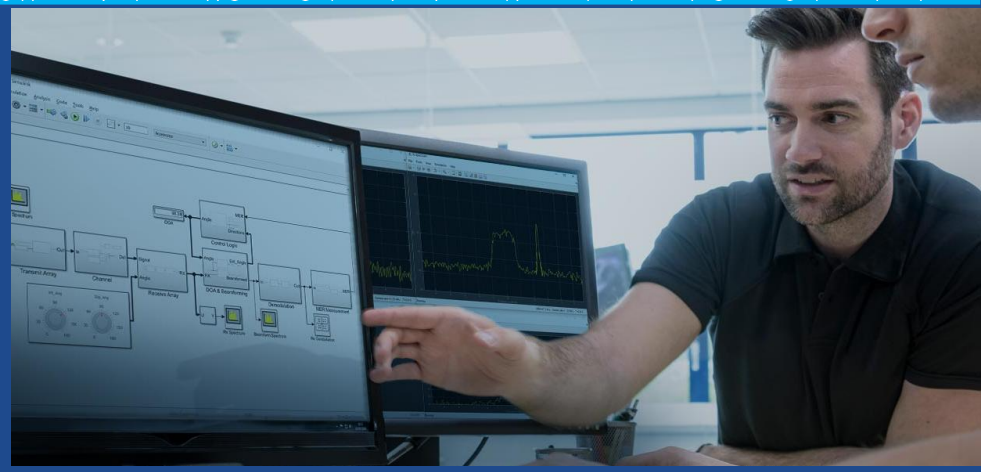
SIMULINK®

# Signal Processing with Simulink for particle accelerators and RF systems



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# Motivation and Context

**CERN Super Proton Synchrotron: Modeling, design optimization and performance stability**

## Context:

- CERN SPS accelerates protons from from 26 to 450 Gev/c before injection into the LHC
- Beam intensity at SPS directly impacts LHC luminosity
- At high intensity, the RF and LLRF systems become limiting factor

## Key physical effects at high intensity: :

- Transient beam loading
- Phase perturbations
- Beam losses during injection/extraction
- Increased sensitivity to instabilities

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 021002 (2022)

**CERN's Super Proton Synchrotron 200 MHz cavity regulation upgrade: Modeling, design optimization, and performance estimation**

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CERN's Super Proton Synchrotron (SPS) accelerates protons to 450 GeV/$c$ and transfers them into the Large Hadron Collider (LHC). It is currently one of the limiting factors in increasing the beam intensity and thus the luminosity of the LHC. As part of the LHC injectors upgrade project, the SPS 200 MHz rf system has been modified during the CERN long shutdown 2 (January 2019–April 2021), resulting in a new layout containing two additional cavities. The goal is to improve longitudinal stability required for the planned doubling of the beam intensity for the high luminosity LHC. In parallel with the upgrade of the high-power rf, a new low-level rf (LLRF) system has been designed, including a new cavity field regulation system. This work presents a model of the beam-rf interaction which includes a detailed representation of the LLRF controlling the cavity. This model is used to determine the optimal LLRF design for maximum loop stability and beam loading compensation. Finally, the performance of the upgraded LLRF is estimated.

DOI: 10.1103/PhysRevAccelBeams.25.021002

link to the paper

# What changed & Why It matters

## SRS RF upgrade (200 MHz system)

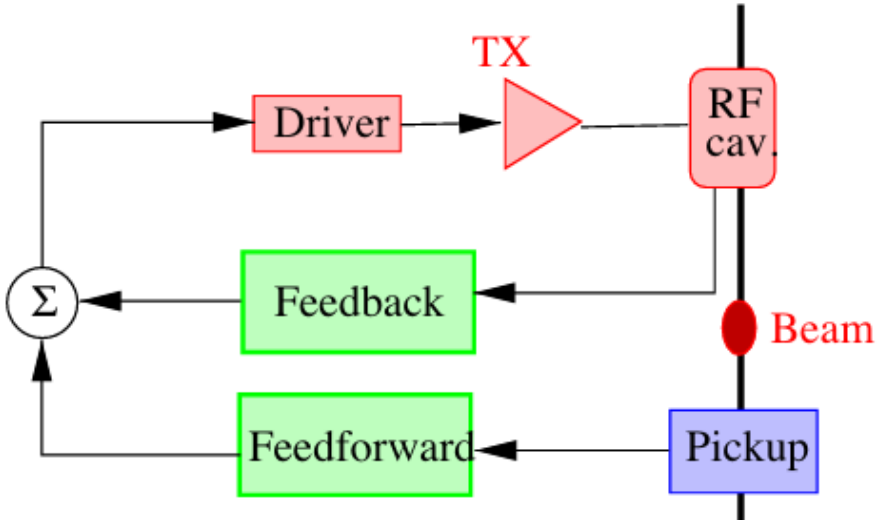
- New RF layout with additional cavities
- **Goal:** Improve longitudinal beam stability at high intensity

## LLRF Redesign:

- New cavity field regulation
- Improved beam-loading compensation
- Required because beam loading effects grow rapidly with intensity

## Critical Insight:

- System Performance is not limited by a single component hardware alone
- A system-level, closed-loop simulaton is required



# DigitalGlobe Stimulates Complete Satellite-To-Ground Communication Systems

## Challenge

- Ensure rapid and reliable transmission of satellite imagery data from space to ground

## Solution

- Use Simulink to model the entire RF and digital communications system and perform simulations to calculate BER and verify link performance

## Results

- Simulation speed increased tenfold
- Distortion effects included in simulation
- Data rate increased by 50%

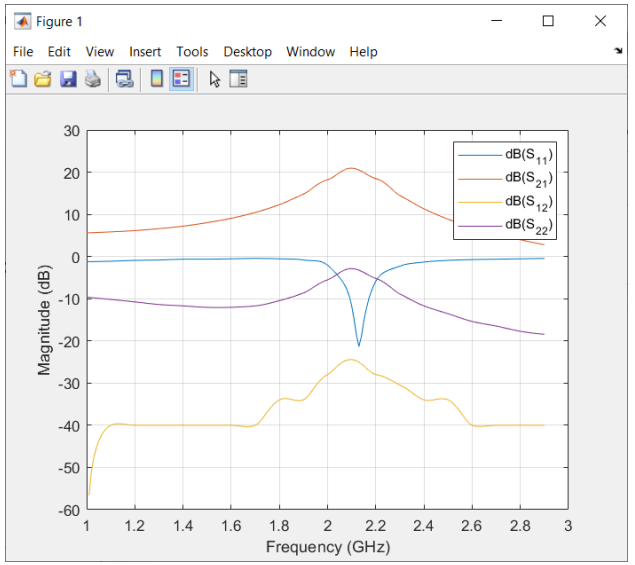
[DigitalGlobe Simulates Complete Satellite-to-Ground Communications Systems]

# Agenda

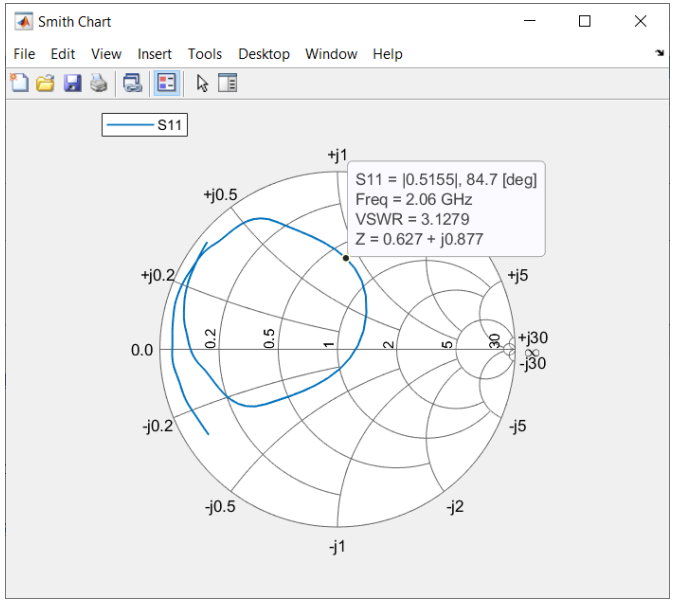
- Get started with RF data analysis
- RF system design
- Signal Processing with Simulink
- Integration custom or external code into Simulink models

# S-Parameters Data Import and Visualization

```
help rf
s_param = sparameters('default.s2p')
rfplot(s_param)
smithplot(s_param,1,1)
```




```
Analysis
  abcd2h            - Convert ABCD-parameters to hybrid H-parameters
  abcd2s            - Convert ABCD-parameters to S-parameters
  abcd2y            - Convert ABCD-parameters to Y-parameters
  abcd2z            - Convert ABCD-parameters to Z-parameters
  g2h               - Convert hybrid G-parameters to hybrid H-parameters
  h2abcd            - Convert hybrid H-parameters to ABCD-parameters
  h2g               - Convert hybrid H-parameters to hybrid G-parameters
  h2s               - Convert hybrid H-parameters to S-parameters
  h2y               - Convert hybrid H-parameters to Y-parameters
  h2z               - Convert hybrid H-parameters to Z-parameters
  snp2smp           - Convert N-port S-parameters to M-port S-parameters
  s2t               - Convert S-parameters to T-parameters
  t2s               - Convert T-parameters to S-parameters
  rlgc2s            - Convert transmission line RLGC-parameters to S-parameters
  s2rlgc            - Convert S-parameters to transmission line RLGC-parameters
  s2abcd            - Convert S-parameters to ABCD-parameters
  s2h               - Convert S-parameters to hybrid H-parameters
  y2abcd            - Convert Y-parameters to ABCD-parameters
  y2h               - Convert Y-parameters to hybrid H-parameters
  z2abcd            - Convert Z-parameters to ABCD-parameters
  z2h               - Convert Z-parameters to hybrid H-parameters
  rationalfit       - Perform rational function fitting to broadband data
  iscausal          - Check causality of N-port S-parameters
```



