrate Processes Between Development and Operations

Across full system life cycle…

- Achieve more rigor
- Smooth transitions across phases
- Enable continuous integration of models



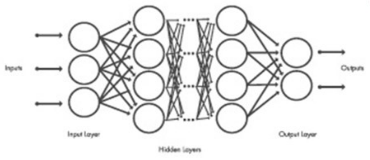
PHYSICS-BASED



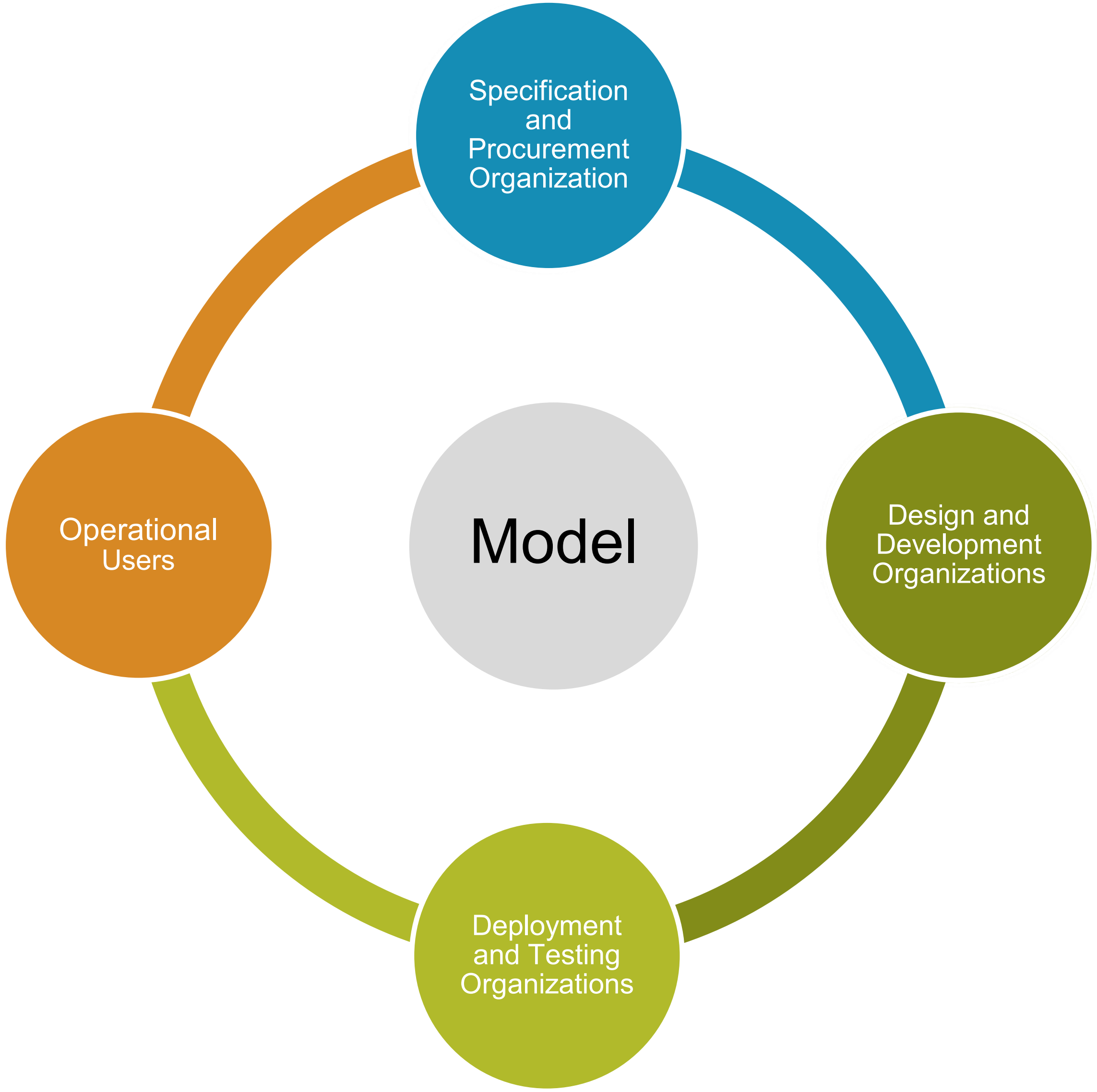
DATA-DRIVEN

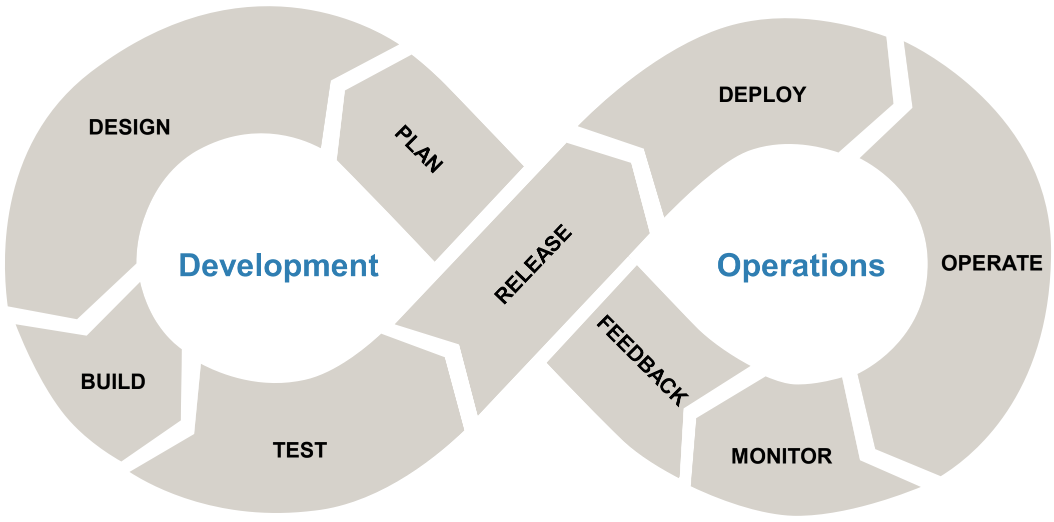
$$\hat{x}_k = \underbrace{\hat{x}_k^-}_{\text{Predict}} + \underbrace{K_k(y_k - C\hat{x}_k^-)}_{\text{Update}}$$

AI-BASED

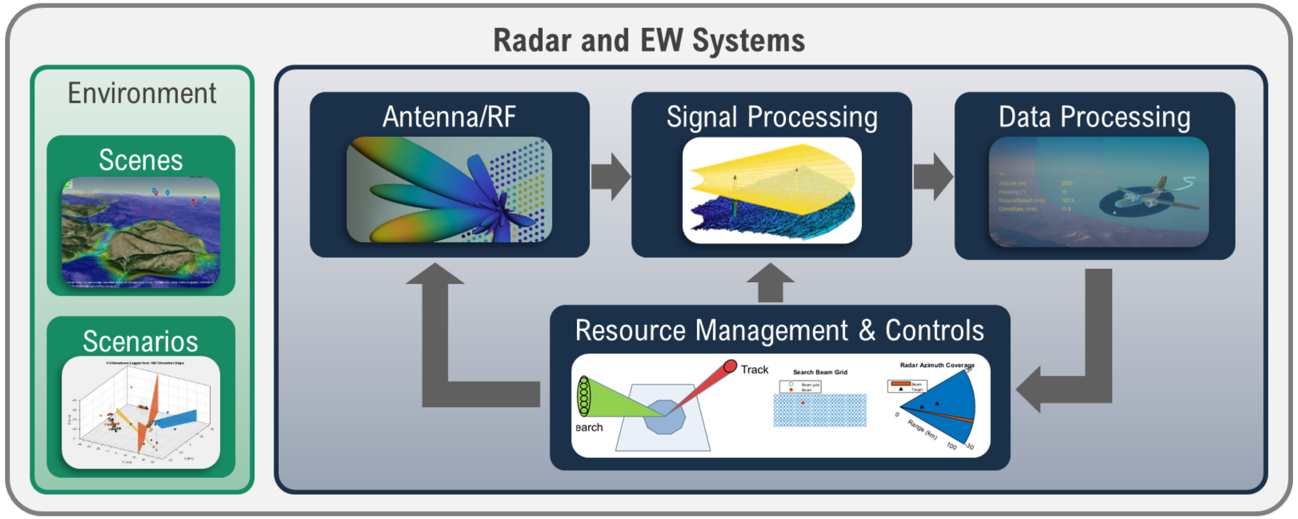


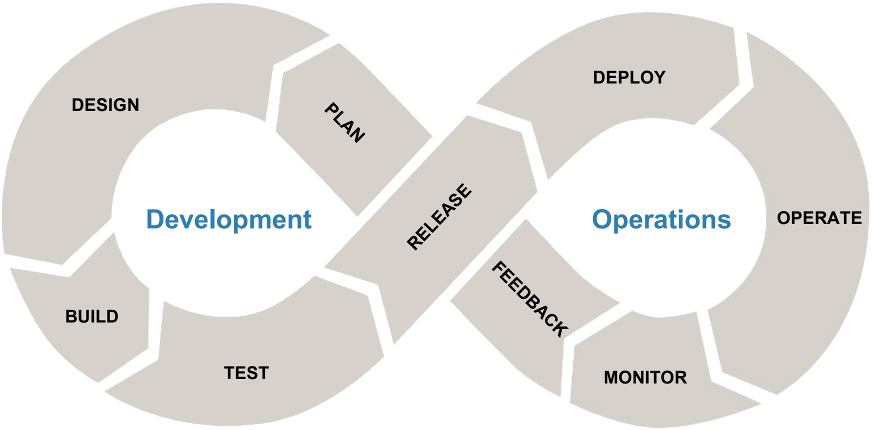
DevOps brings agile processes to the System Life Cycle

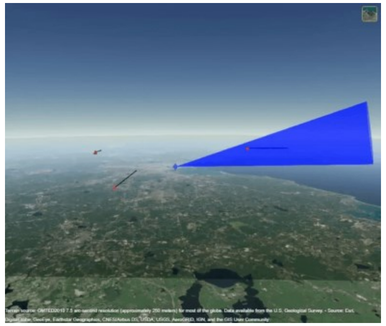
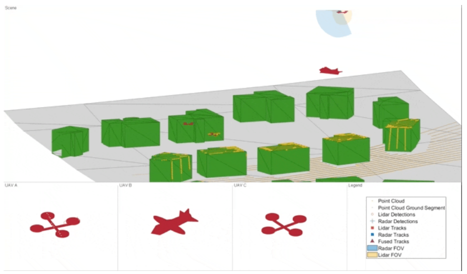
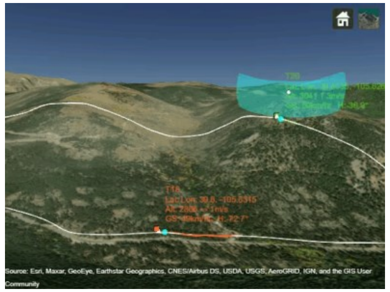
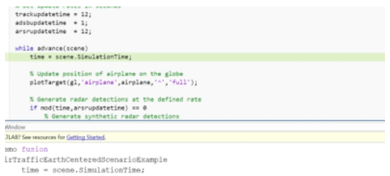
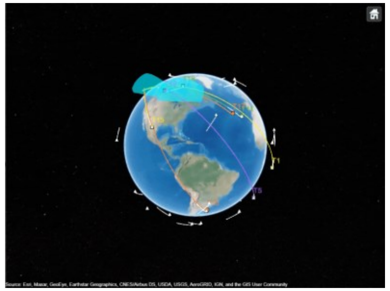
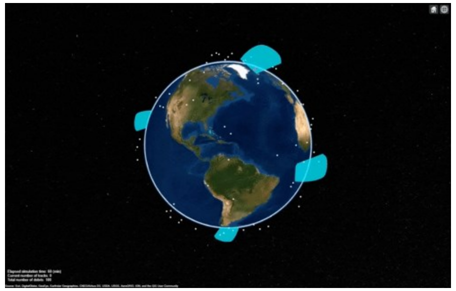




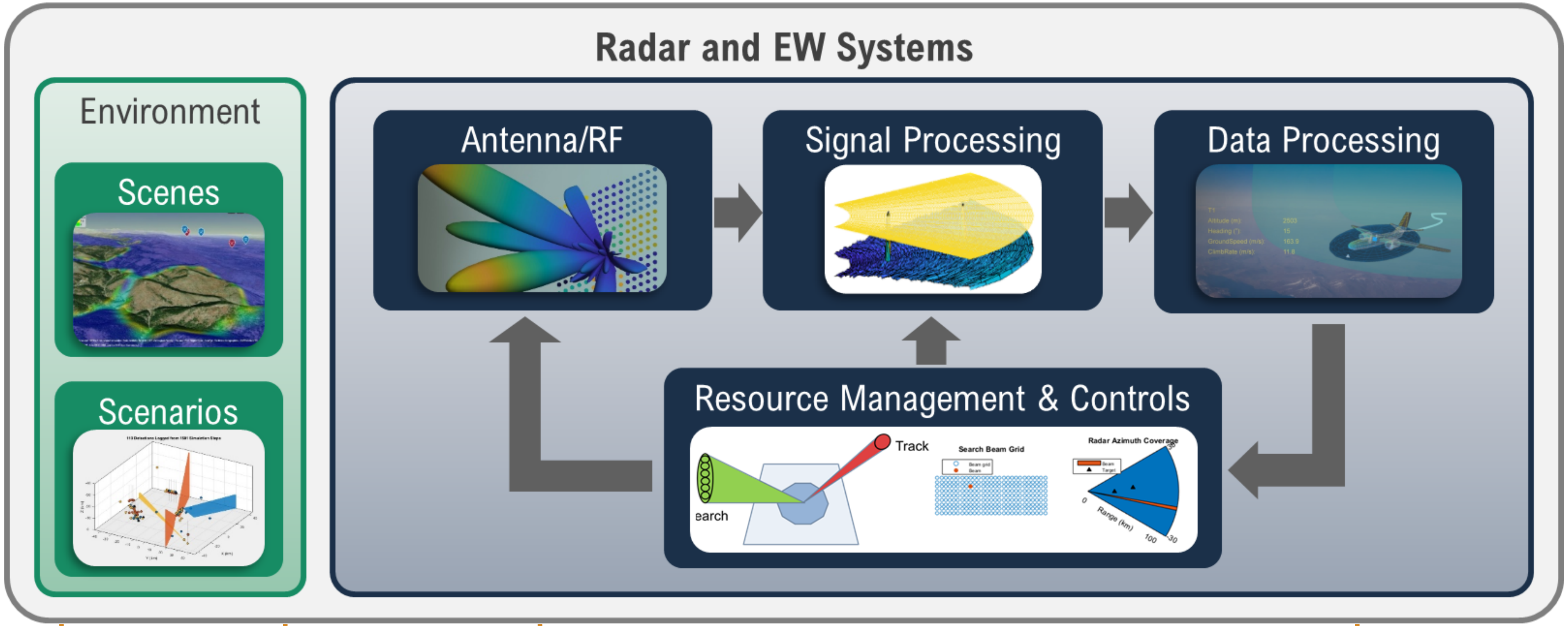
System simulation is possible for a range of complex systems





Models need to account for a range of environments and scenarios



- **Target attributes**
- **Surface clutter**
- **Atmospheric conditions**
- **Precipitation**

- **Operating parameters**
- **Hardware**
- **Processing**
- **Scanning**

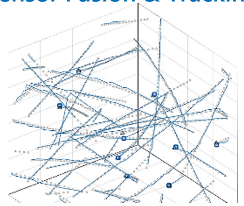
OODA = observe, orient, decide, act

Broad Support for Wireless and Radar System Design

Data Processing

- Sensor Fusion & Tracking Toolbox
- Statistics & Machine Learning Toolbox
- Reinforcement Learning Toolbox
- Deep Learning Toolbox

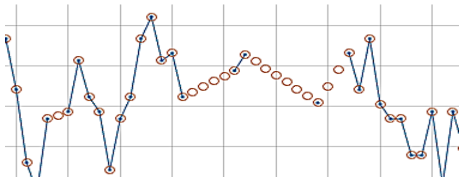
Sensor Fusion & Tracking



Classification

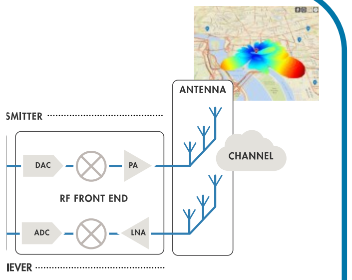
Signal Processing

- 5G Toolbox
- Satellite Comms Toolbox
- Radar Toolbox
- LTE Toolbox
- Phased Array System Toolbox
- DSP System Toolbox
- Communications Toolbox
- Signal Processing Toolbox



Antenna/RF

- RF Blockset
- Phased Array System Toolbox
- RF Toolbox
- Antenna Toolbox

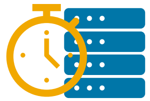


Scenario Models

- Radar Toolbox
- Satellite Comms Toolbox
- UAV Toolbox
- Sensor Fusion & Tracking Toolbox
- Communications Toolbox

Propagation Models

- Satellite Comms Toolbox
- 5G Toolbox
- LTE Toolbox
- Antenna Toolbox
- Communications Toolbox
- Radar Toolbox



Resource Management & Control

- Radar Toolbox
- SoC Blockset
- Wireless HDL Toolbox
- Instrument Control Toolbox
- Wireless Testbench
- DSP HDL Toolbox

- Standards
- Scenario modeling
- End-to-end simulation
- RF & antenna modeling
- Deployment to hardware

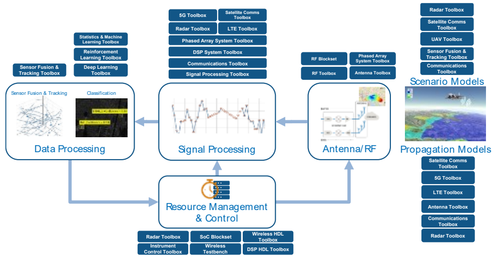
AI Workflow can be applied to Comms and Radar

