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Integrating Radar & Wireless Communication Systems: Navigating the Trend with Modeling & Simulation

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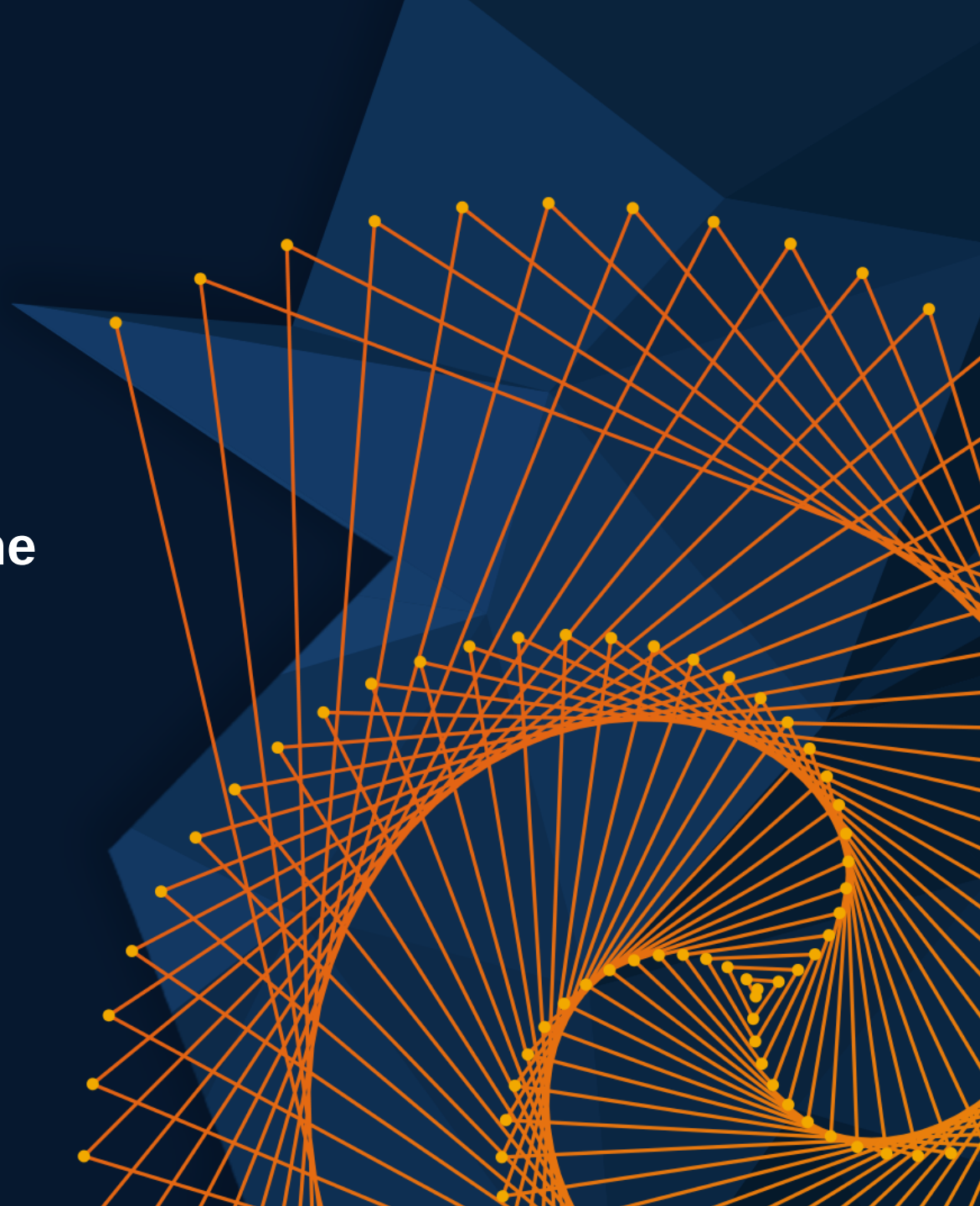


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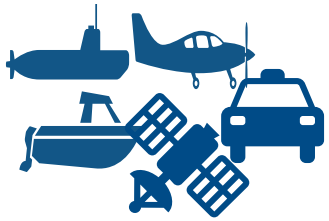
Technology Megatrends

Autonomy

Connectivity

Sensing and communications play critical role

Multifunction



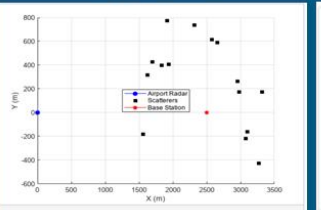
Multidomain

Emerging Trends in Integrated Sensing and Communications

RF Convergence

2000's	2010's	2020's	2030's
Separate Analog and Digital	Shared Analog, Separate Digital and Waveforms	Shared Analog and Digital. Separate Waveforms	Shared Analog and Digital. Shared Waveforms

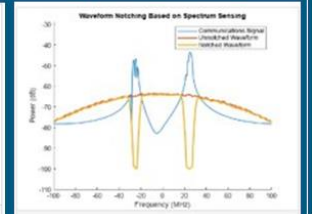
Primary
Radar has exclusive rights to the spectrum



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

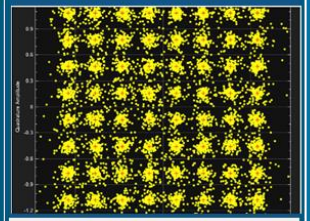


Spectrum Sharing using Spectrum Sensing and Waveform Notching

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

Open Live Script

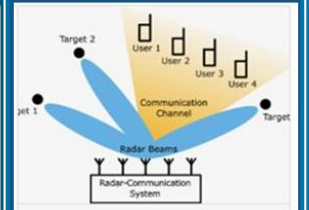
Co-Design
Both systems follow a common protocol



Joint Radar-Communication Using PMCW and OFDM Waveforms

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

Multi-Function
Parameters modified for signal embedding

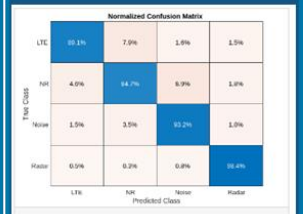


Waveform Design for a Dual-Function MIMO RadCom System

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

Open Live Script

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.

[Multifunction & Cognitive Examples]

[Coexistence Examples]

Mega Trends to Provide Ubiquitous Connectivity

Cellular

Satellite communications

WLAN

LTE

5G

5G advanced

6G

GNSS

CCSDS

DVB-S*

Bluetooth

Wi-Fi

Personal Area Network

Local Area Network

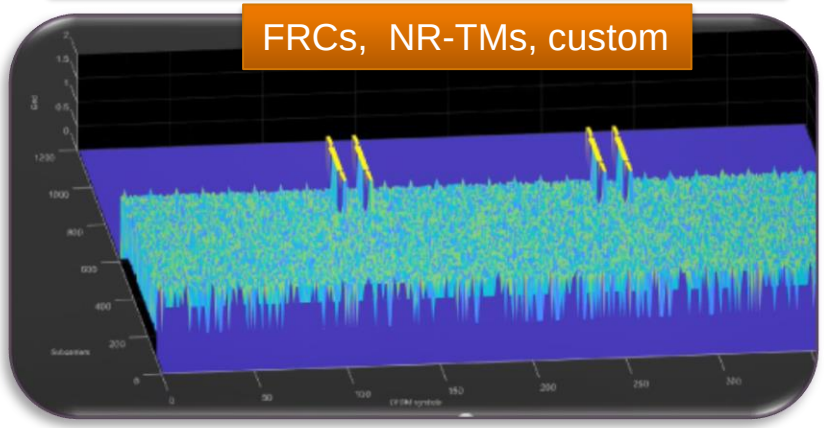
Wide Area Network

Non-Terrestrial Network

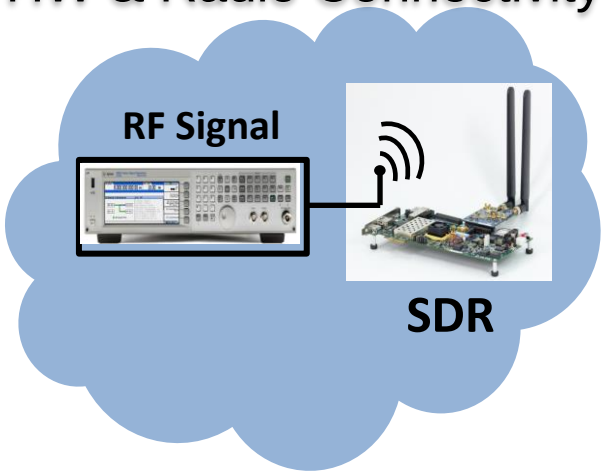
Wireless Communication Workflow Challenges

Waveform Generation

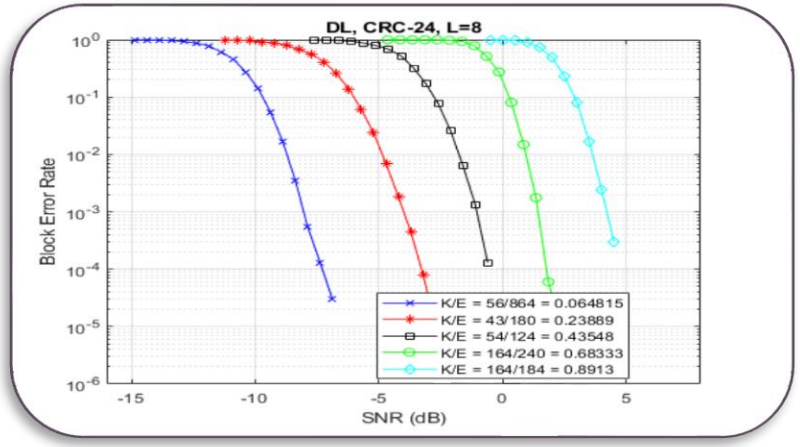
FRCs, NR-TMs, custom



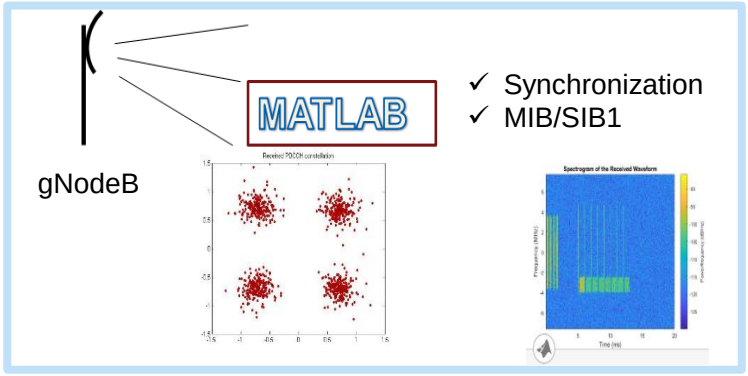
HW & Radio Connectivity



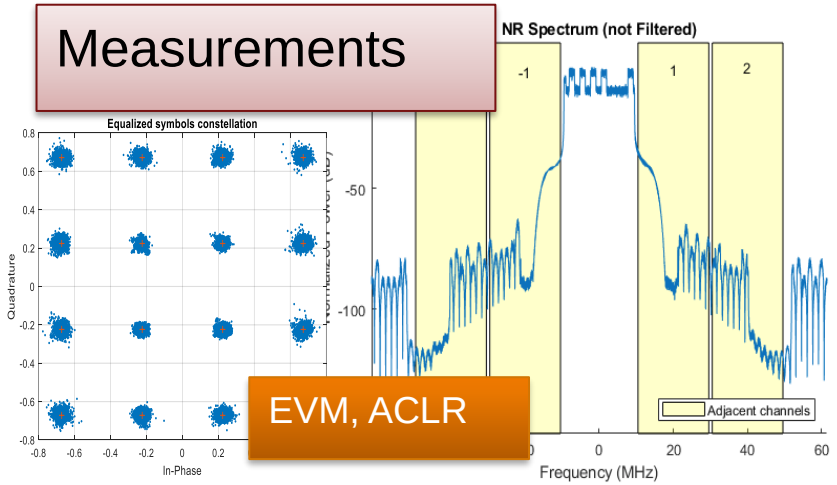
End-to-End Simulations



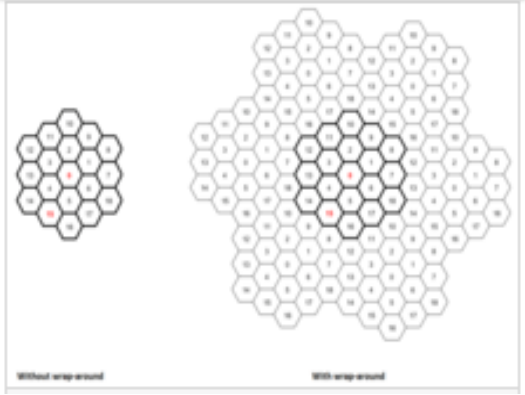
Signal Detection



Measurements

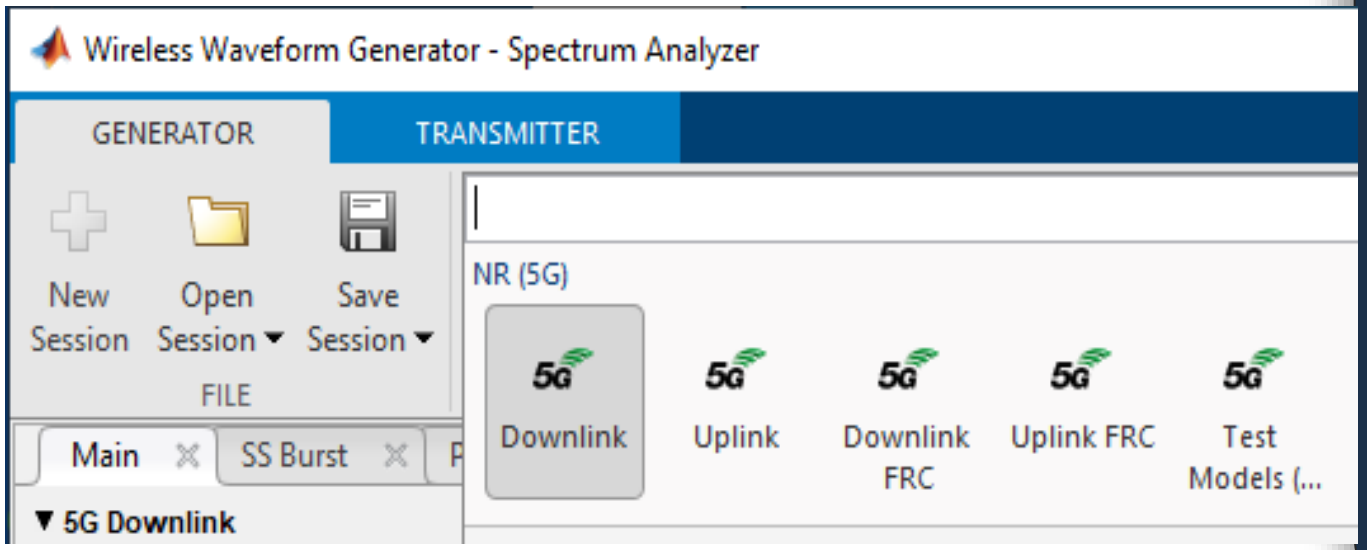


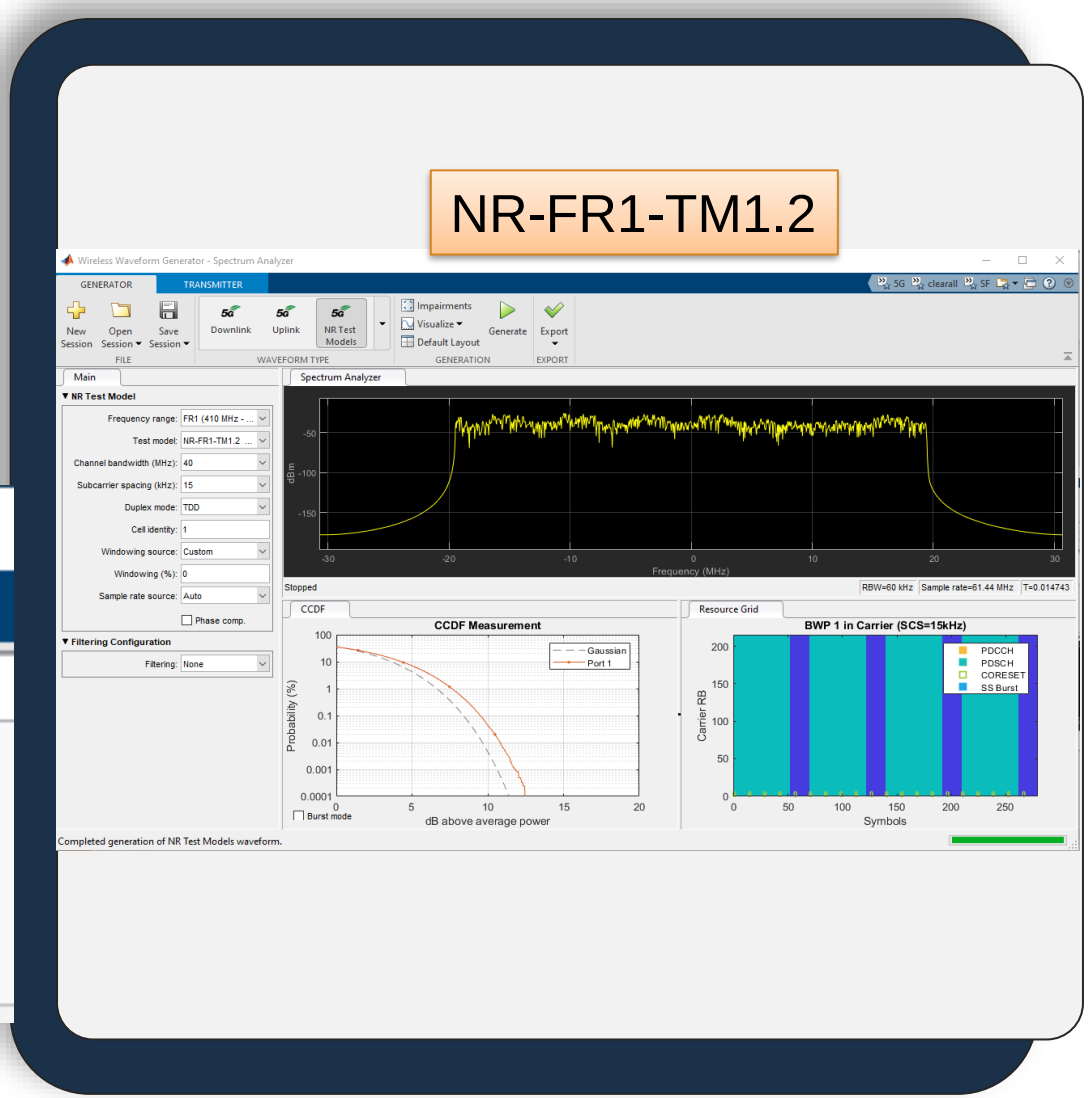
Network Simulations



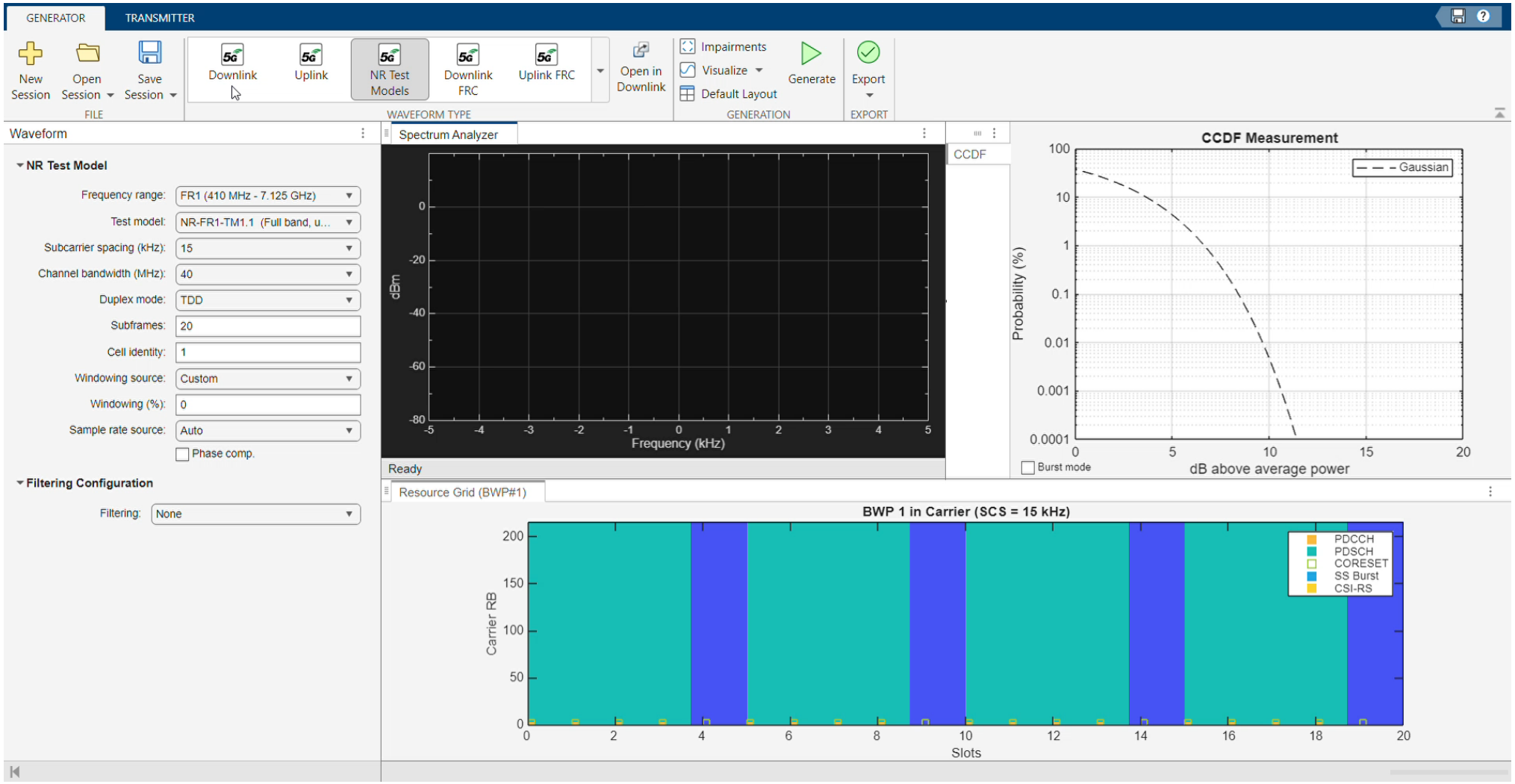
Wireless Waveform Generator App

- Off-the-shelf waveforms : NR-TMs / FRCs
- Custom downlink & uplink waveforms
- Export waveform or generate code