# Programmatically Construct an RF Network:
# Automate the Analysis, Explore the design space, Create Reports

Follow four steps:

- Create a **`circuit`**
- Add the components
  - Defines nodes and connections
  - RLC, S-parameters, PCB components
- Define the analysis ports
- Perform the analysis and extract results

**Programmatically Construct Circuit**

Create a `circuit` and use the `add` function to populate the circuit with named `resistor` and `capacitor` objects

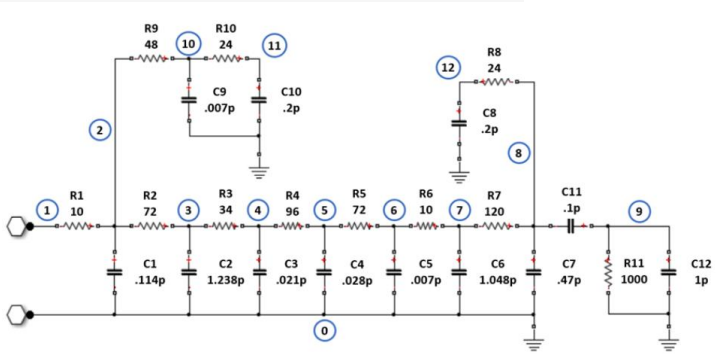
```
ckt = circuit('crosstalk');

add(ckt,[2 1],resistor(10,'R1'))
add(ckt,[2 0],capacitor(0.114e-12,'C1'))
add(ckt,[3 2],resistor(72,'R2'))
add(ckt,[3 0],capacitor(1.238e-12,'C2'))
add(ckt,[4 3],resistor(34,'R3'))
add(ckt,[4 0],capacitor(0.021e-12,'C3'))
add(ckt,[5 4],resistor(96,'R4'))
add(ckt,[5 0],capacitor(0.028e-12,'C4'))
add(ckt,[6 5],resistor(72,'R5'))
add(ckt,[6 0],capacitor(0.007e-12,'C5'))
add(ckt,[7 6],resistor(10,'R6'))
add(ckt,[7 0],capacitor(1.048e-12,'C6'))
add(ckt,[8 7],resistor(120,'R7'))
add(ckt,[8 0],capacitor(0.47e-12,'C7'))

add(ckt,[12 8],resistor(24,'R8'))
add(ckt,[12 0],capacitor(0.2e-12,'C8'))

add(ckt,[10 2],resistor(48,'R9'))
add(ckt,[10 0],capacitor(0.007e-12,'C9'))
add(ckt,[11 10],resistor(24,'R10'))
add(ckt,[11 0],capacitor(0.2e-12,'C10'))

add(ckt,[9 8],capacitor(0.1e-12,'C11'))
add(ckt,[9 0],resistor(1000,'R11'))
add(ckt,[9 0],capacitor(1e-12,'C12'))
```



# Example#1: Create and Analyze a Network Using RF Measured Data

```
% Read the data
adapter1 = sparameters('coax.s1p');
elbow    = sparameters('elbow.s2p');
coupler  = sparameters('coupler.s4p');
adapter2 = sparameters('adapter.s2p');
% Build the network
ckt = circuit('circuit');
add(ckt,[1 2], adapter1);
add(ckt,[2 3], elbow);
add(ckt,[3 4 5 6], coupler);
add(ckt,[5 0], resistor(50));
add(ckt,[6 0], resistor(50));
add(ckt,[4 7], adapter2);
% Analyze the network
setports(ckt, [1 0], [7 0])
freq = linspace(347e6, 357e6, 51);
S = sparameters(ckt, freq);
%% Save to Touchstone file
rfwrite(S,'line.s2p');
```

Import Touchstone files

Create circuit object

Add network of components

Define ports and perform the analysis

Save and share results

# How Can I Get Started with S-Parameter Analysis in MATLAB?

mathworks.com/products/rftoolbox.html

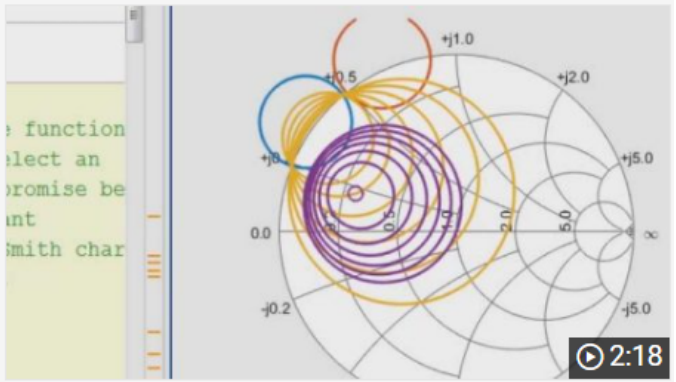
RF Toolbox

Search MathWorks.com

## S-Parameter Analysis

Use functions to transform and manipulate S-parameter data. Import and export N-port Touchstone® files. Visualize S-parameters on cartesian, polar, or Smith charts. Measure VSWR, reflection coefficients, phase delay, and group delay.

Choose the appropriate format by converting among S, Y, Z, ABCD, h, g, and T network parameter formats. De-embed measured 2N-port S-parameter data by removing the effects of test fixtures and access structures. Transform single-ended measurements into differential or other mixed-mode formats. Convert and reorder single-ended N-port S-parameters to single-ended M-port S-parameters.




Working with S-Parameters

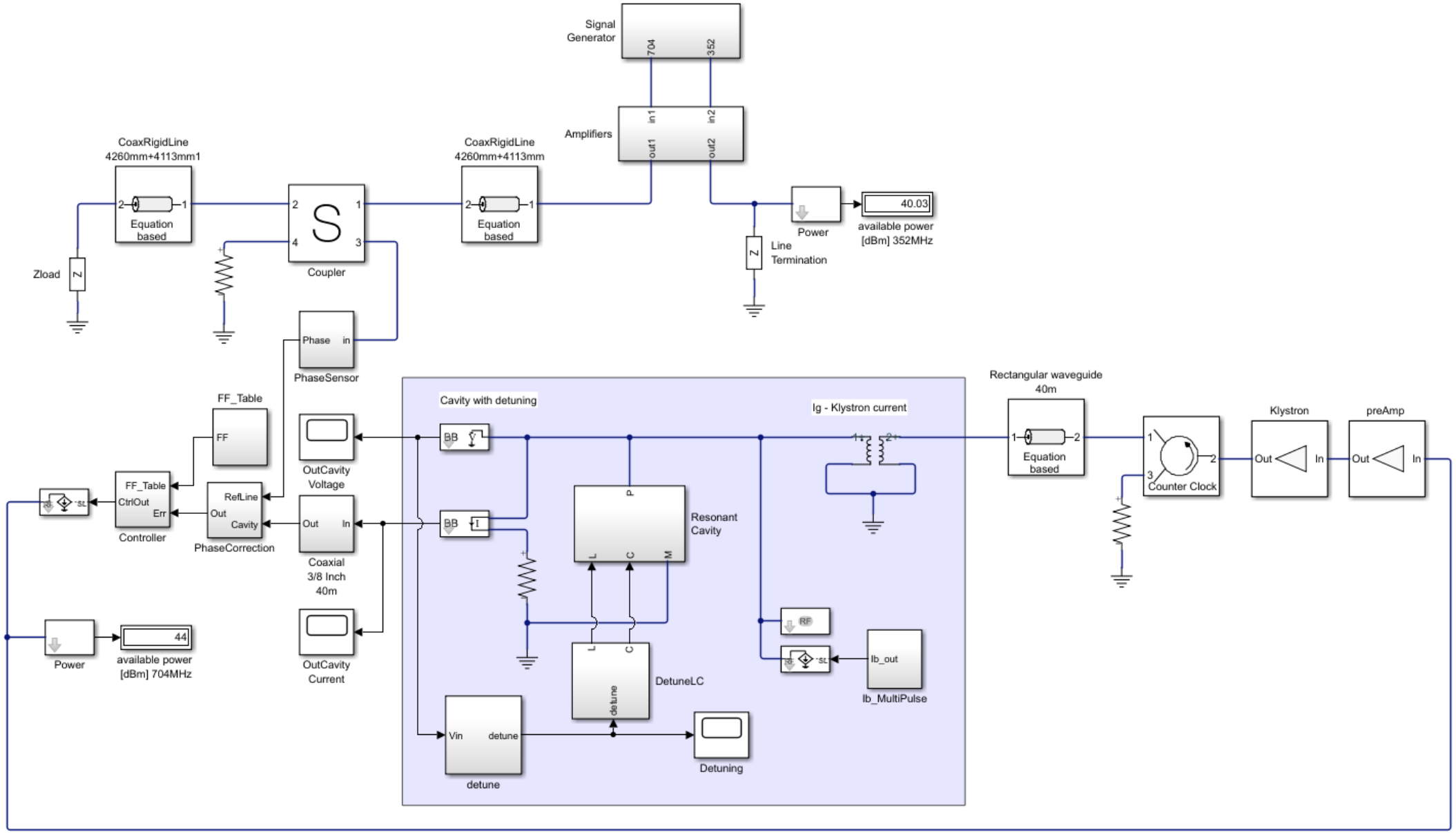
- Getting Started with S-Parameters (5 videos)
- Data Analysis on a Set of S-Parameters for an RF Filter
- De-Embedding S-Parameters
- Convert Scattering Parameters to Impulse Response for SerDes System Design