Data Preparation → **AI Modeling** → **Simulation & Test** → **Deployment**

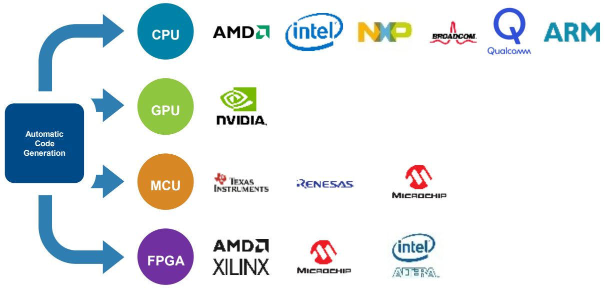
Data Preparation
- MATLAB
- Signal Processing Toolbox

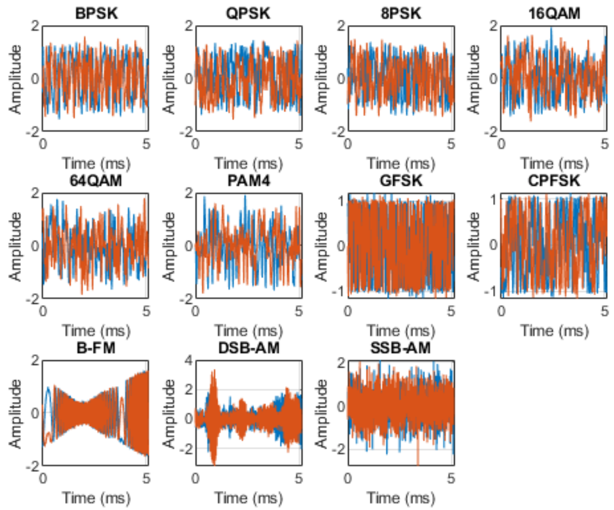
AI Modeling
- Statistics and Machine Learning Toolbox
- Deep Learning Toolbox
- Reinforcement Learning Toolbox

Simulation & Test



Deployment





- Synthetic Dataset Generation
- Modulation Classification
- Channel Estimation & Digital Predistortion
- Signal Recovery / Reconstruction
- Spoofing Detection (Cybersecurity / EW)

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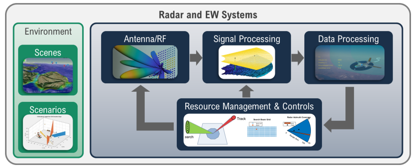
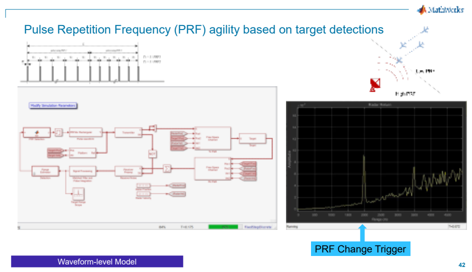
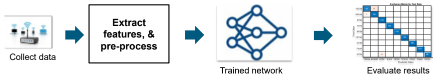