Wireless Waveform Generator App



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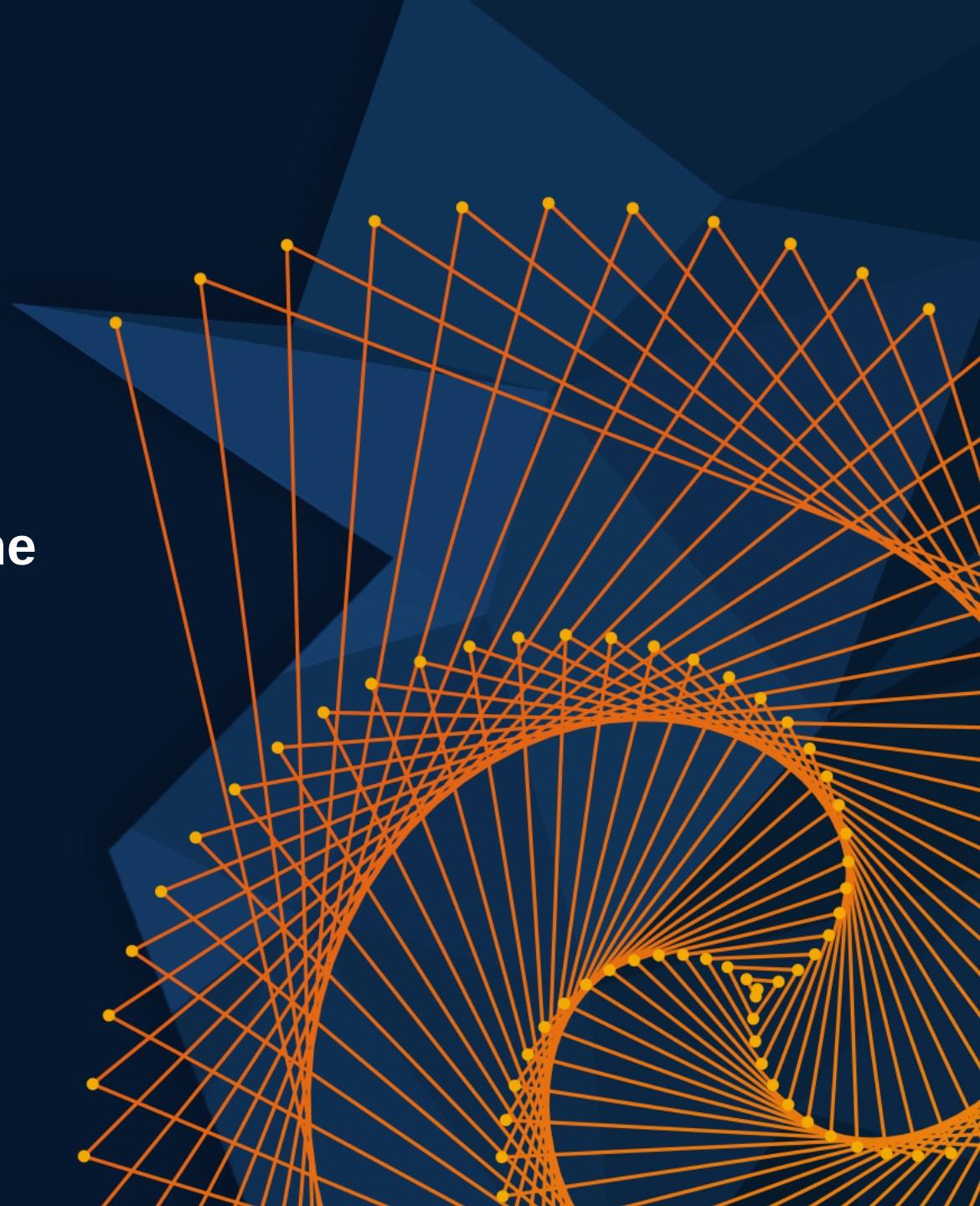

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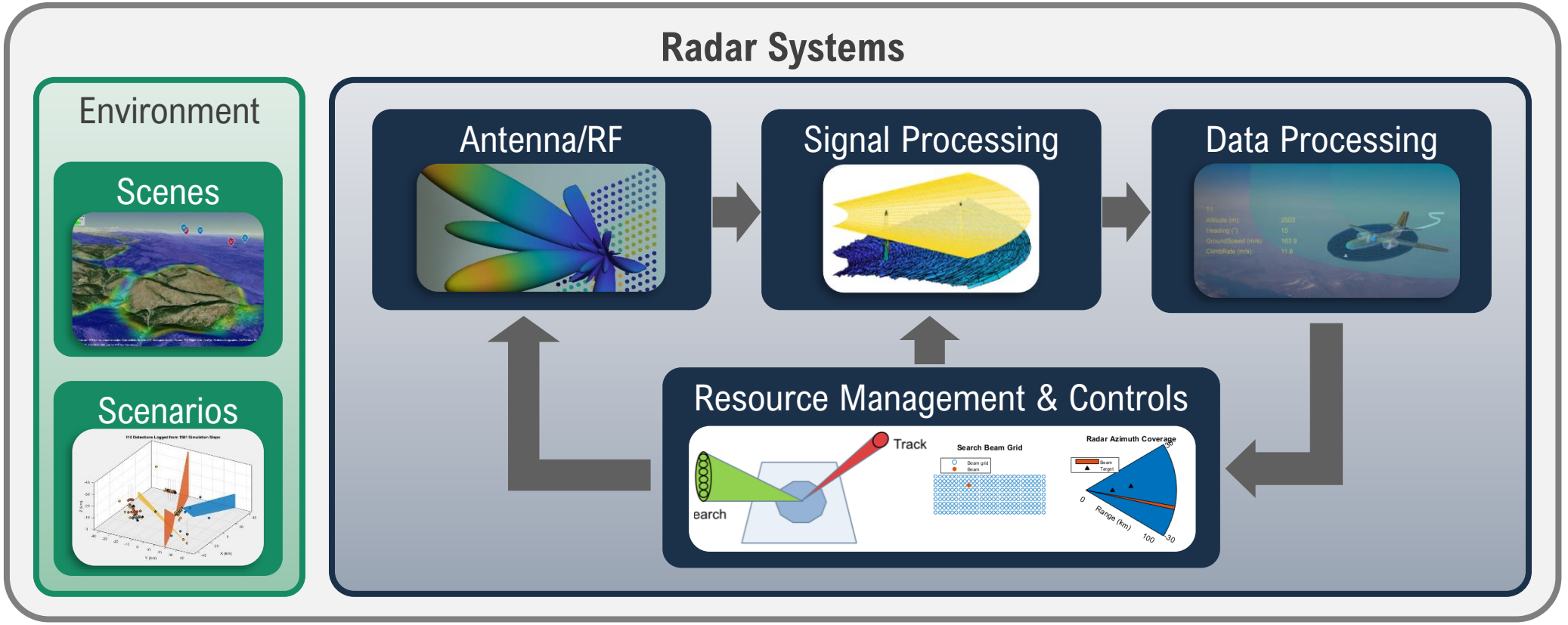
Develop radar systems with MATLAB and Simulink

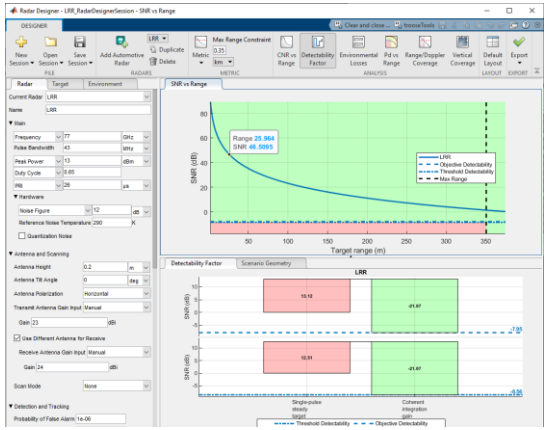


Three Abstraction Levels for Support of Full Radar Life Cycle

Less — **Fidelity** — More

Power-level

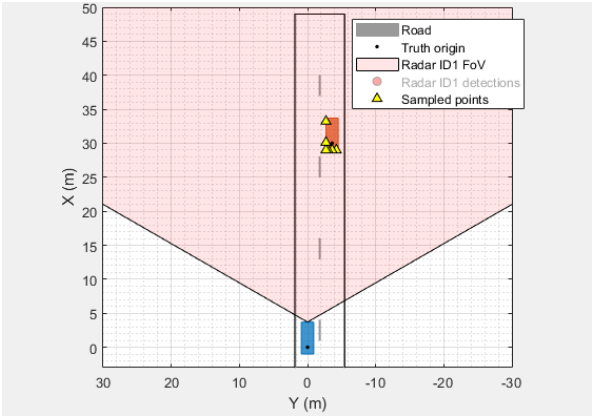
Link Budget



Applications: Concept Dev/Design, Systems Analysis

Measurement-level

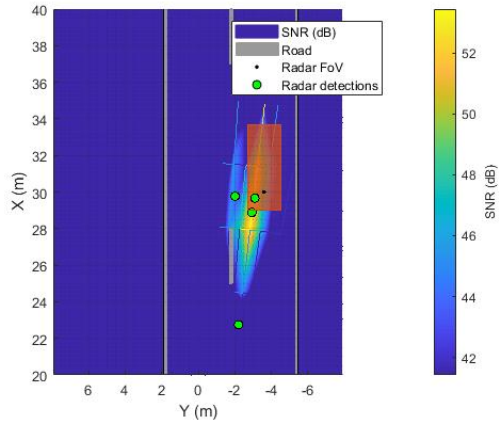
Detections



Applications: Systems Analysis, Scenario Analysis, Tracker Design

Waveform-level

Raw IQ



Applications: Algorithm Development, End-to-End Performance Assessment

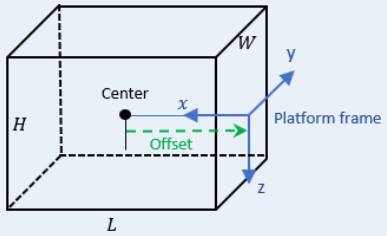
Less — **Computational Resources** — More

** See Design and Simulate an FMCW Long-Range Radar (LRR) Example here*

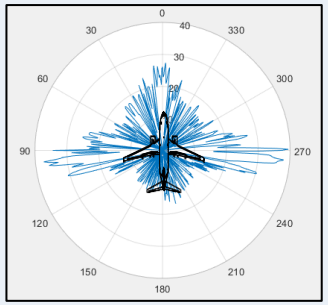
Author and simulate radar scenarios

Model Platforms and Targets

Object Dimensions
bounding box



RCS signature
Az, el pattern
frequencies dependency



Model Environment

Land Surface Clutter
DTED, Custom
Land Reflectivity Models

Sea Surface Clutter
Spectral Model
Sea reflectivity models

Reflectivity Models
Built-in models
Custom models
Reflectivity maps

Atmospheric Refraction
Effective Earth radius
Refractivity gradient

Model Trajectories

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)

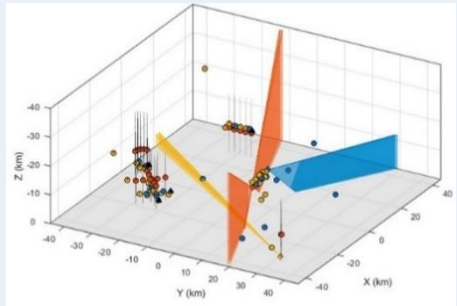
Model Sensors

Measurement Level
Scenario Analysis,
Tracker Design

Waveform Level
Algorithm Development,
End-to-End Performance Assessment

Simulate Scenarios

Generate radar data
I/Q signals, detections, tracks



Monte Carlo
perturb ground truth and sensor to increase testing robustness

Tracking Algorithm Development Workflow

Recorded Sensor Data

Scenario Definition and Sensor Simulation

Trajectory Generation → INS Sensor Simulation

Actors/ Platforms → Radar, IR, & Sonar Sensor Simulation

objectDetection

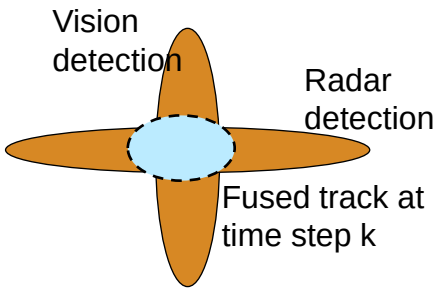
Trackers

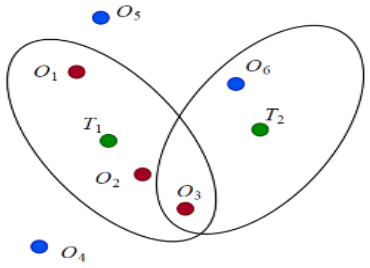
GNN, JPDA, MHT, PHD, etc..

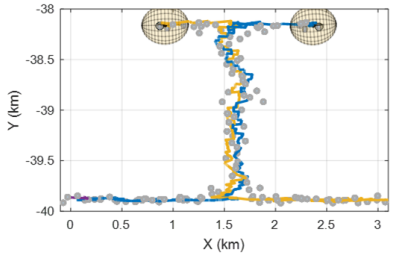
objectTrack

Visualization & Metrics

A rich library of tracking algorithms







Filters

- Alpha Beta filter
- Kalman filters
  - Linear, EKF, UKF, CKF, MSCEKF
- Particle filter
- Multiple models
  - GSF, IMM

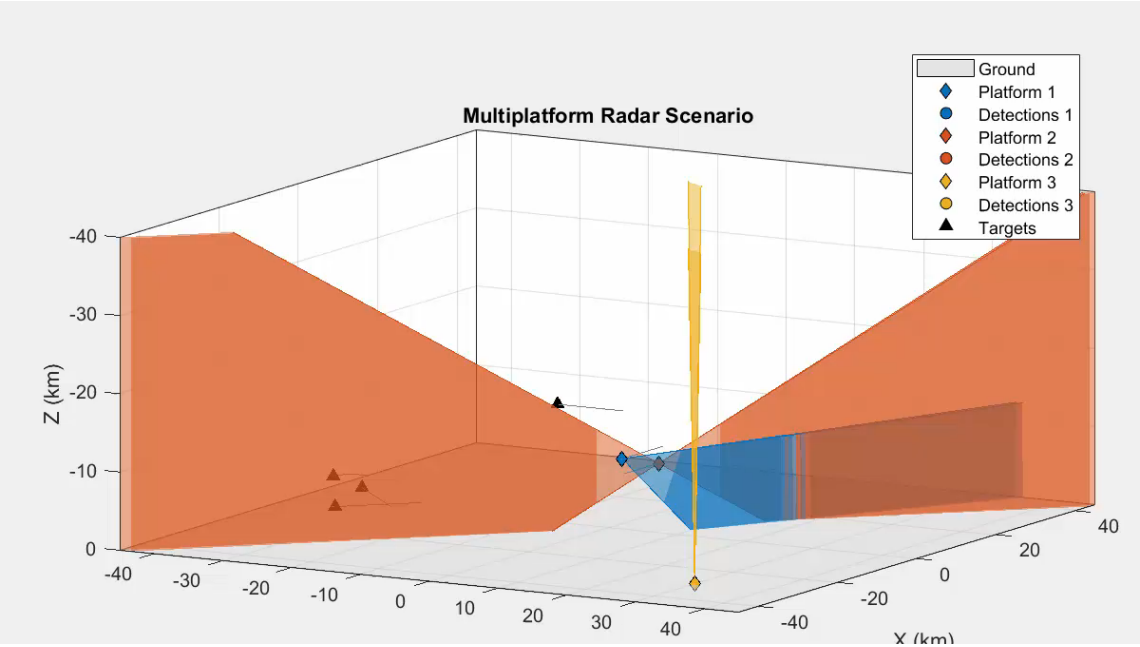
Data Association

- 2D assignment
- S-D assignment
- K-best assignmemt

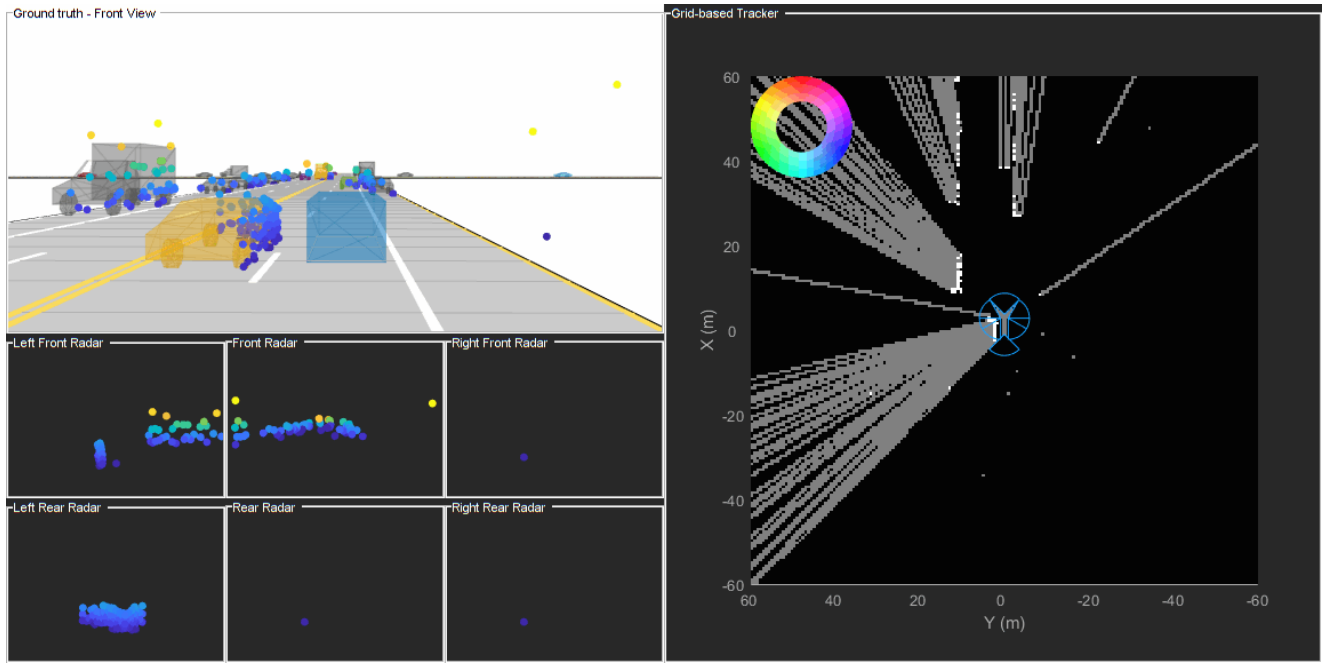
Trackers

- GNN
- MHT (track-oriented)
- Trackers components
  - History and score logic
  - etc……

Complex scenes include multiple radars and targets



Multiplatform Radar Network



Grid-based Tracking using Multiple Radars

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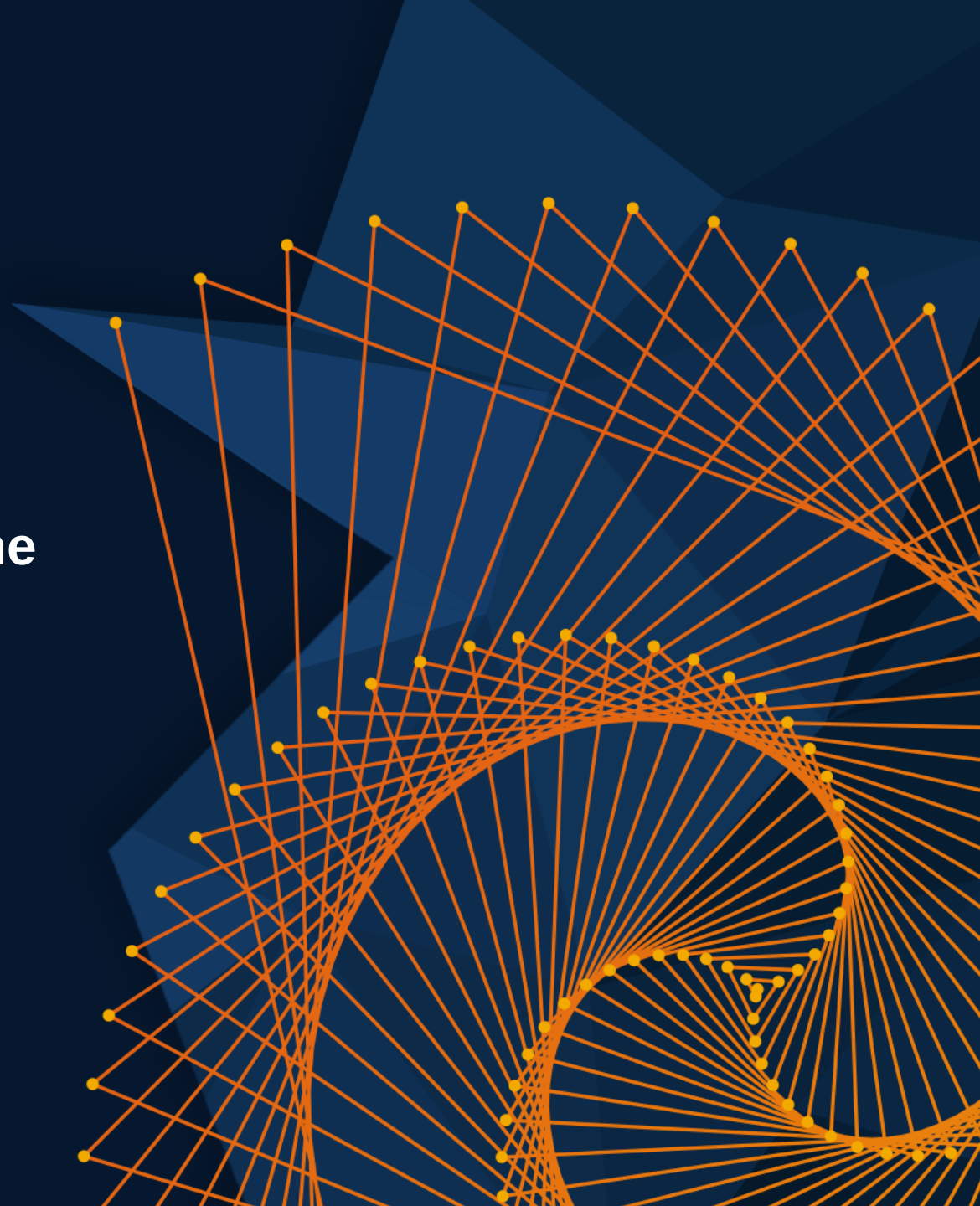

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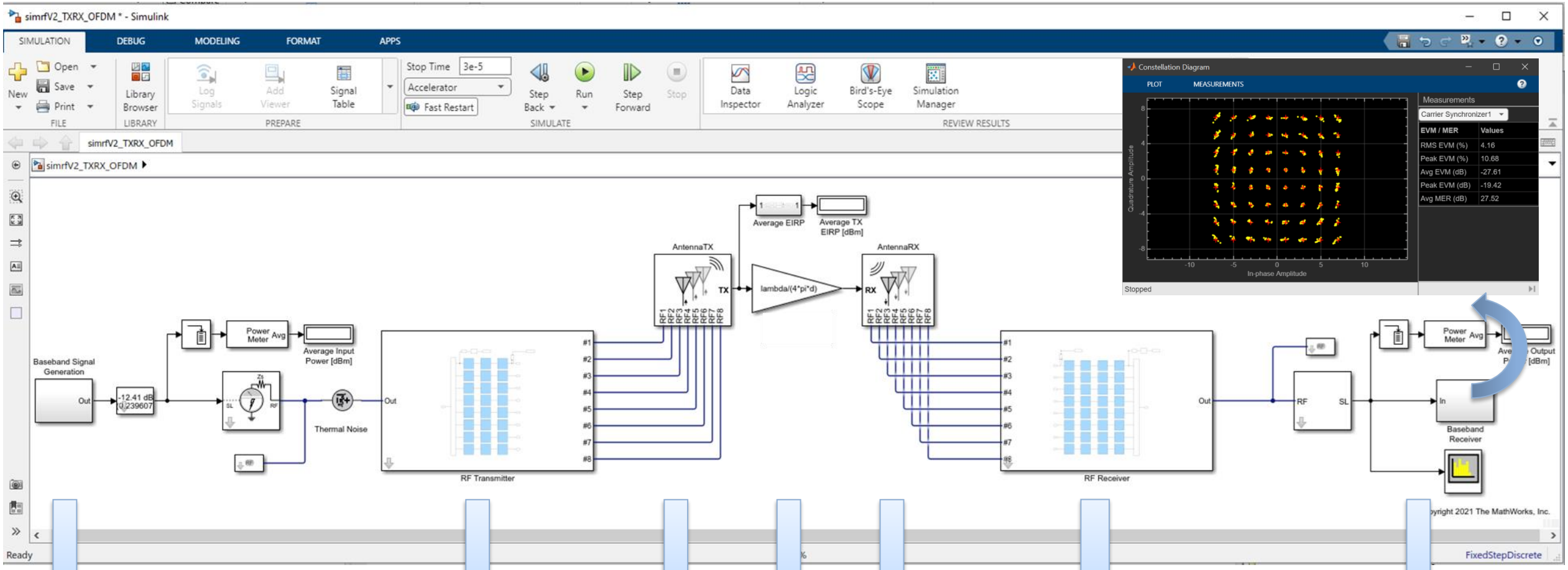
End-To-End MIMO Transceiver Simulation Including Antenna Arrays

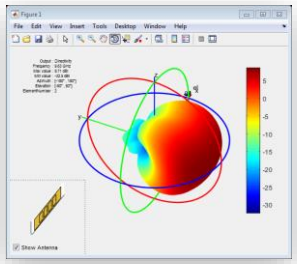


Tx_Baseband | Tx_RF Front-end | Tx_Antenna Array | Channel | Rx_Antenna Array | Rx_RF Front-end | Rx_Baseband

