AHEAD OF WHAT'S POSSIBLE™

Phased Array Radar Workshop

using Open Source Software and Hardware

June 20, 2022

wiki.analog.com/phaser

Phased Array Radar Workshop

Using Open Source Software and Hardware

- This workshop is divided into ~10 min presentations followed by ~10 min of lab time.

- Please find a seat near one of the lab setups
- You'll need to share with 2 or 3 other people on one setup.

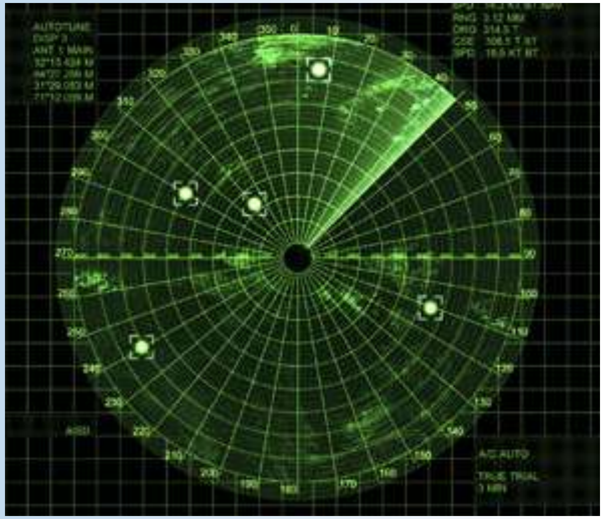
- During the lab time, we'll do a general overview of the lab that you can follow along with.

What is beamforming?
Who uses it?
Why does it matter?

Jon Kraft, Analog Devices

What is Phased Array Beamforming?

Rotating Antennas (mechanical gimbles)



Phased Array antennas accomplish the same, but without mechanical movement

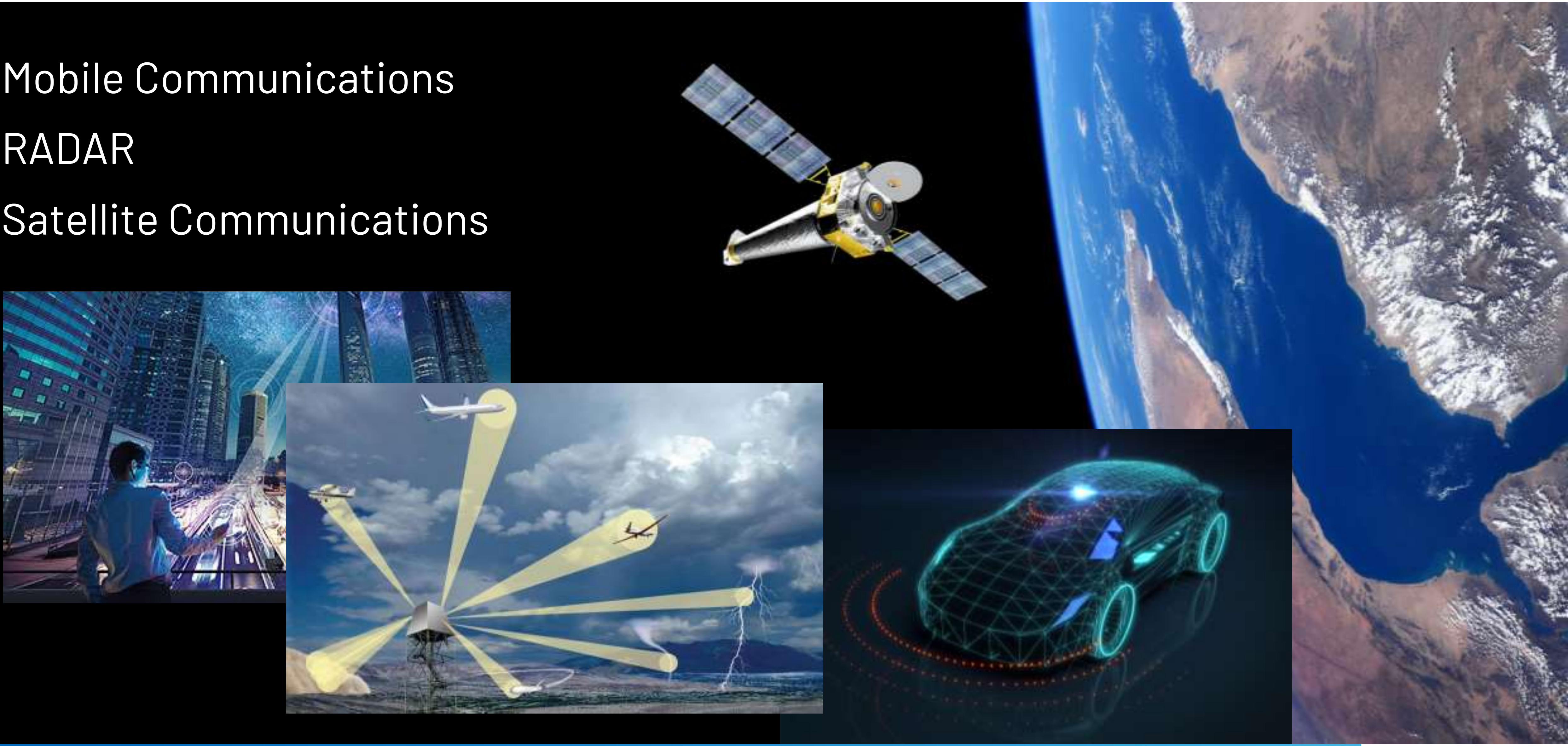
figure from https://www.analog.com/en/technical-articles/an-interview-with-analog-devices-discussing-rf-electronics-for-phased-array-applications.html