Power-level Model

Measurement-level Model

Signal-level Model





Modeling & Simulation Pyramid – Mission Engineering View

Example Stakeholders

Mission Commanders
Policymakers & Advocates

+

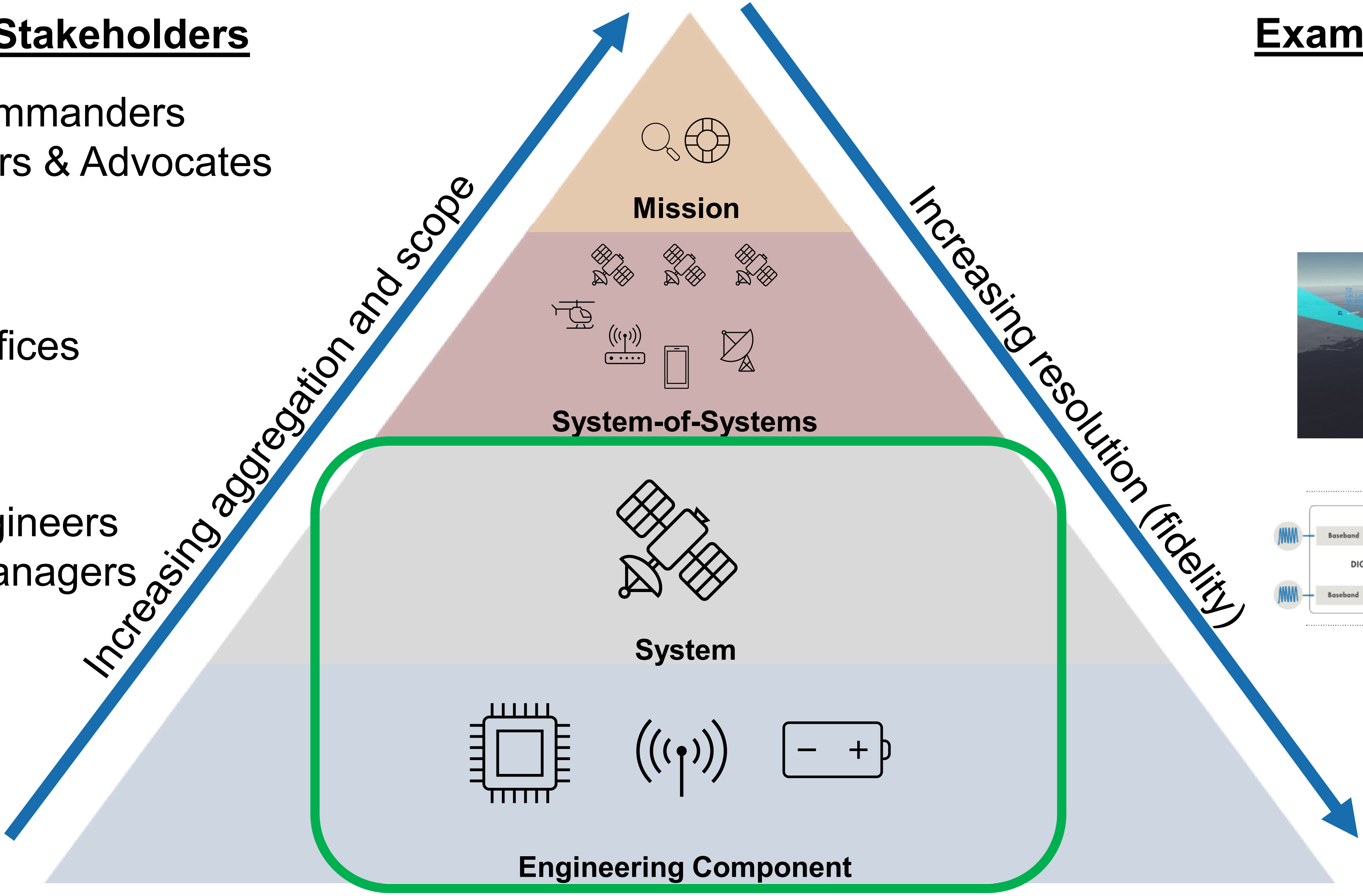
Integrators
Program Offices

+

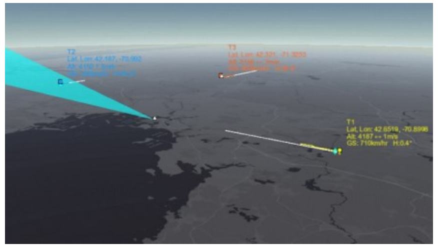
System Engineers
Program Managers

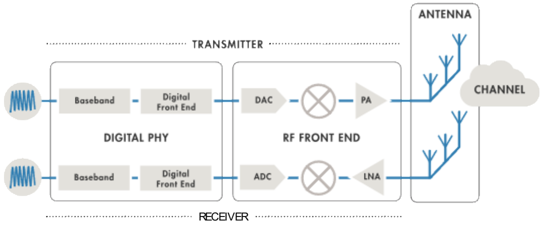
+

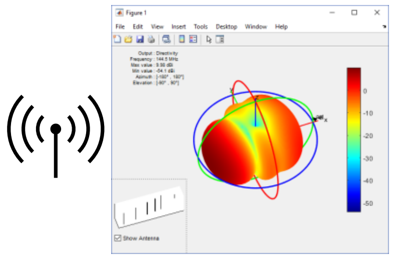
Engineers
Developers
Scientists



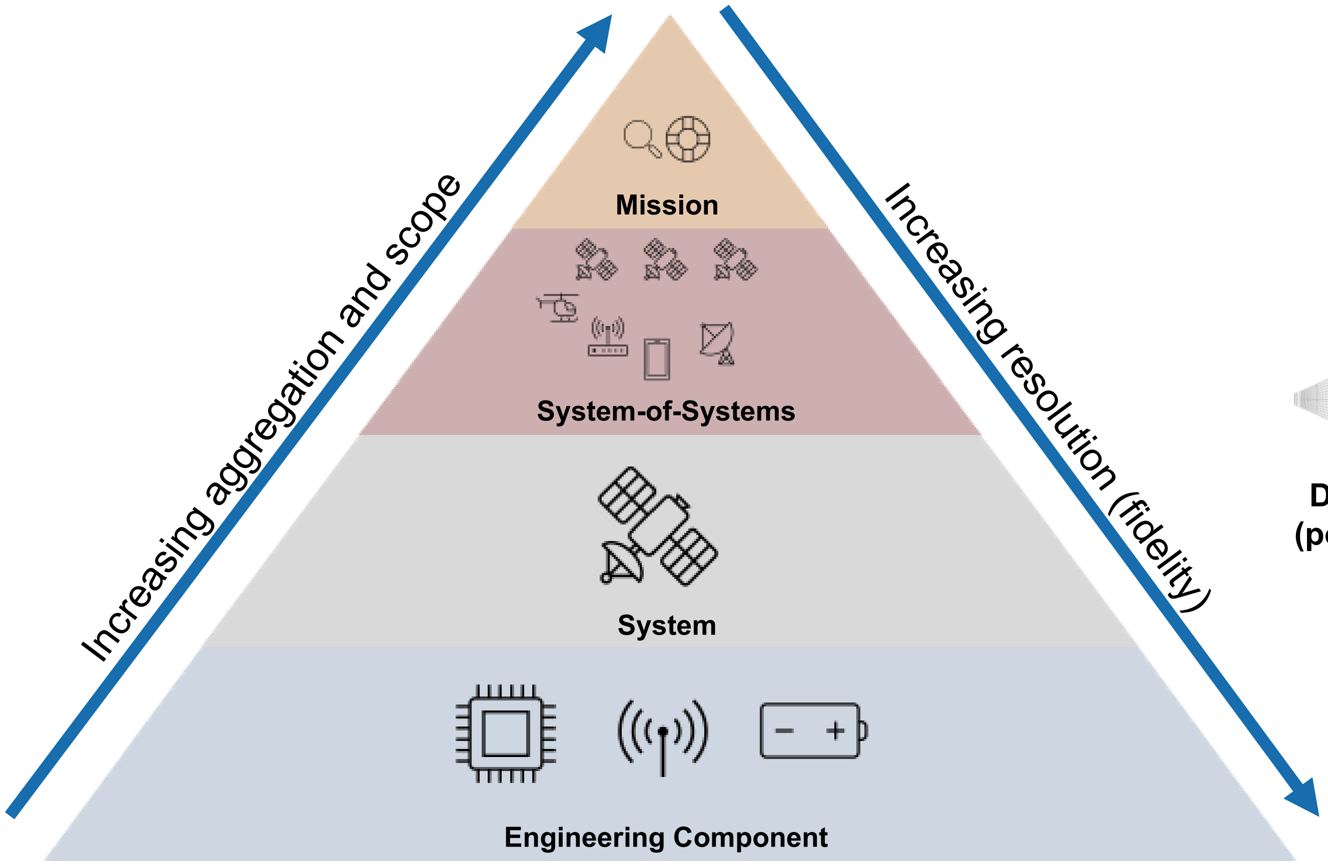
Example Perspective

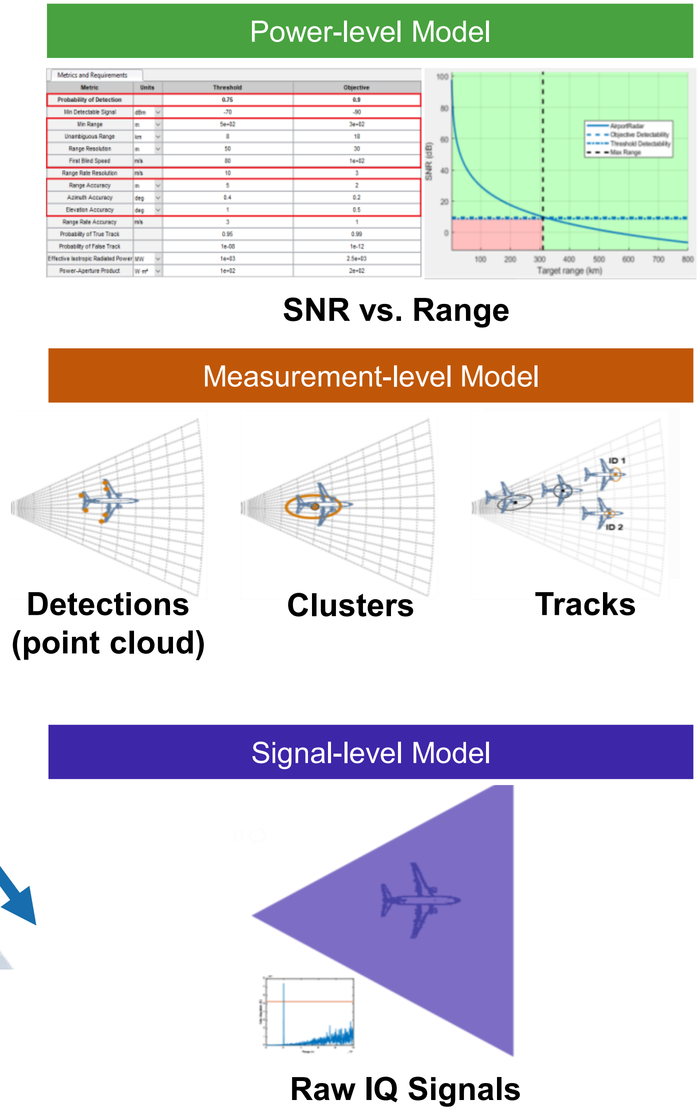




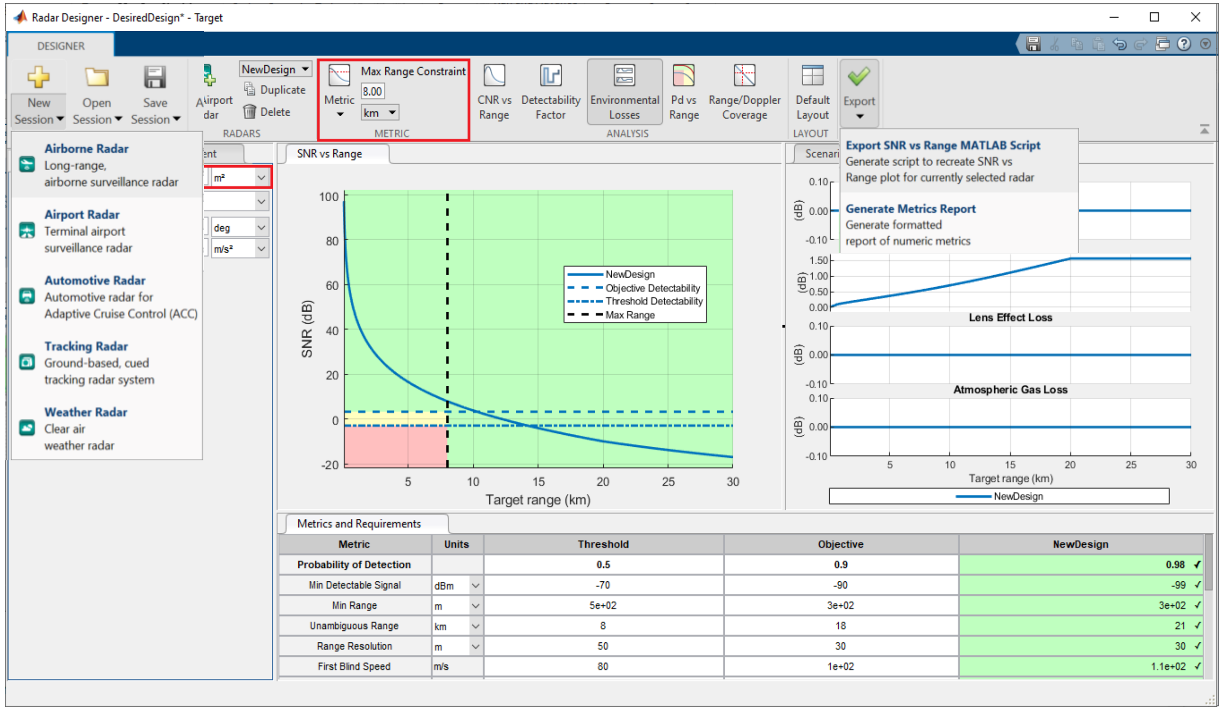


Multifunction RF systems can be modeled across multiple abstraction levels

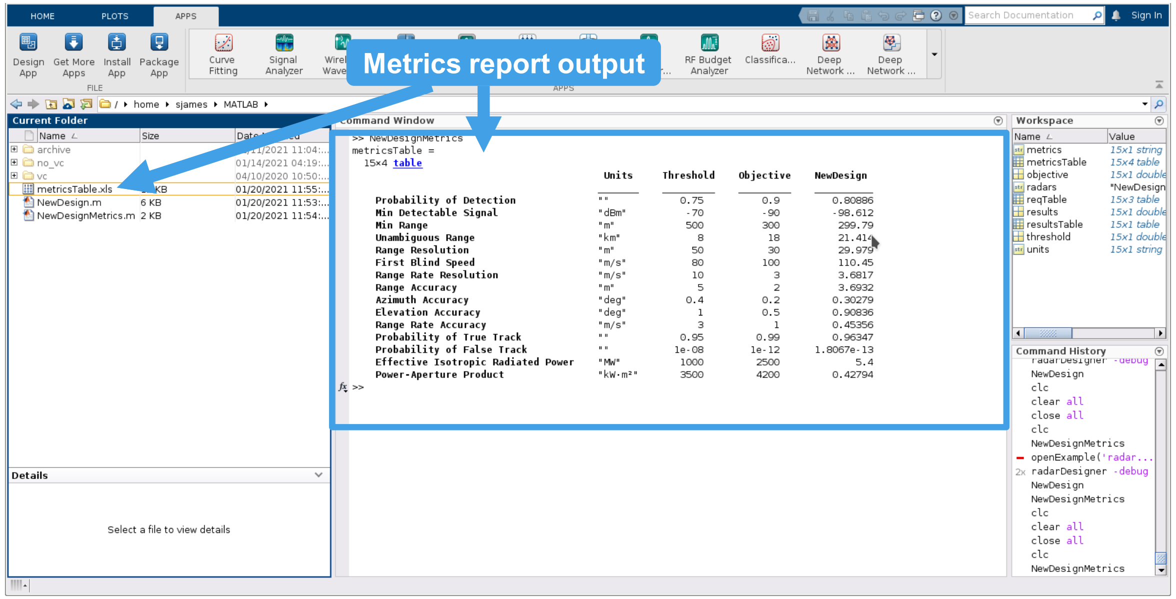




Interactively design and evaluate radar systems



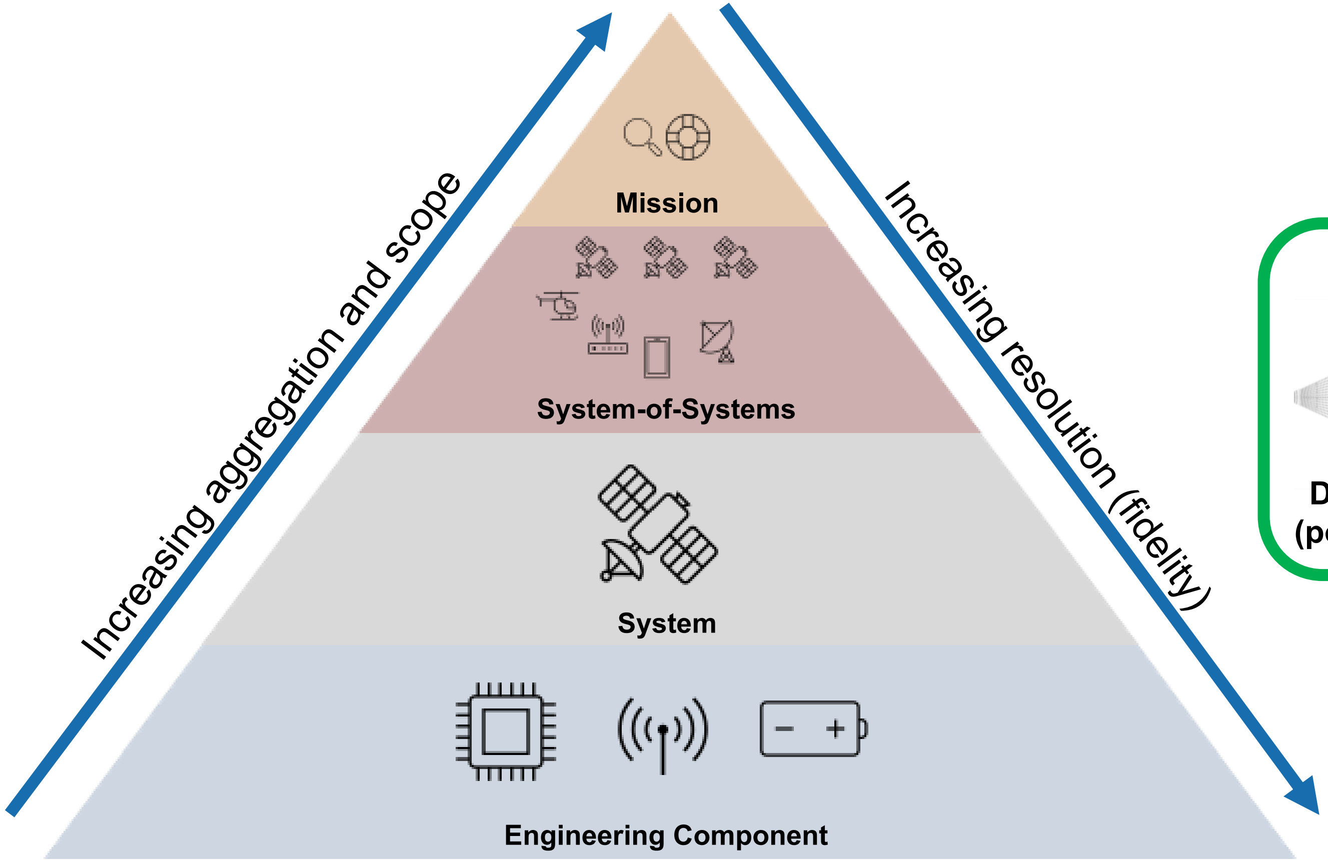
Metric	Units	Threshold	Objective	NewDesign
Probability of Detection		0.5	0.9	0.98 ✓
Min Detectable Signal	dBm	-70	-90	-99 ✓
Min Range	m	5e+02	3e+02	3e+02 ✓
Unambiguous Range	km	8	18	21 ✓
Range Resolution	m	50	30	30 ✓
First Blind Speed	m/s	80	1e+02	1.1e+02 ✓

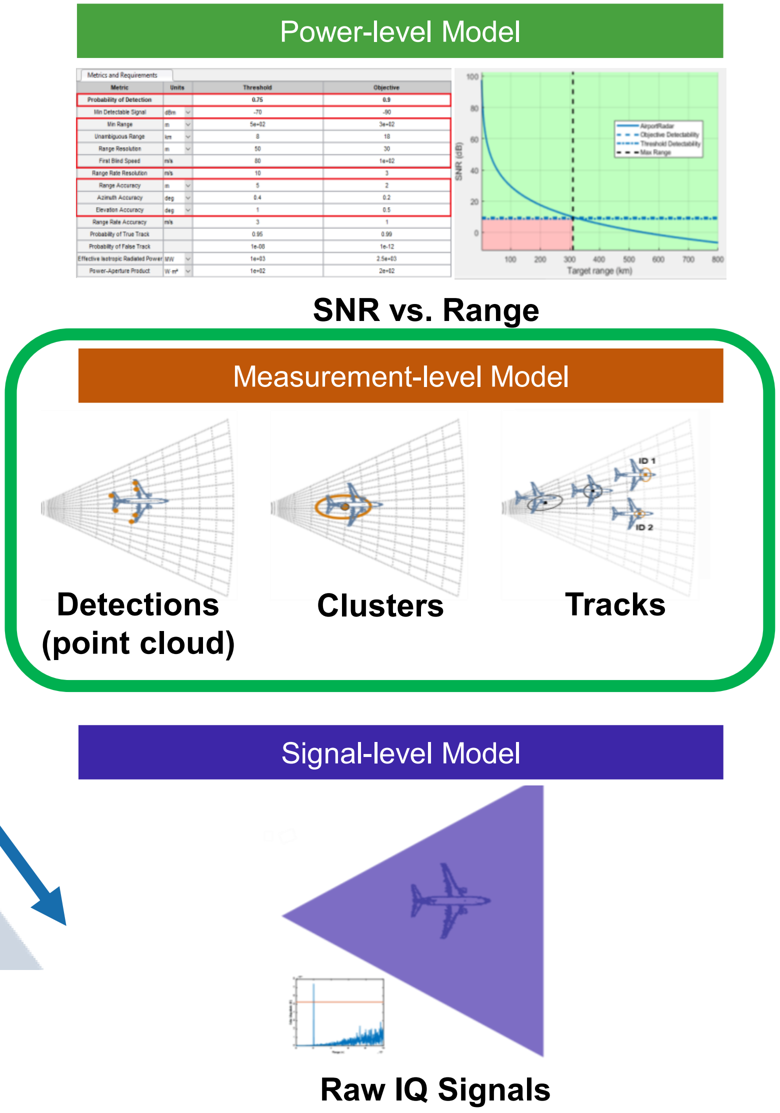



```
>> NewDesignMetrics
metricsTable =
  15×4 table
                                    Units     Threshold   Objective   NewDesign
    Probability of Detection        ""        0.75        0.9         0.80886
    Min Detectable Signal           "dBm"     -70         -90         -98.612
    Min Range                       "m"       500         300         299.79
    Unambiguous Range               "km"      8           18          21.414
    Range Resolution                "m"       50          30          29.979
    First Blind Speed               "m/s"     80          100         110.45
    Range Rate Resolution           "m/s"     10          3           3.6817
    Range Accuracy                  "m"       5           2           3.6932
    Azimuth Accuracy                "deg"     0.4         0.2         0.30279
    Elevation Accuracy              "deg"     1           0.5         0.90836
    Range Rate Accuracy             "m/s"     3           1           0.45356
    Probability of False Track      ""        0.95        0.99        0.96347
    Probability of False Track      ""        1e-08       1e-12       1.8067e-13
    Effective Isotropic Radiated Power  "MW"  1000        2500        5.4
    Power-Aperture Product          "kW·m²"   3500        4200        0.42794
```

Power-level Model

Multifunction RF systems can be modeled across multiple abstraction levels

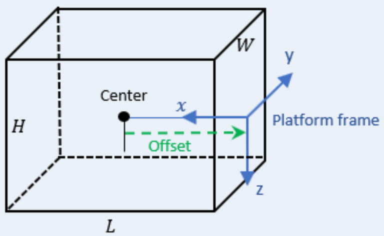




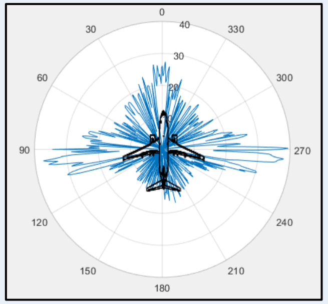
Dynamic radar and EW scenario models can be used to build and test cognitive systems

Model **Platforms** and **Targets** → Model **Surfaces** and **Clutter** → Model **Trajectories** → Model **Sensors** → **Simulate** scenarios

Object Dimensions
bounding box



RCS signature
Az, el pattern
frequencies dependency



Terrain
DTED, Custom

Sea Surface
Spectral Model

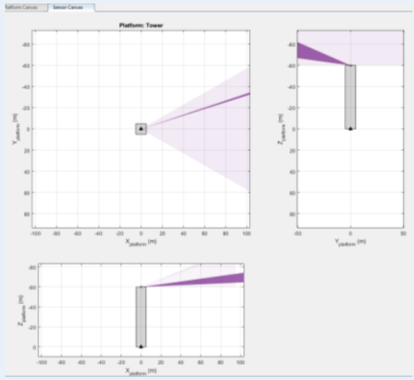
Reflectivity Models
Built-in models
Custom models
Reflectivity maps

Use kinematic properties
acceleration, angular velocity

Use waypoints
position, orientation, time of arrival,
ground speed, climb rate

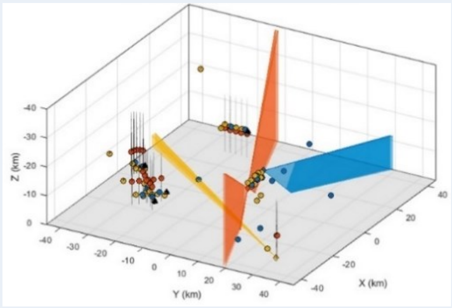
fixed NED or ENU frame (x,y,z) or,
geo-referenced (lat, lon, alt)

Radars on platforms
Mounting position and orientation of radar sensor on platform



INS sensor
platform self-awareness
sensor to platform frame conversion

Generate radar data
I/Q signals, detections, tracks

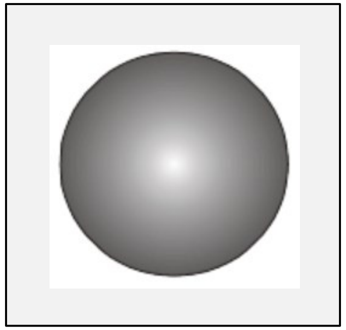


Monte Carlo
perturb ground truth and sensor to increase testing robustness

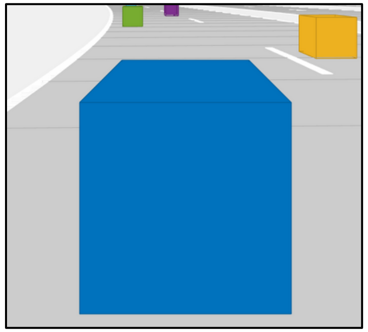
Targets can be modeled across a range of fidelity levels

Model **Platforms** and **Targets** → Model Surfaces and Clutter → Model Trajectories → Model Sensors → Simulate scenarios

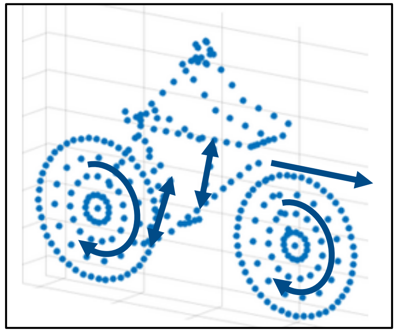
Low — Modeling Complexity — High



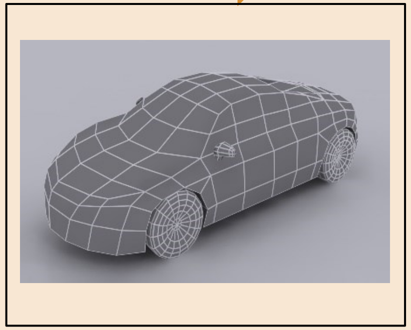
Point



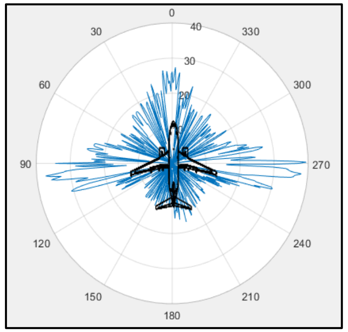
Cuboid
(Multi-scatterer)



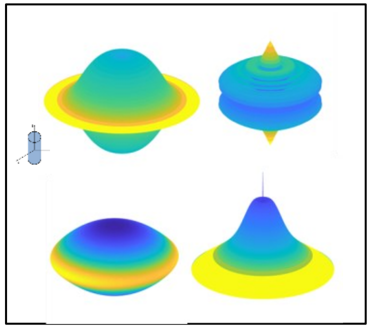
Multi-scatterer
(non-rigid body)



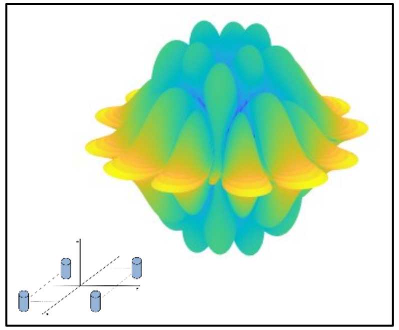
Mesh



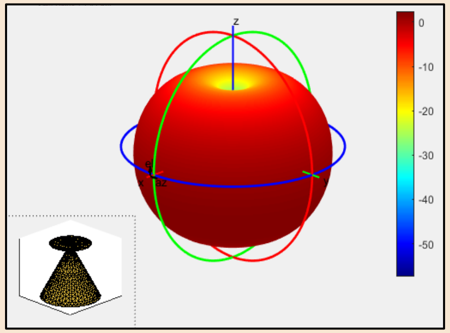
RCS Pattern



Analytic results
(for basic shapes)



Superposition
(of basic shapes)



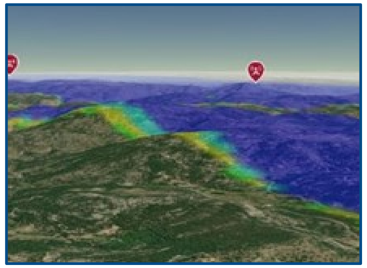
EM Solver
using Antenna Toolbox™

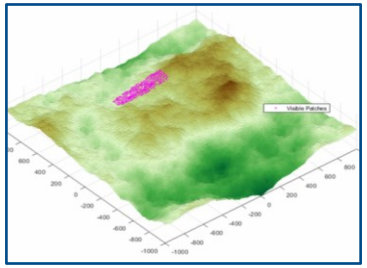
Land & sea surfaces increase the fidelity of scenarios

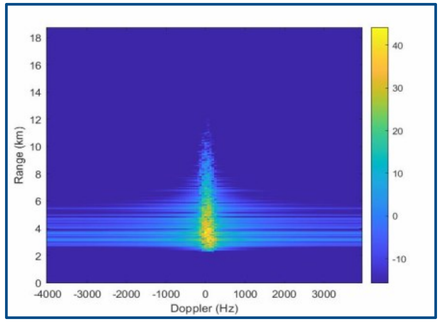
Model Platforms and Targets → **Model Surfaces and Clutter** → Model Trajectories → Model Sensors → Simulate scenarios