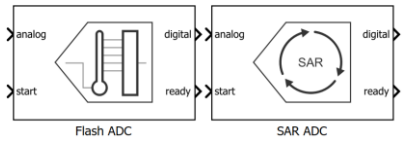
Signal Flow Domain | RF Circuit Envelope Simulation | EM Simulation | EM Simulation | RF Circuit Envelope Simulation | Signal Flow Domain

Antenna to Bits - Unified Design Platform

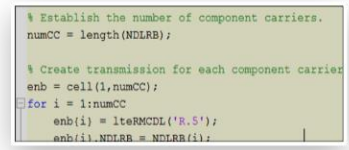
Antenna, Antenna arrays
type of element, # elements, coupling, edge effects

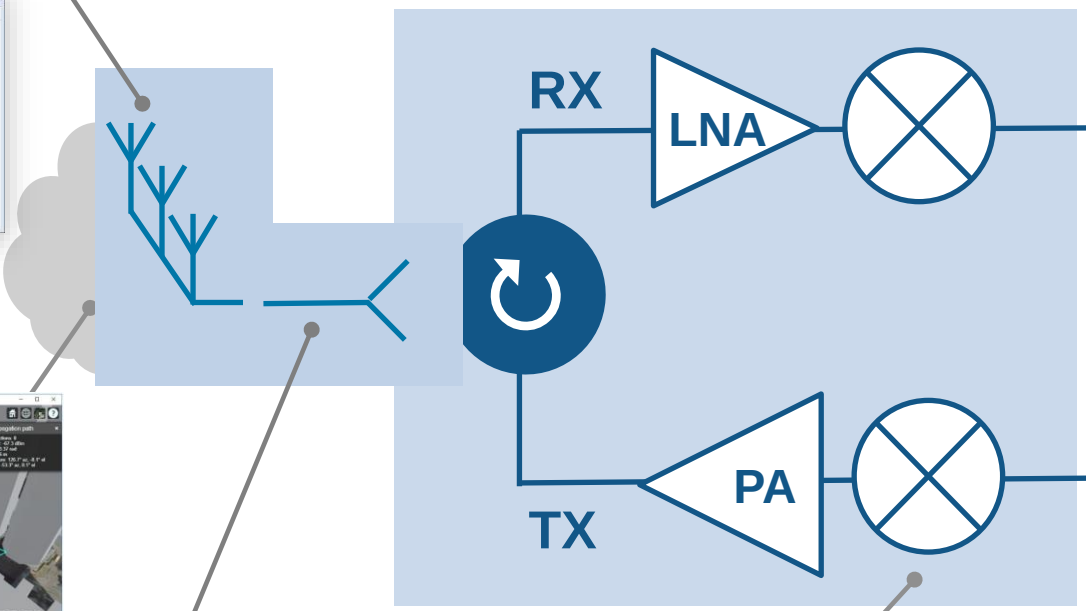


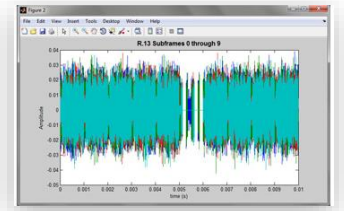
Mixed-Signal
Continuous & discrete time



Algorithms
beamforming, beamsteering, MIMO

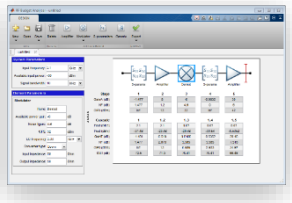






PCB Components
frequency dependency, noise, mismatches

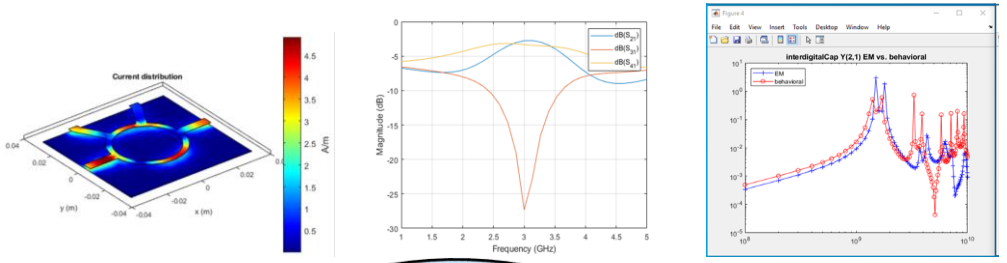
Channel
interference, clutter, noise



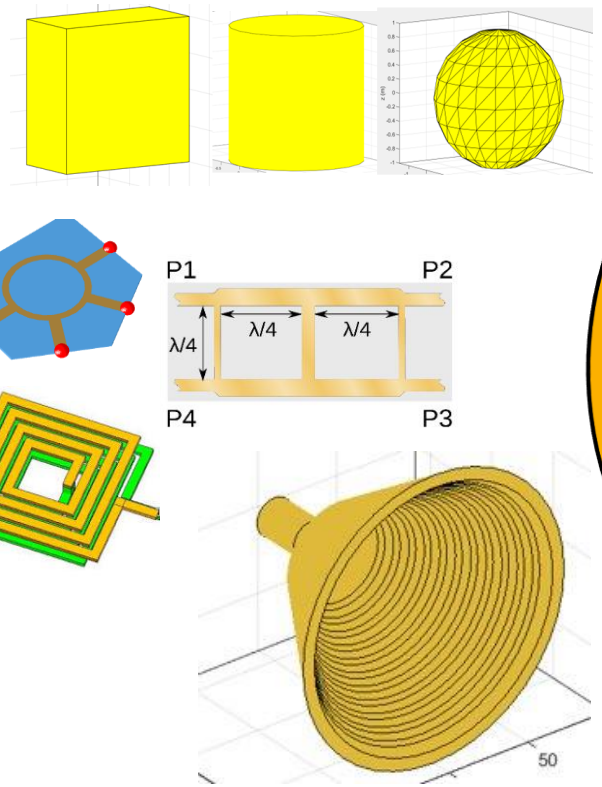
RF Impairments
frequency dependency, non-linearity, noise, mismatches

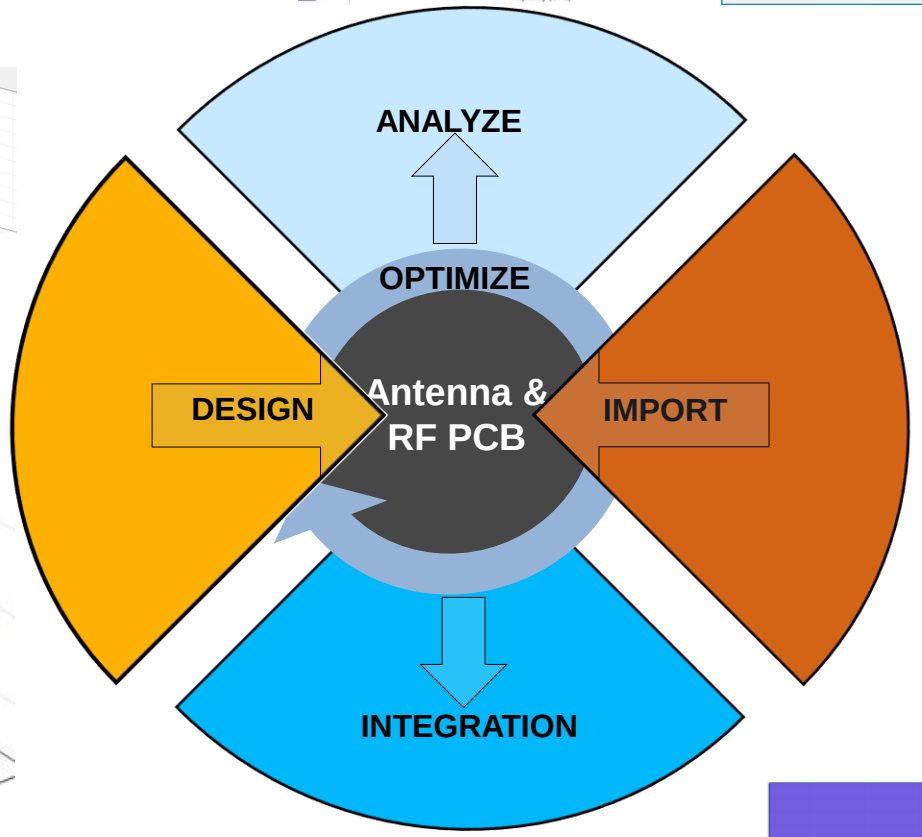
Waveforms

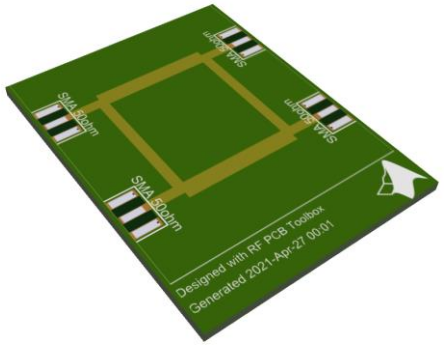
3D Modeling of Antenna and RF models



Optimization and analysis

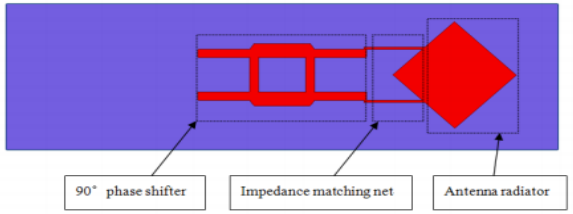






Import STL file to create a custom 3D antenna

Design 3-D custom antenna geometry and PCB Components



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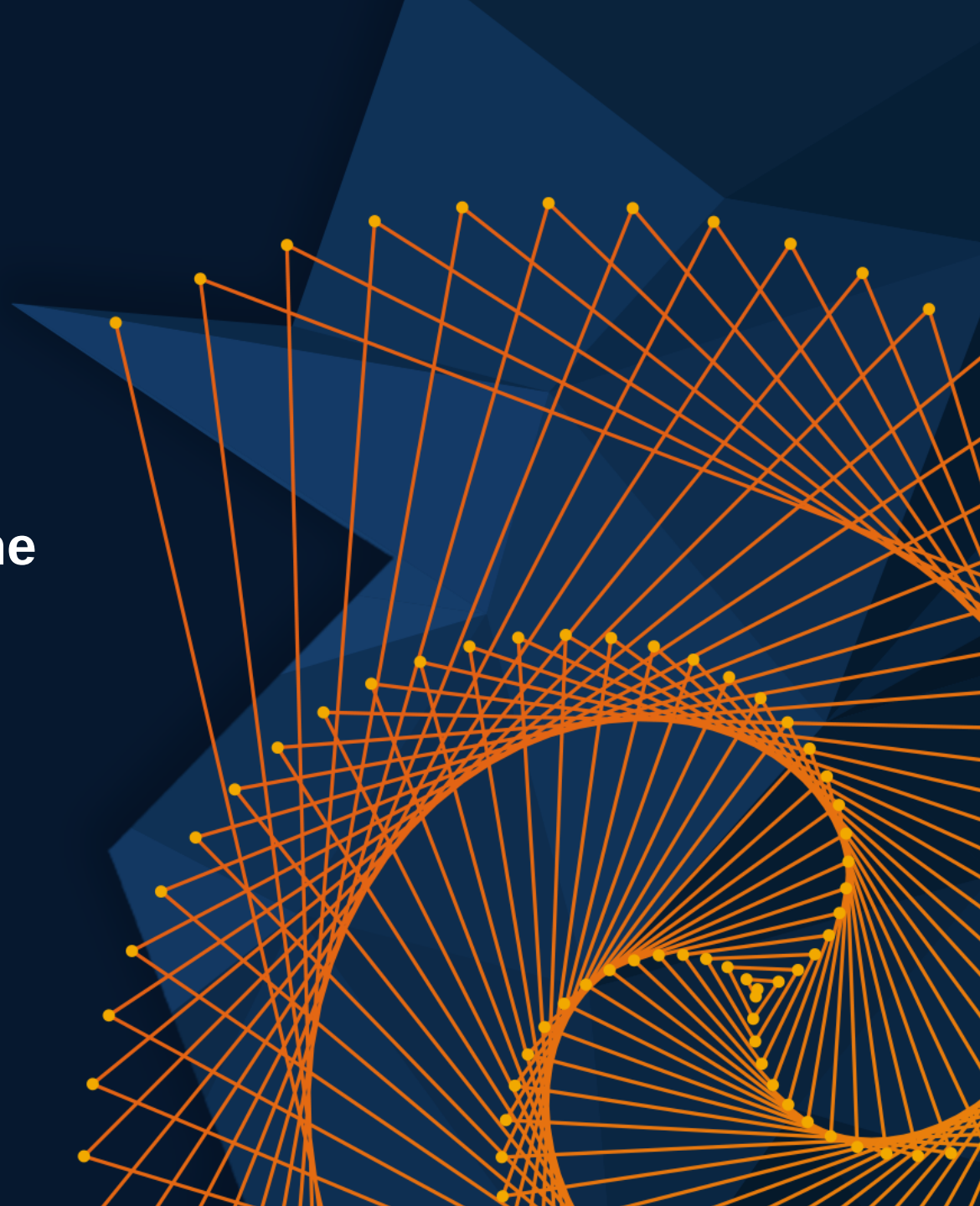

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Traditional v/s Model-Based Design for FPGA/ASIC Implementation

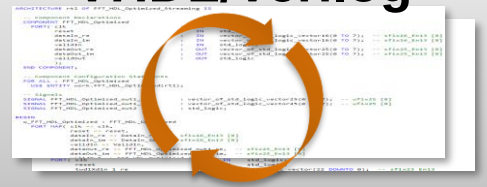
MATLAB

```
fftlen = numel(xd);
Xd = fft(xd);
figure
Ld   = L/BWFactor;
Fsd = Fs/BWFactor;
F    = Fc + Fsd/fftlen*(0:fftlen-1)-Fsd/2;
stem(F,abs(fftshift(Xd))/Ld)
```

Algorithm Development

Specification Doc

VHDL/Verilog



Hand write hardware structure

Integration & Test

Verify and Debug

MATLAB

```
fftlen = numel(xd);
Xd = fft(xd);
figure
Ld   = L/BWFactor;
Fsd = Fs/BWFactor;
F    = Fc + Fsd/fftlen*(0:fftlen-1)-Fsd/2;
stem(F,abs(fftshift(Xd))/Ld)
```

Golden Reference Algorithm

Design System Architecture

Streaming Algorithm + Hardware architecture Implementation + Fixed Point Quantization

Simulink | DSP/Wireless HDL Toolbox | Fixed- Point Designer

Target FPGA hardware

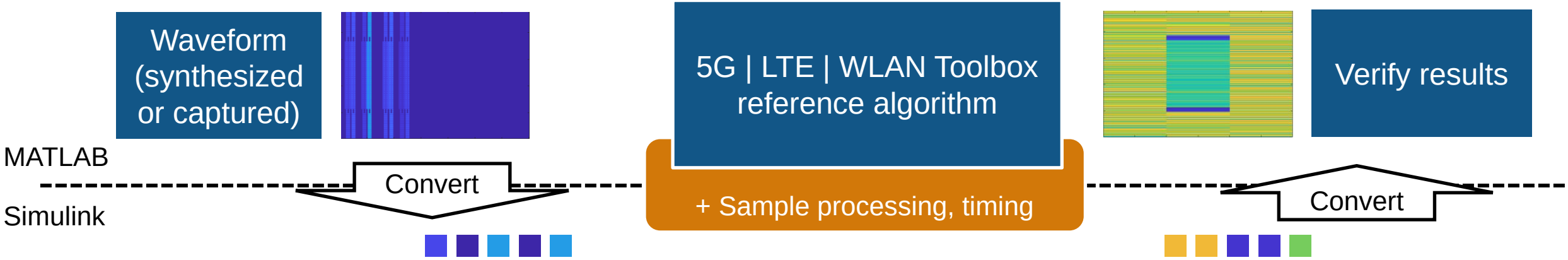
Simulink | HDL Coder

Test and Verification

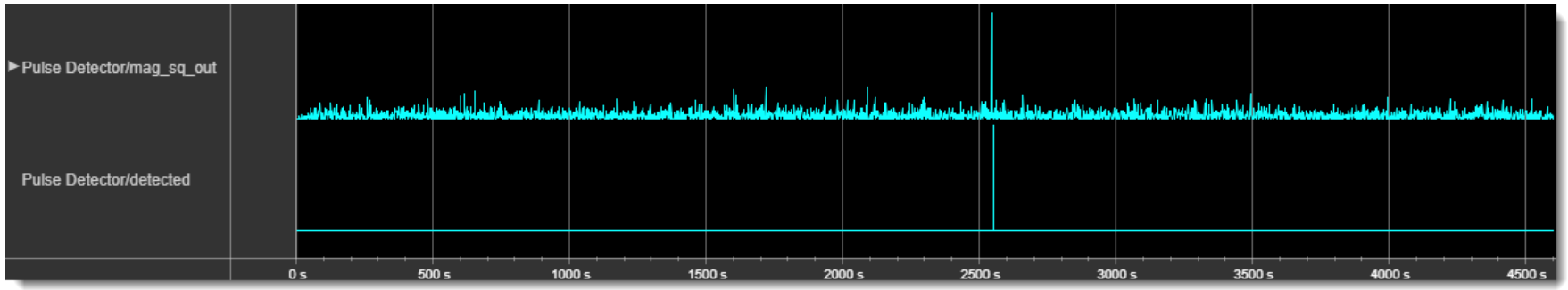
Simulink V&V

HDL Verifier

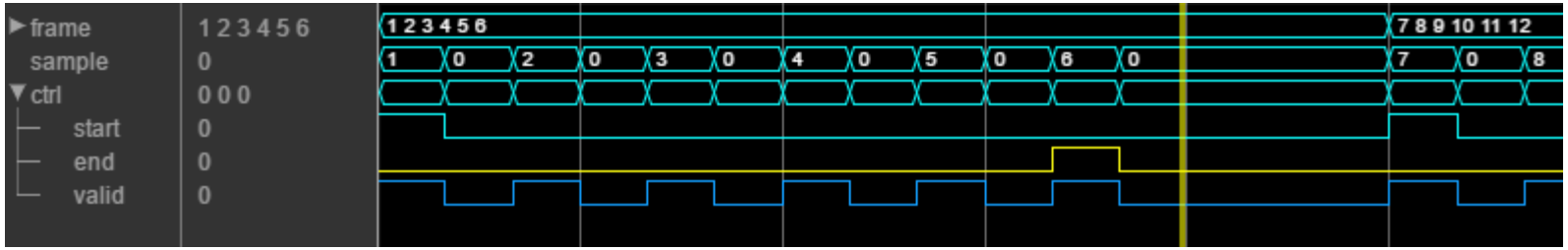
Top-Down Workflow : Convert Frame to Sample Based Processing



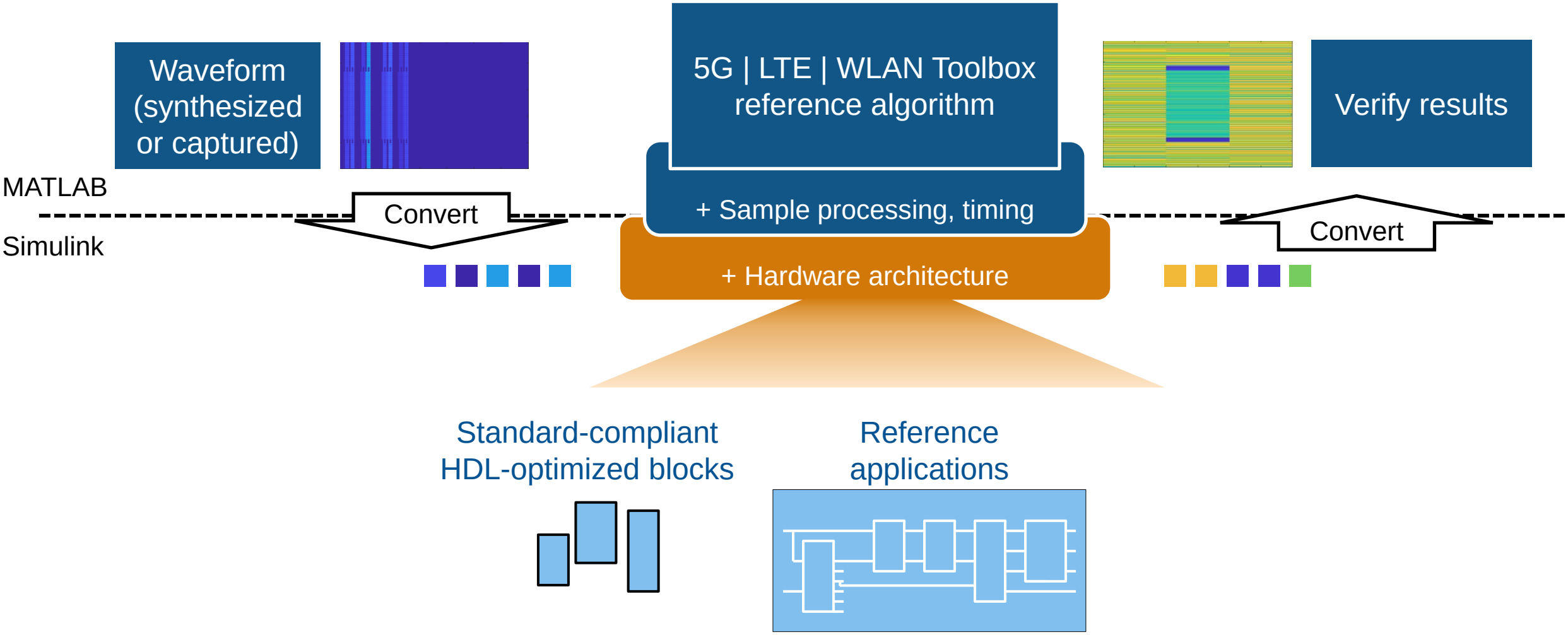
- Adapt algorithms



- Use control signals

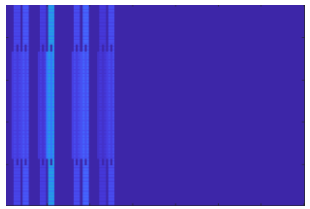


Top-Down Workflow: Floating Point to Fixed Point Conversion

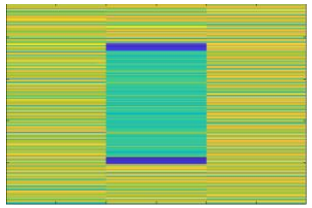


Top-Down Workflow: Floating Point to Fixed Point Conversion

Waveform (synthesized or captured)



5G | LTE | WLAN Toolbox reference algorithm



Verify results

MATLAB

Simulink

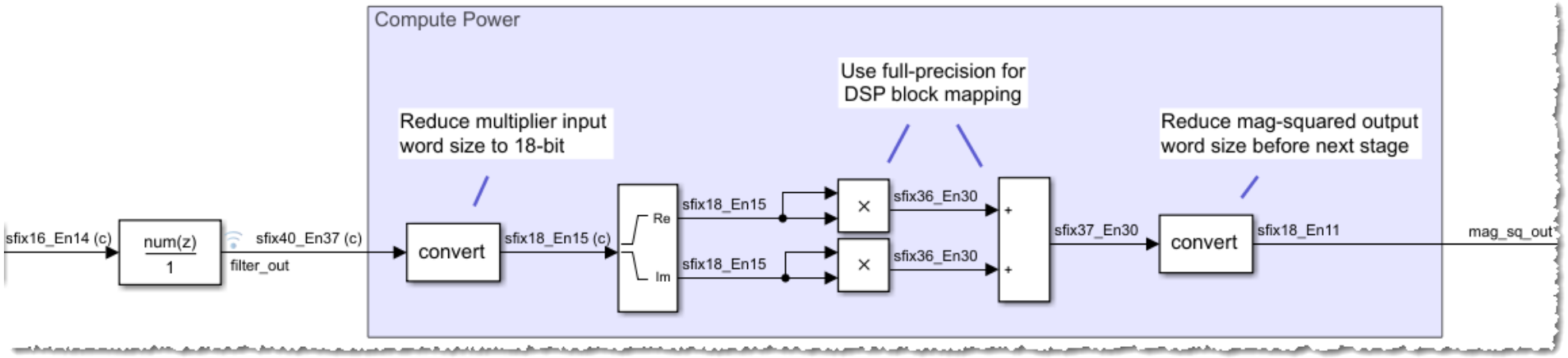
Convert

+ Sample processing, timing

+ Hardware architecture

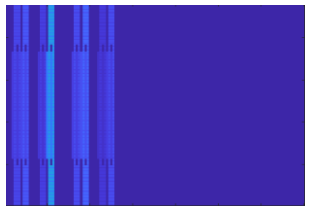
+ Fixed-point quantization

Convert



Top-Down Workflow: Generate HDL Codes

Waveform (synthesized or captured)