Getting Started with S-Parameters - MATLAB & Simulink

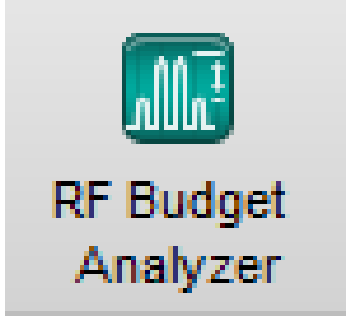
# Agenda

- Get started with RF data analysis
- **RF system design**
- Signal Processing with Simulink
- Integration custom or external code into Simulink models

# Inspiration: Cavity Resonator Model for Linear Particle Accelerator

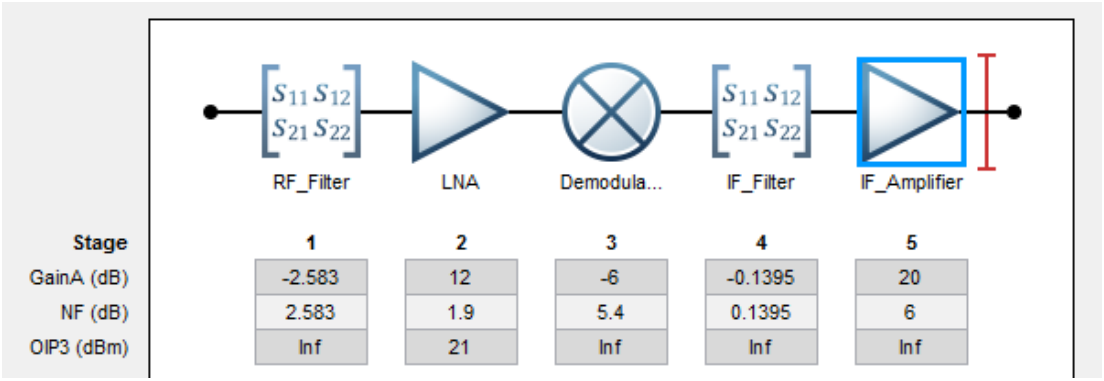


# RF Design – Where To Start?




**RF Budget Analyzer App**

- Analytical computation and visualization of power/noise/IP3 RF budget
- Improvement over custom-made spreadsheets - taking into account mismatches
- Generates Circuit Envelope models/testbenches for super-heterodyne and homodyne architectures
- Generates MATLAB scripts for automation and complex scenario analysis
- Delivers consistent results between analytical equations and simulation



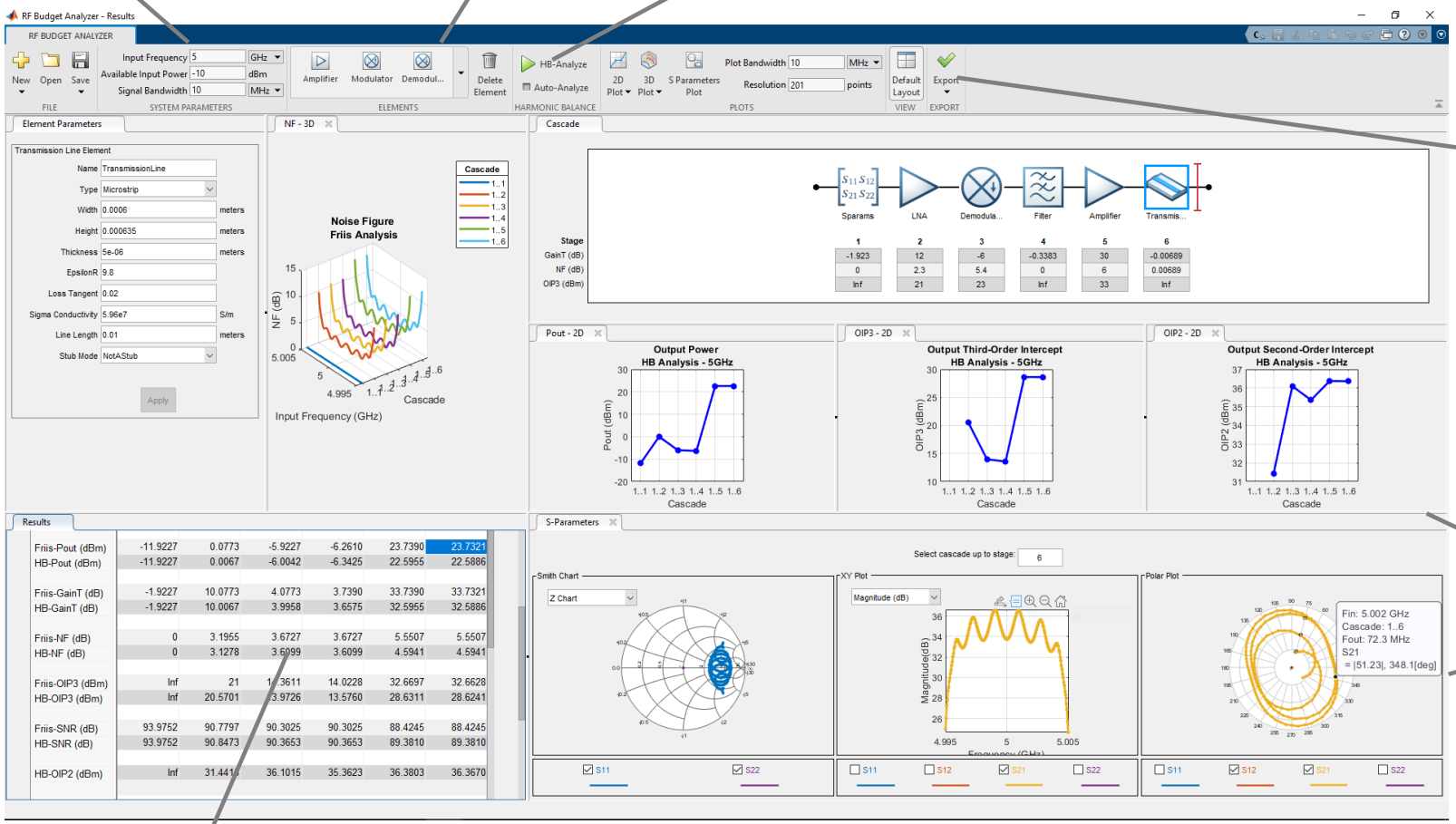

| Stage | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| GainA (dB) | -2.583 | 12 | -6 | -0.1395 | 20 |
| NF (dB) | 2.583 | 1.9 | 5.4 | 0.1395 | 6 |
| OIP3 (dBm) | Inf | 21 | Inf | Inf | Inf |