Where is Phased Array Beamforming Used?

Mobile Communications

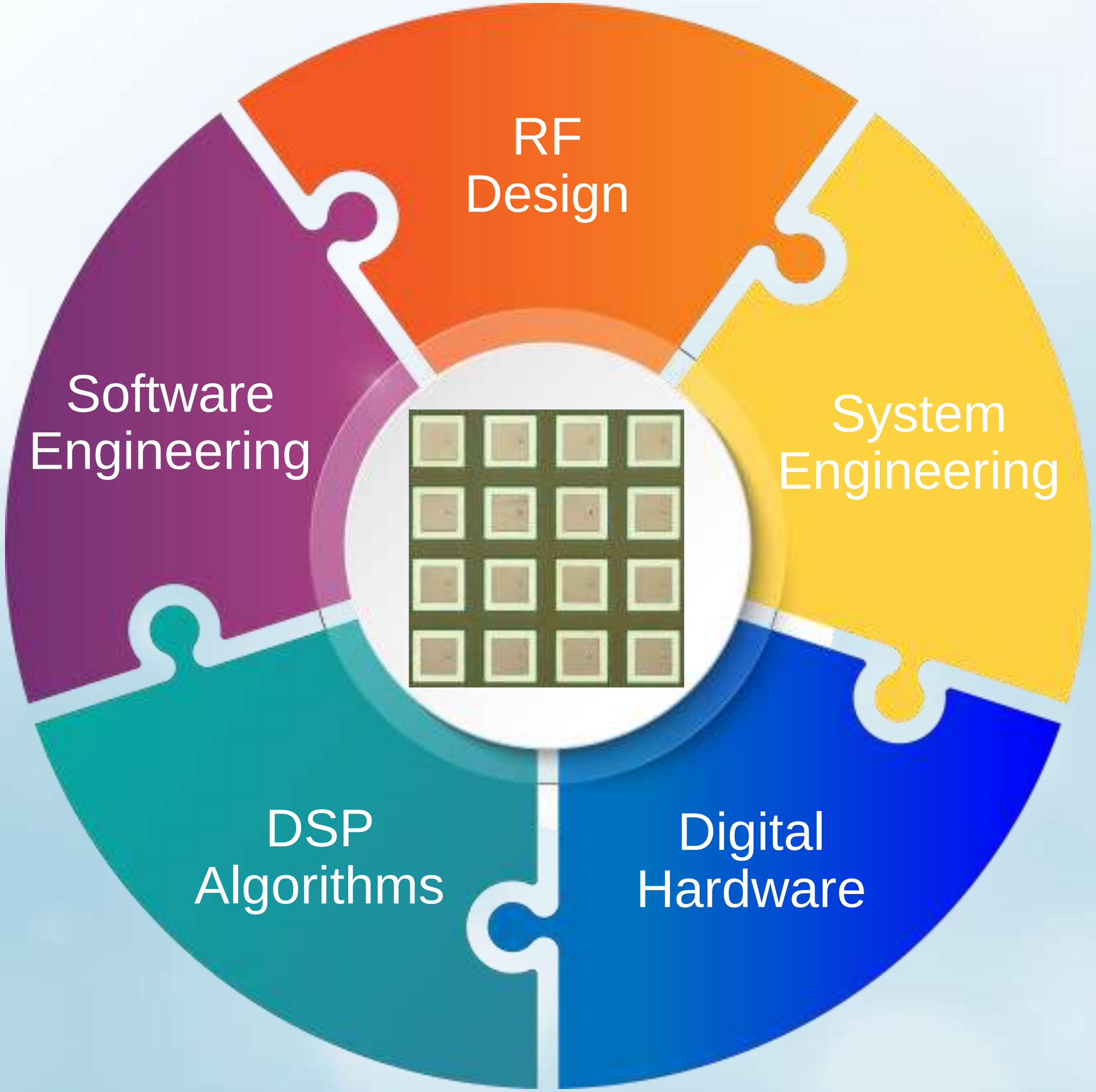
RADAR

Satellite Communications



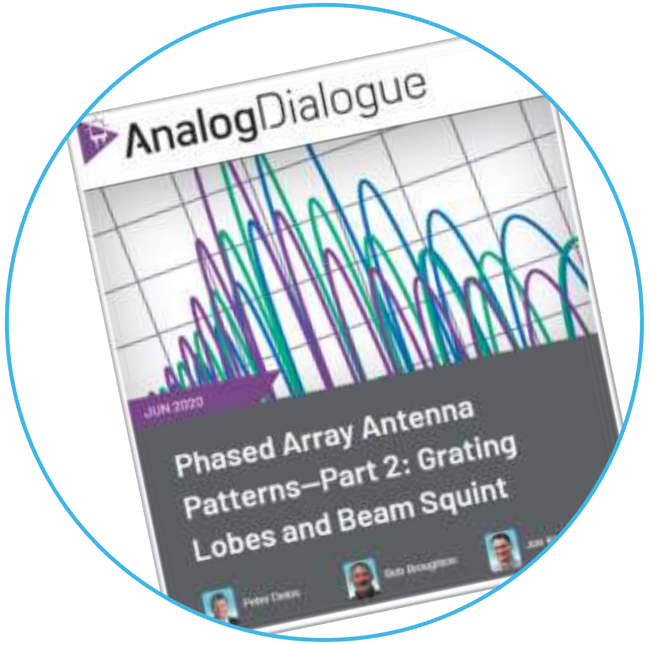
Overview of the Phased Array Workshop Series

- Phased Array Radar Requires:
  - RF Hardware Design
  - Software Engineering
  - System Design
  - Algorithm Design (comms and radar)
  - HDL Engineering
- So with so much entailed, how can we get started?



Workshop Goals:

1. Gain an **intuitive** understanding of beamforming concepts
2. **Hands on** experimenting with these concepts
3. Path to quickly **prototype** your own phased array system