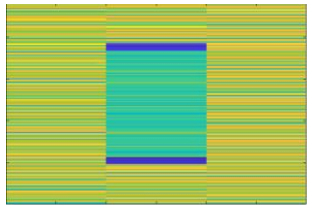


5G | LTE | WLAN | RADAR Toolbox reference algorithm

+ Sample processing, timing

+ Hardware architecture

+ Fixed-point quantization



Verify results

MATLAB

Simulink

Convert

Convert

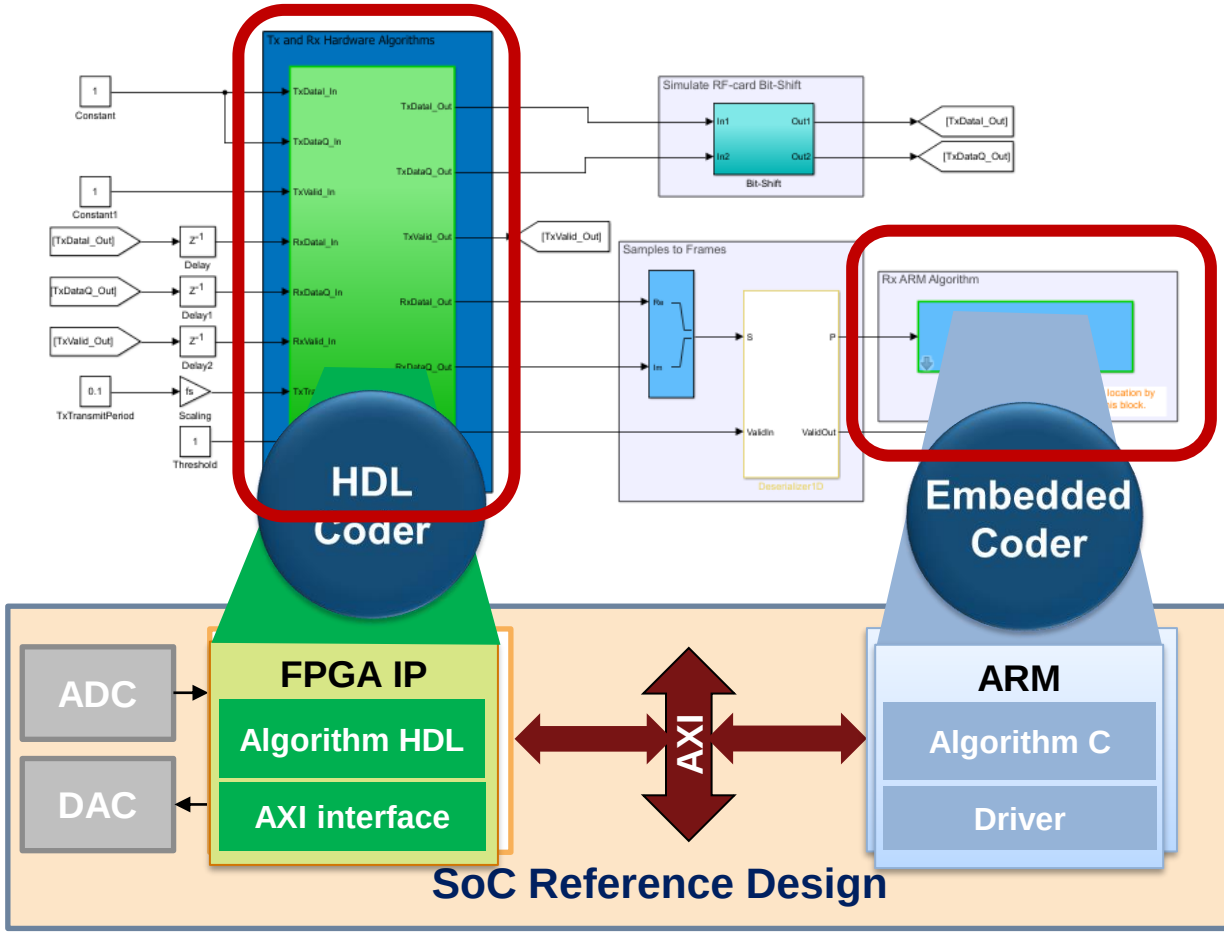
HDL Coder

```
-- -------------------------------------------------------------
--
-- Module: Peak_Detector
-- Source Path: pulse_detector_v4/Peak Detector
-- Hierarchy Level: 0
--
-- -------------------------------------------------------------
LIBRARY IEEE;
USE IEEE.std_logic_1164.ALL;
USE IEEE.numeric_std.ALL;

ENTITY Peak_Detector IS
  PORT( clk                               :   IN    std_logic;
        reset                             :   IN    std_logic;
        clk_enable                        :   IN    std_logic;
        In1_re                            :   IN    std_logic_vector(15 DOWNTO 0);  -- sfix16_En14
        In1_im                            :   IN    std_logic_vector(15 DOWNTO 0);  -- sfix16_En14
        valid_in                          :   IN    std_logic;
        ce_out                            :   OUT   std_logic;
        Out1                              :   OUT   std_logic_vector(17 DOWNTO 0);  -- sfix18_En11
        Out2                              :   OUT   std_logic;
        valid_out                         :   OUT   std_logic
        );
END Peak_Detector;


ARCHITECTURE rtl OF Peak_Detector IS
```

HDL Coder

- Target-independent, readable, traceable code
- Resource Utilization and Critical Path Estimation Reports
- Generate Test bench
- Optimize for area-speed constraint
- Hardware support package for direct targeting of popular prototype boards

Generate C and HDL code for deployment on SoC platforms



Xilinx Zynq RFSoC
- ZCU111
- ZCU208
- ZCU216

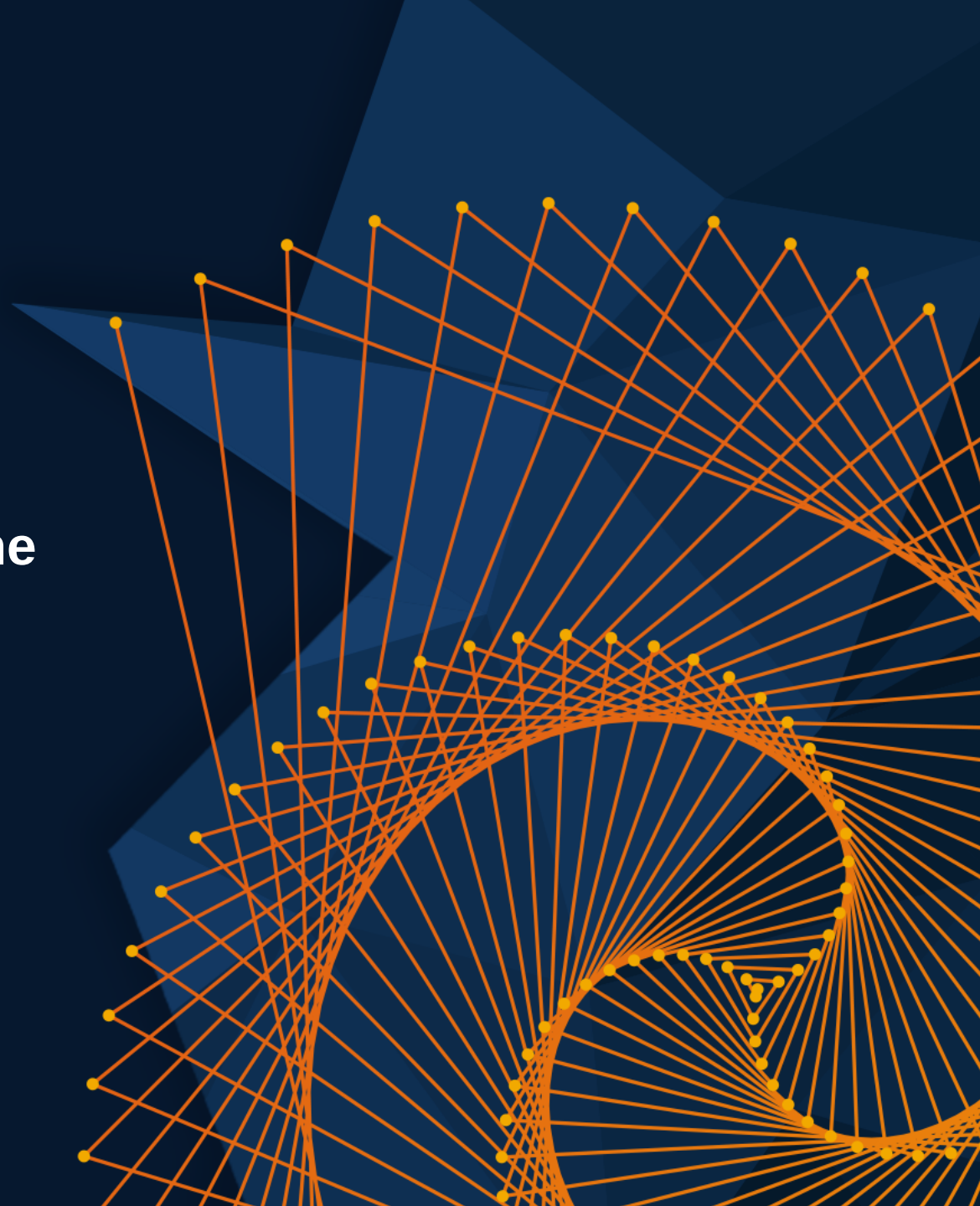
FPGA / SoC Board

Zynq platform with AD9361 RF card

Program AMD, Intel and Microchip boards

MATLAB EXPO
INDIA

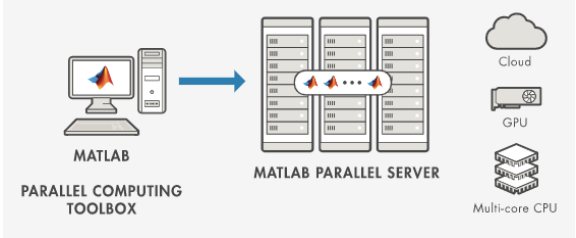
Integrating Radar & Wireless Communication Systems: Navigating the Trend with Modeling & Simulation



MathWorks

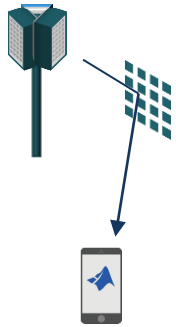
6G Key Enabling Technologies

Waveform exploration

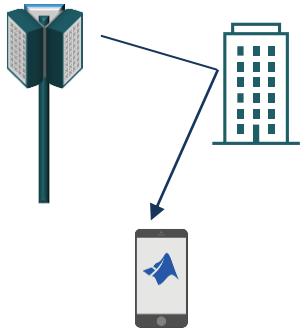


Scale: managing large and long running simulations

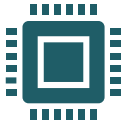
AI/ML for wireless



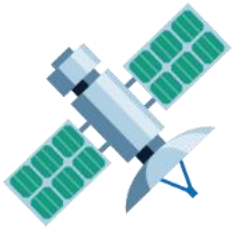
RIS



mmWave: propagation loss and channel models



mmWave: RF impairment modelling



Non-terrestrial Networks (NTN)

Joint communications and sensing (JCAS)

[6G Exploration Library]

Waveform Exploration – Extended 5G Waveform

- Explore the properties and capabilities of extended 5G-waveforms:
  - Large bandwidths beyond 275 RBs
  - SCS beyond 960 kHz

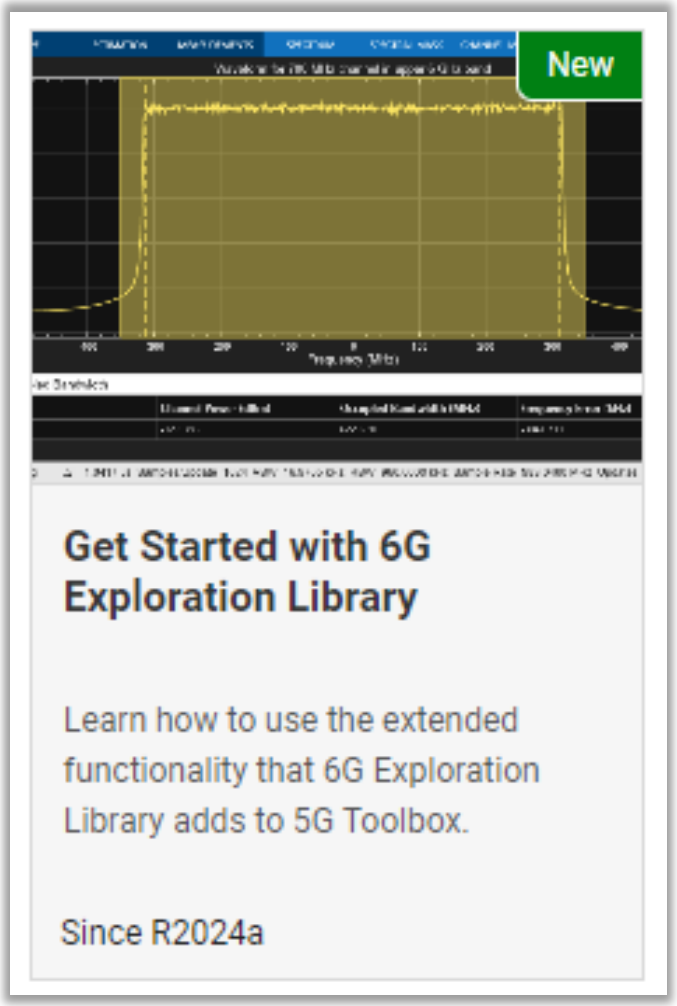
6G Exploration Library											
SCS	15	30	60	120	240	480	960	1920	3840	7680	…
Max NRB	No limit										

290 RBs

SCS = 3840 kHz

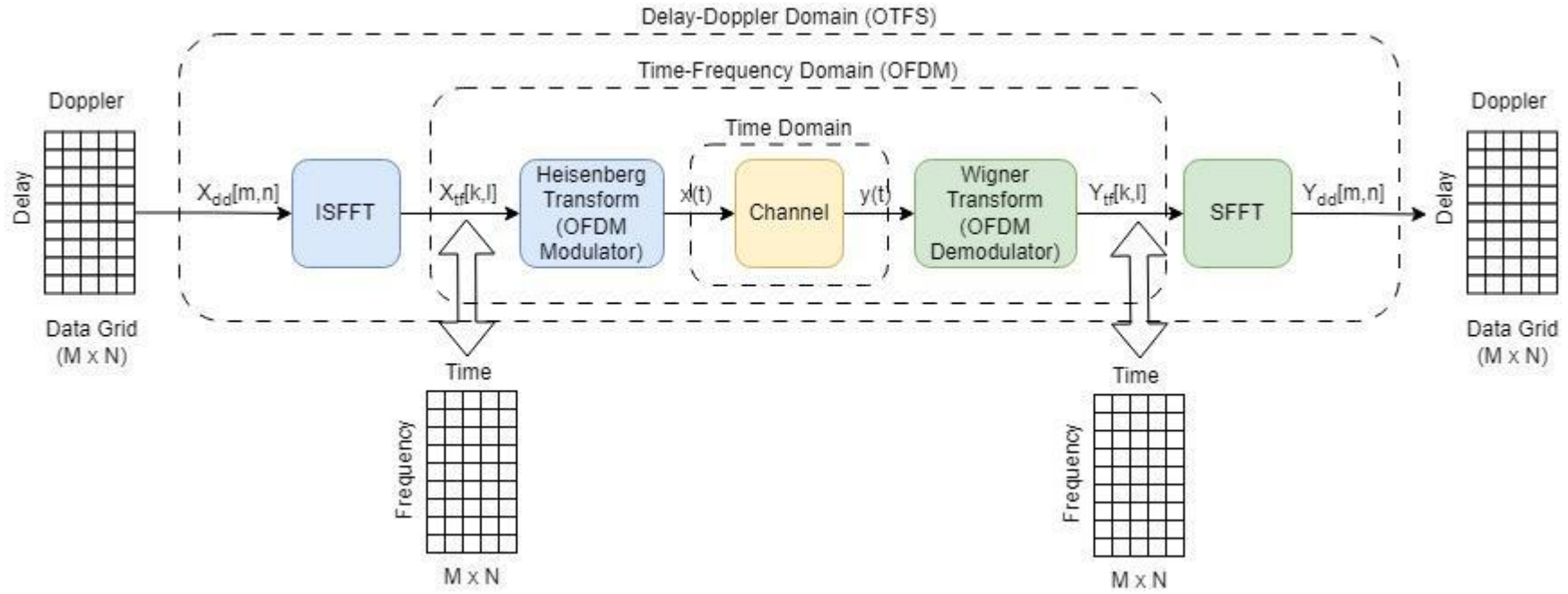
BW = 13.36 GHz

Fs = 15.73 GHz



OTFS: A New Waveform Candidate for 6G

- OTFS can be seen as an OFDM code with pre-coding (ISFFT)
  - Equivalence only when Heisenberg Transform identical to OFDM modulation



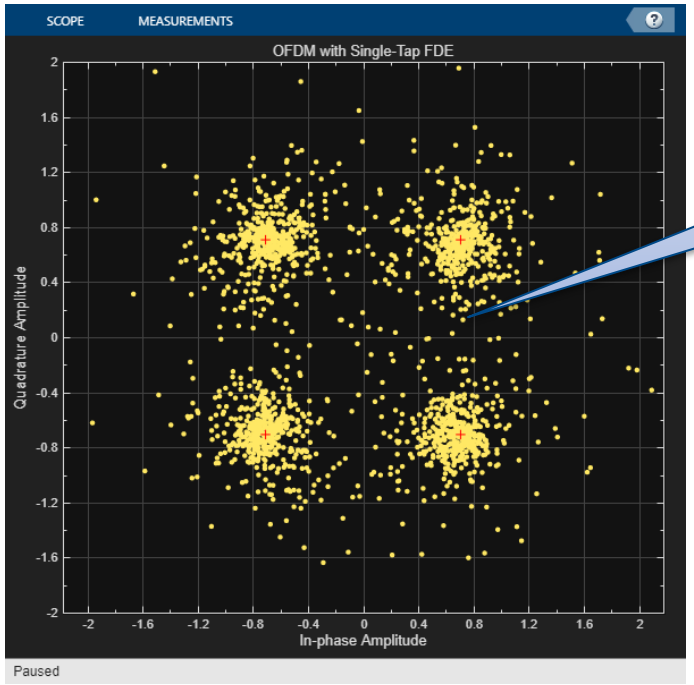
ISFFT = Inverse Symplectic Finite Fourier Transform

✓ Heisenberg Transform is a generalized OFDM with a pulse shaping filter. When pulse shaping filter is rectangular, Heisenberg Transform is identical to OFDM.

OTFS: Equalization in the Presence of High Doppler

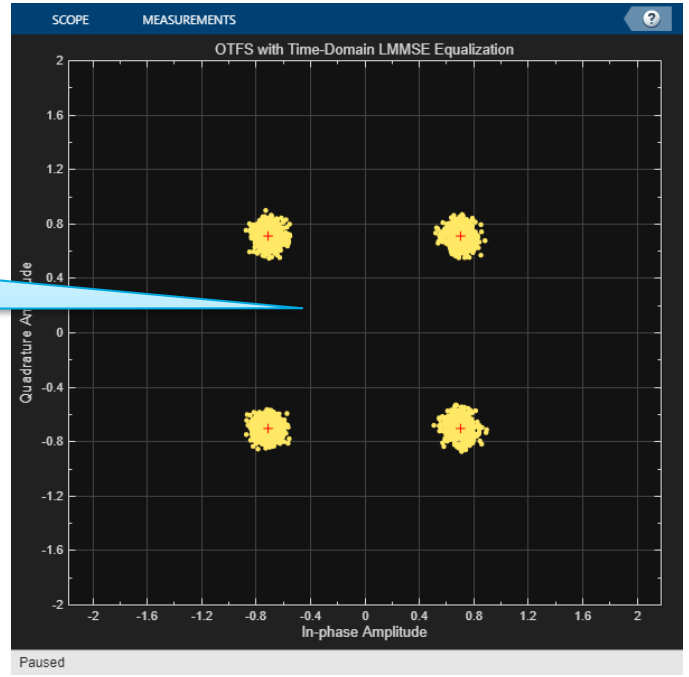
- High Doppler with LOS and 2 additional paths

	Delay (μs)	Doppler (Hz)	Speed (km/h)
Path 1	4.50	-1297	-280
Path 2	7.21	2162	467



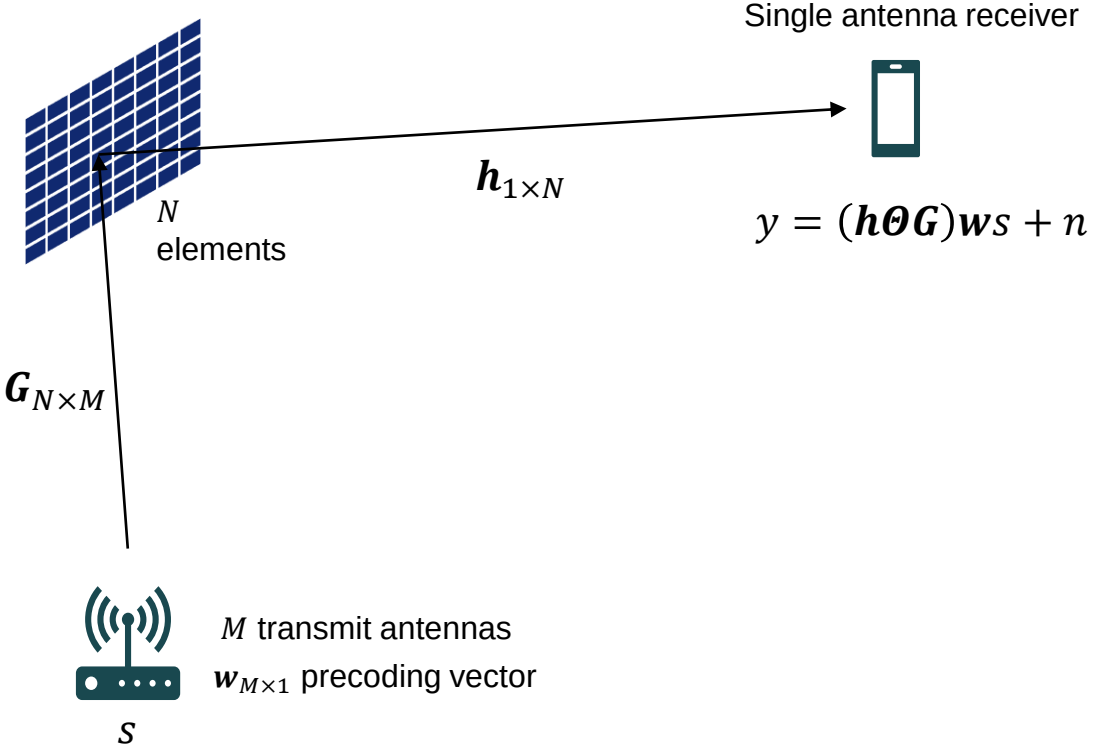
OFDM has strong residual ICI

OTFS compensates for Doppler



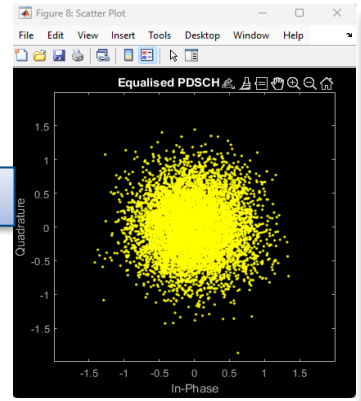
Reconfigurable Intelligent Surfaces (RIS)

$$\boldsymbol{\Theta} = \mathrm{diag}(\beta_1 e^{j\theta_1}, \ldots, \beta_N e^{j\theta_N})$$