# Analyze, Understand, and Debug RF Data and RF Budget

System specifications

RF components

Harmonic Balance (non-linear) analysis

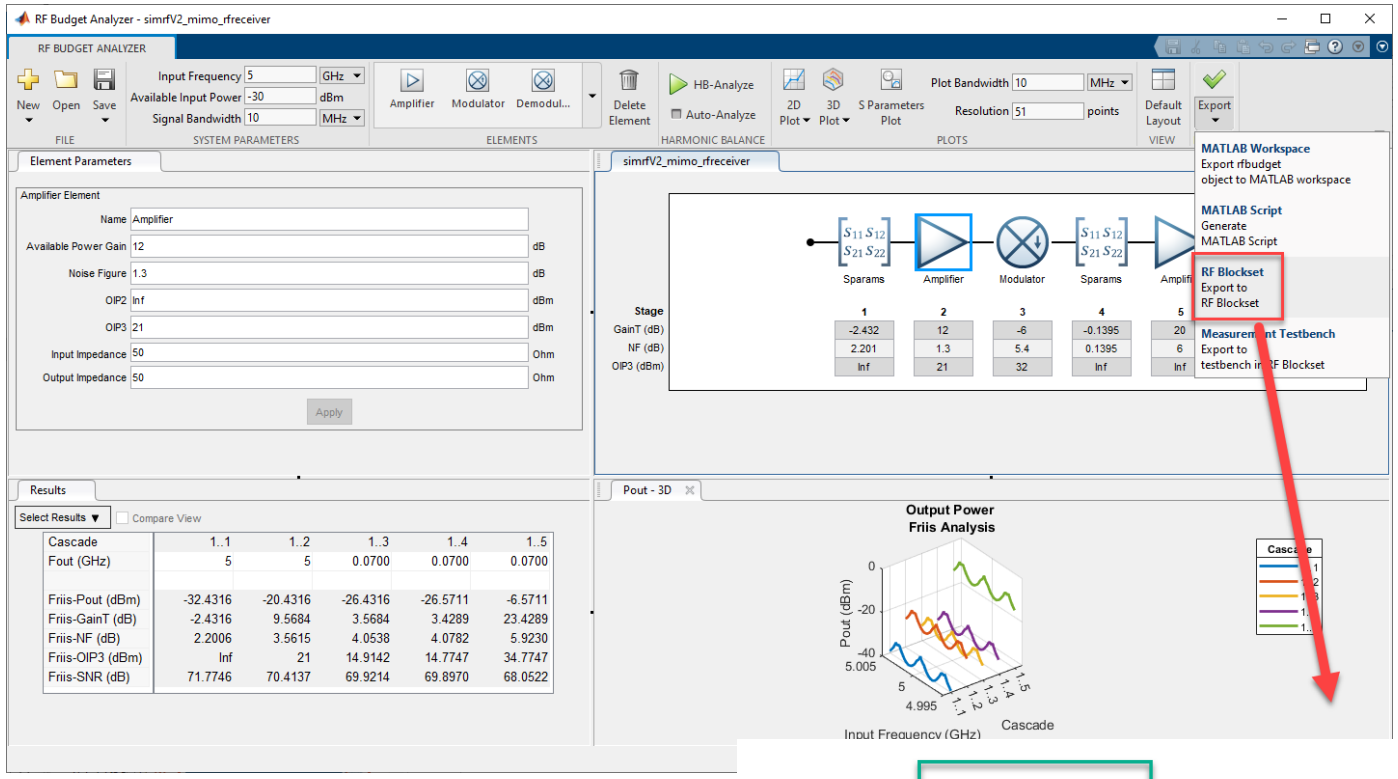



Export to MATLAB / RF Blockset

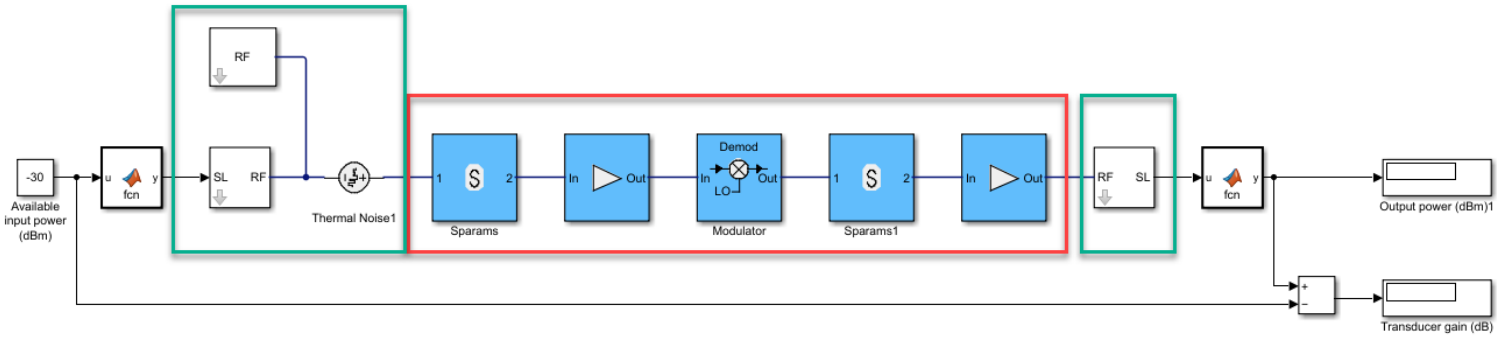
New visualization

Cascaded Budget Analysis (Friis and Harmonic Balance)

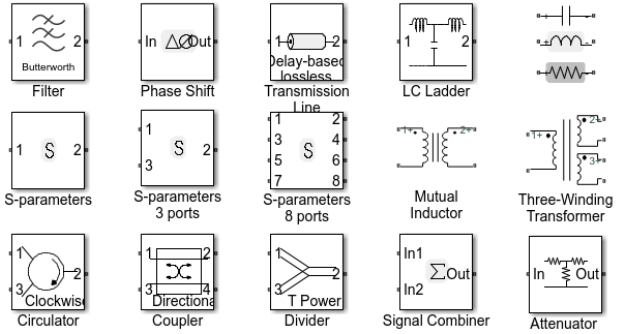
# Export the RF Receiver to RF Blockset and add to PHY layer model.



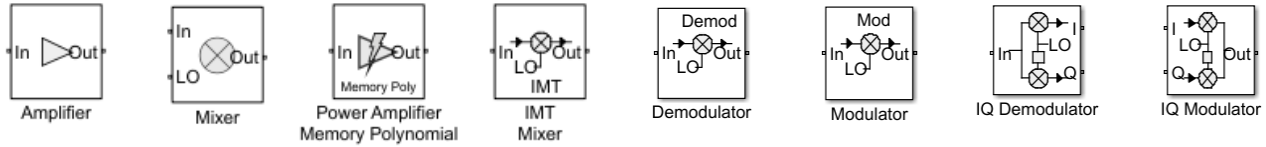

***May I do this in MATLAB?***



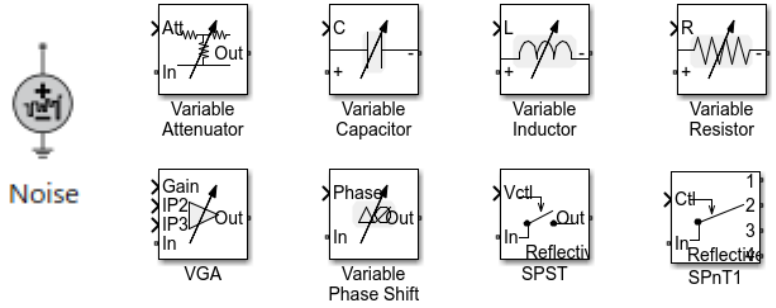
# Circuit Envelope Available Blocks




- Frequency dependent (linear) elements
  - S-parameters
  - RLC, transmission lines
  - Filter, attenuator, coupler, circulator, divider/combiner, phase shifter
  - Antenna and antenna array
- Nonlinear elements
  - Amplifier
  - Power Amplifier (Memory polynomial and AM/AM-AM/PM)
  - Mixer (IM table)
  - System blocks: Modulator, Demodulator, IQ Modulator, IQ Demodulator

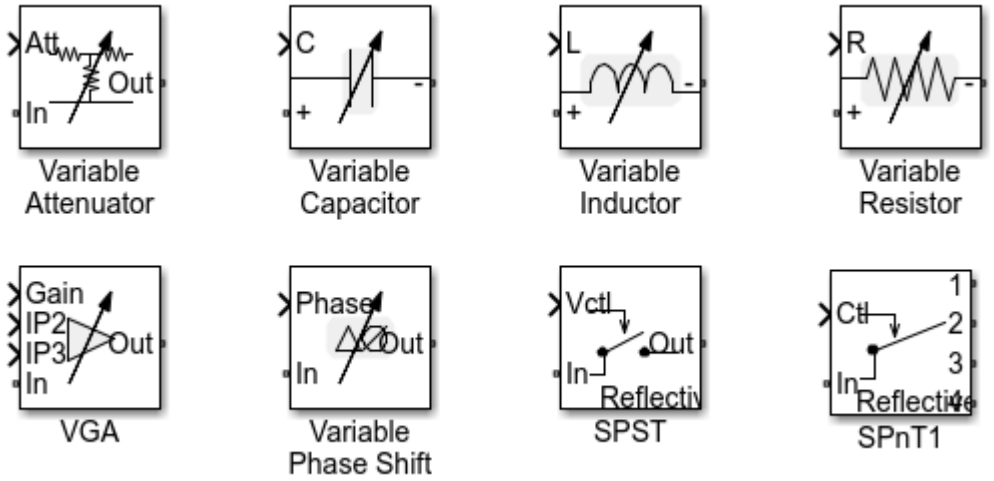


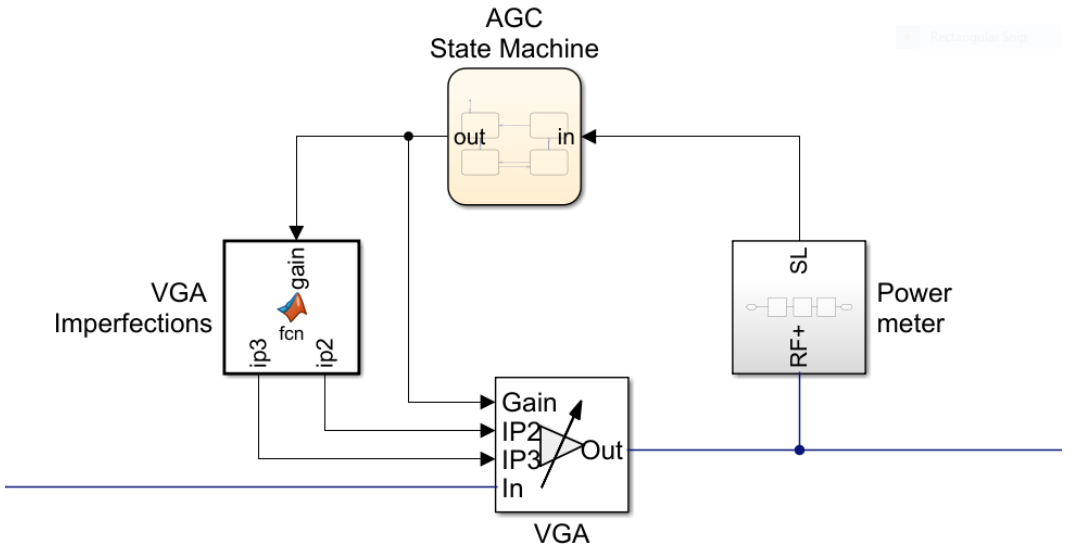

- Noise generation included for linear and non-linear elements
  - Thermal Noise, Phase Noise
- Variable (Simulink controlled) elements for tunable networks
  - Non-linear VGA, attenuator, shifter, RLC