Surface Models → Radar Reflectivity Models → Radar Surface Return

Land

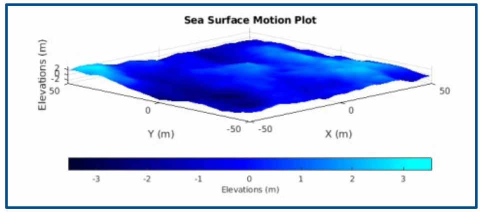


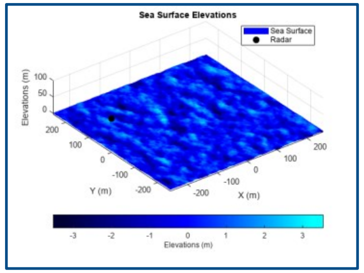


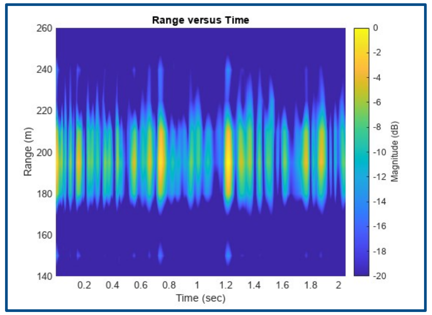


Power-level Model | Measurement-level Model | Signal-level Model

Sea

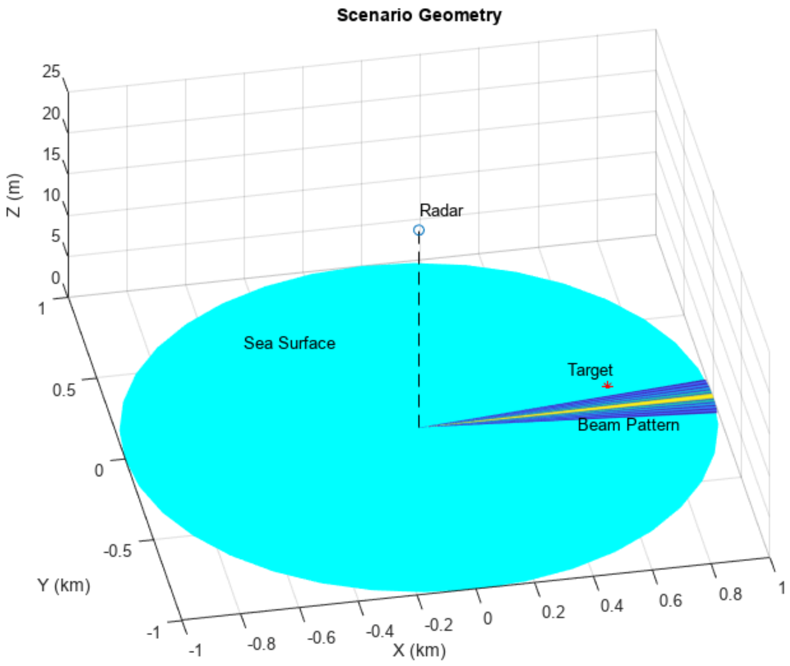


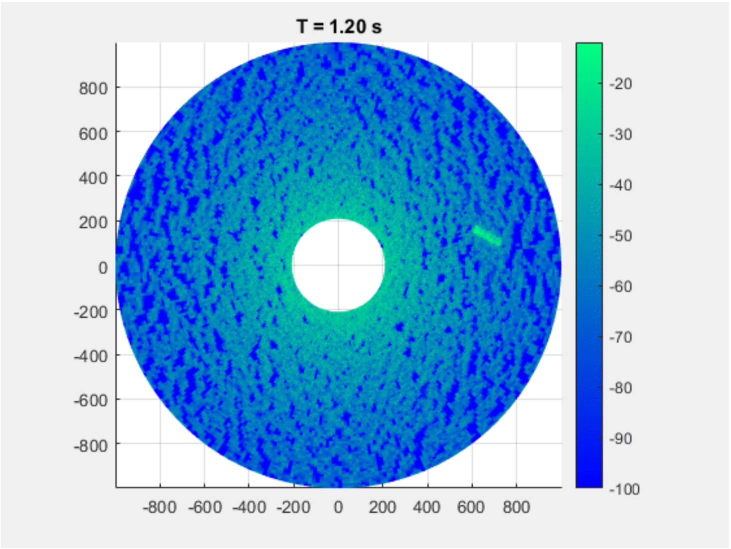


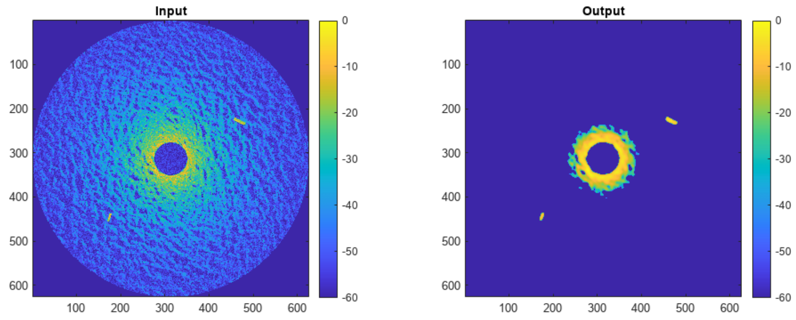


Land & sea surfaces increase the fidelity of scenarios

Model Platforms and Targets → Model Surfaces and Clutter → Model Trajectories → Model Sensors → Simulate scenarios





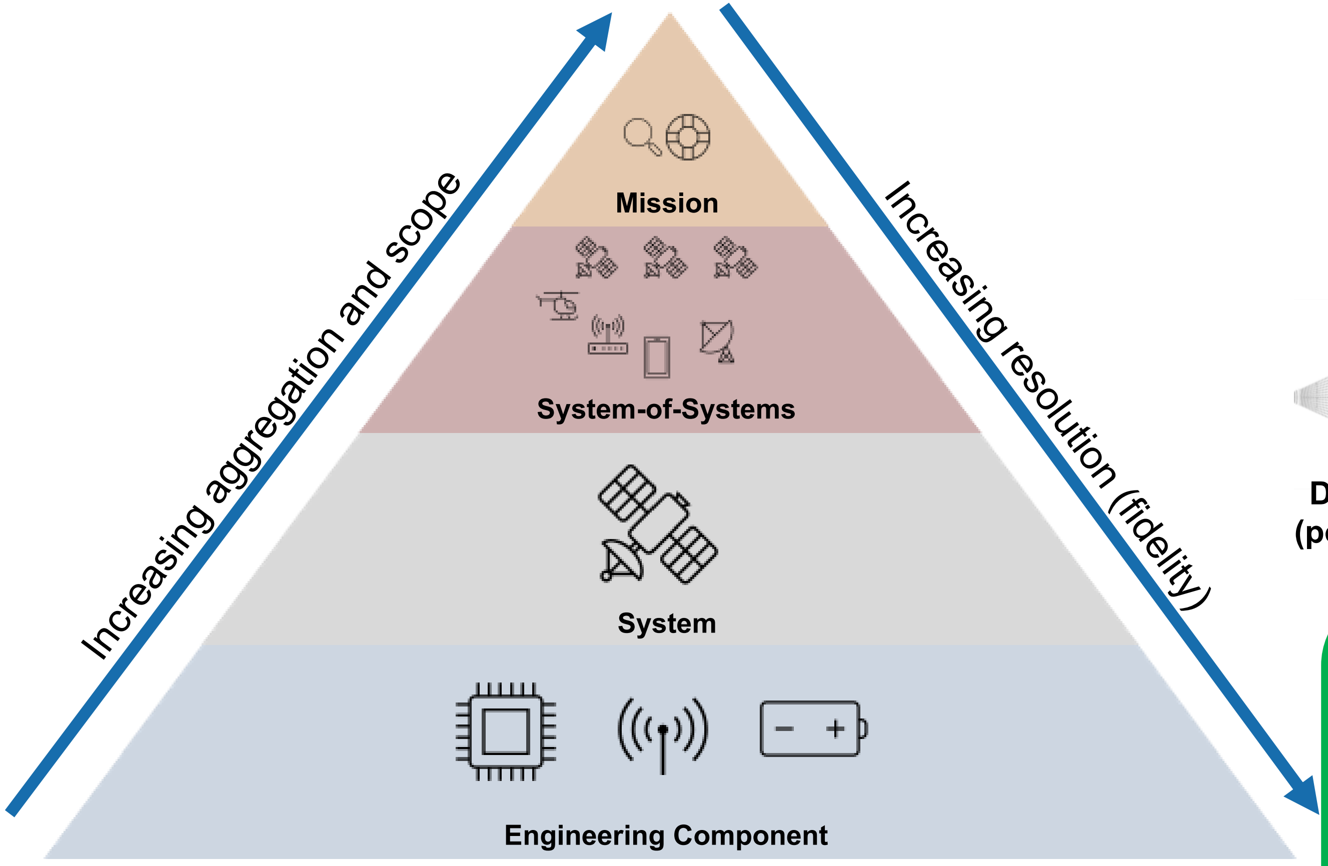


PPI = plan position indicator

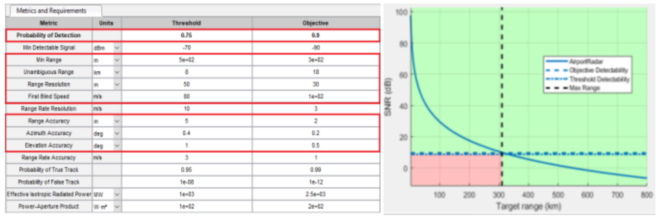
[Example](#)

[Example](#) / [Tech Article](#)

Multifunction RF systems can be modeled across multiple abstraction levels

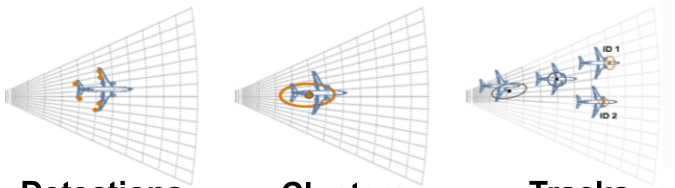


Power-level Model



SNR vs. Range

Measurement-level Model

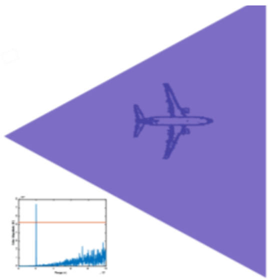


Detections (point cloud)

Clusters

Tracks

Signal-level Model

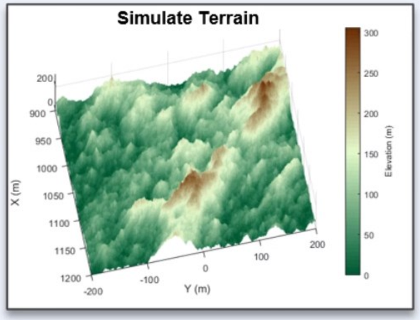


Raw IQ Signals

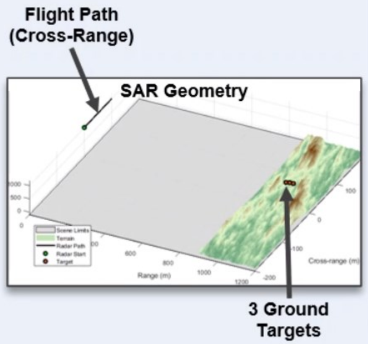
Example Workflows to Generate IQ Data from Scenarios

Model Platforms and Targets → **Model Surfaces and Clutter** → Model Trajectories → Model Sensors → Simulate scenarios

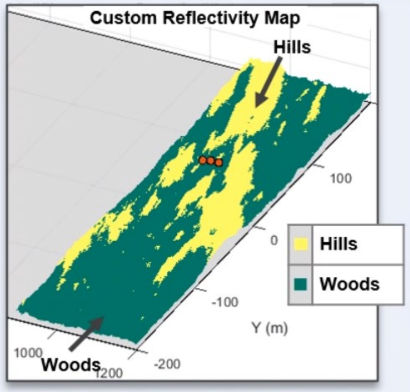
Simulate Random Terrain → **Configure Stripmap SAR** → **Set Custom Reflectivity** → **Generate IQ**



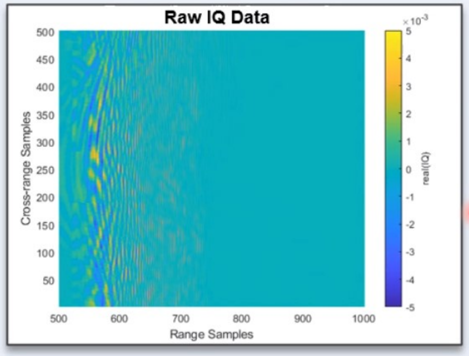
- Simulate random, rough terrain



- Define L-band SAR using `radarScenario` and `radarTransceiver` workflow



- Specify custom reflectivity map for woods and hills



- Generate raw IQ using `receive` method on `radarScenario`

Signal-level Model

See Example

Simulate a Coastal Surveillance Radar

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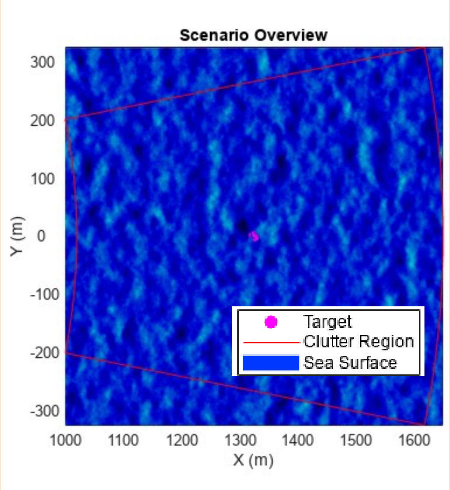
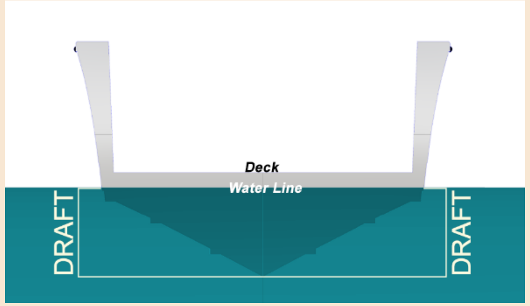
Configure Radar	Generate Sea Surface	Configure Target	Simulate IQ

Example inspired by IPIX radar

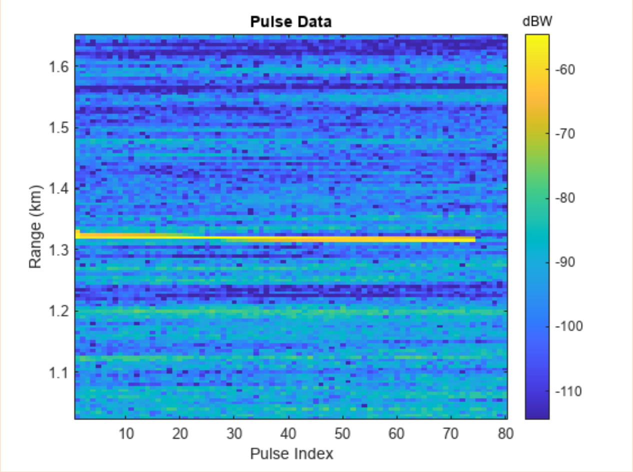
- **Define X-band radar**
- **Memory efficient simulation of low-PRF system**



- **Define sea surface reflectivity and motion model**



- **Simulate extended target**
- **Include wave movement in trajectory**



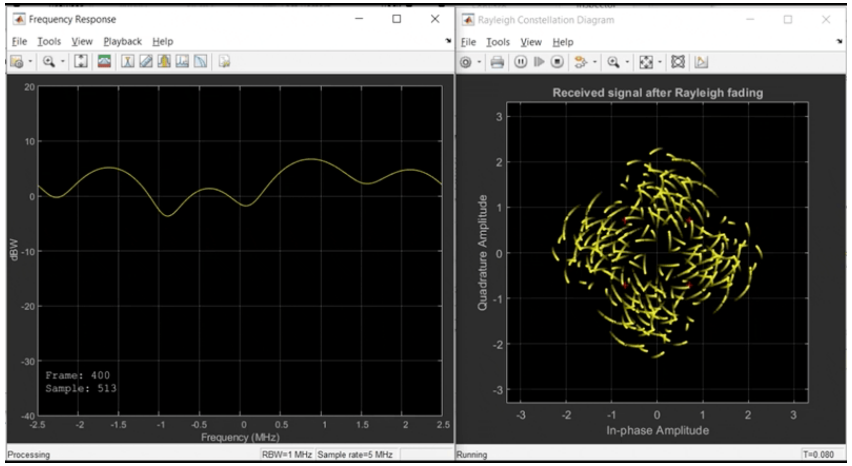
- **Generate IQ using `receive` method on the scenario**
- **Visualize target range migration**

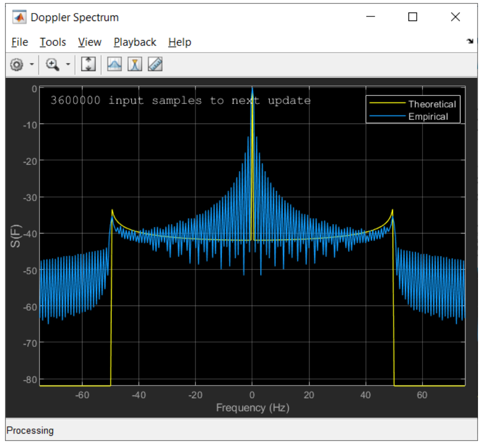
Signal-level Model

Example

Channel modeling also adds to the fidelity level

- Propagation Loss
  - Free space, ITU P.618, rain, fog, Longley-Rice, TIREM
- Stochastic
  - AWGN, Rayleigh, Rician, 5G TDL
- Spatial
  - 5G NR CDL
  - 802.11n/ac/ah/ax
  - WINNER II
- Ray tracing
  - 802.11ay
  - Shoot and bounce ray (SBR)



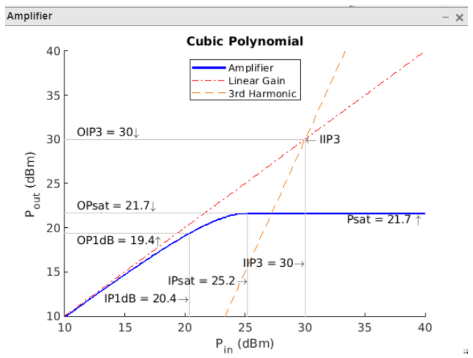


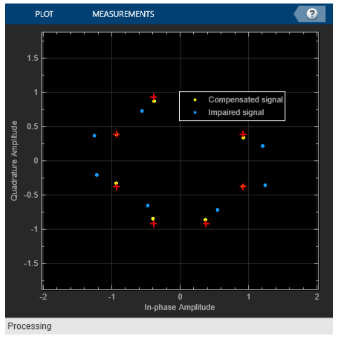
Signal-level Model

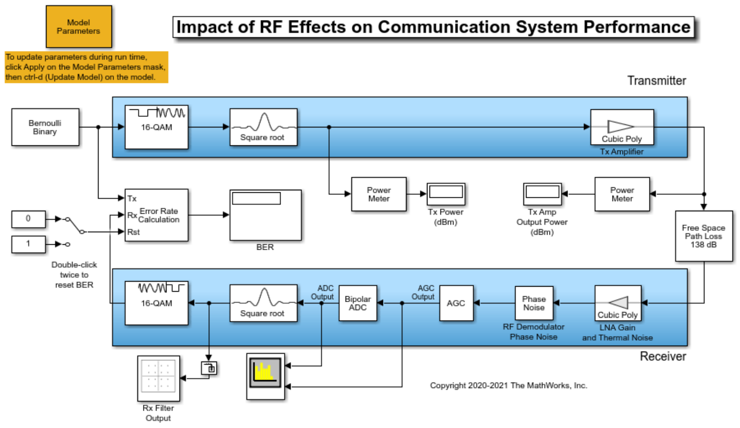
See more

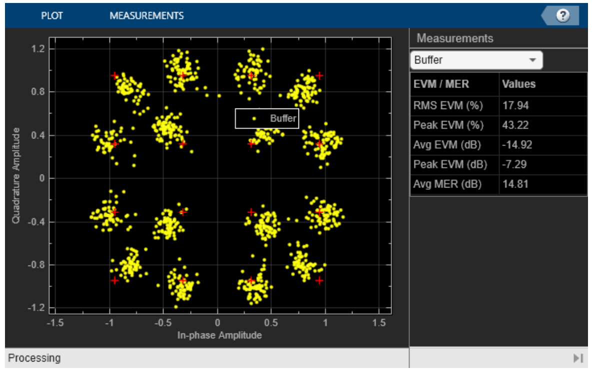
This can also include RF component/subsystem designs