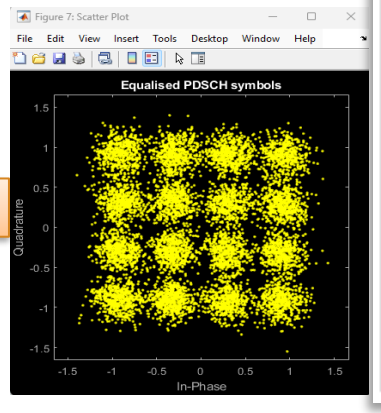


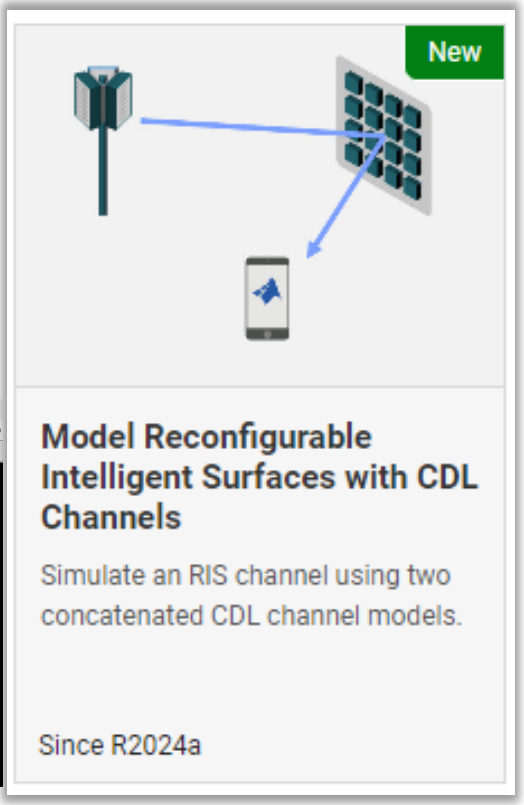
$$y = (\boldsymbol{h\Theta G})\boldsymbol{w}s + n$$

RIS disabled



RIS enabled





Rx/Tx CDL array and a phase shift models the RIS

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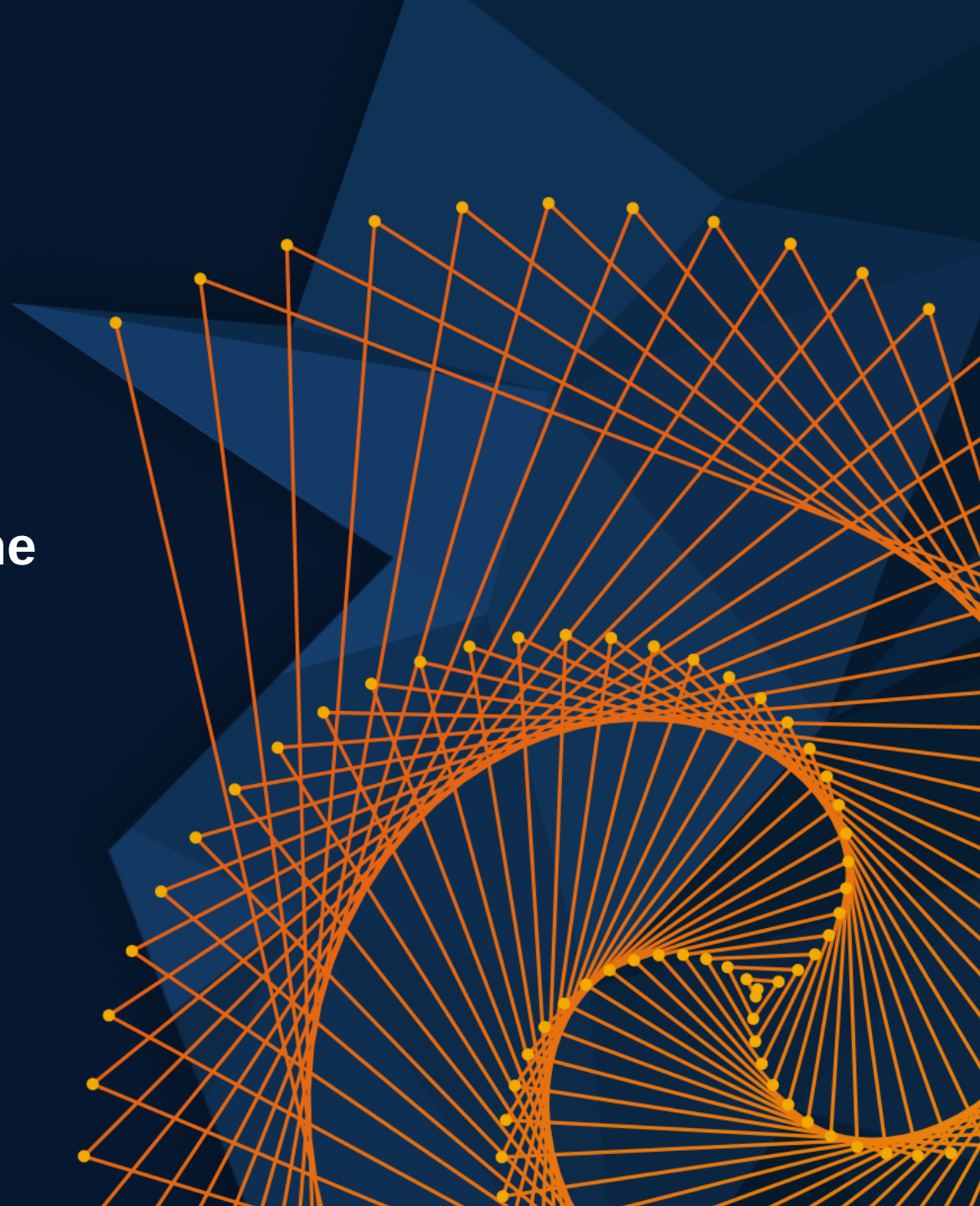
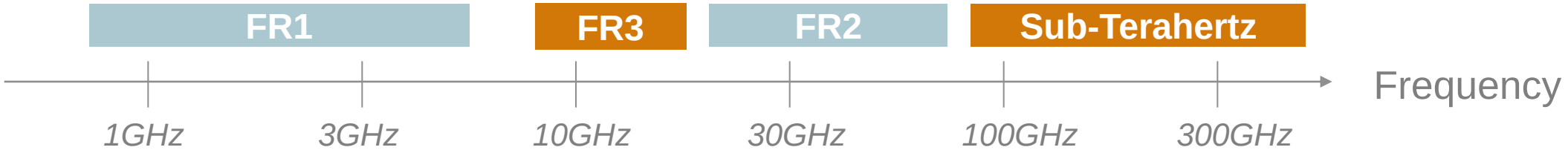
Integrating Radar & Wireless Communication Systems: Navigating the Trend with Modeling & Simulation



MathWorks

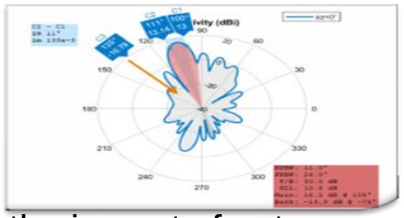
MIMO Architectures at Higher frequencies

- Frequency extension and improved spectrum utilization
  - FR2, FR3, sub-Terahertz (FR4, FR5)…
  - Carrier aggregation
- Further enhanced (massive) MIMO architectures
  - Massive MIMO, intelligent reflective surfaces
- Integration of various wireless technologies
  - Use of cellular and satellite networks NTN



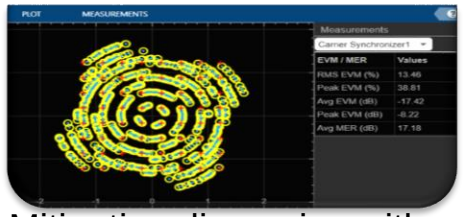
MIMO Systems: Impairments and Mitigation Strategies

Impairment	Mitigation strategy
Antenna coupling, leakage, reduction of diversity	Placement, defected ground, parasitic structures



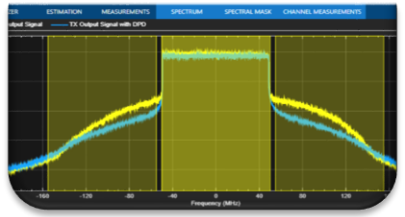
Estimating the impact of antenna coupling on beamforming algorithms

Impairment	Mitigation strategy
Impedance mismatches, dispersion, losses	Equalization, calibration



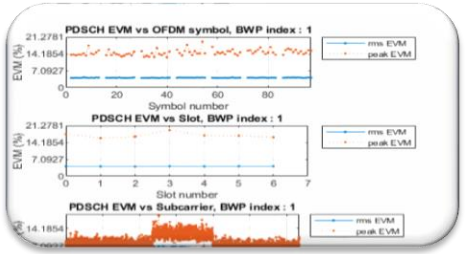
Mitigating dispersion with gain calibration and equalization

Impairment	Mitigation strategy
Non-linearity, distortion, saturation, spectral regrowth	Digital pre distortion, envelope tracking, back-off



Linearizing power amplifiers with digital pre-distortion

Impairment	Mitigation strategy
Interfering signals, desensitization	Filtering, gain control, digital receivers



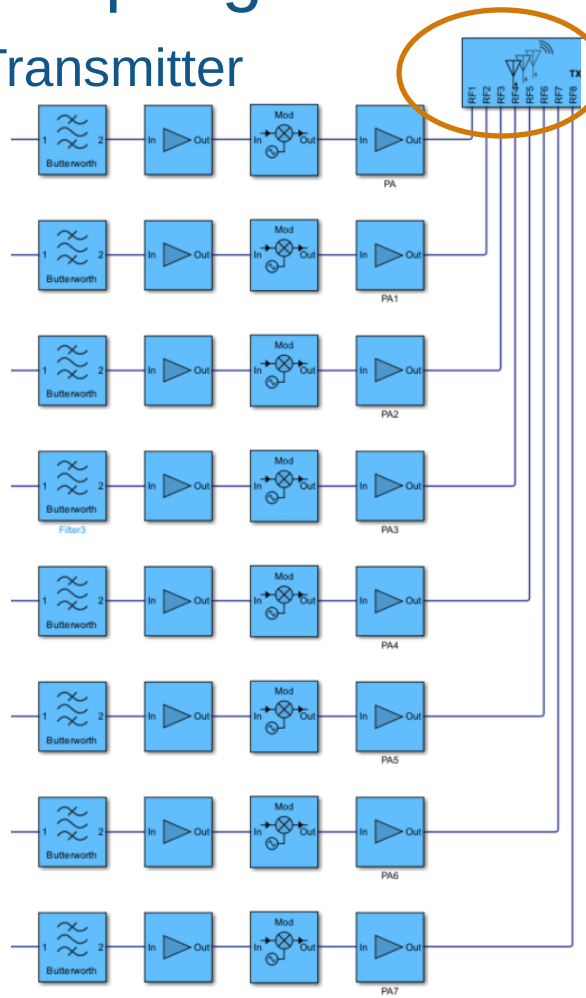
Estimating the impact of interfering signals on wideband receivers

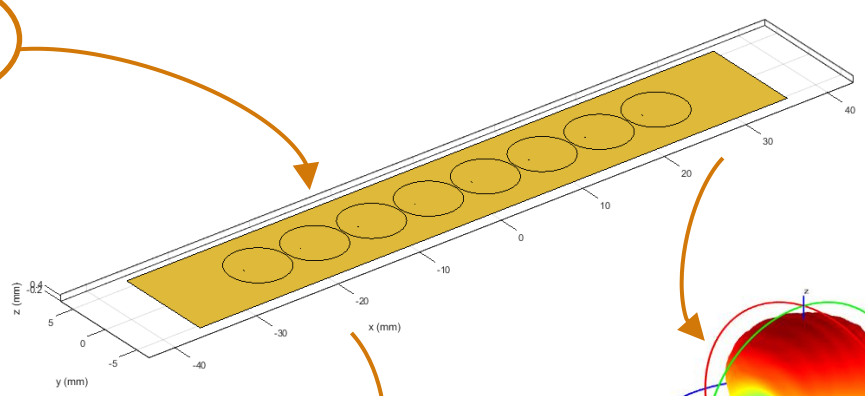
Impairment	Mitigation strategy
Multi-path, fading, losses, polarization	Beamforming, equalization, diversity

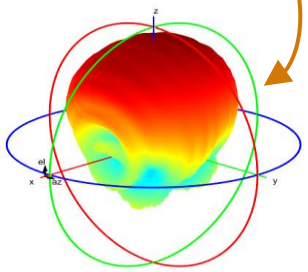
Modeling RF propagation effects with ray tracing

Coupling in Antenna Arrays: Near and Far Field Effects

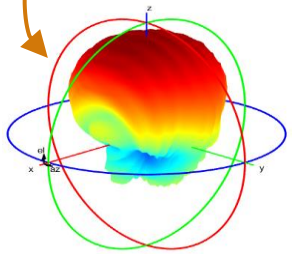
RF Transmitter







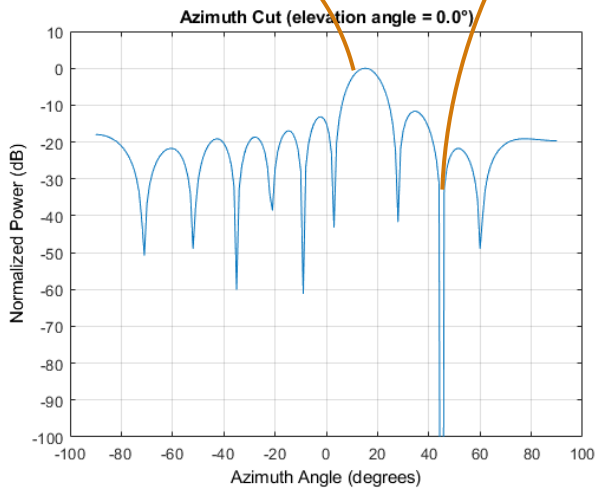
Embedded element #1



Embedded element #8

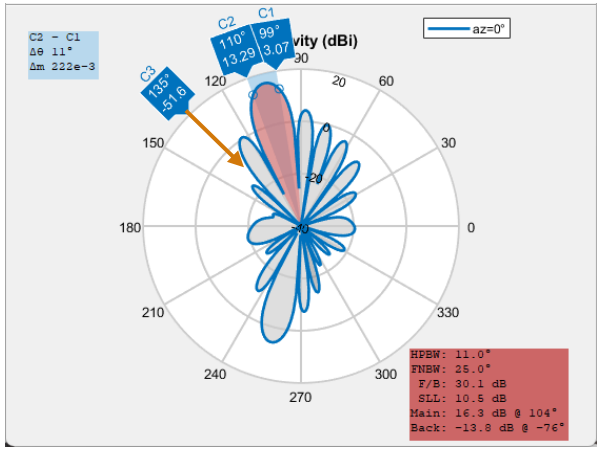
Beam at 15deg from boresight

Null at 45deg from boresight



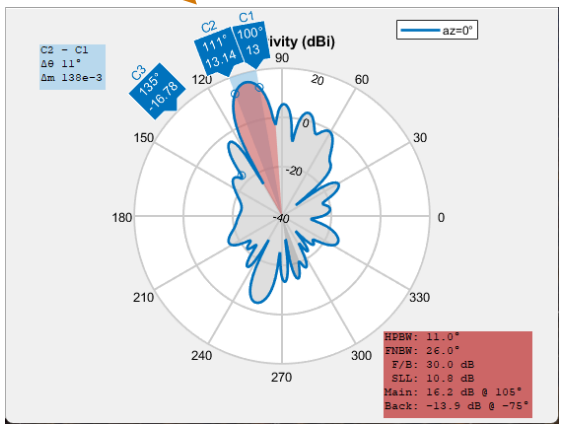
Without coupling

Attenuation = 16.3+51.6 = 67.9dB



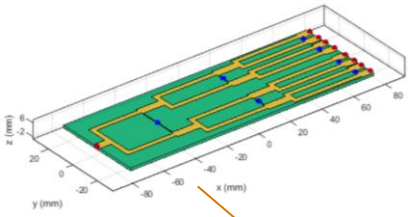
With coupling

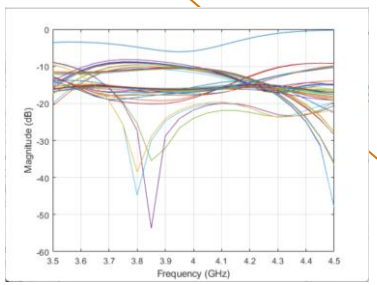
Attenuation = 16.2+16.8 = 33dB



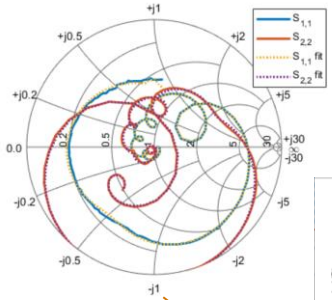
Antenna Coupling Affect Beamforming Algorithms