# Circuit Envelope Tunable Blocks

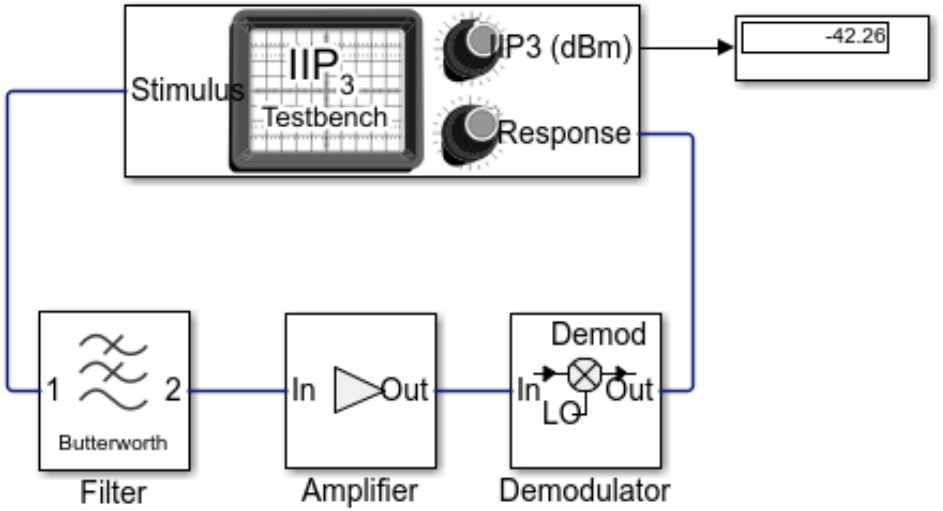
- RF elements with Simulink controlled characteristics
- Build tunable networks such as AGC, adaptive matching network, beamformer, butler matrix
  - Non-linear VGA, attenuator, phase shifter, RLC
  - Switches for building configurable networks

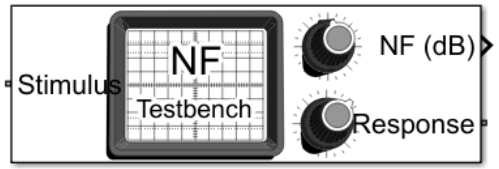


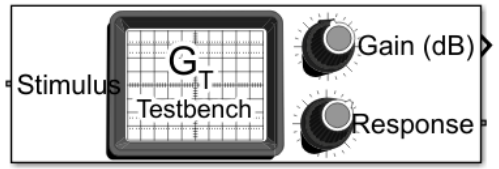



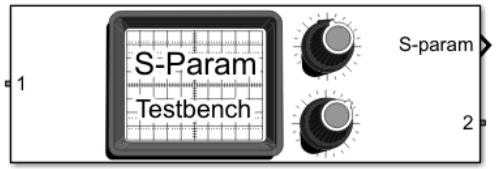
# Circuit Envelope Testbenches

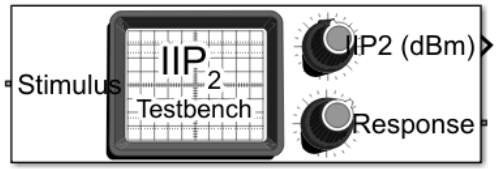
- Measure and verify the performance of your DUT
  - Generate stimuli and measure response
  - Noise, gain, non-linearity, S-parameters

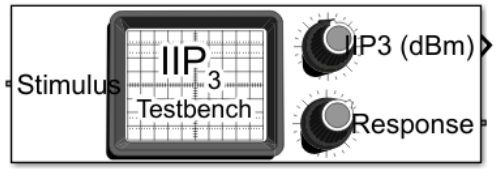


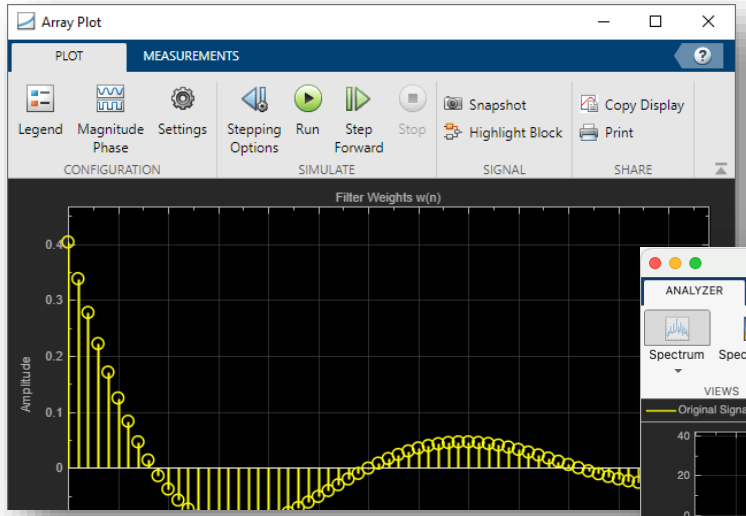
# Agenda

- Get started with RF data analysis
- RF system design
- **Signal Processing with Simulink**
- Integration custom or external code into Simulink models

# Modern Responsive Soft Scopes

## Analyze and measure dynamic simulation signals and filters

R2021a

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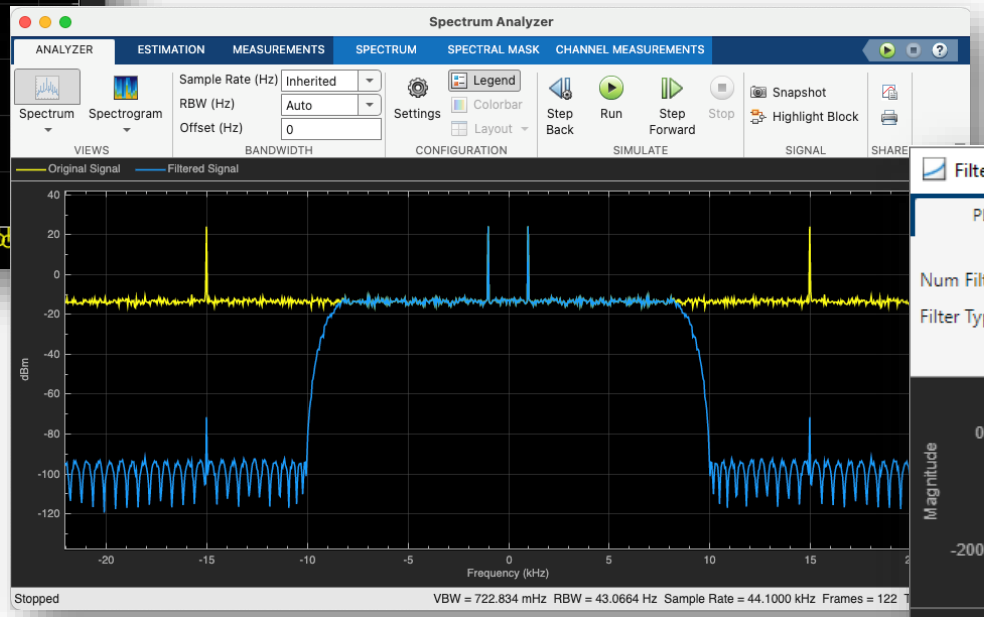