- **Combine RF effects** with digital baseband simulation
  - Phase noise, memoryless nonlinearity, carrier frequency offset, I/Q imbalance, PA with memory
- **Compensate** for those effects
  - Carrier synchronizer loop, symbol timing synchronizer loop, DC blocker, OFDM sync, DPD









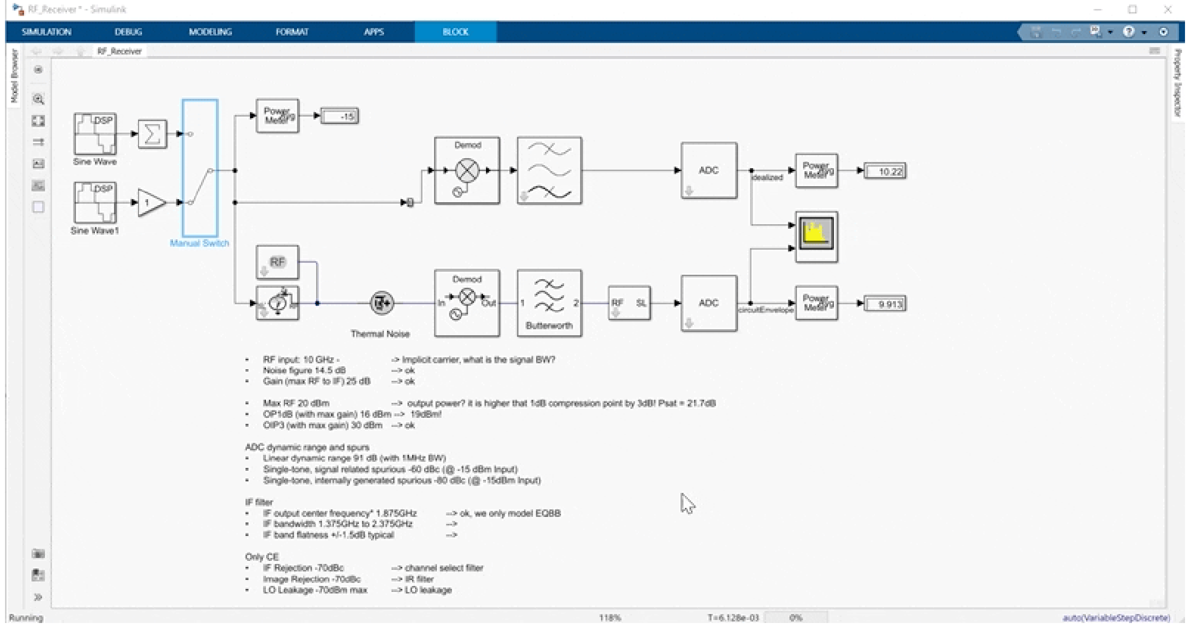
Signal-level Model

See more

This can also include RF component/subsystem designs

RF Downconverter specifications

- RF input: 10 GHz
- Noise figure 14.5 dB
- Gain (max RF to IF) 25 dB
- Max RF 20 dBm
- OP1dB (with max gain) 16 dBm
- OIP3 (with max gain) 30 dBm
- Linear dynamic range 91 dB (with 1MHz BW)
- Single-tone, signal related spurious -60 dBc (@ -15 dBm input)
- Single-tone, internally generated spurious -80 dBc (-15d Bm input)
- IF output center frequency* 1.875GHz
- IF bandwidth 1.375GHz to 2.375GHz
- IF band flatness +/-1.5dB
- IF Rejection -70dBc
- Image Rejection -70dBc
- LO Leakage -70dBm max

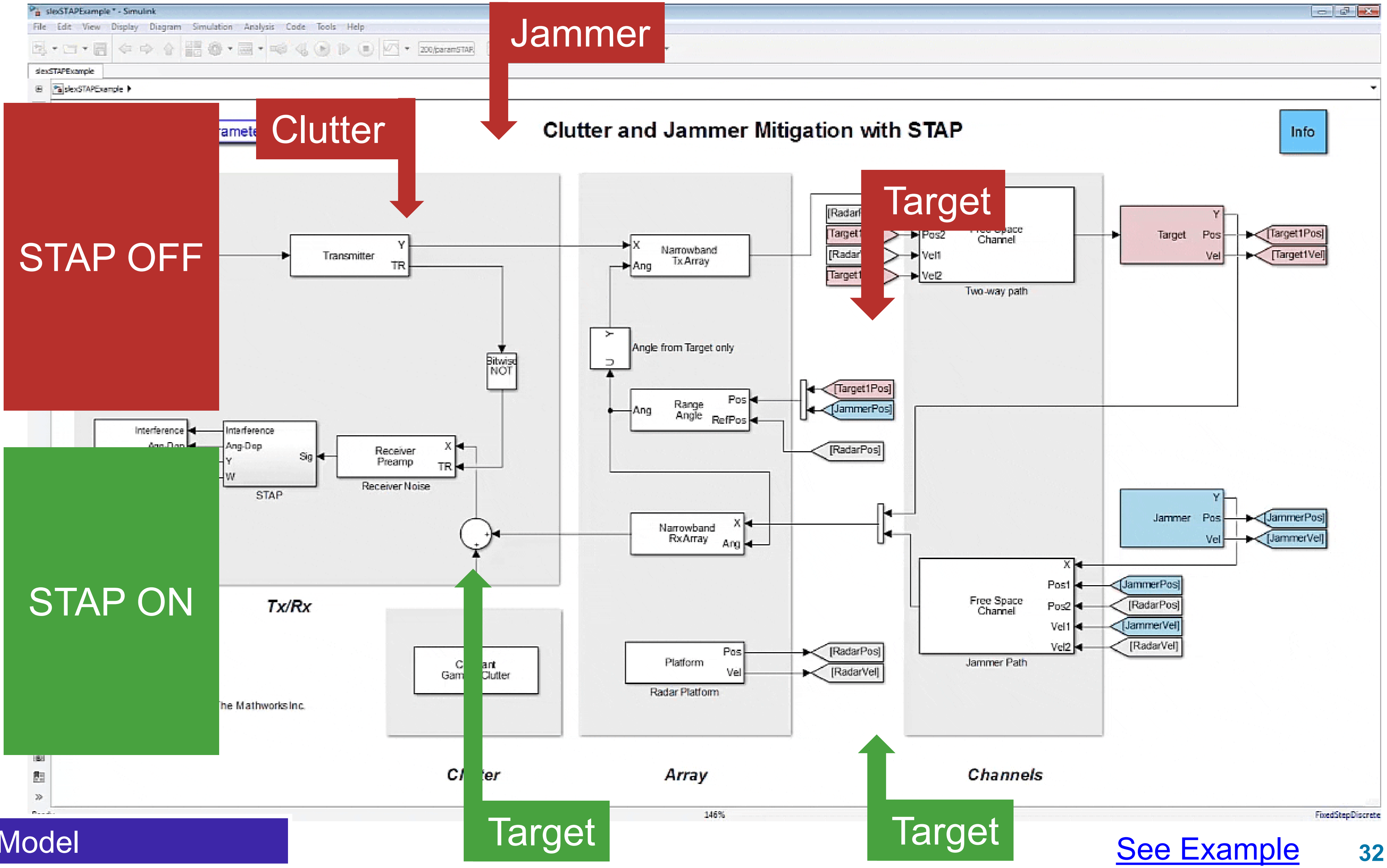


Signal-level Model

You can build interference models and test mitigation techniques

Model includes:

- Waveform
- Antenna
- Polarization
- Frequency
- Tx gain
- Rx gain
- Peak power
- Noise figure
- Etc. …



Signal-level Model

See Example

Model interference using standards-based or custom waveforms

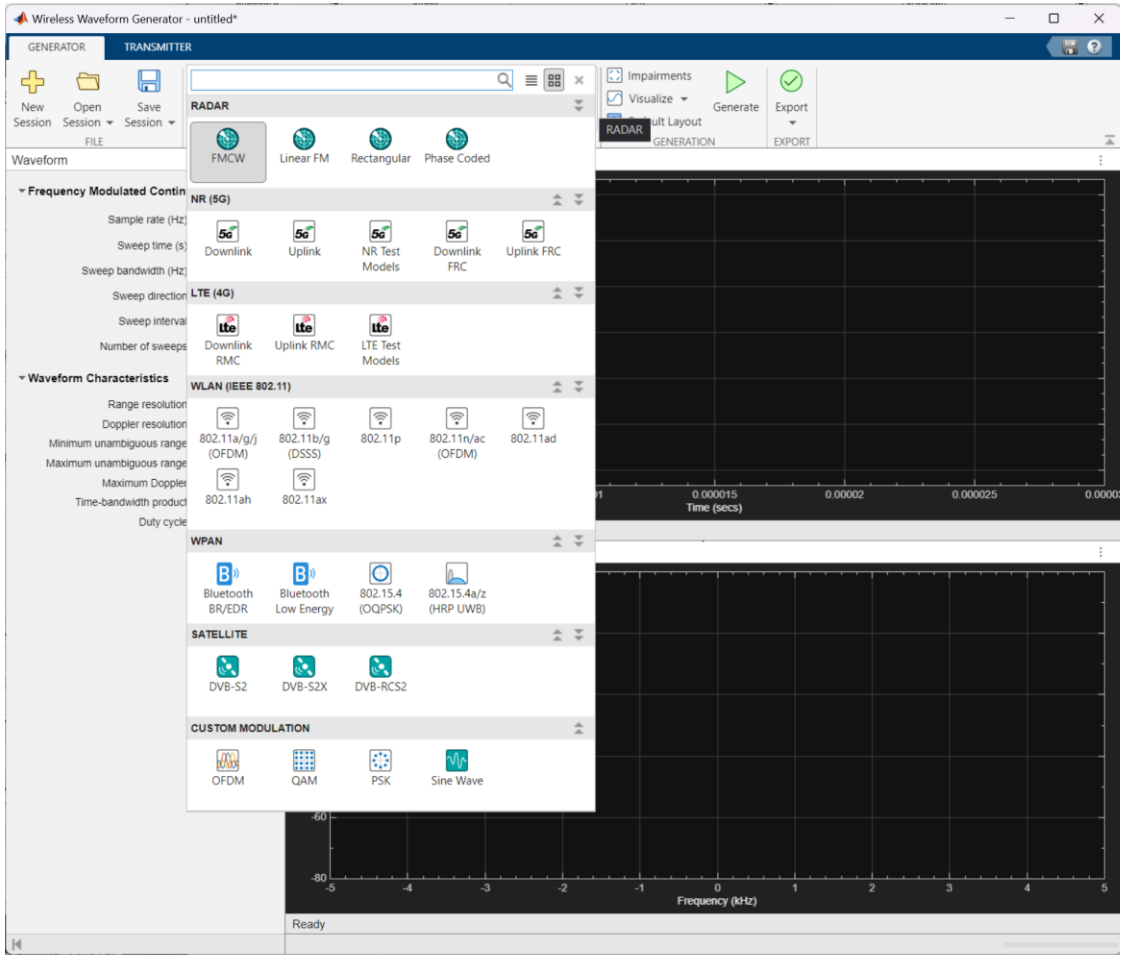
Congested, contested, and complex RF environment

5G LTE Radar

IoT

Satcom GPS WiFi

EW Tactical Data Links

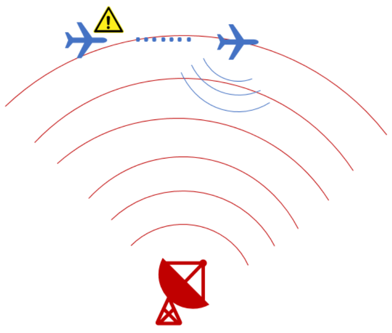


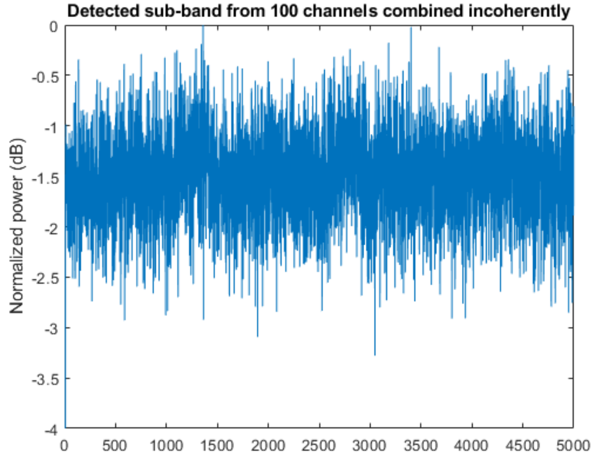
Signal-level Model

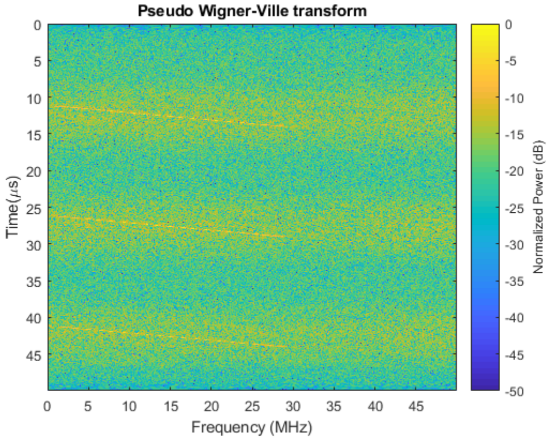
Interference Modeling Example

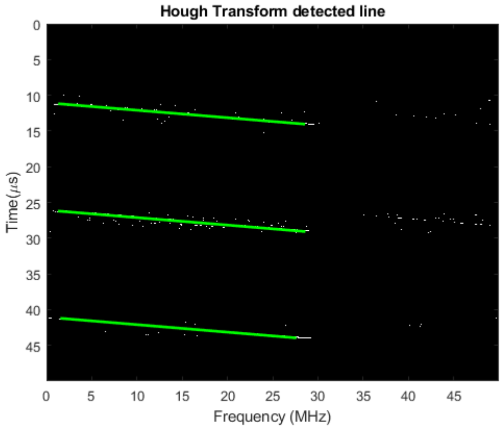
Learn about Wireless Waveform Generator

Leverage Signal-Level modeling for Radar Warning Receiver Algorithm Development



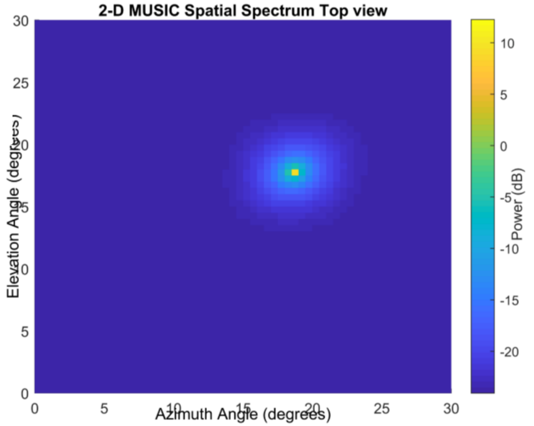






Pulse Repetition Interval = 15 us
Pulse Duration = 2.97 us
Pulse bandwidth = 28.31 MHz
Center frequency = 4.5286 GHz

Can be used to build Pulse Descriptor Words (PDWs)



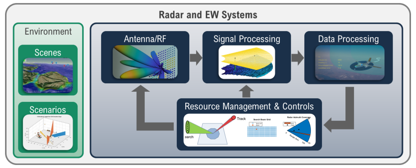
Azimuth angle of arrival = 18.5 degrees
Elevation angle of arrival = 17.5 degrees
Emitter location is 3325.5 m from the RWR

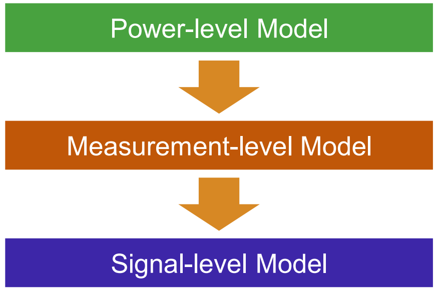
Signal-level Model

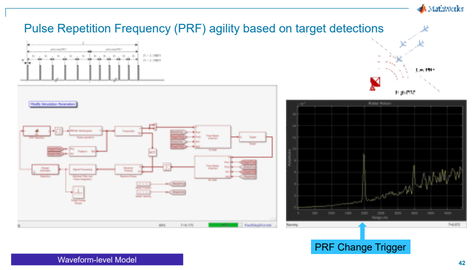
See Example

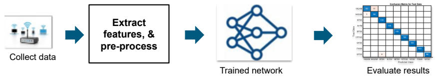
Outline

- How **Digital Engineering** helps teams collaborate
- **Modeling and Simulation** at multiple abstraction levels
- **Multifunction** RF Mode-Agility Examples
- **AI Workflow** Overview and Example