Sources of Dispersion and Impedance Mismatches

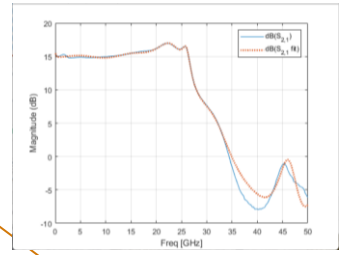


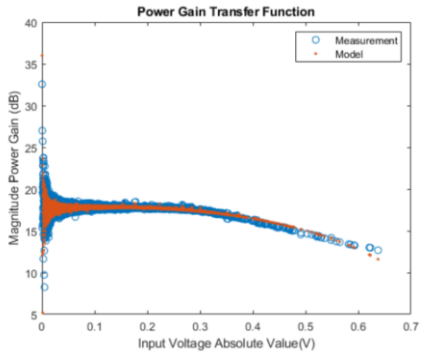


Passive distributed elements

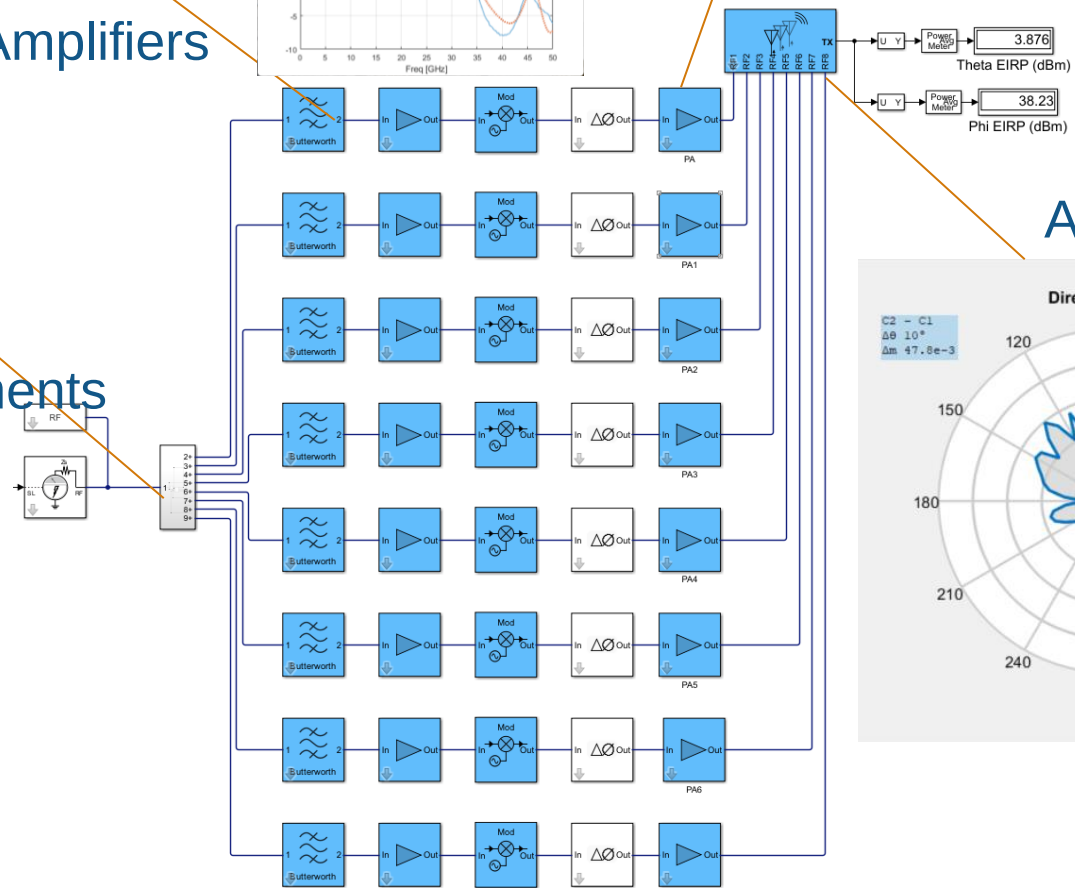


Amplifiers

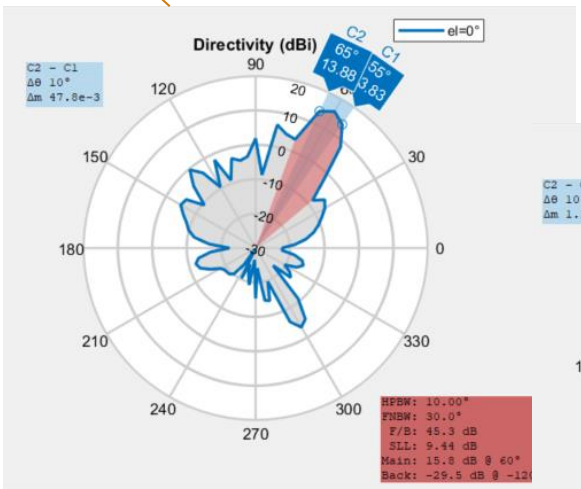


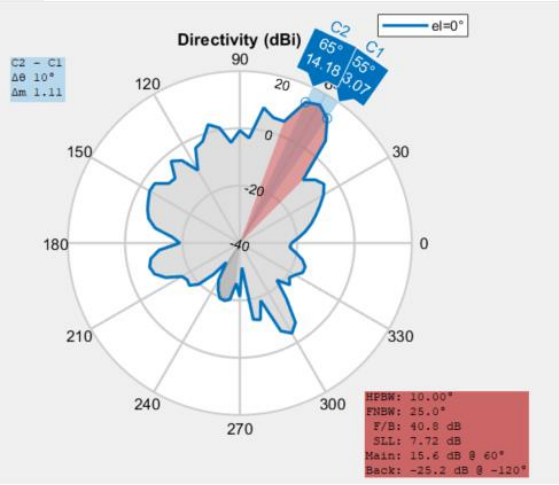


Power amplifiers memory effects



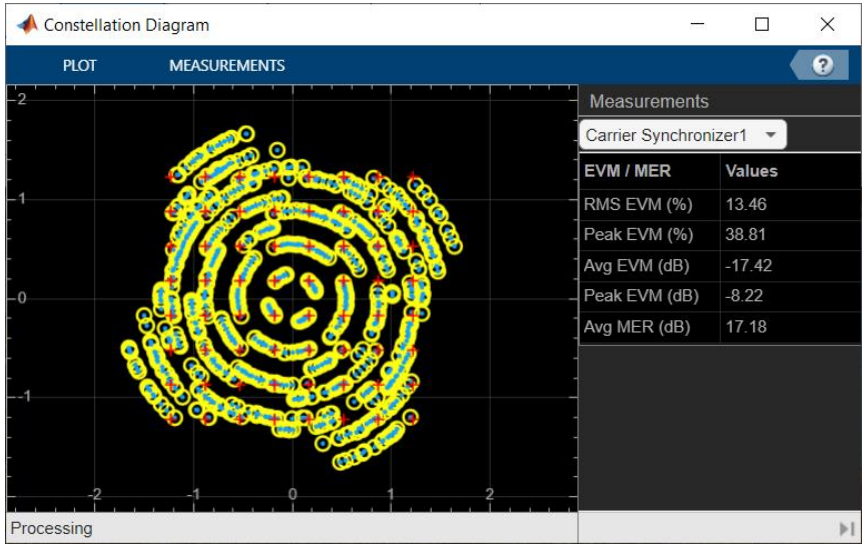
Antennas impedance and pattern



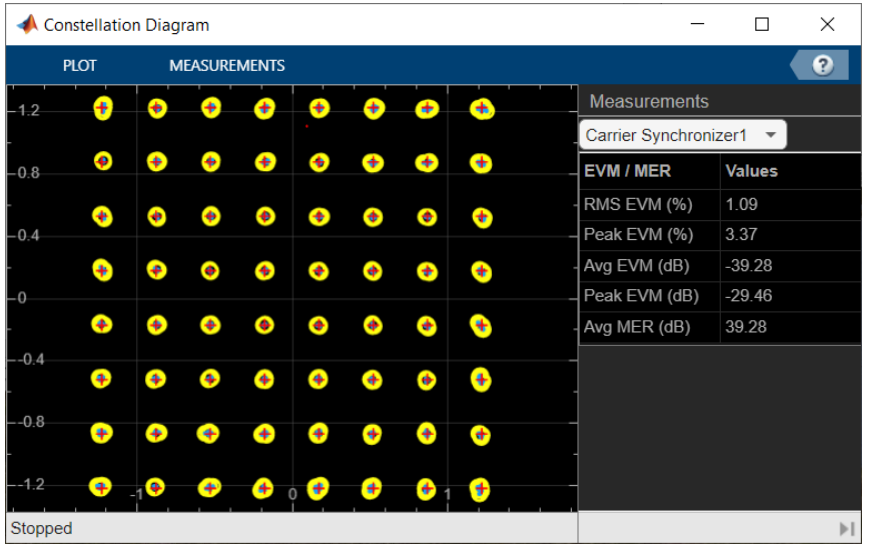


Dispersion Requires Equalizer Compensation / Calibration

Without equalizer

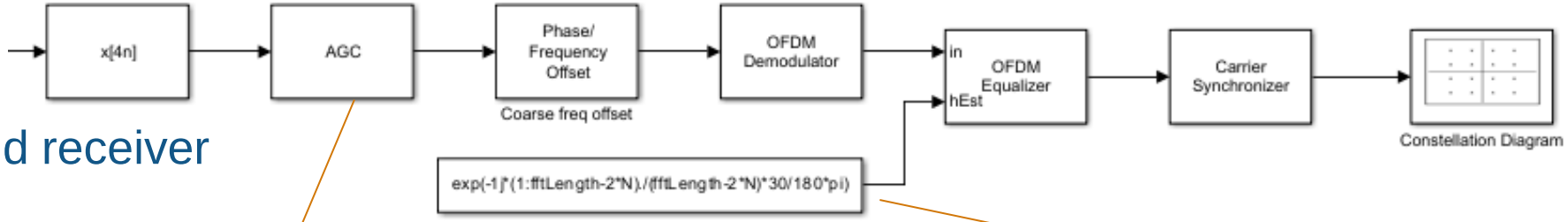


With equalizer



1024 carriers
120kHz spacing
122.88MHz bandwidth

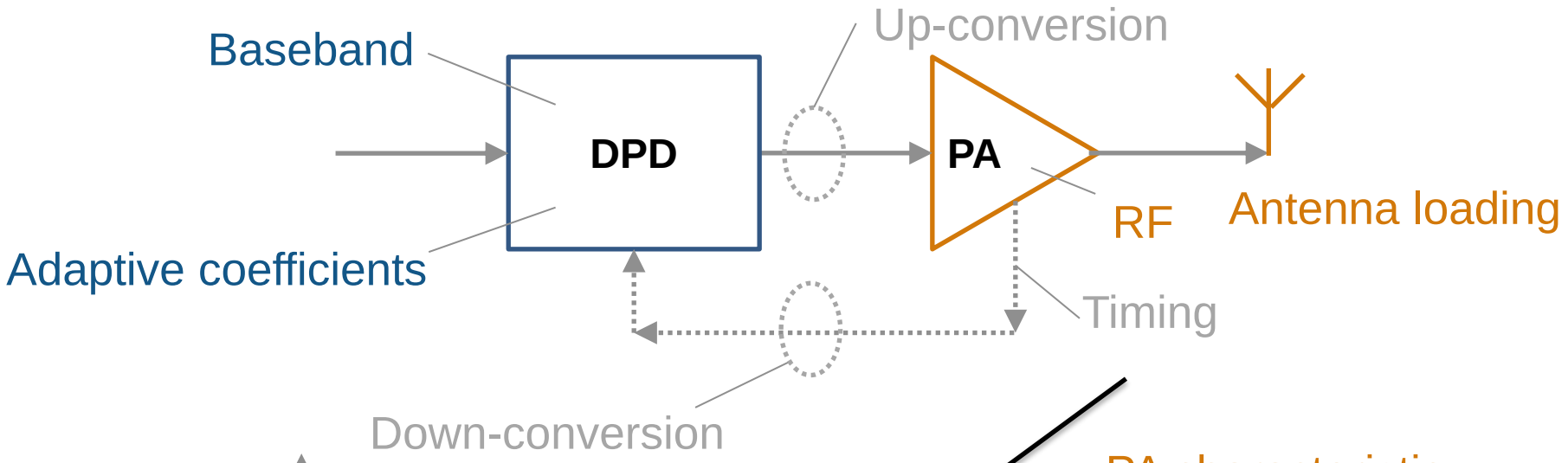
Baseband receiver

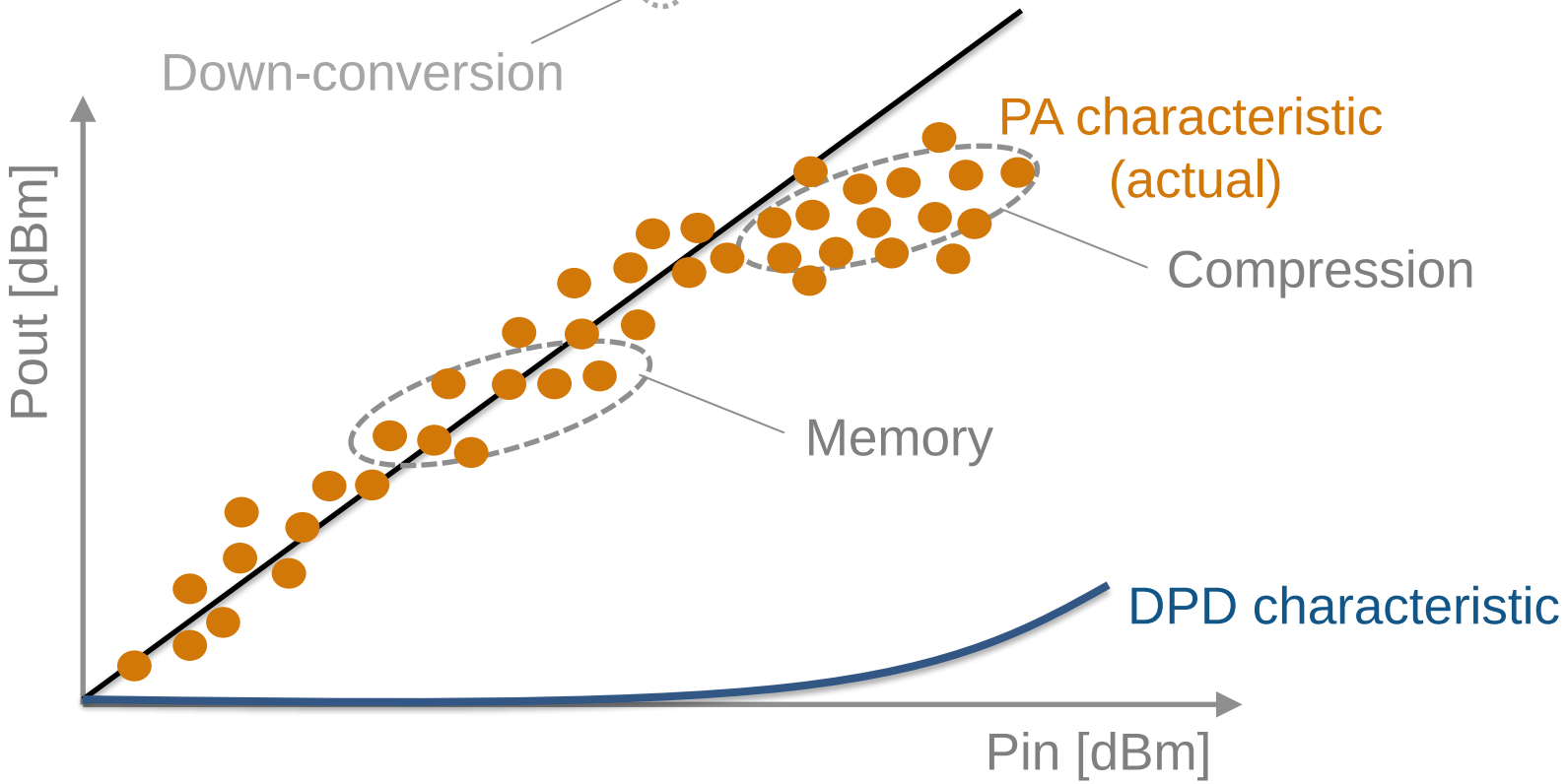


Automatic gain control

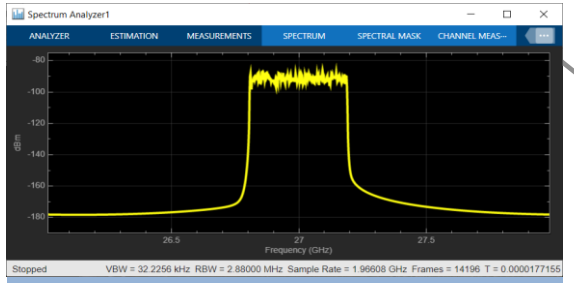
Static phase equalizer

PA Linearization: Digital Pre-Distortion (DPD) in Practice

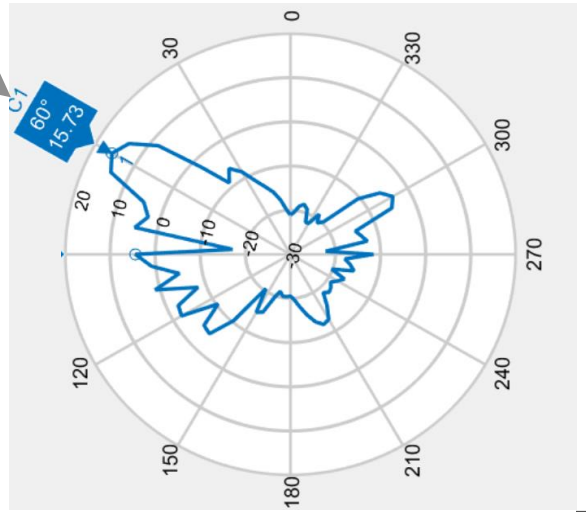


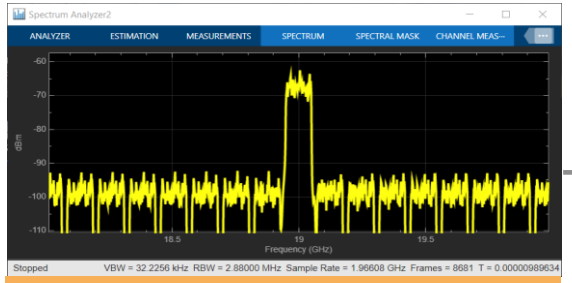


Interfering Signals and Wideband Receivers

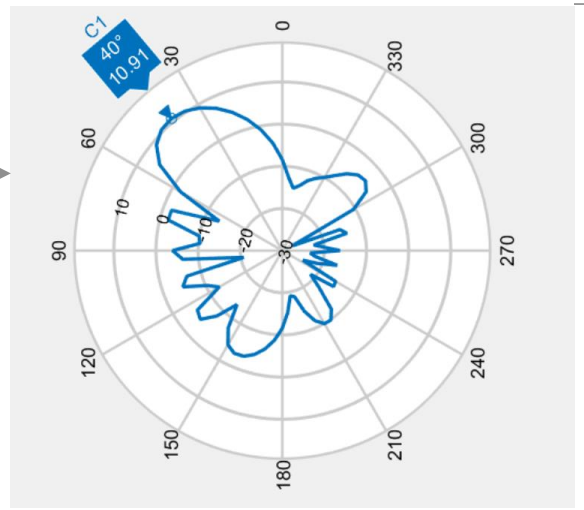


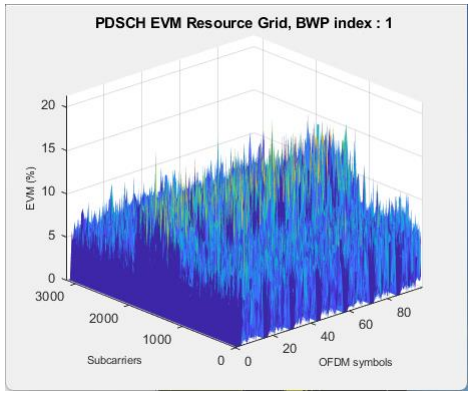
3GPP FR2 TM3.1
Desired signal @27GHz
Az El = [60 0]
Power = -70dBm

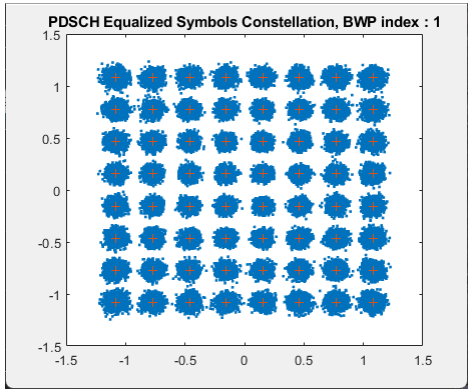


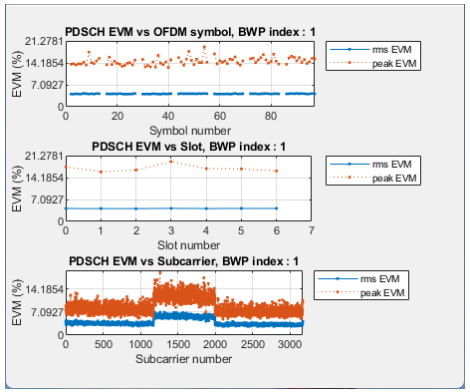


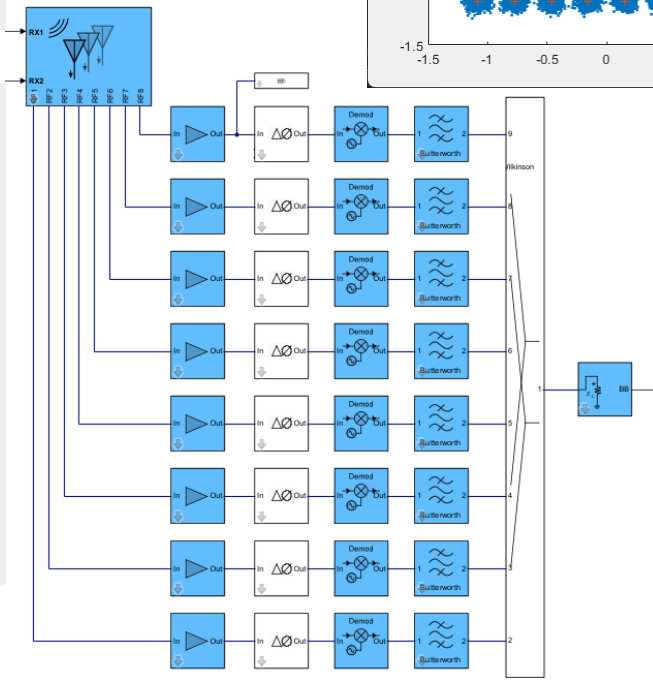
OFDM 100MHz BW
Interferer @19GHz
(image frequency)
Az El = [40 0]
Power = -70dBm

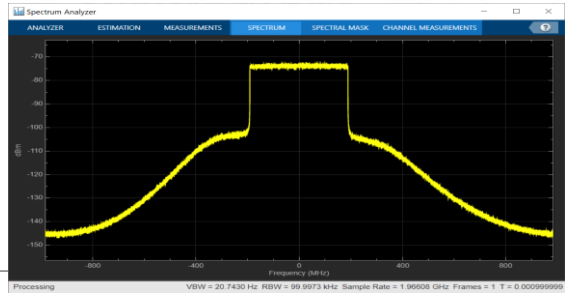










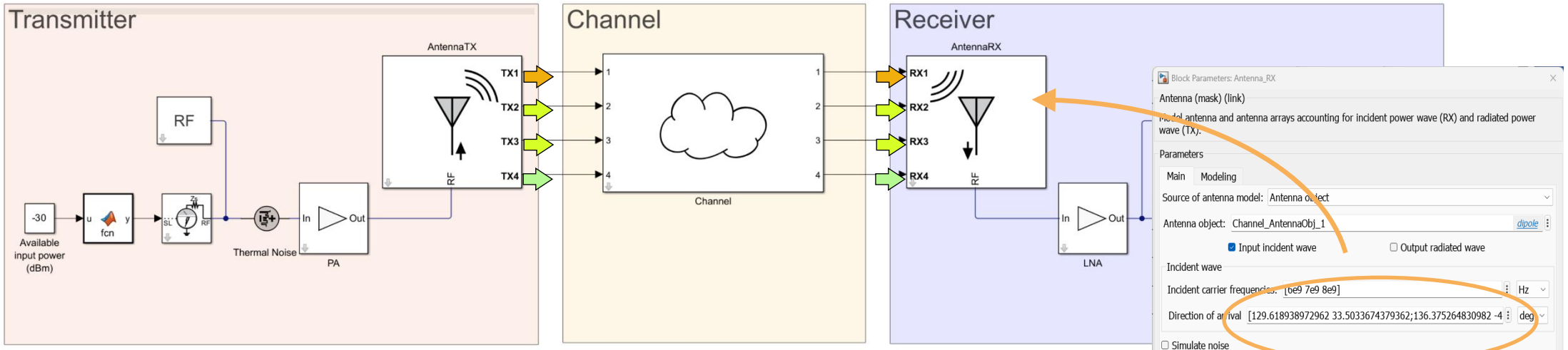


RMS EVM = 3.6%

With interfering signal
RMS EVM = 4.2%

Ray Tracing Channel Modeling and Integration into RF Simulation

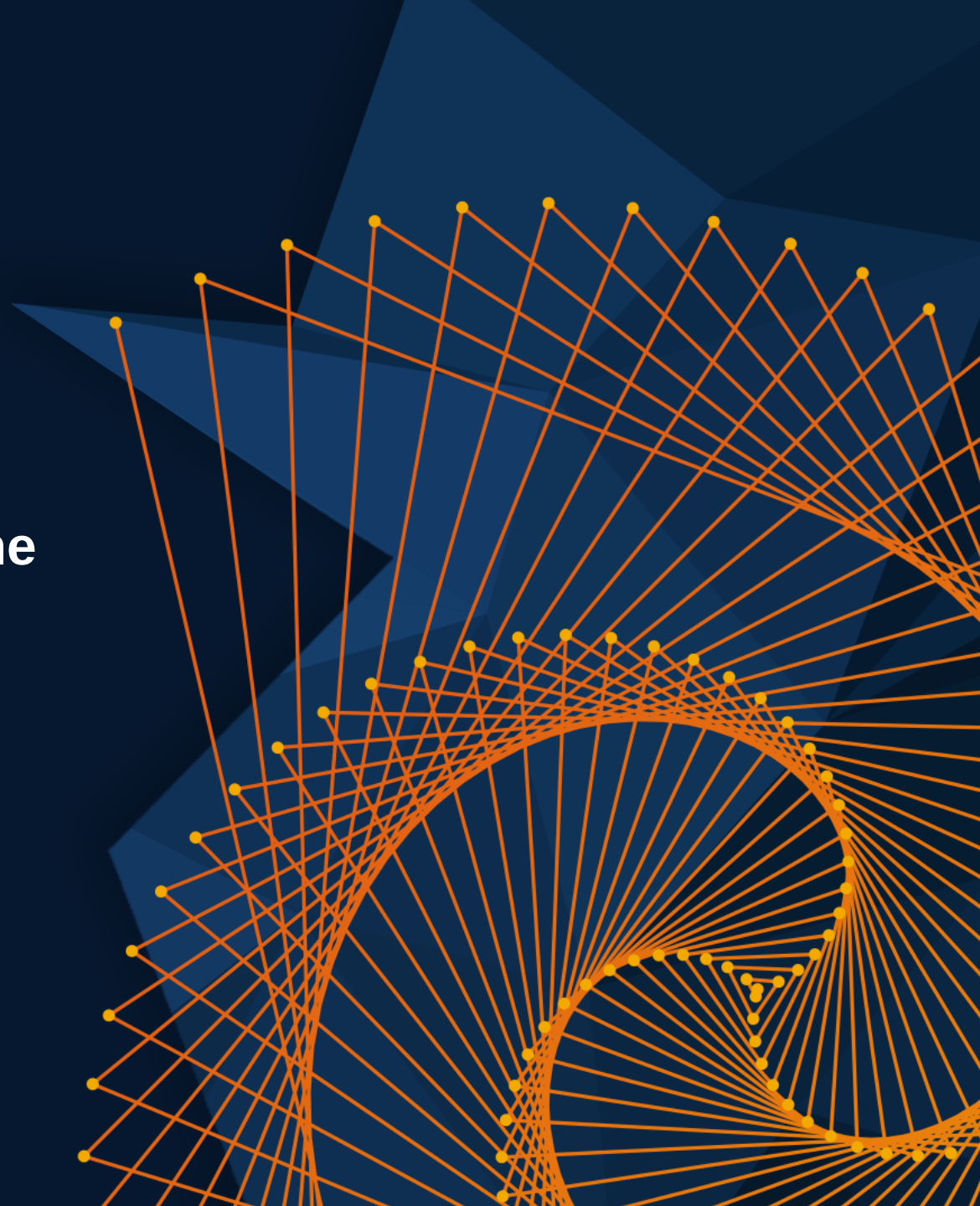
- Use ray tracing to account for multiple paths in channel between antennas:



- Scenario modelling including buildings
- Multiple radiated/incident directions
- Path loss and phase shift for each path
- Model coupling in between antenna elements
- Take into account frequency dependency

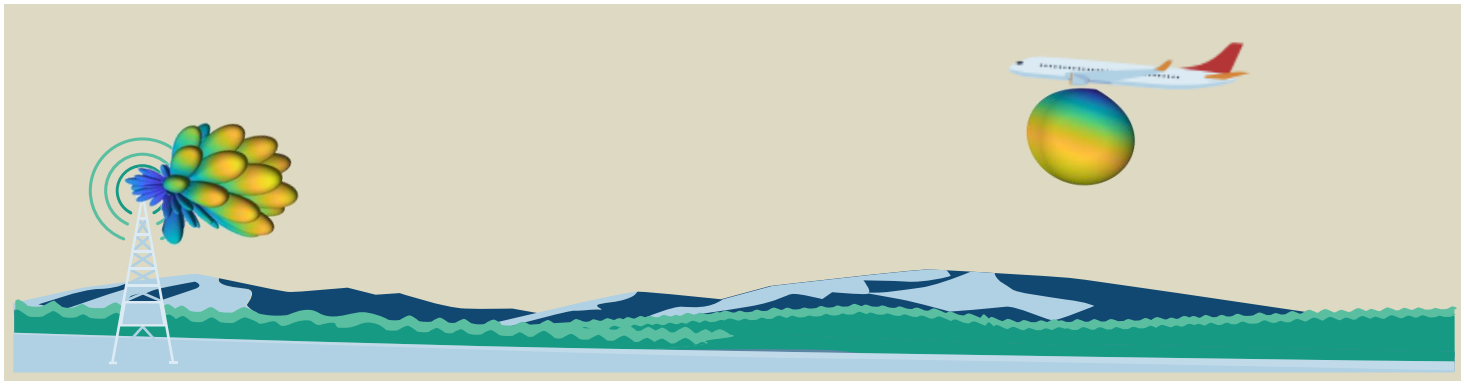
MATLAB EXPO
INDIA

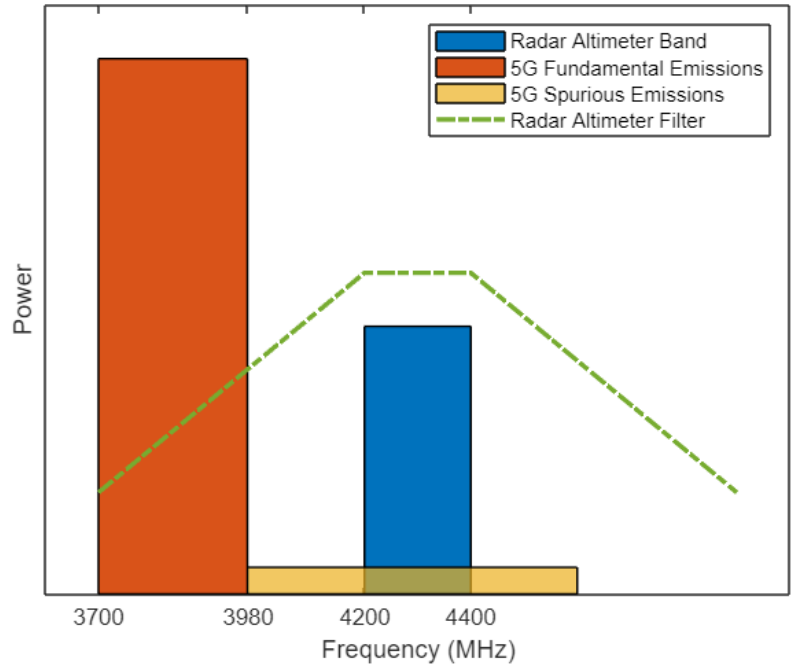
Integrating Radar & Wireless Communication Systems: Navigating the Trend with Modeling & Simulation