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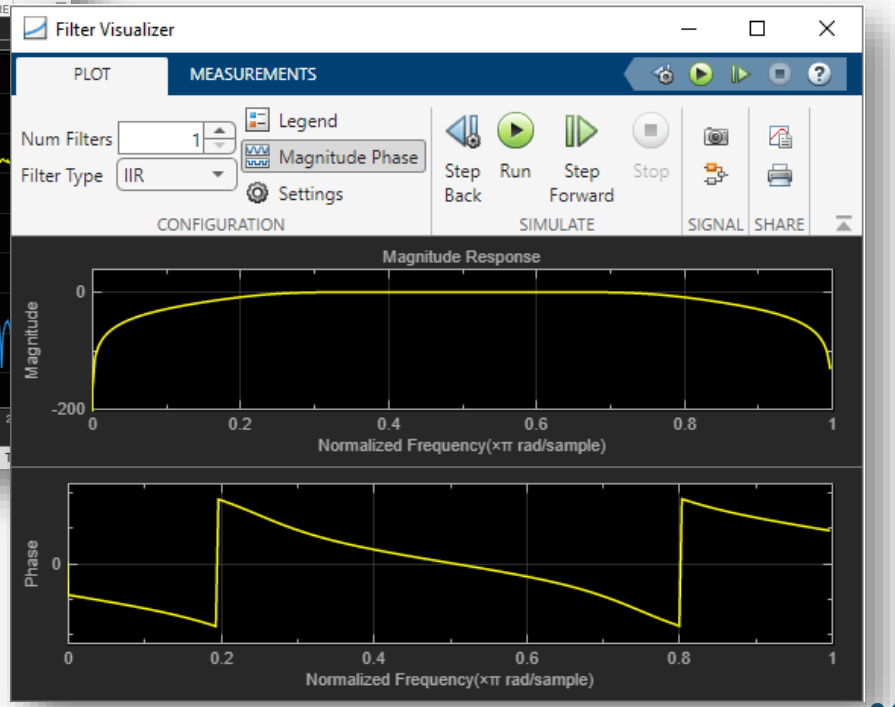
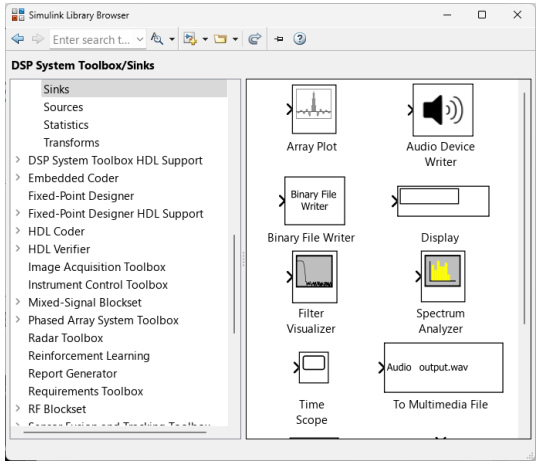
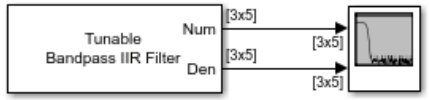
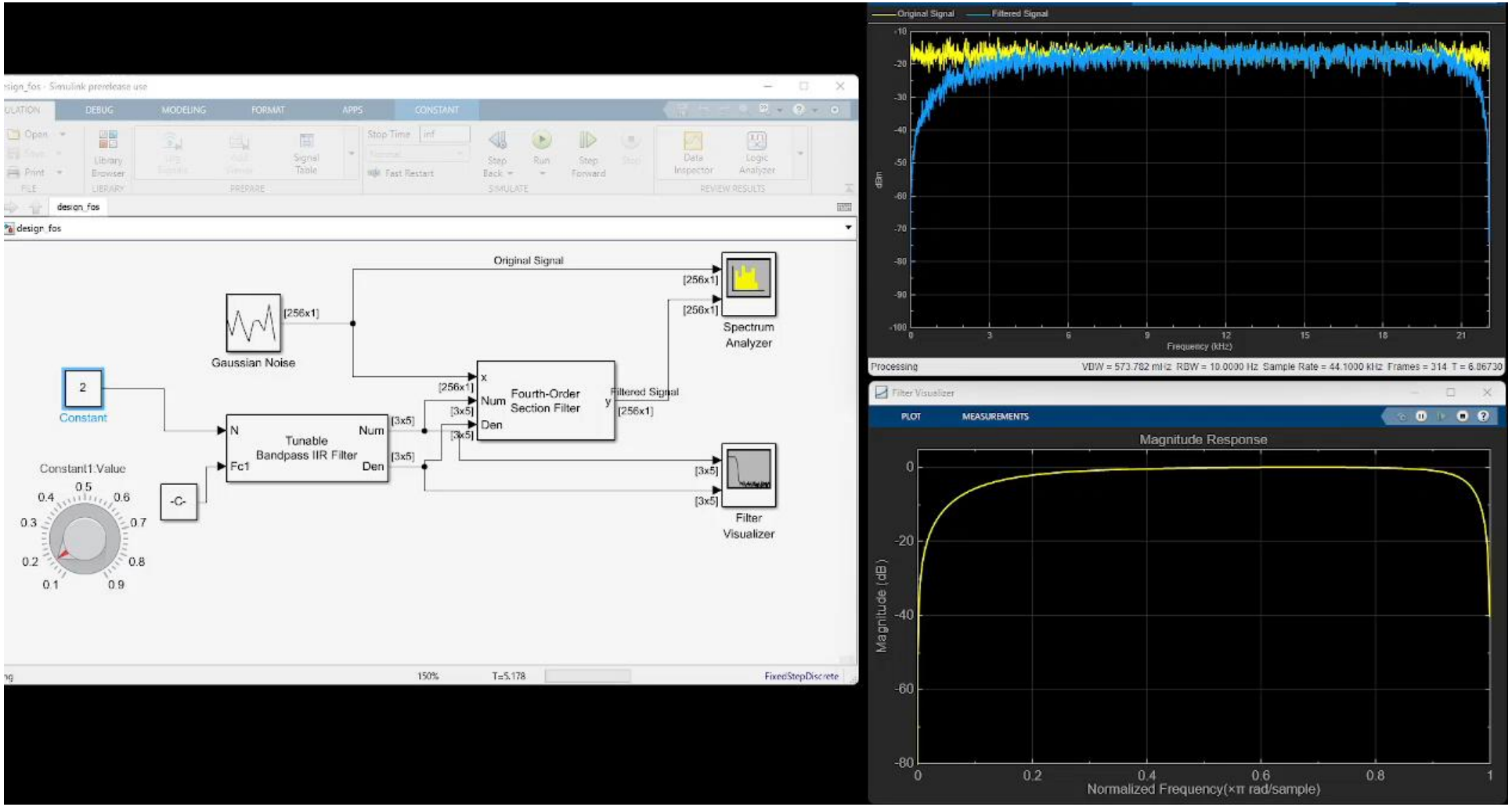


# Dynamic Visualization of Filter Response and Signal Spectra Example

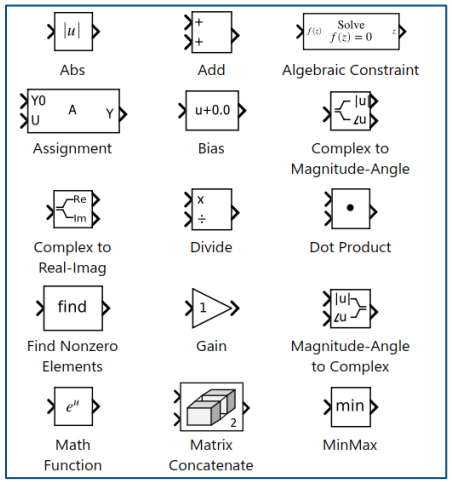
R2023a



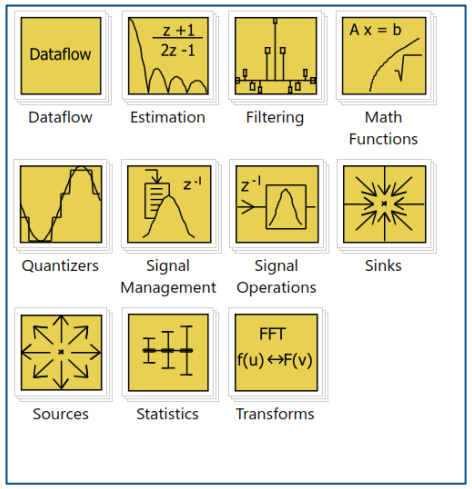
# Working with multiple domains?

- Incorporate multiple domains all in <u>one</u> model. Choose from hundreds of blocks in different domains:

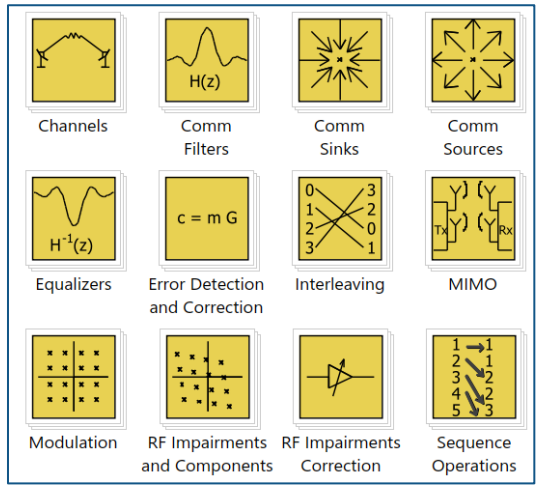
Math Operations



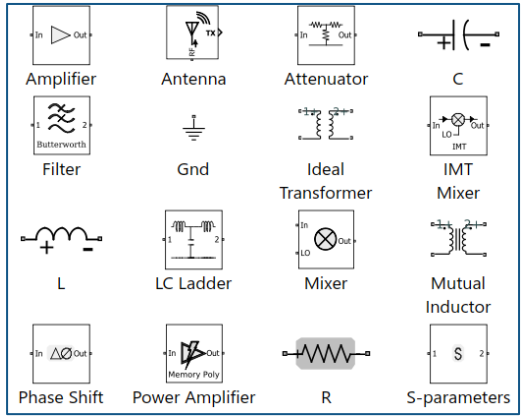

Signal Processing



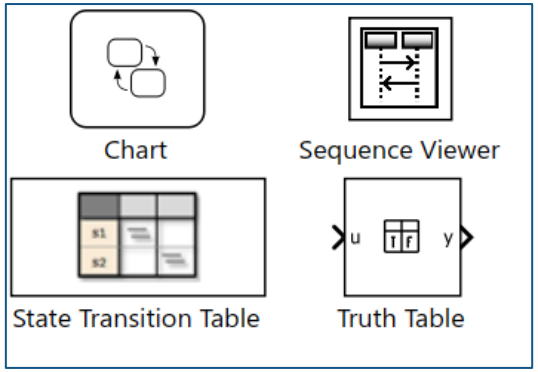

Communications Systems



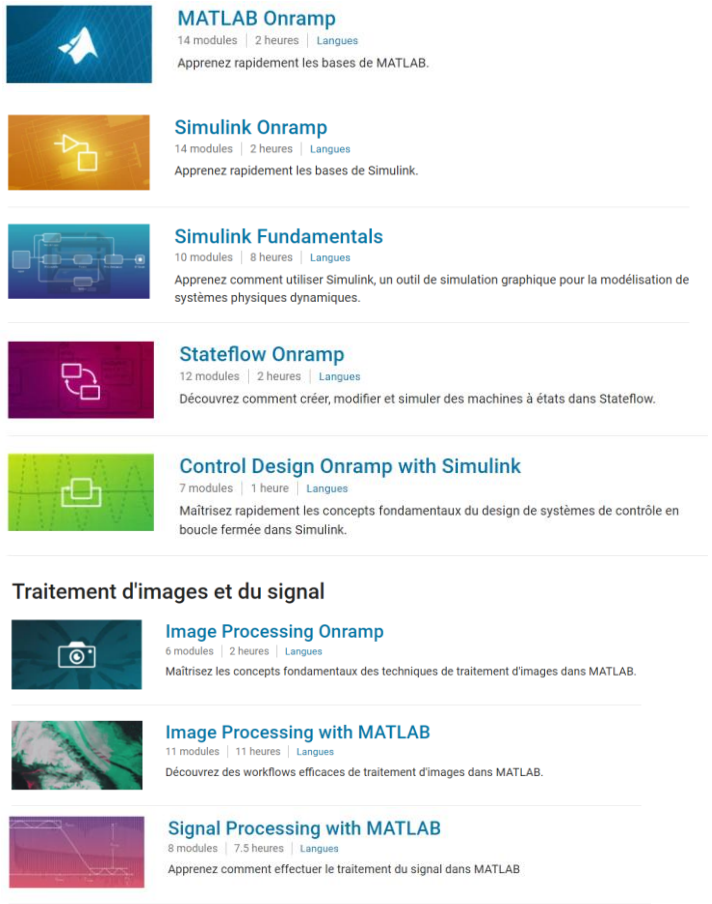

RF

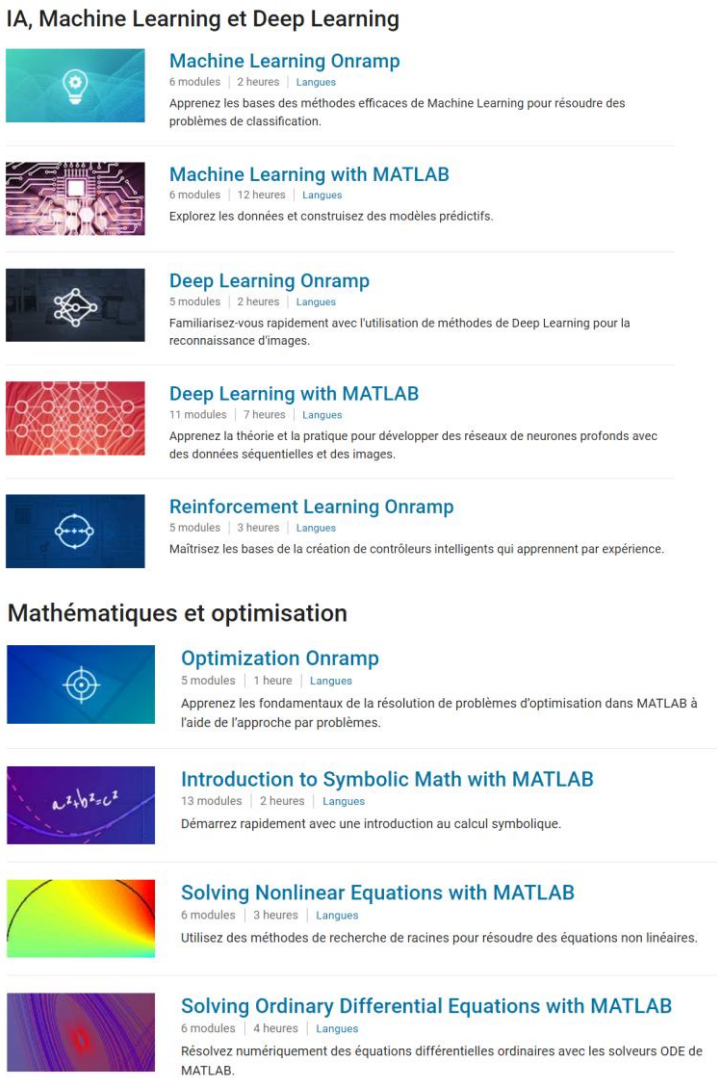



State Machines



# How to learn
## MATLAB Academy




https://matlabacademy.mathworks.com/

# Instructor led Training:
## RF system Design

- Build RF system models
- Import and Simulate S-parameters
- Model Linear and non-Linear RF components
- Analyze the impact of noise and nonlinearities


### Course Details

This two-day course shows how to use RF Blockset™ and RF Toolbox™ for modeling wireless front ends. You will learn when to use two different modeling paradigms to speed up the simulation of RF signals: Equivalent Baseband and Circuit Envelope. The fundamentals of the simulation techniques will be discussed, and best modeling practices will be highlighted.

Topics include:

- Importing S-parameters and modeling linear elements
- Simulating thermal and phase noise
- Modeling amplifiers and mixers operating in nonlinear conditions
- Developing custom models
- Integrating antennas and arrays in RF transceivers

**Level:** Intermediate

**Prerequisites:**

- Signal Processing with Simulink
- A good understanding of RF theory

**Duration:** 2 days

**Languages:** English

View schedule and enroll

Day 1 of 2

**What is RF Blockset?**

**Objective:** Give an overview of RF simulation using MathWorks tools; the goal of this section is to familiarize the audience with RF Blockset and its terminology. Attendees who never used RF Blockset before will be able to recognize which applications can be modeled with RF Blockset and which approach is most suitable.

- Describe what can be done with RF Blockset
- Describe the benefits of using RF simulation techniques
- Articulate why and when RF Blockset is needed

**Fundamentals of RF Simulation**

**Objective:** Describe the fundamentals of Equivalent Baseband and Circuit Envelope simulation techniques. We will

RF System Design Using MathWorks Tools

# Agenda

- Get started with RF data analysis
- Simulating RF controlled components at the system-level
- Signal Processing with Simulink
- **Integration custom or external code into Simulink models**

# Implement MATLAB Functions in Simulink

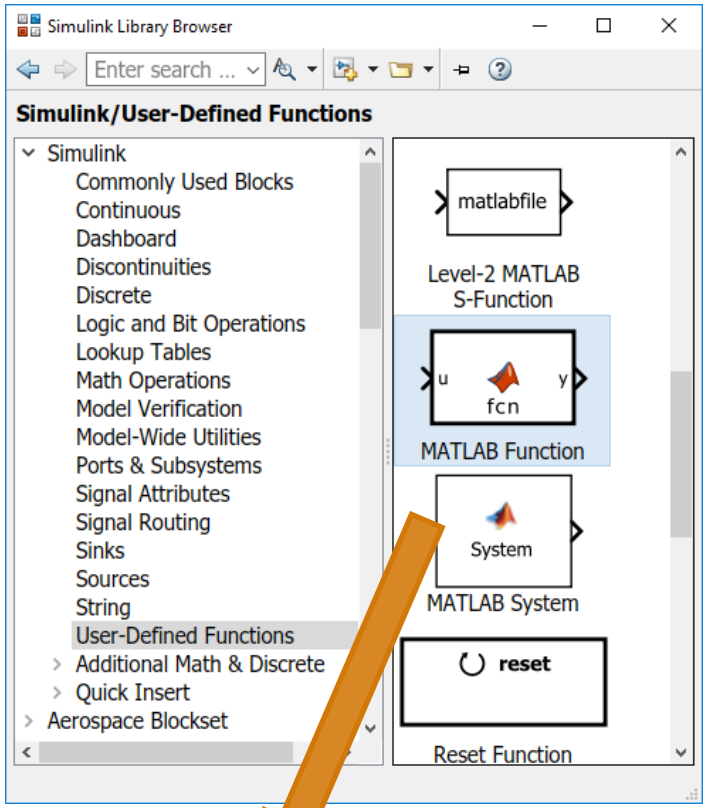
Write a MATLAB function that runs in a Simulink model

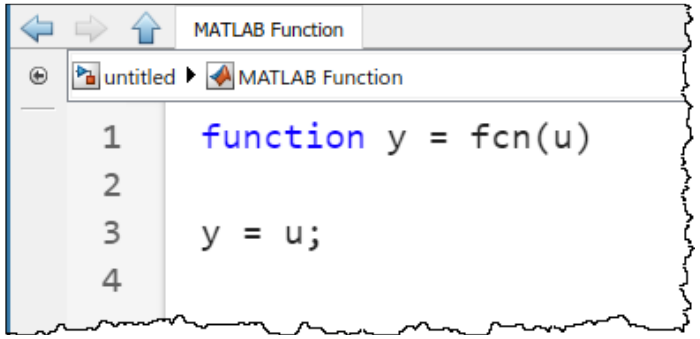
Can accept multiple input and reproduce multiple output signals