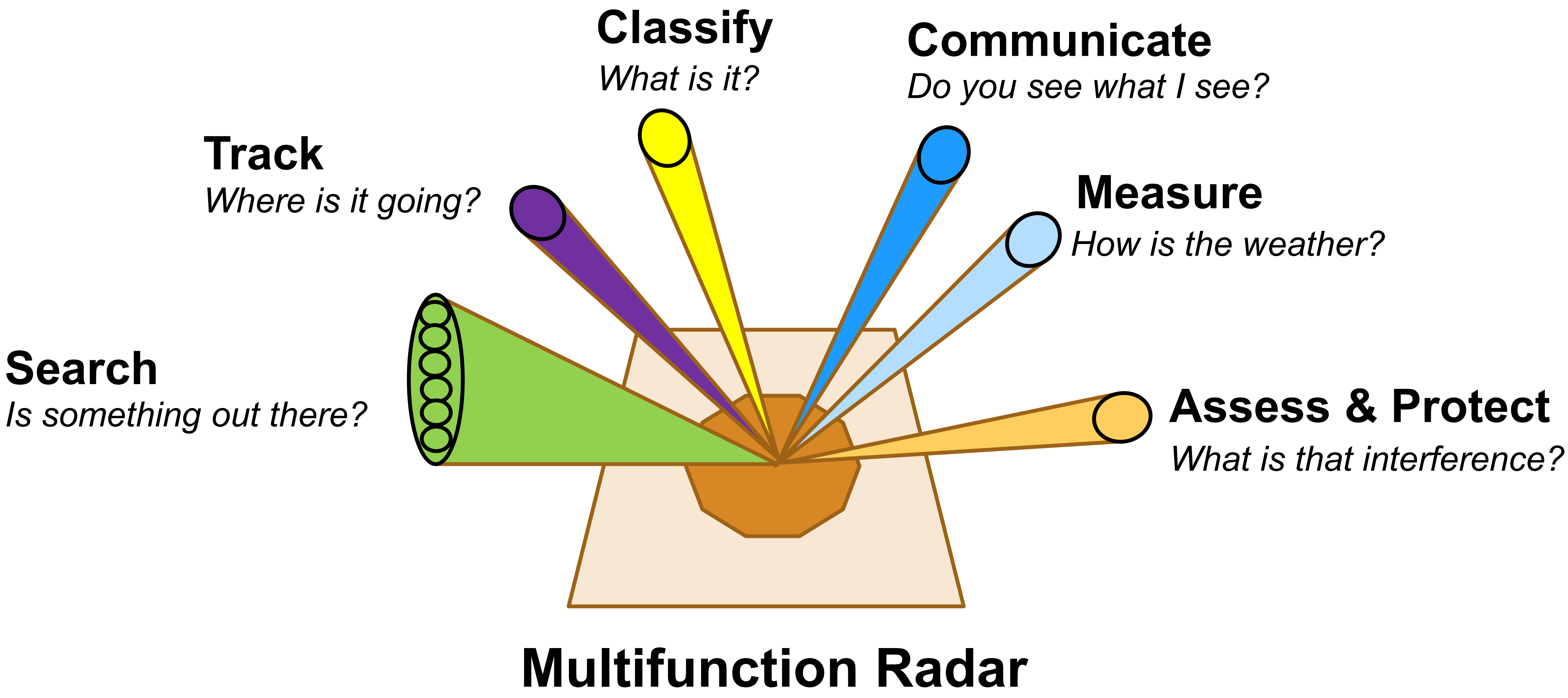




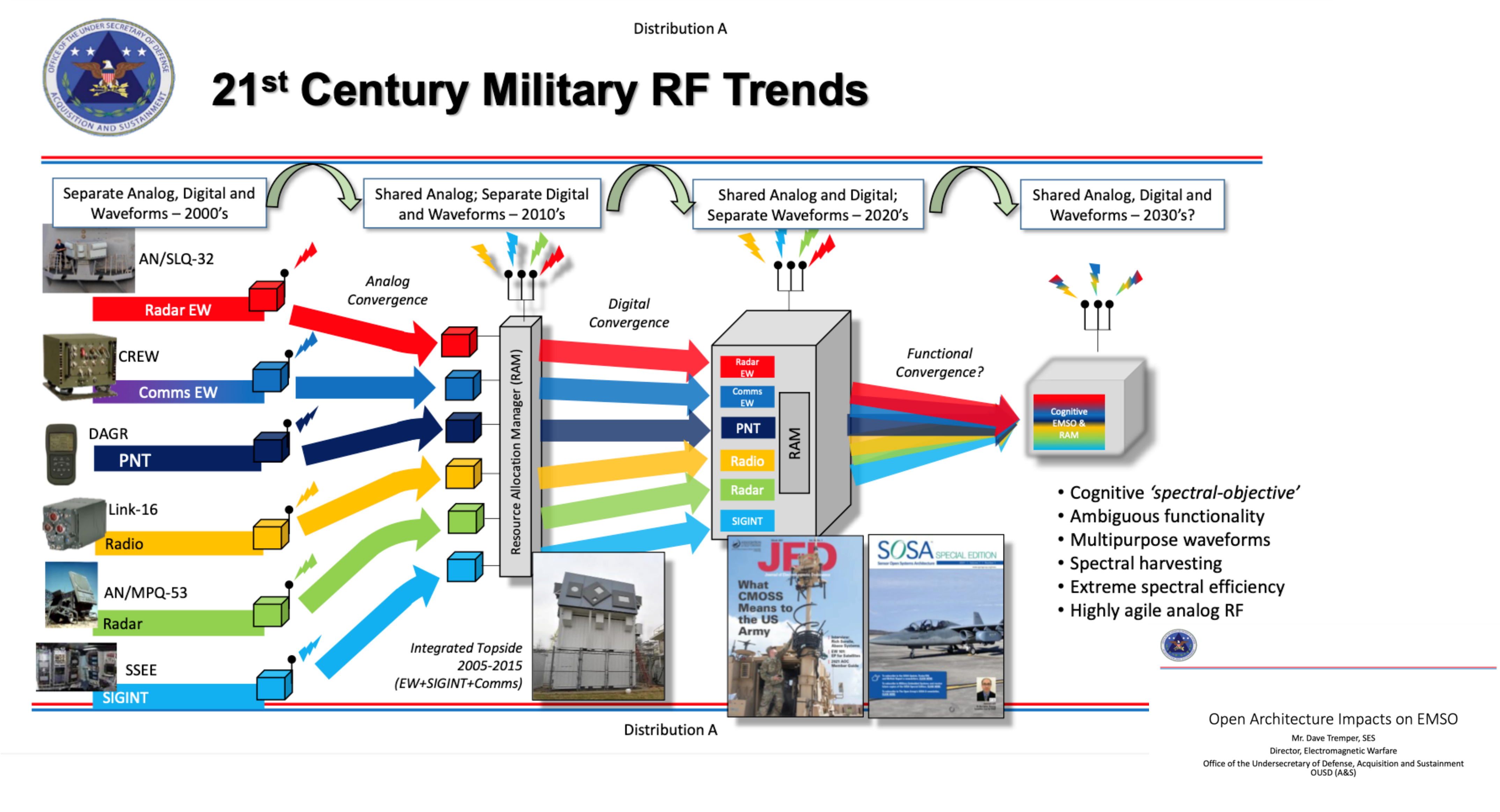




What does a Multifunction Radio do?



Multifunction Trend: Functional Convergence



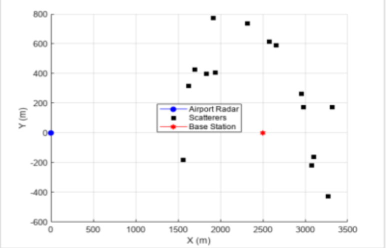
Source: https://tsoa-id.net/wp-content/uploads/2022/03/David-Tremper-OUSD-AS-Presentation.pdf

Multifunction and Coexistence

Radar & Communication Systems Coexistence

Non-Cooperative
Radar is an independent system with main goal to maximize performance while mitigating mutual interference

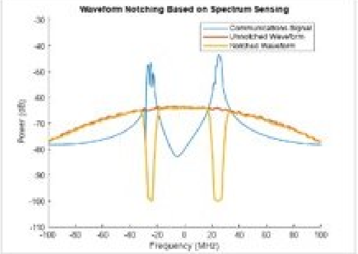
Primary
Radar has exclusive rights to the spectrum



Evaluating Interference from 5G New Radio (NR) Signals at an Airport Surveillance...

Model an air traffic control radar which operates in the vicinity of a 5G base station.

Secondary
Radar opportunistic spectrum access



Spectrum Sharing using Spectrum Sensing and Waveform Notching

Implementation and analyze techniques for reducing mutual interference between non-cooperative radar and

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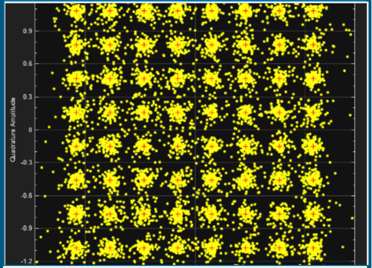
Multi-Role
Role changes dynamically based on priority

Cooperative
Radar and other RF Systems exchange information to mitigate interference

Co-Design
Both systems follow a common protocol



Joint Radar-Communication Using PMCW and OFDM Waveforms

Model a joint radar-communication (JRC) system using the Phase Array System Toolbox.

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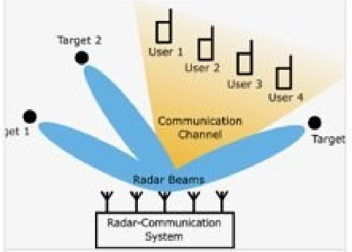
Multi-Function
Parameters modified for signal embedding



Waveform Design for a Dual-Function MIMO RadCom System

Design a set of waveforms for a dual-function multiple-input-multiple-output (MIMO) radar-communication (RadCom) system.

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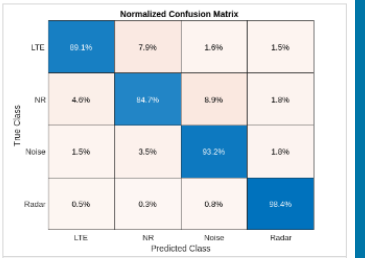
Passive Radar
Signals of opportunity



Spectrum Sensing with Deep Learning for Radar and Wireless Communications

Train a deep learning neural network using deep learning to identify radar and wireless communication signals in the air.

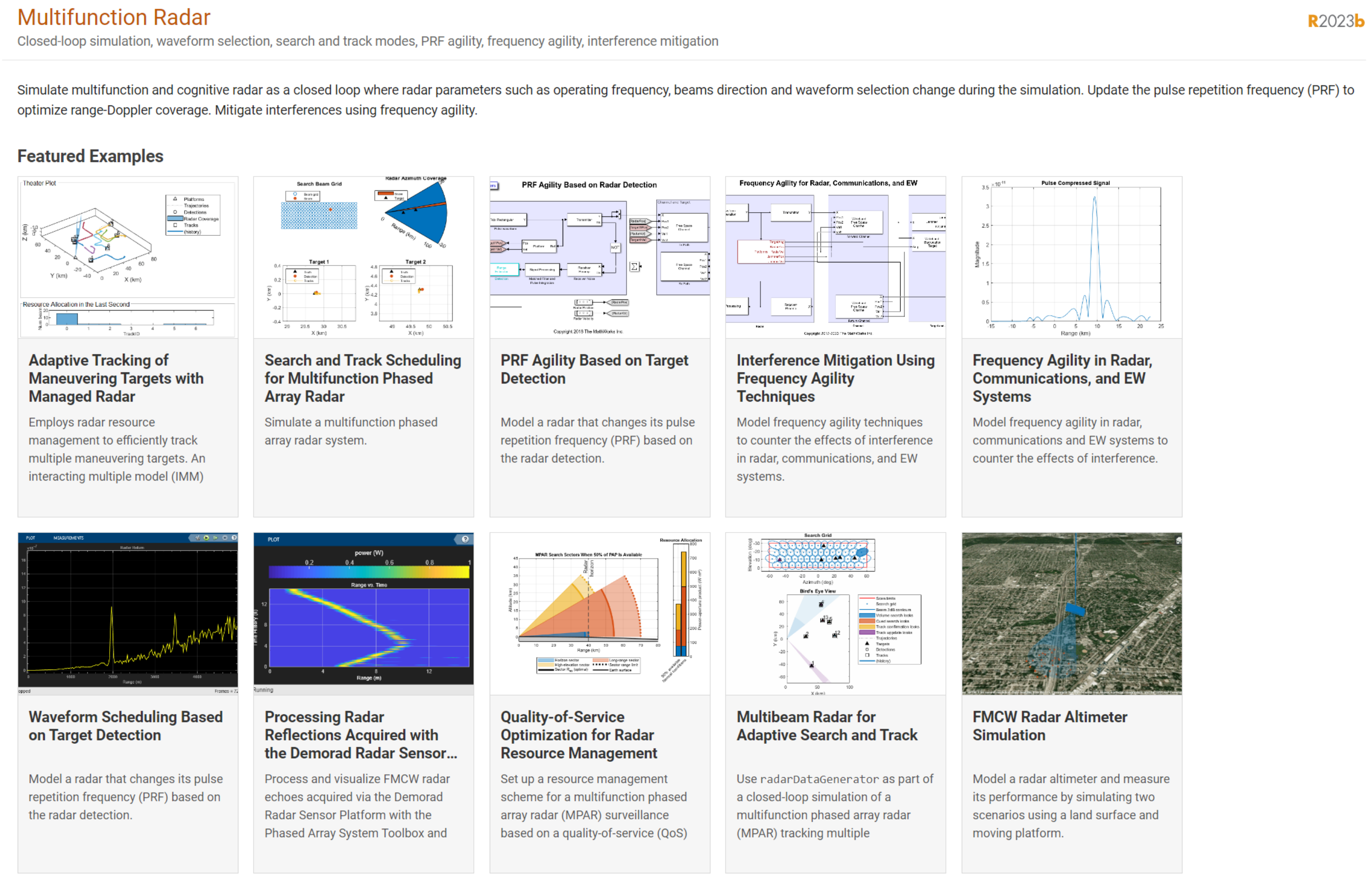
Figure adapted from Martone & Amin
https://doi.org/10.1016/j.dsp.2021.103135

Multifunction & Cognitive Examples

Coexistence Examples

Multifunction RF System mode-agility can be modeled as well

- Pulse repetition frequency (PRF) Agility
- Frequency Agility
- Waveform Agility
- Quality-of-Service Optimization
- Beam Steering



Multifunction Radar

R2023b

Closed-loop simulation, waveform selection, search and track modes, PRF agility, frequency agility, interference mitigation

Simulate multifunction and cognitive radar as a closed loop where radar parameters such as operating frequency, beams direction and waveform selection change during the simulation. Update the pulse repetition frequency (PRF) to optimize range-Doppler coverage. Mitigate interferences using frequency agility.

Featured Examples

Adaptive Tracking of Maneuvering Targets with Managed Radar
Employs radar resource management to efficiently track multiple maneuvering targets. An interacting multiple model (IMM)

Search and Track Scheduling for Multifunction Phased Array Radar
Simulate a multifunction phased array radar system.

PRF Agility Based on Target Detection
Model a radar that changes its pulse repetition frequency (PRF) based on the radar detection.

Interference Mitigation Using Frequency Agility Techniques
Model frequency agility techniques to counter the effects of interference in radar, communications, and EW systems.

Frequency Agility in Radar, Communications, and EW Systems
Model frequency agility in radar, communications and EW systems to counter the effects of interference.

Waveform Scheduling Based on Target Detection
Model a radar that changes its pulse repetition frequency (PRF) based on the radar detection.

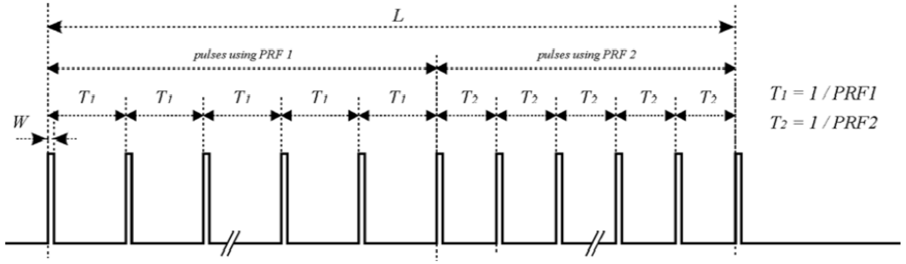
Processing Radar Reflections Acquired with the Demorad Radar Sensor...
Process and visualize FMCW radar echoes acquired via the Demorad Radar Sensor Platform with the Phased Array System Toolbox and

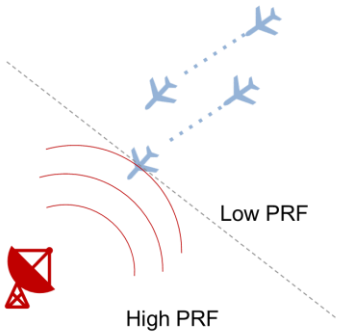
Quality-of-Service Optimization for Radar Resource Management
Set up a resource management scheme for a multifunction phased array radar (MPAR) surveillance based on a quality-of-service (QoS)

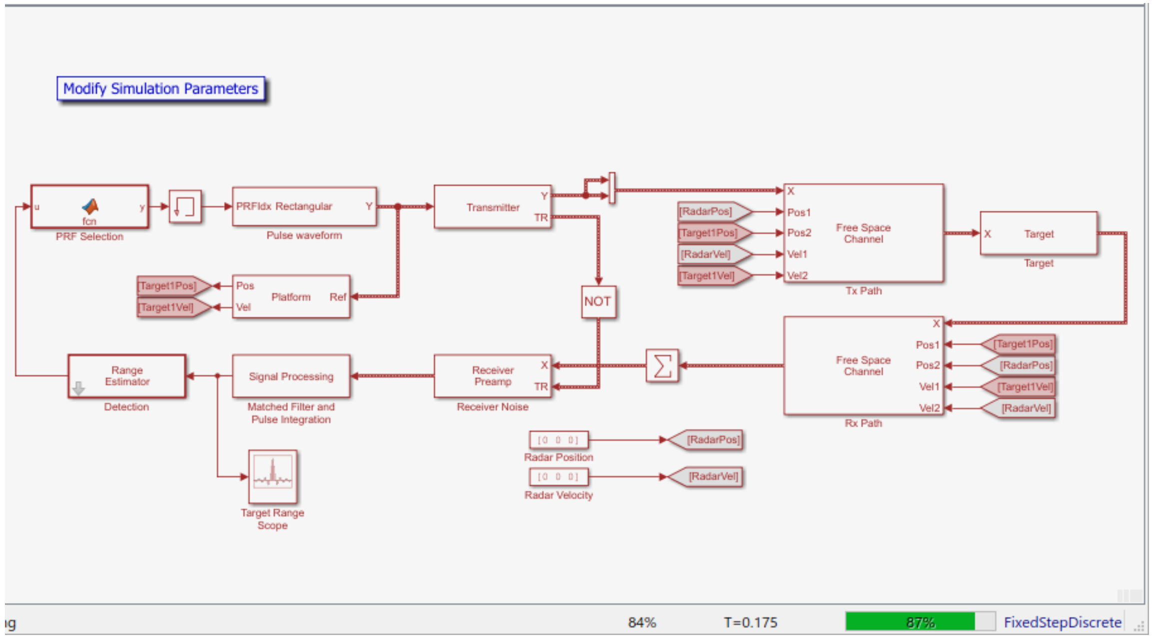
Multibeam Radar for Adaptive Search and Track
Use `radarDataGenerator` as part of a closed-loop simulation of a multifunction phased array radar (MPAR) tracking multiple