MathWorks

Model interference between radar altimeter and 5G base station





Radar Altimeter Model

Radar Altimeter + 5G

- Fundamental Emissions - Blocking

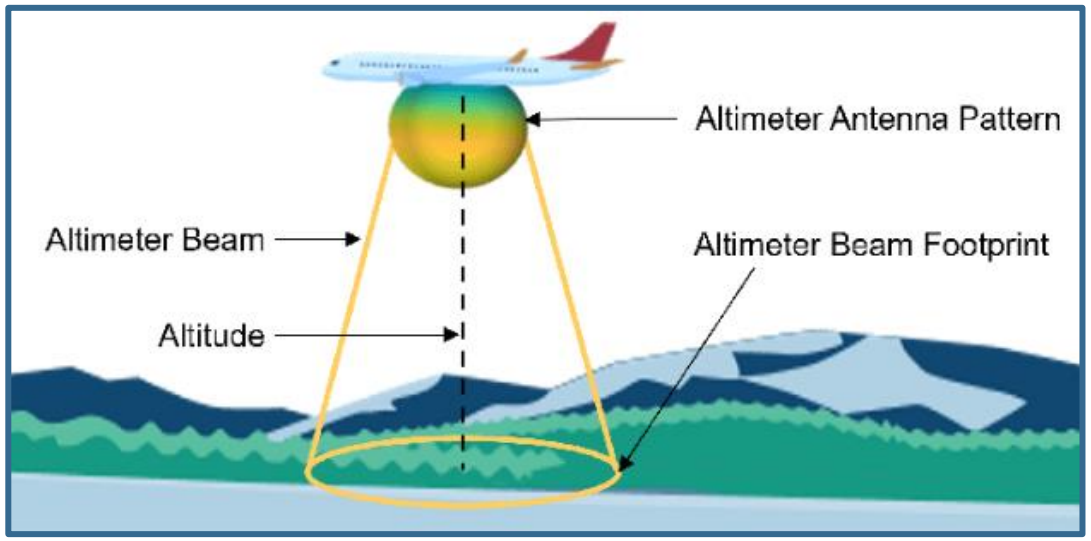
Radar Altimeter + 5G

- Spurious Emissions - Desensitization

Reference: RTCA Report

Author a Scenario for Simulating Radar Altimeter

Model Platforms and Targets → Model Environment → Model Trajectories → Model Sensors → Simulate scenarios

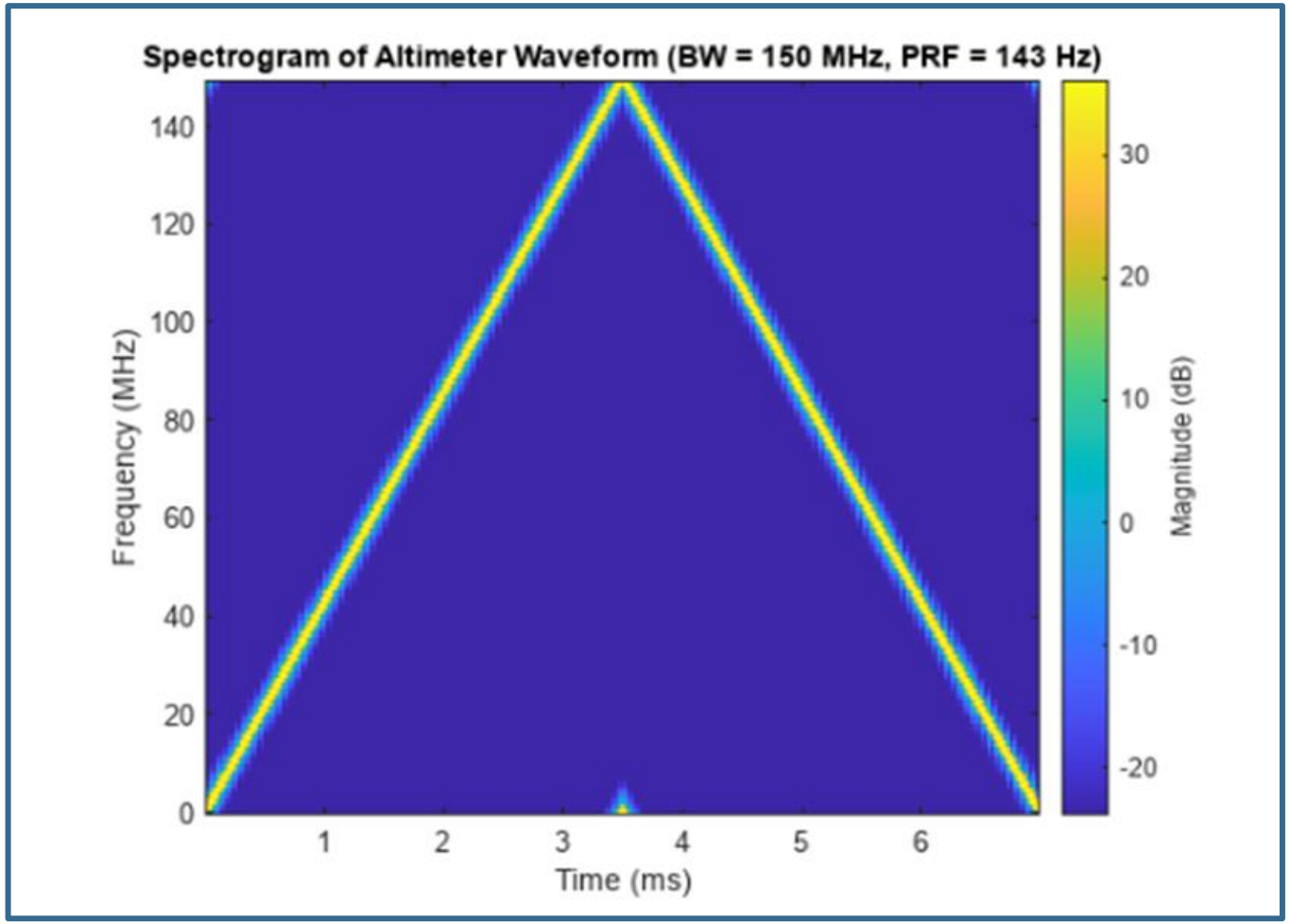


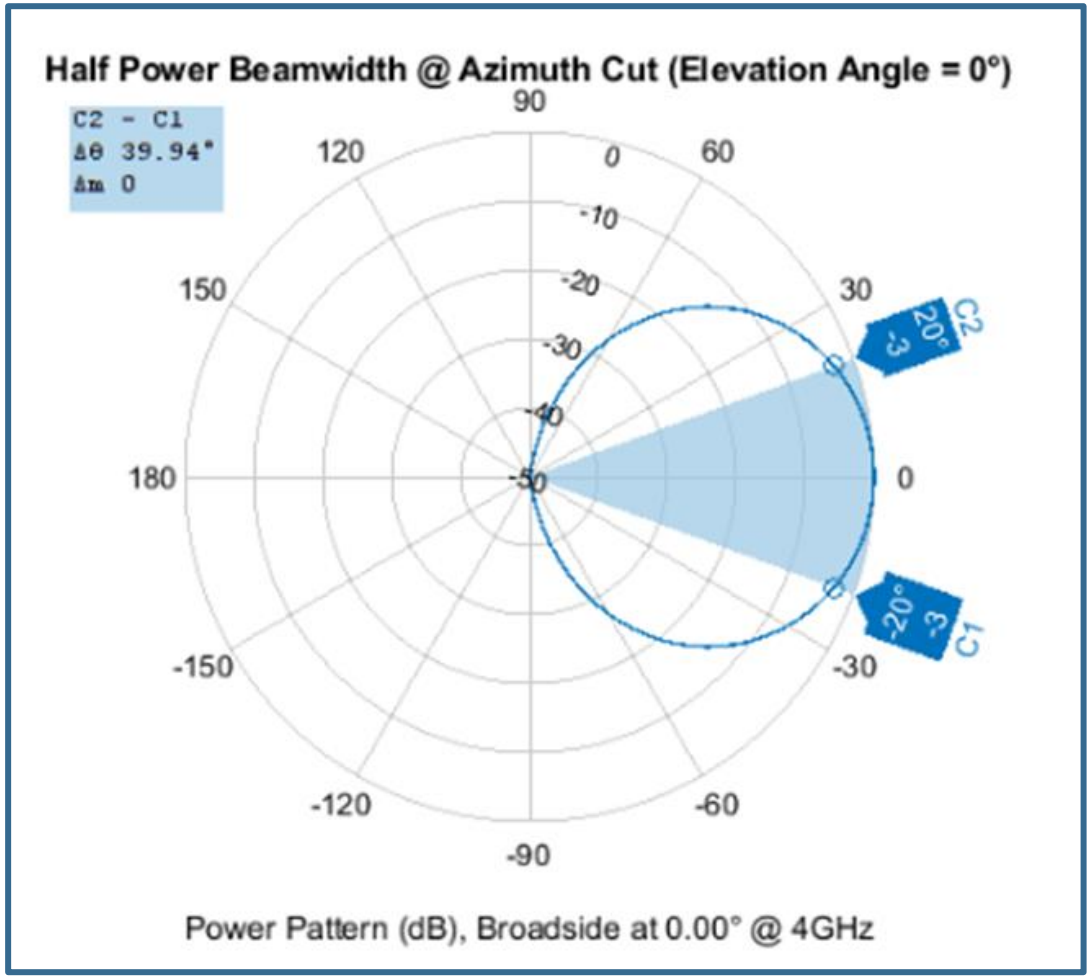
Landing 3D View

Waveform-level

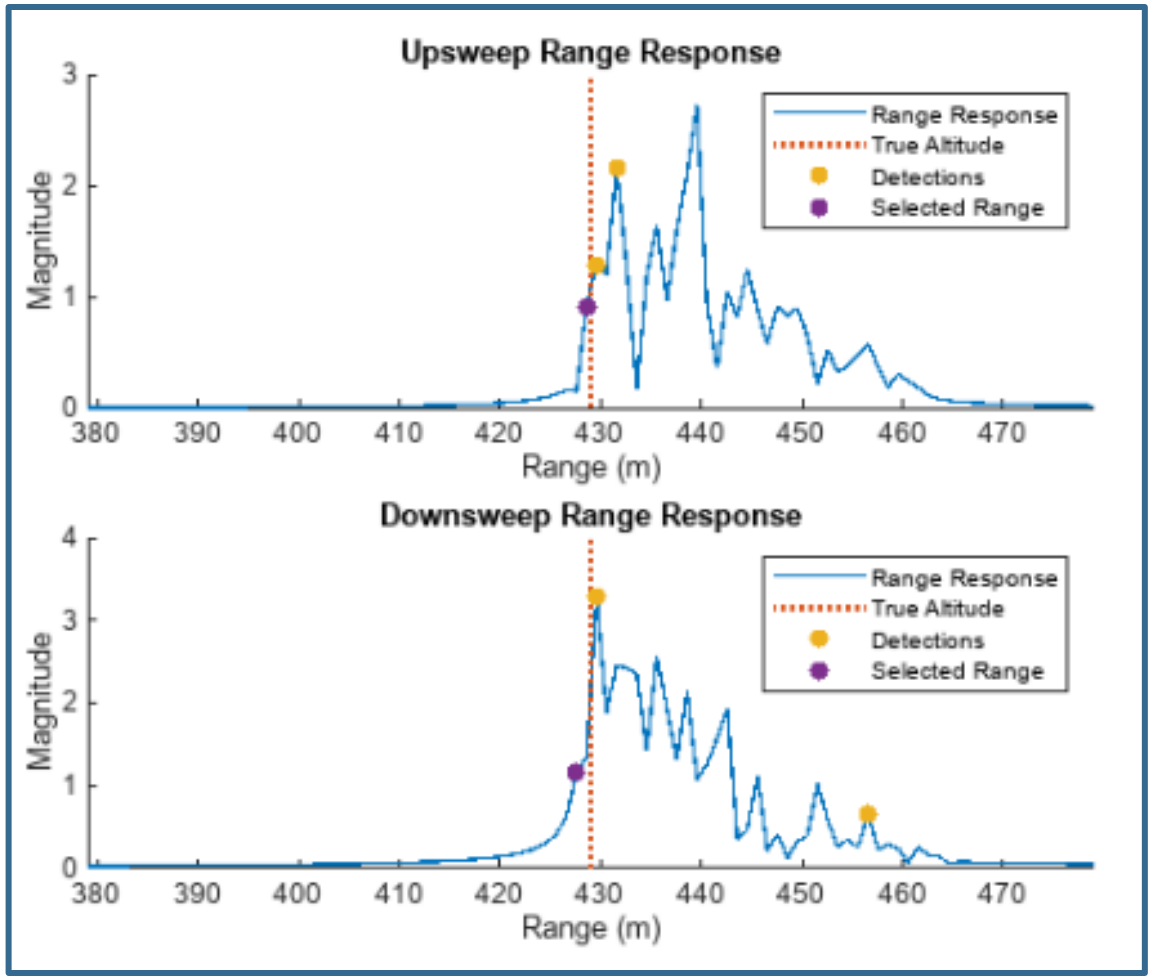
Link to Example

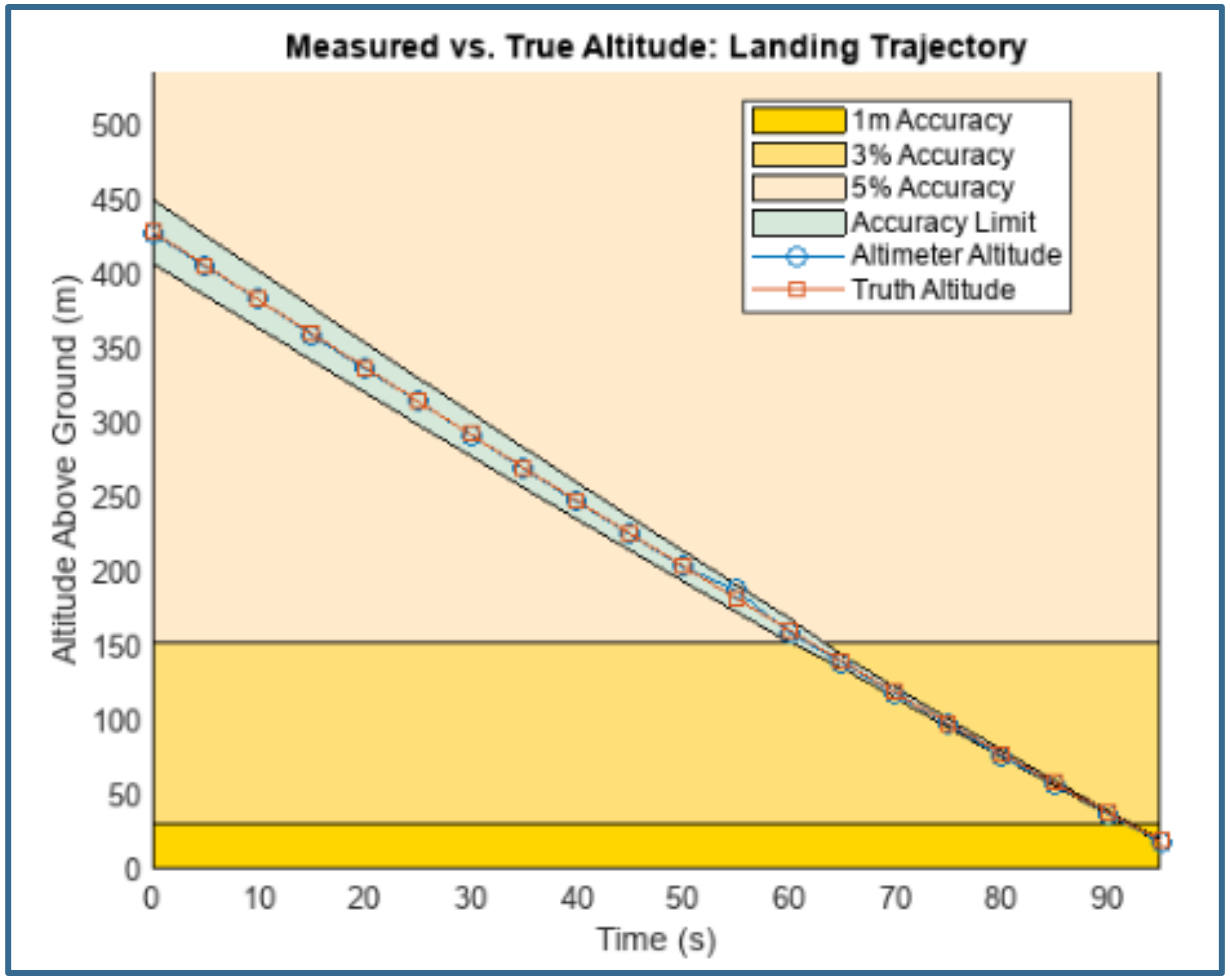
User Waveform Level Radar Model to Generate IQ Signal





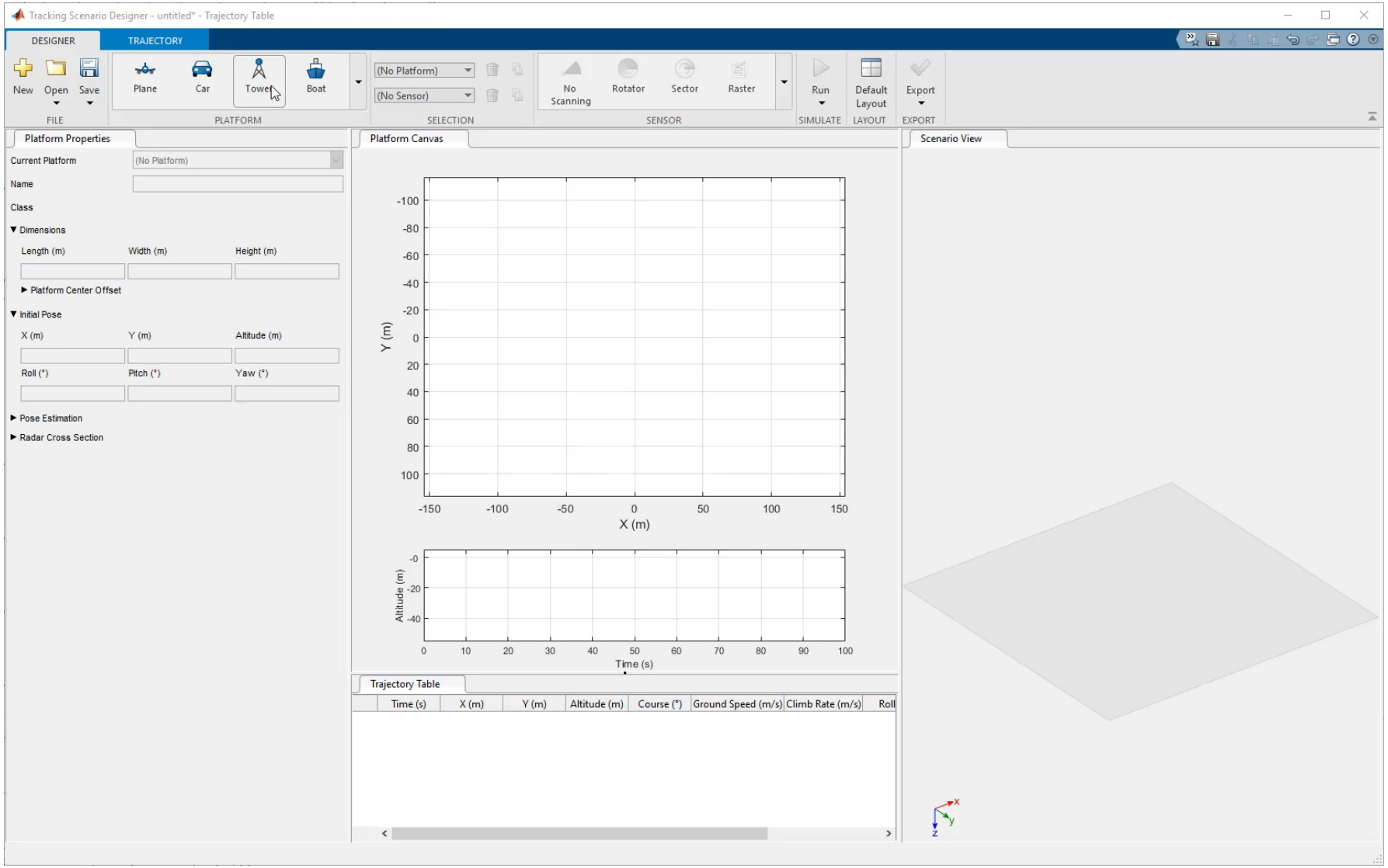
Apply Signal Processing and Evaluate Radar Altimeter Performance