**Why use it?:**

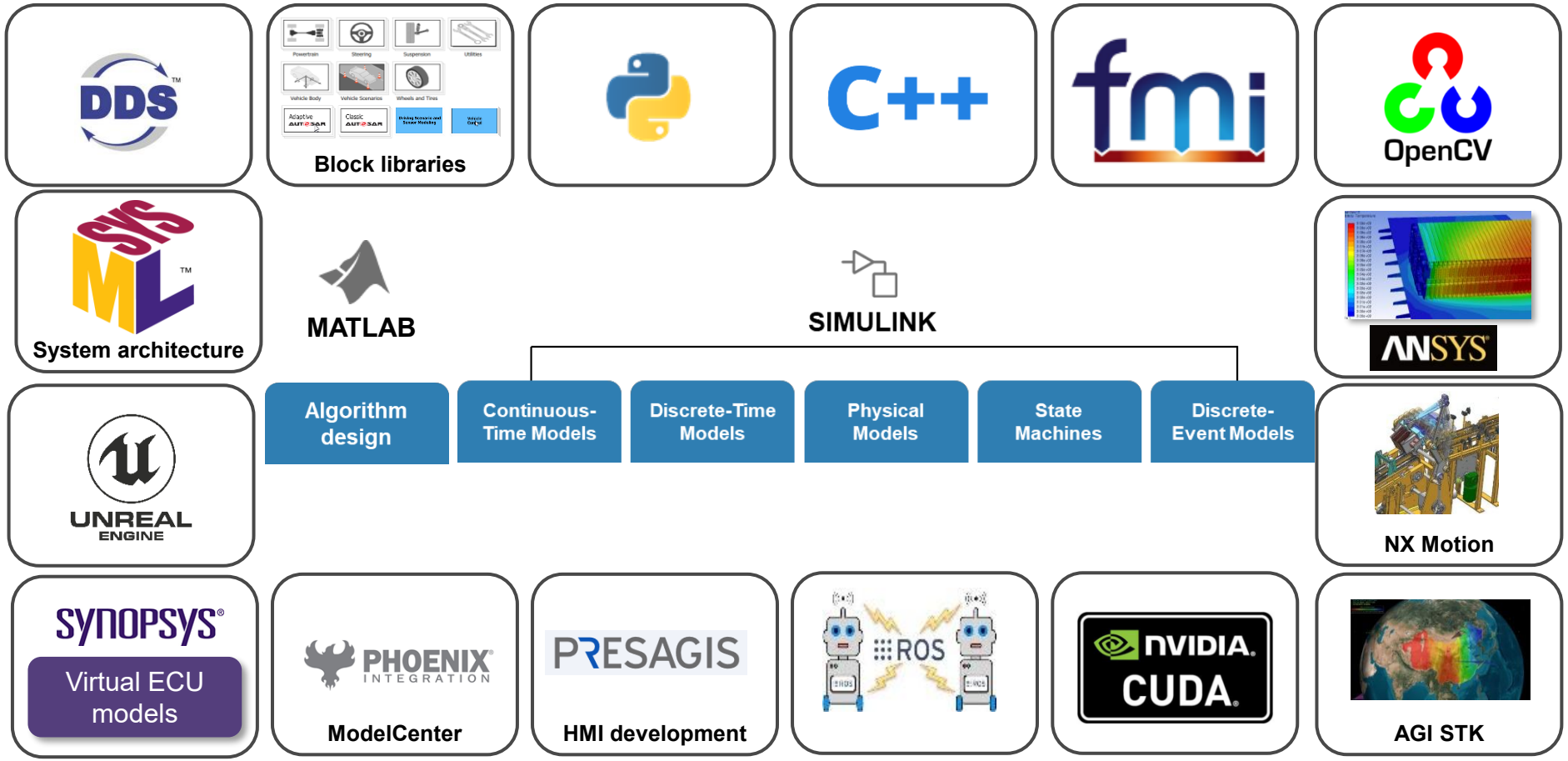
Include existing MATLAB algorithms into Simulink

Write simple algorithms without the graphical overhead



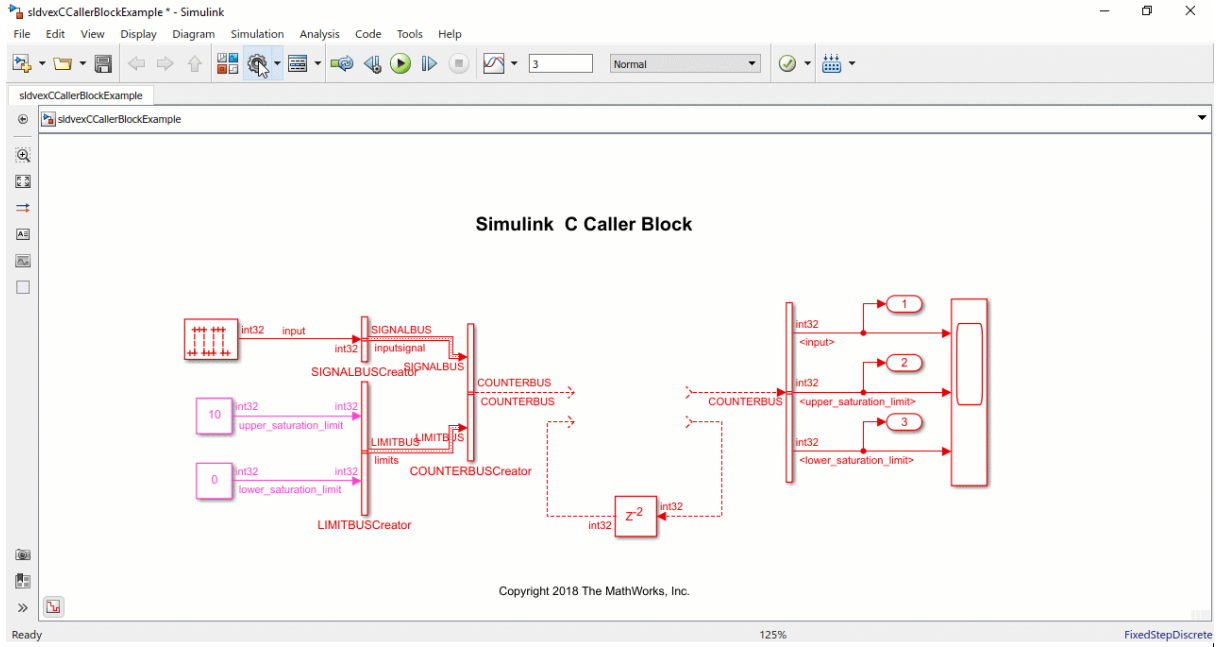



# Integrate **external components & code** into your Simulink models

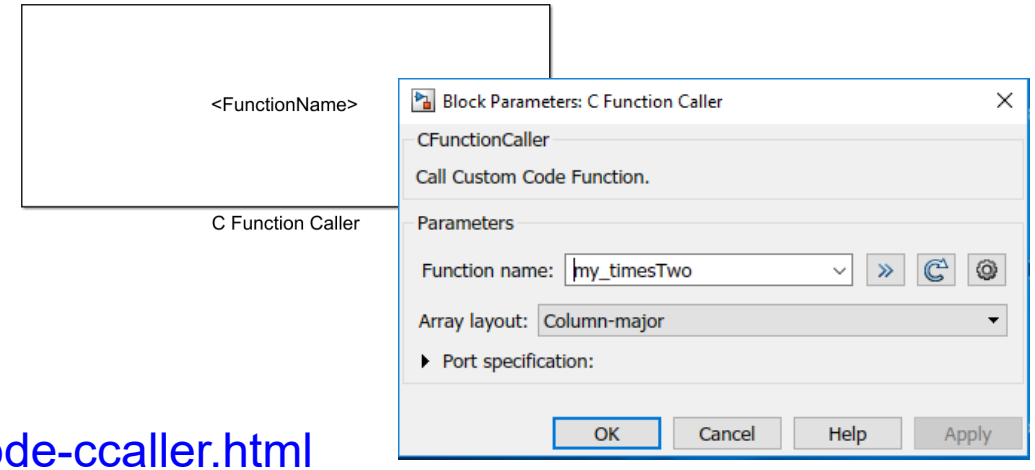


# Integrating your C code into Simulink is simple

## C Caller Block: Call external C functions directly from the model




Supports simulation and code generation




https://www.mathworks.com/help/simulink/ug/integrate-ccode-ccaller.html

# There are multiple methods to bring your **Python code** into Simulink

Learn which approach will work for your application

## Python Importer

*Use to bring an existing Python function into Simulink.*

+ Graphical interface with minimal code
+ Creates reusable blocks from Python functions

– Cannot edit Python code once the block is created


## Python Code Block

*Use to write native Python code in Simulink.*

+ Easily edit code from the block dialog
+ Supports all simulation modes

– No debugging capabilities in the block dialog


*For releases prior to R2023a, you can use MATLAB Function or System blocks to use Python code in Simulink.*

# Key Takeaways

- Closed-loop, time-domain simulation is essential
- Start with RF data analysis using RF Toolbox
- Reuse validated RF models at the system level
- Simulink enables live observation of system behavior

# Merci !

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