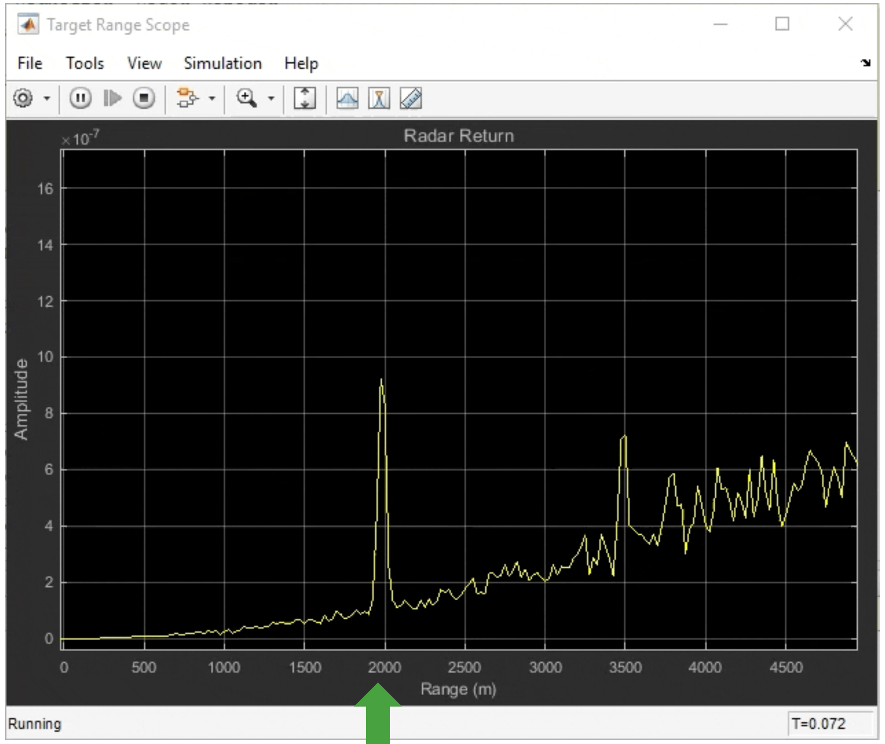
FMCW Radar Altimeter Simulation
Model a radar altimeter and measure its performance by simulating two scenarios using a land surface and moving platform.

Pulse Repetition Frequency (PRF) agility based on target detections







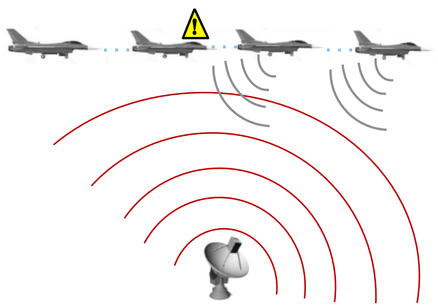


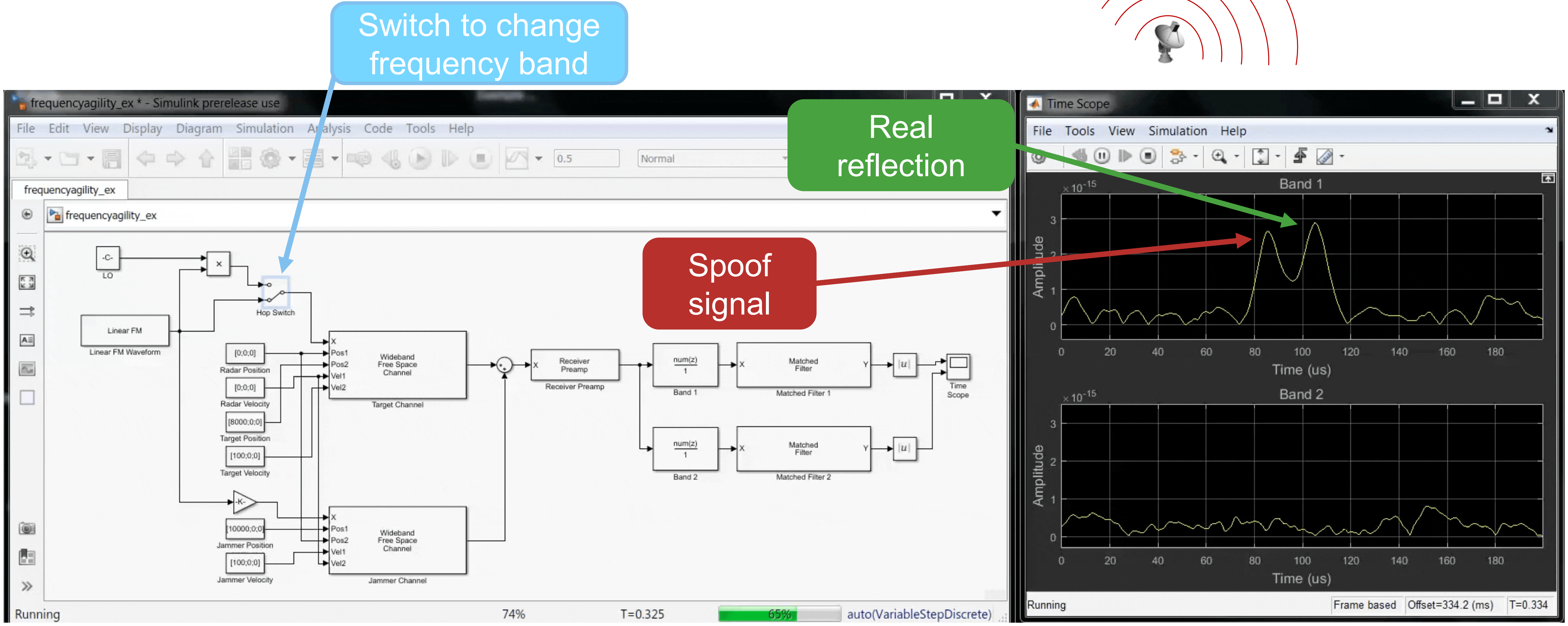
PRF Change at 2 km

Signal-level Model

See Example

Frequency Agility for Interference Mitigation

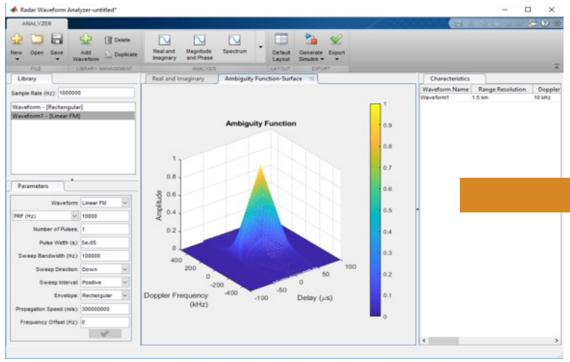


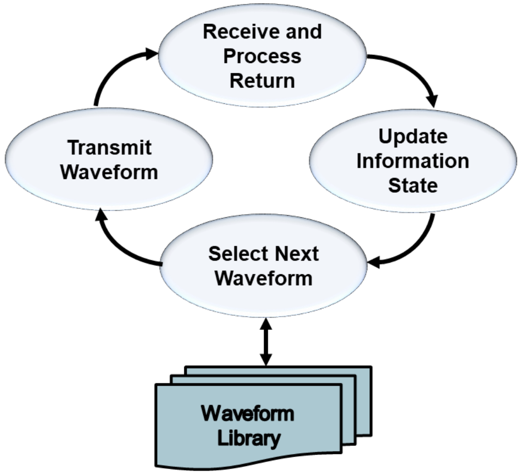


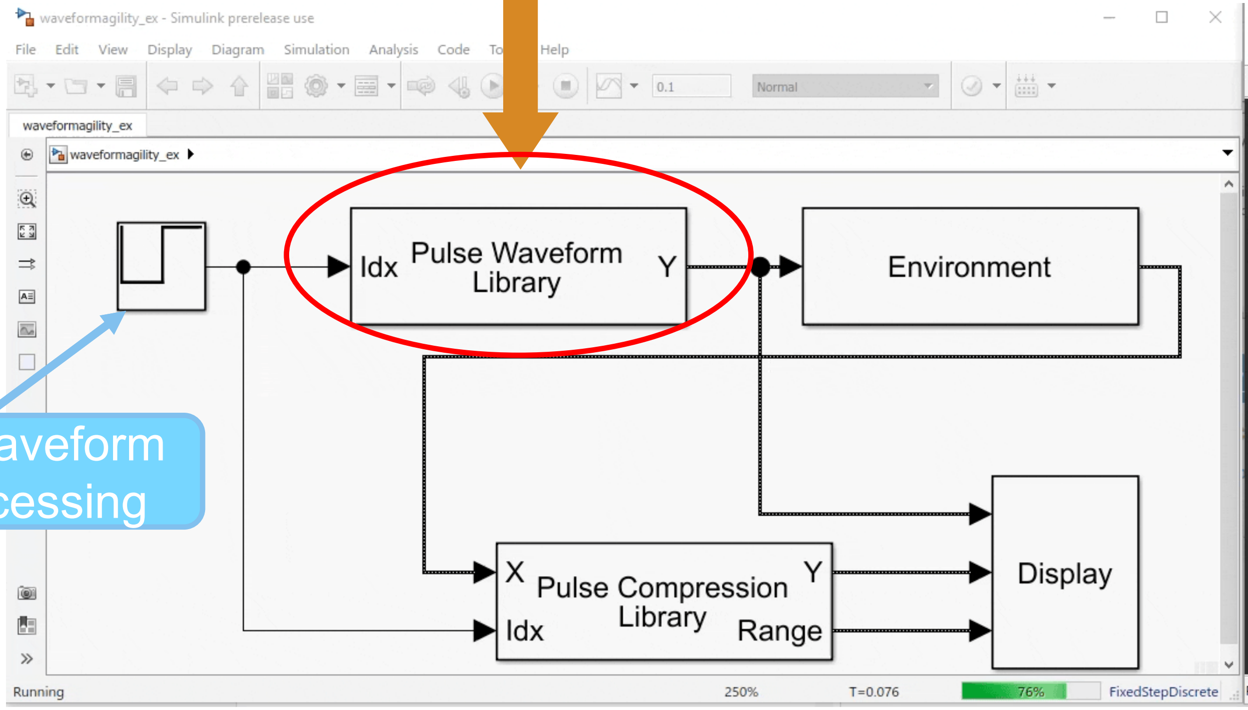
Signal-level Model

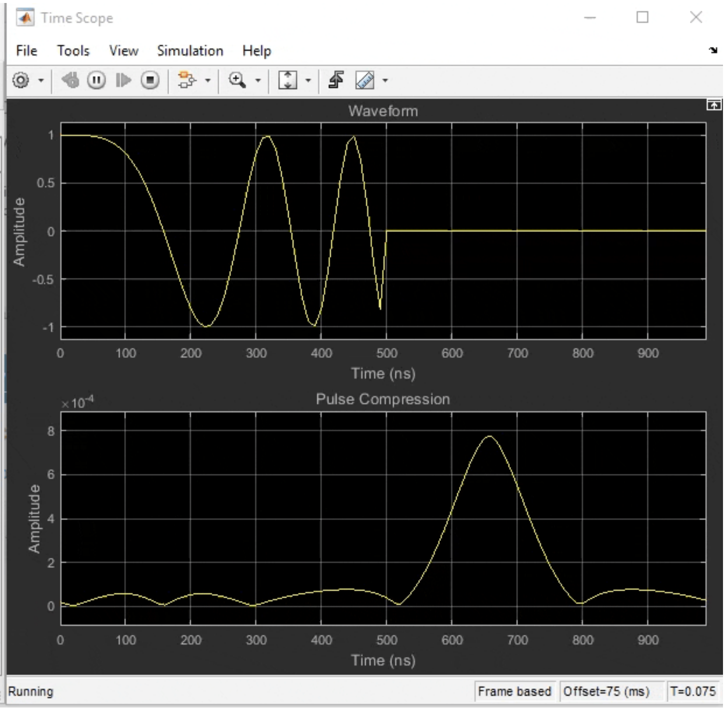
See Example

Waveform Agility







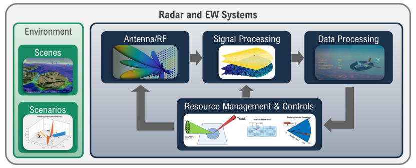


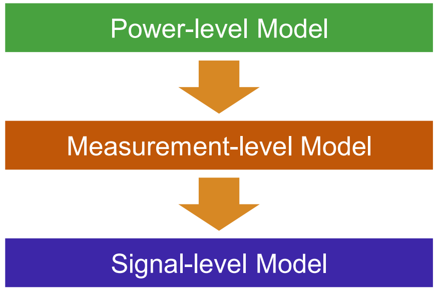
Switch waveform and processing

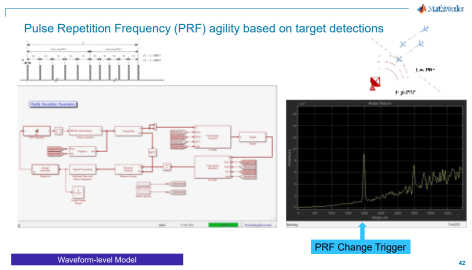
Signal-level Model

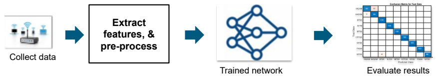
Outline

- How **Digital Engineering** helps teams collaborate
- **Modeling and Simulation** at multiple abstraction levels
- **Multifunction** RF Mode-Agility Examples
- **AI Workflow** Overview and Example

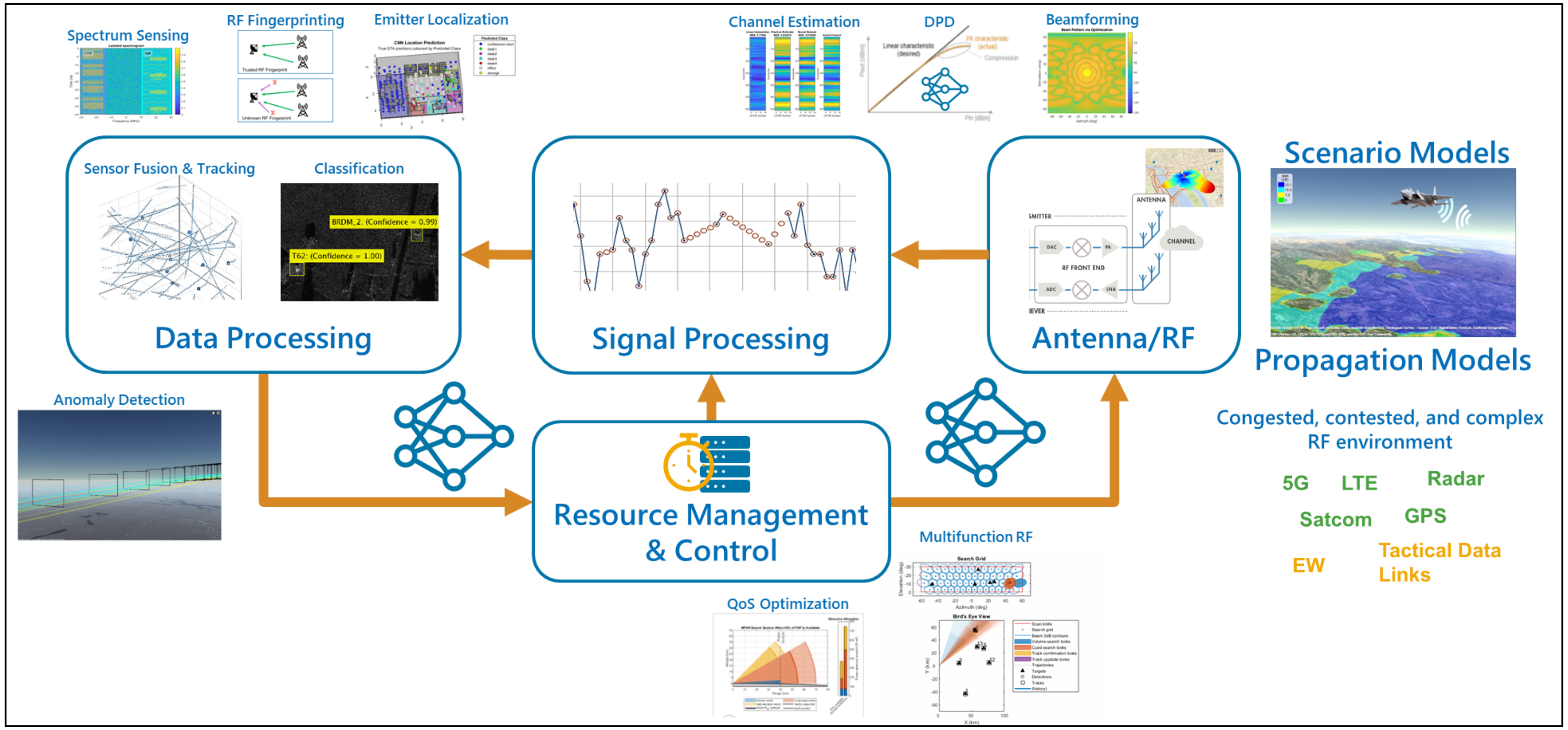


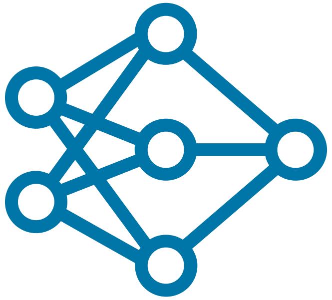






You can apply AI techniques to various radar, EW, and multifunction RF system components