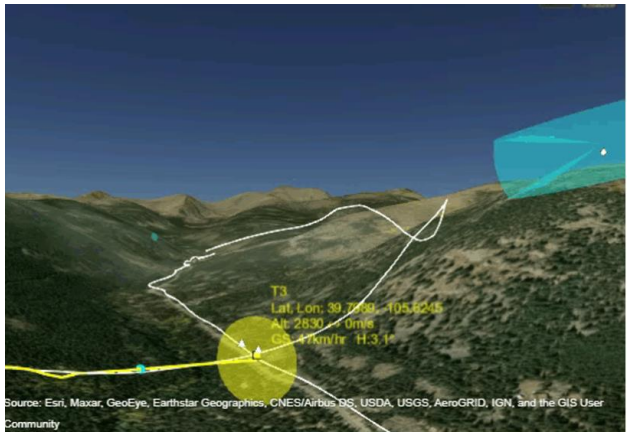
Waveform-level

Tracking Scenario Designer App

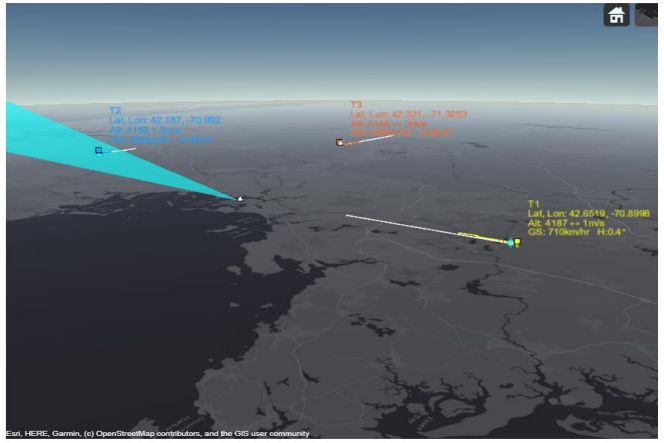


Simulation & Tracking in Autonomous Surveillance Technologies

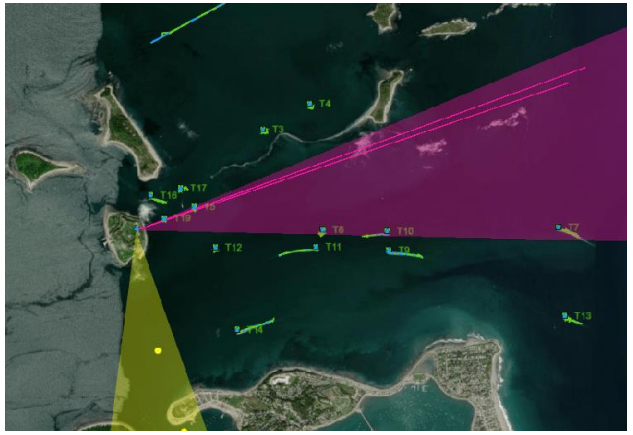
Point objects



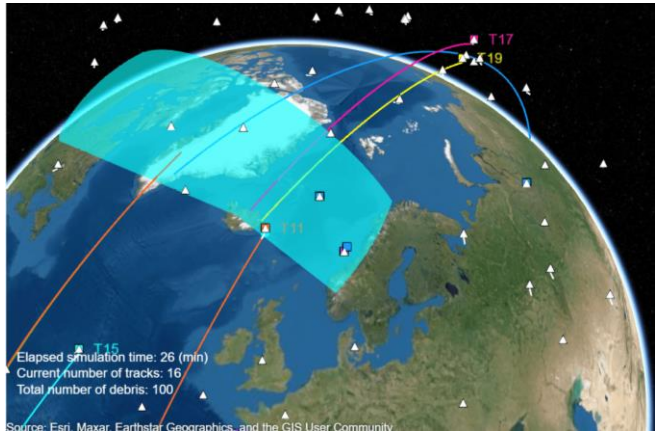
Land



Air

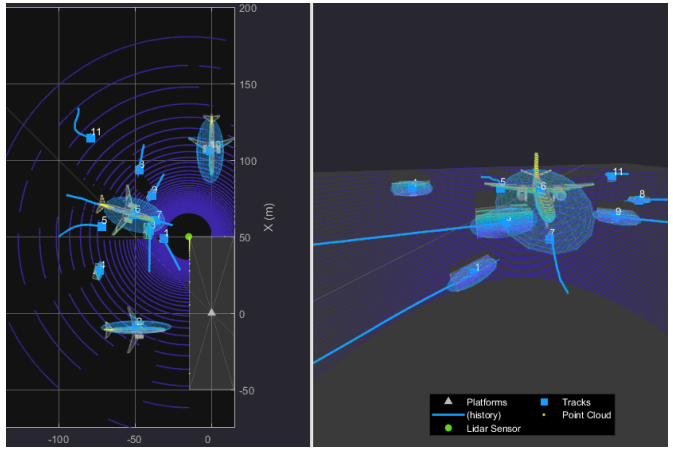


Maritime



Space

Extended objects

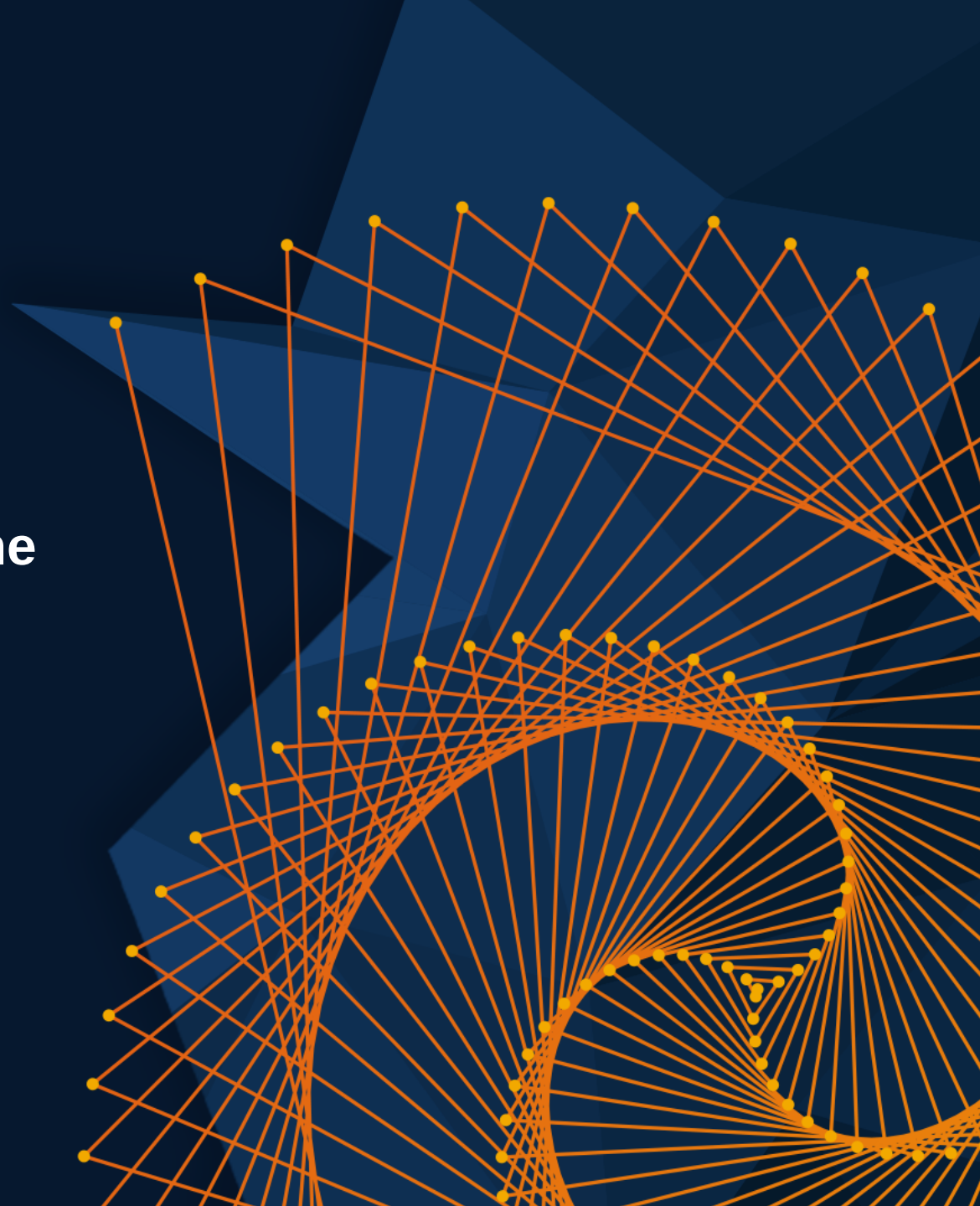


Outdoor

Indoor

MATLAB EXPO
INDIA

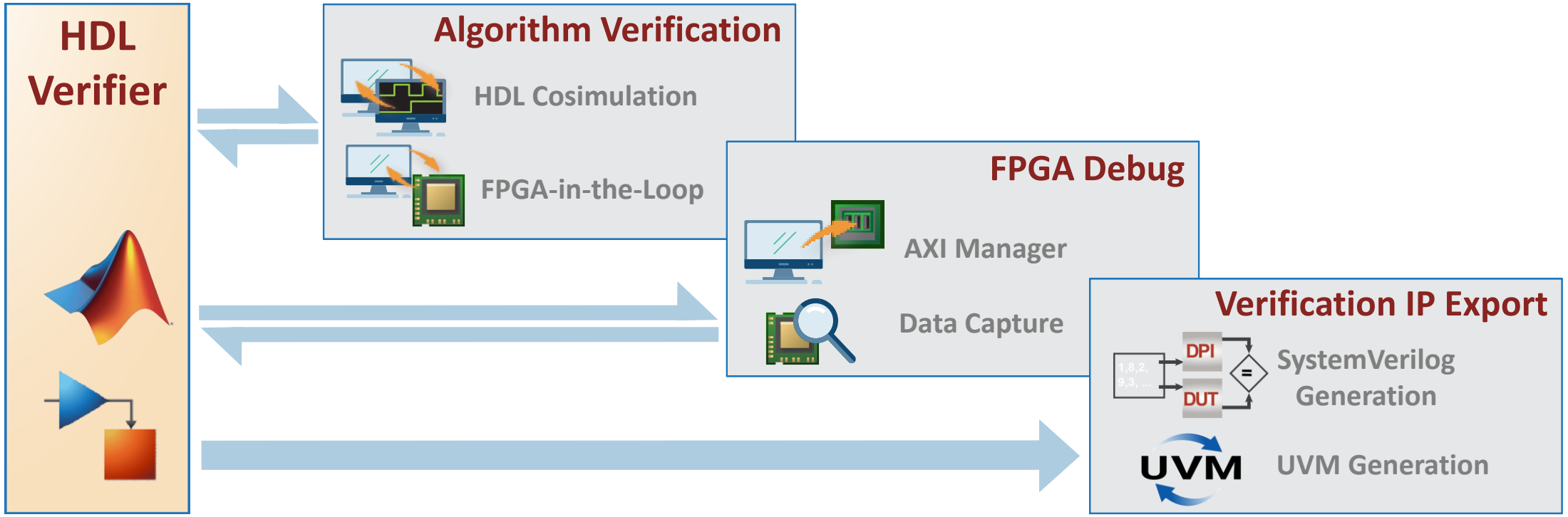
Integrating Radar & Wireless Communication Systems: Navigating the Trend with Modeling & Simulation



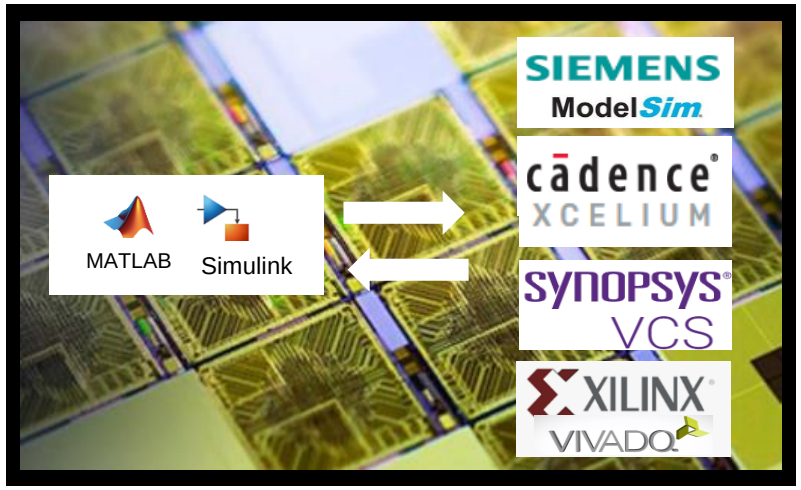
MathWorks

Verification Made Easy!

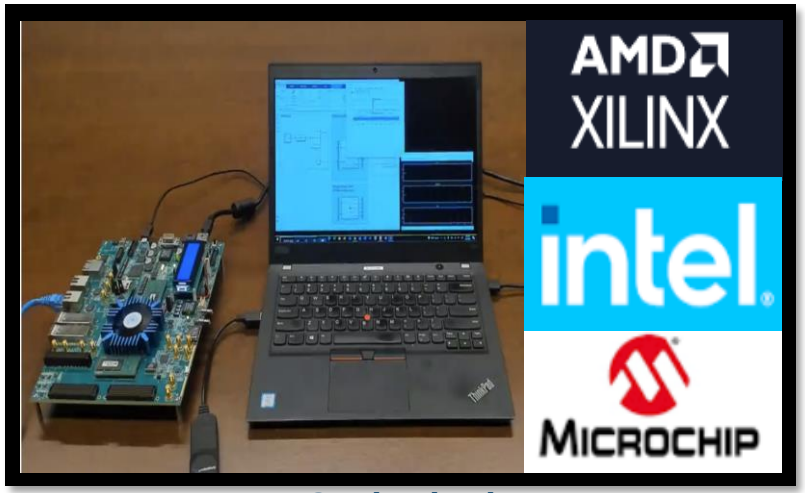
Test and verify Verilog and VHDL using HDL simulators and FPGA boards



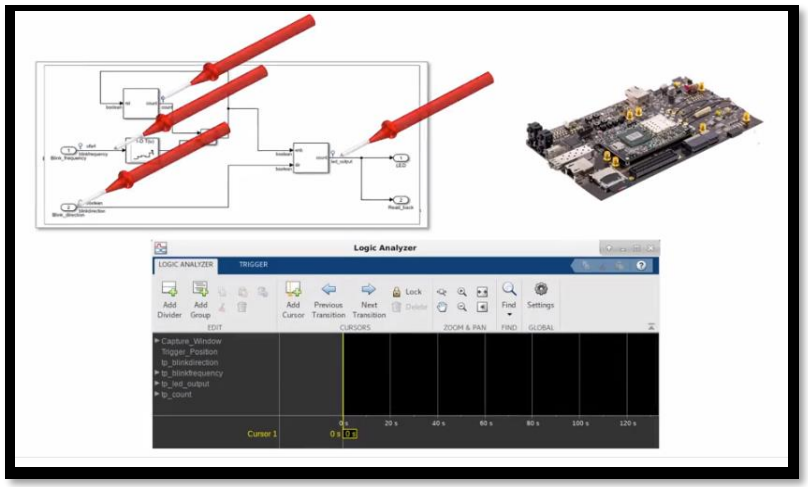
Verification Methodologies for FPGA/ASIC designs



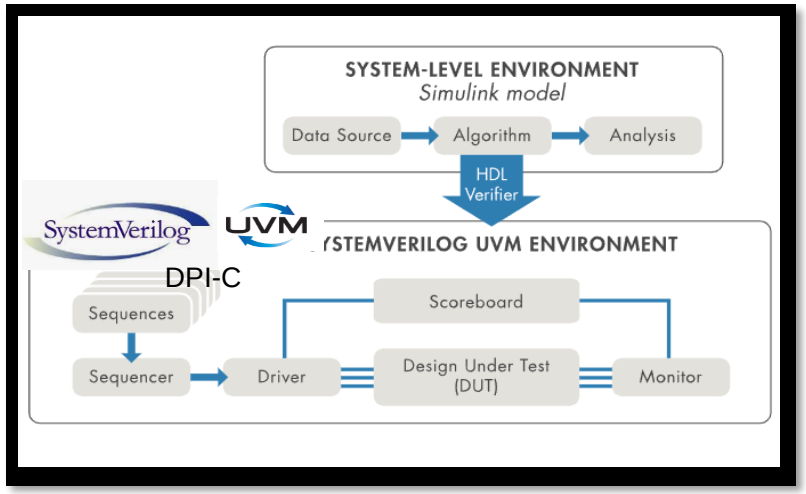
HDL Co-simulation



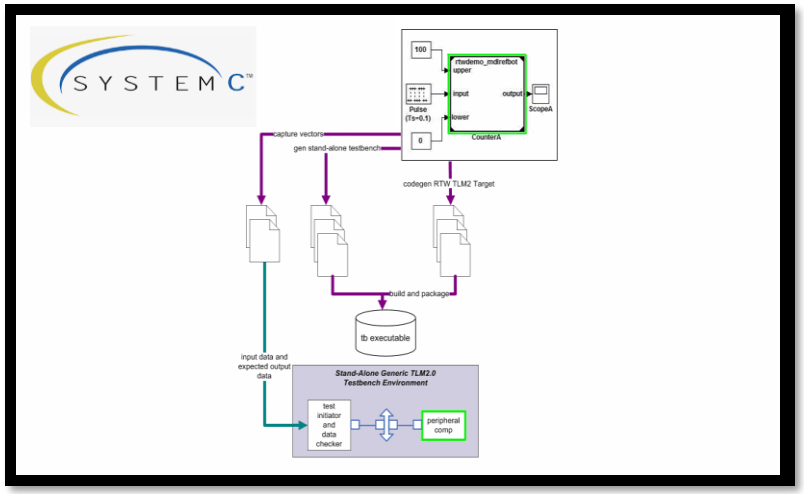
FPGA-in-the-loop



FPGA Debugging (Data Capture and AXI Manager)



UVM Testbench / SystemVerilog DPI-C Test Components Generation



System-C TLM 2.0 Components Generation

MathWorks Tools for Wireless and Radar System Design

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

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

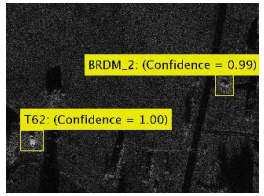
RF Blockset
Phased Array System Toolbox
RF Toolbox
Antenna Toolbox

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

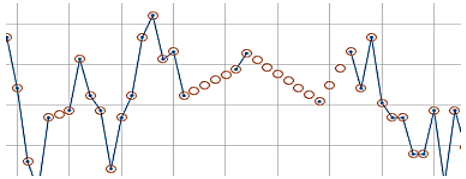
Scenario Models

Sensor Fusion & Tracking

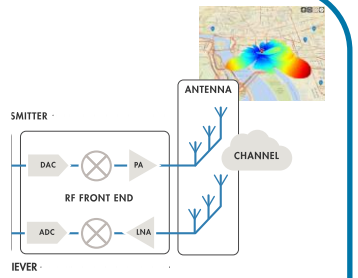
Classification



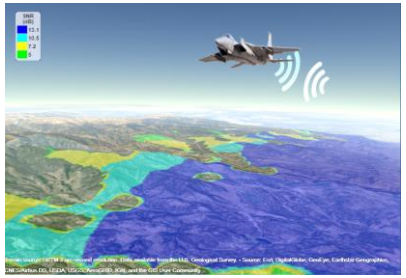
Data Processing



Signal Processing



Antenna/RF



Propagation Models

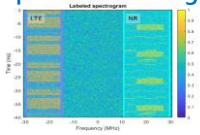
Satellite Comms Toolbox
5G Toolbox
LTE Toolbox
Antenna Toolbox
Communications Toolbox
Radar Toolbox

Resource Management & Control

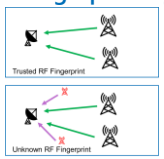
Radar Toolbox
SoC Blockset
Wireless HDL Toolbox
Instrument Control Toolbox
Wireless Testbench
DSP HDL Toolbox

Integrate AI into Communication and Radar Systems

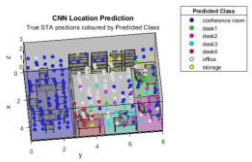
Spectrum Sensing



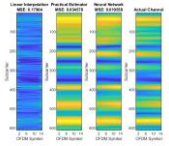
RF Fingerprinting



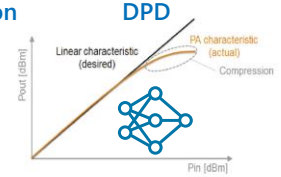
Emitter Localization



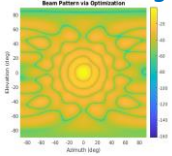
Channel Estimation



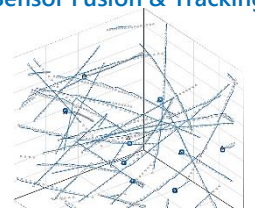
DPD



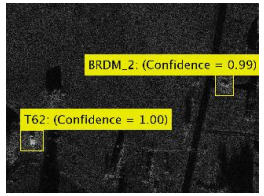
Beamforming



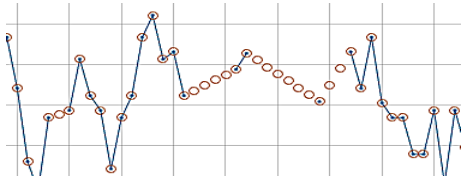
Sensor Fusion & Tracking



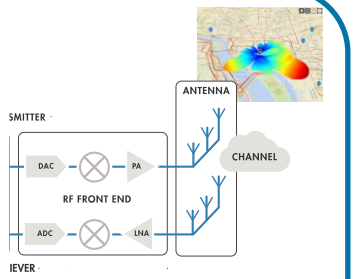
Classification



Data Processing

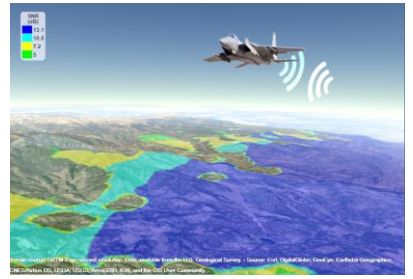


Signal Processing



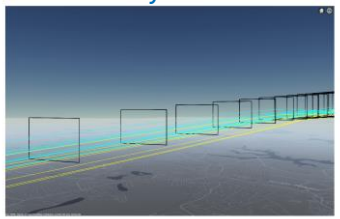
Antenna/RF

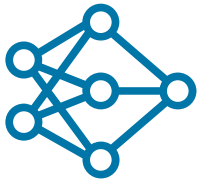
Scenario Models



Propagation Models

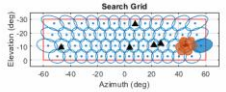
Anomaly Detection

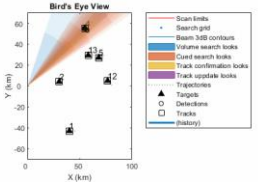




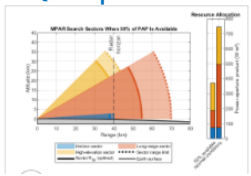
Resource Management & Control

Multifunction RF





QoS Optimization



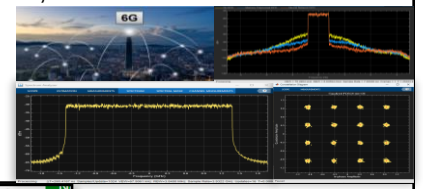
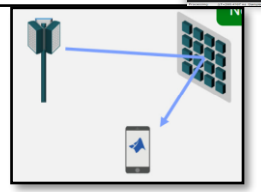
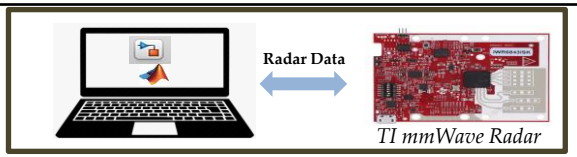
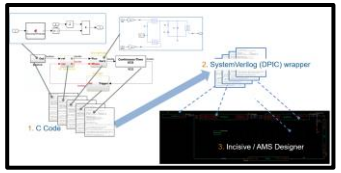
Congested, contested, and complex RF environment

5G LTE Radar

Satcom GPS

EW Tactical Data Links

Demo Booth : Communications and Radar Systems: From Design to Deployment

Demo Booth Title	Demo Description
System-Level Simulation of Pre6G, 5G, WLAN, and Bluetooth Networks	▪ Model 5G networks: SRS-based SU-MIMO, custom scheduler, 3GPP reference scenario results, 38.901 channel model ▪ Model Pre6G networks ▪ Model WLAN 802.11be networks: Multilink operation (MLO) STR and eMLSR modes ▪ Model Bluetooth networks: Piconet, LE Audio, periodic advertisements, Bluetooth Me 
RF System Design and Analysis	▪ Showcasing FMCW application with integration of RF, RF PCB, and antenna ▪ Using AI in antenna design, analysis, and pattern reconstruction ▪ Modeling intelligent reflecting surfaces 
Space Mission Modeling and Analysis	▪ Satellite dynamic and CubeSat modeling ▪ GNC algorithm and attitude control development ▪ Mission planning and analysis, constellation access mission analysis ▪ Satellite scenario generation and visualization 
Live Stream Radar Data to MATLAB from TI mmWave Radars for Signal Processing and Tracking Applications	▪ Stream data for real-time object detection and tracking ▪ Process real-time IQ radar data instantly for radar signal processing ▪ Simplify TI® radar integration with MATLAB 
Rapid Prototyping of Radar and Wireless Communications Systems on RFSoCs	▪ Model and simulate systems together with hardware architectures ▪ Deploy and verify radar target emulator and adaptive beamforming on RFSoCs ▪ Interface and tune RF data converter parameters directly from MATLAB 
Accelerating Design and Verification of Mixed-Signal Systems	▪ Model architectural-level mixed-signal systems using specifications ▪ Generate SystemVerilog DPI-C for analog mixed-signal verification ▪ Integrate with EDA tools for behavioral-level simulation  

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Thank You

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