[AI for Comms]

[AI for Radar]

AI-driven system design

Data Preparation

- Data cleansing and preparation
- Human insight
- Simulation-generated data

AI Modeling

- Model design and tuning
- Hardware accelerated training
- Interoperability

Simulation & Test

- Integration with complex systems
- System simulation
- System verification and validation

Deployment

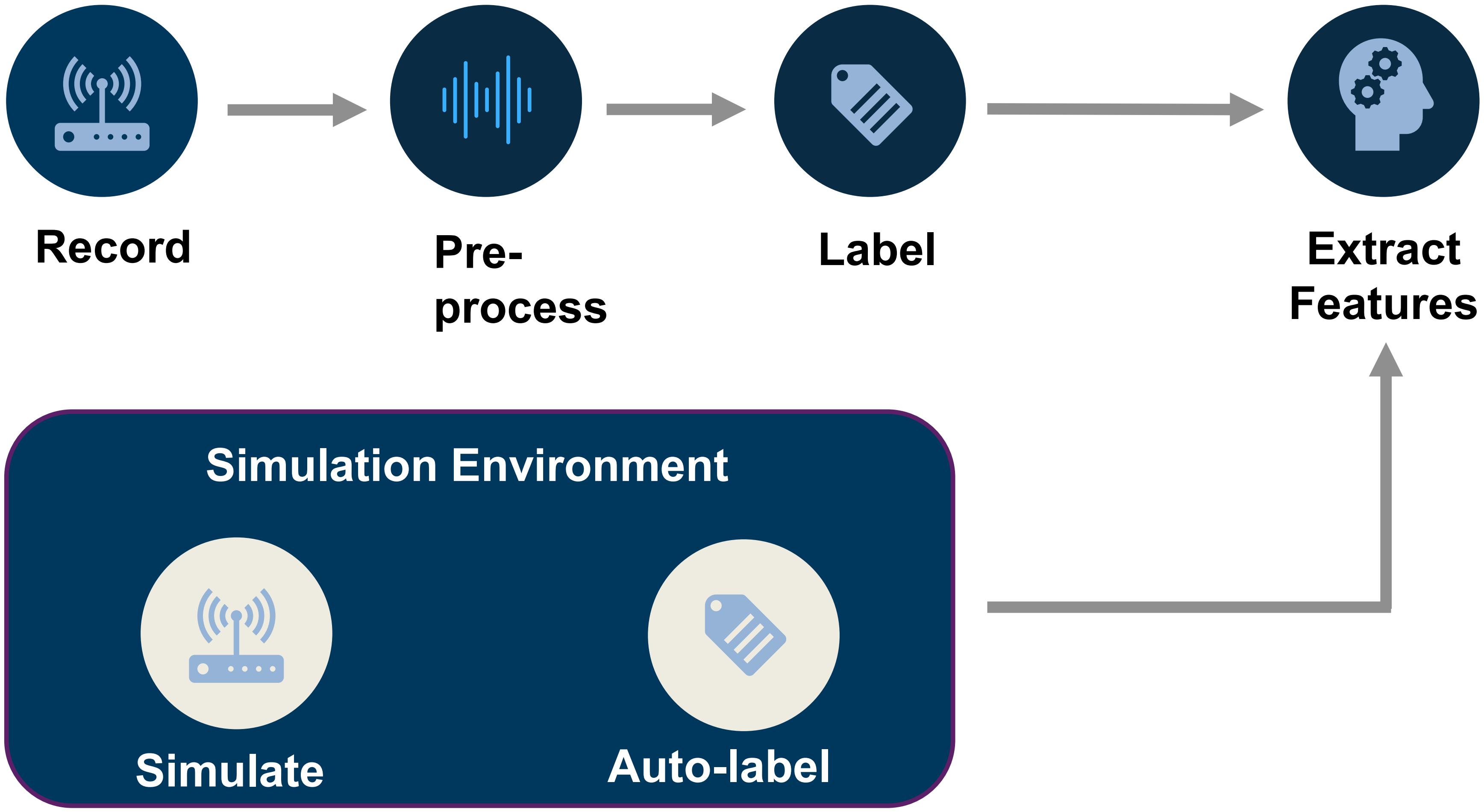
- Embedded devices
- Enterprise systems
- Edge, cloud, desktop

Synthesize labeled data for cognitive radio applications

Data Preparation | AI Modeling | Simulation & Test | Deployment

Data Preparation

- Data cleansing and preparation
- Human insight
- Simulation-generated data
- HW connection Over-the-Air Signal



Start with a complete set of algorithms and pre-built models

Data Preparation | **AI Modeling** | Simulation & Test | Deployment

AI Modeling

- Model design and tuning
- Hardware accelerated training
- Interoperability

Algorithms

Machine learning
Trees, Naïve Bayes, SVM…

Deep learning
CNNs, GANs, LSTM, MIMO…

Reinforcement learning
DQN, A2C, DDPG…

Regression
Linear, nonlinear, trees…

Unsupervised learning
K-means, PCA, GMM…

Predictive maintenance
RUL models, condition indicators…

Bayesian optimization

Pre-built models

Image classification models
AlexNet, GoogLeNet, VGG, SqueezeNet, ShuffleNet, ResNet, DenseNet, Inception…

Reference examples

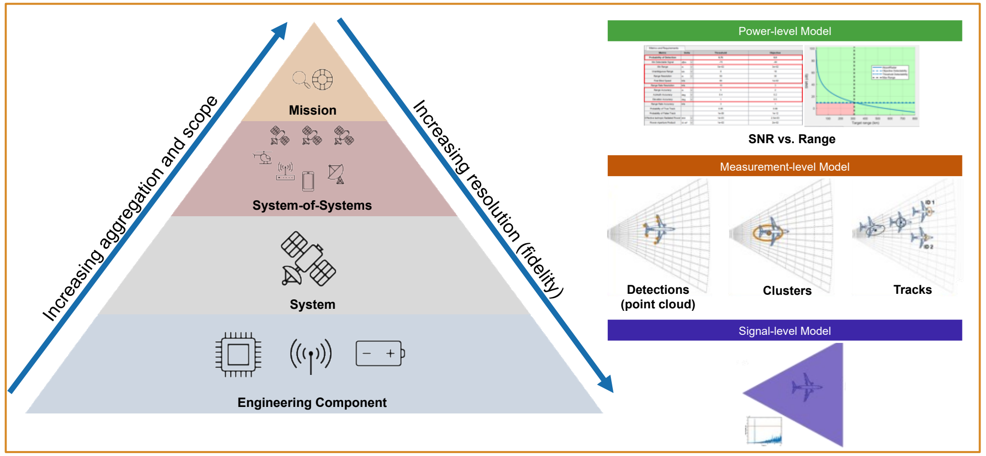
Modulation ID
Spectrum Sensing
Channel Estimation
RF Fingerprinting
Digital Pre-distortion
Radar Target ID
… and many more

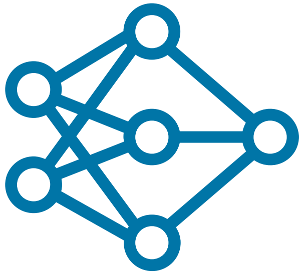
Incorporate AI into System Models and Designs

Data Preparation | AI Modeling | **Simulation & Test** | Deployment

Simulation & Test

- Integration with complex systems
- System simulation
- System verification and validation



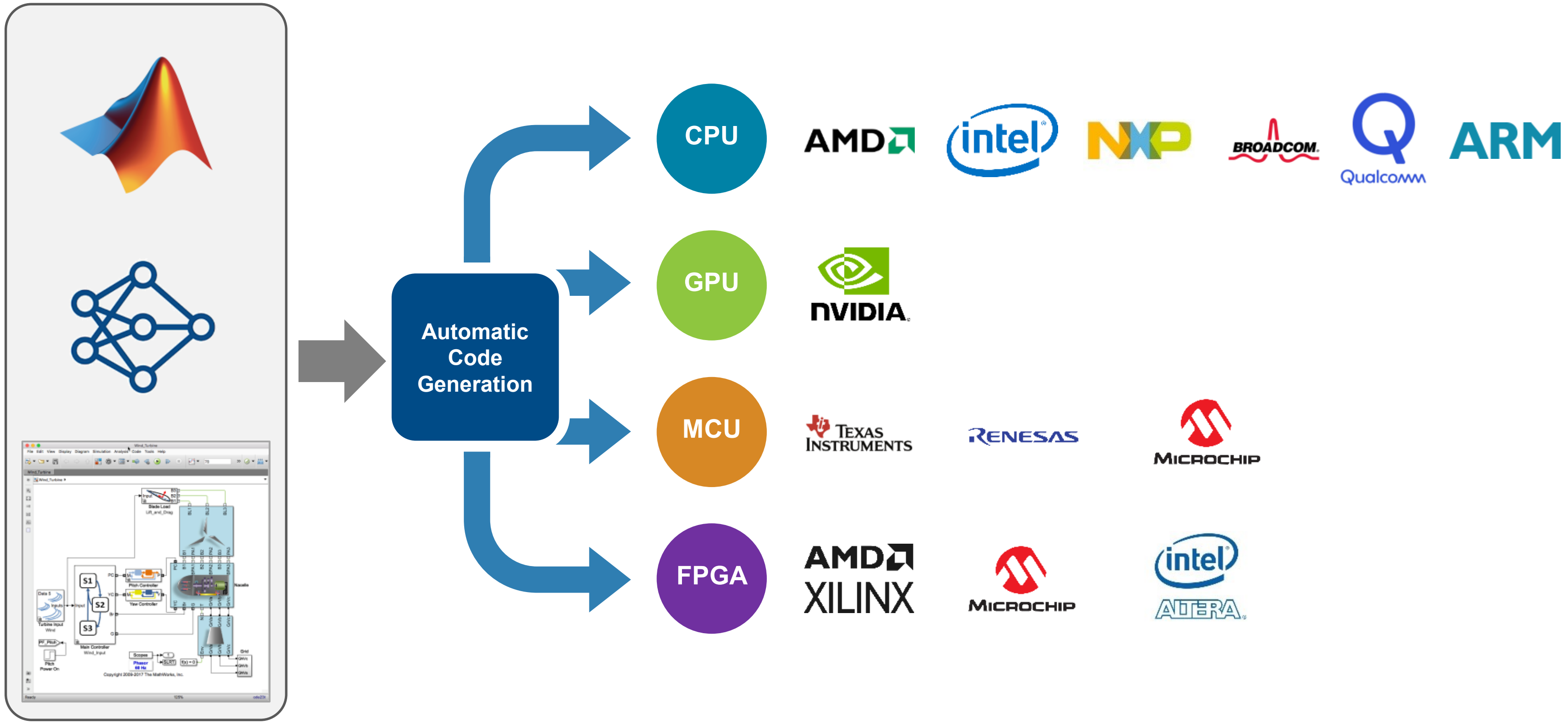


Deploy to any processor with best-in-class performance

Data Preparation | AI Modeling | Simulation & Test | **Deployment**

Deployment

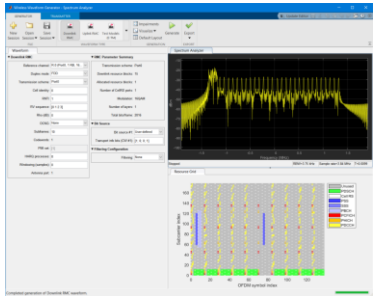
- Embedded devices
- Enterprise systems
- Edge, cloud, desktop

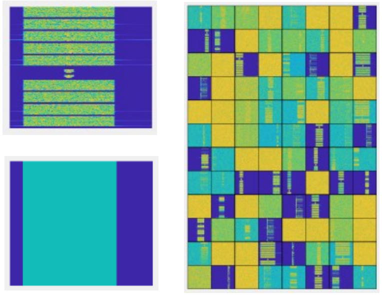


Spectrum sensing using network trained with synthesized data and tested with radio

Data Preparation

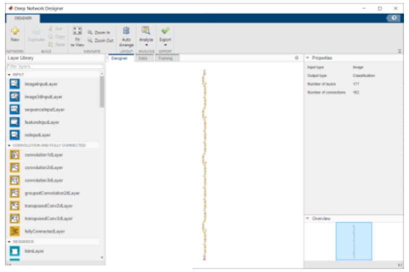
- Generate **standards-based** or **custom synthetic signals**
  - Add channel and RF **impairments**
- **Capture and label** over-the-air or over-the-wire signals
  - Add channel and RF impairments
- **Preprocess** training data
  - Calculate spectrograms
  - Label data

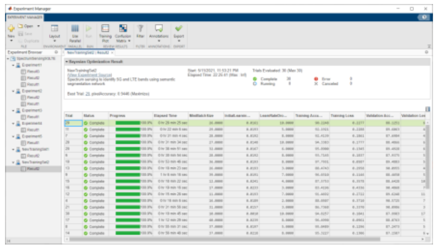




AI Modeling

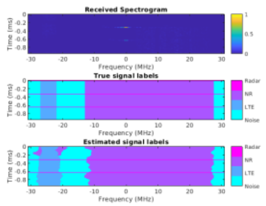
- Train neural network for classification
  - Design or use pretrained deep neural networks
  - Optimize hyperparameters

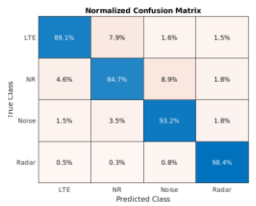




Simulation & Test

- Test using synthetic + over-the-air / over-the-wire signals
  - Update dataset as needed





Deployment

- Deploy to hardware

Signal-level Model

Spectrum Sensing Example

Modulation Classification

Modulation Classificaiton with FPGA

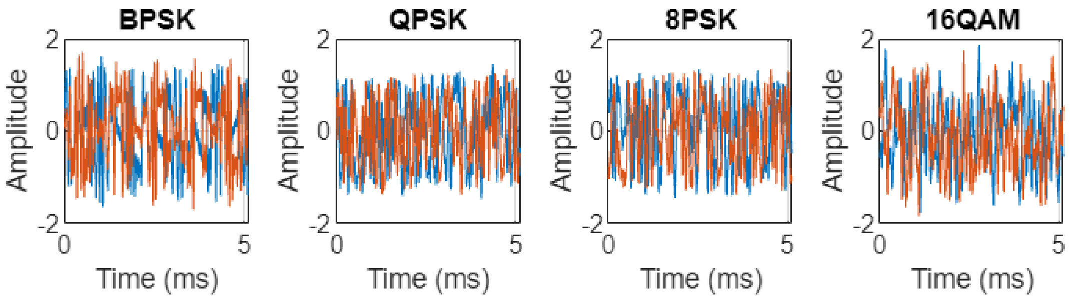
Radar and Comms Waveform Classification

Featured Example

[Modulation Classification with Deep Learning]

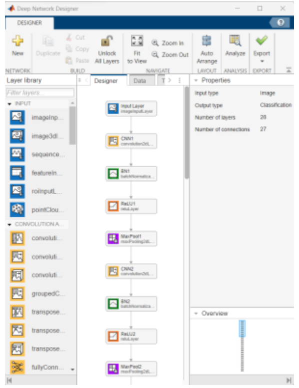
Data Preparation

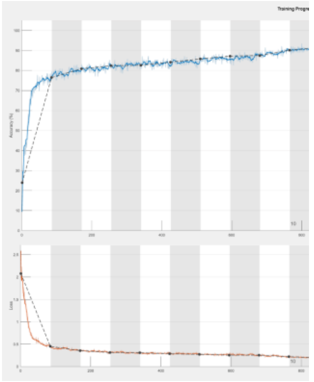
- Generate synthetic channel-impaired waveforms for 11 different modulation types

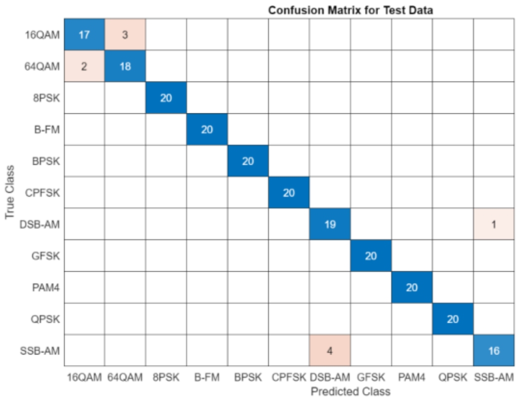


AI Modeling

- Define deep convolutional neural network (CNN) layers
- Train CNN on synthetically-generated waveform data





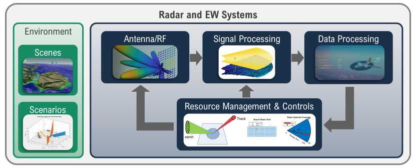


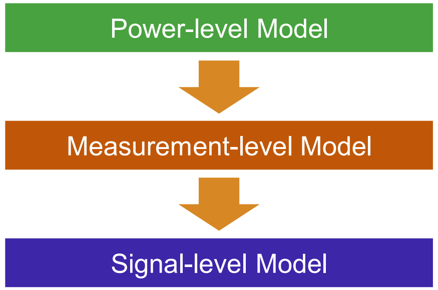
Simulation & Test

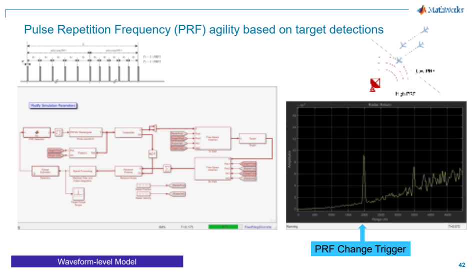
- Classify waveform modulation types using trained CNN, evaluate performance
- Demonstrate classification of over-the-air signals transmitted and received by software-defined radios (SDRs)

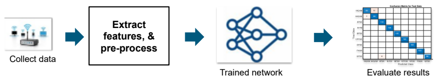
Review

- How **Digital Engineering** helps teams collaborate
- **Modeling and Simulation** at multiple abstraction levels
- **Multifunction** RF Mode-Agility Examples
- **AI Workflow** Overview and Example









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