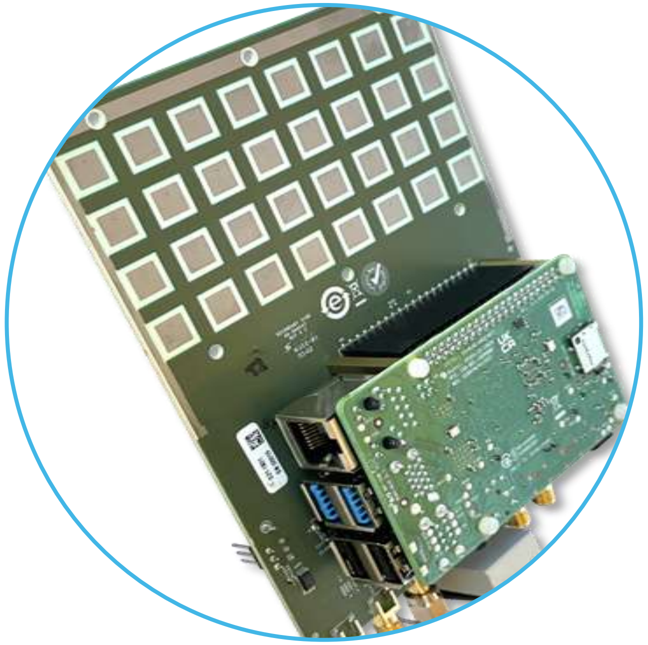
AnalogDialogue

JUN 2020

Phased Array Antenna Patterns—Part 2: Grating Lobes and Beam Squint

Math and Theory

+



Accessible Hardware

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Understanding

Overview of the Phased Array Workshop

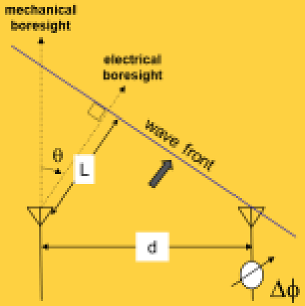
Overview of the Phased Array Workshop

Digitizer

Overview of the Phased Array Workshop

Digitizer

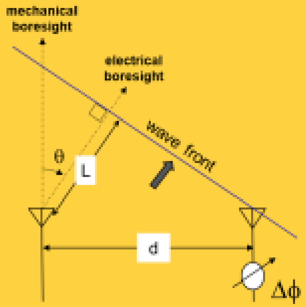
Steering Angle



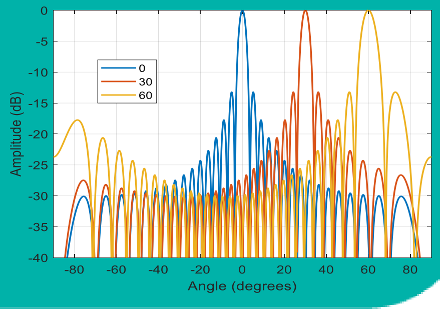
Overview of the Phased Array Workshop

Digitizer

Steering Angle



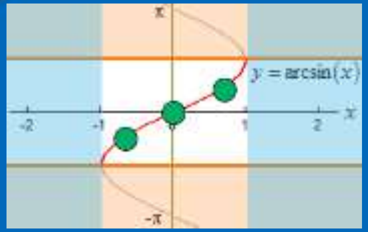
Antenna Patterns



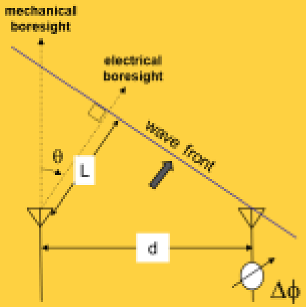
Overview of the Phased Array Workshop

Digitizer

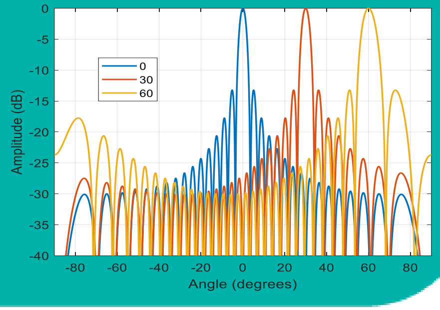
Antenna Impairments



Steering Angle



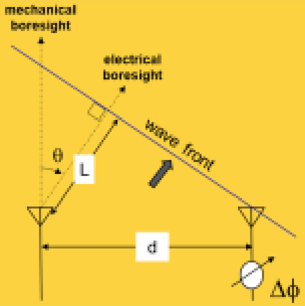
Antenna Patterns



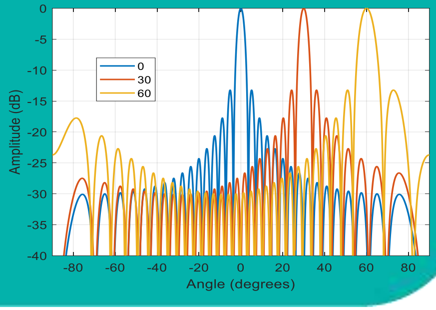
Overview of the Phased Array Workshop

Digitizer

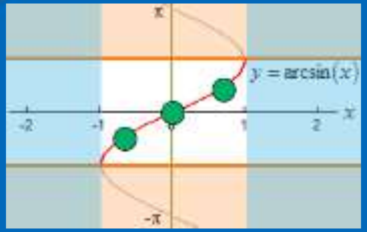
Steering Angle



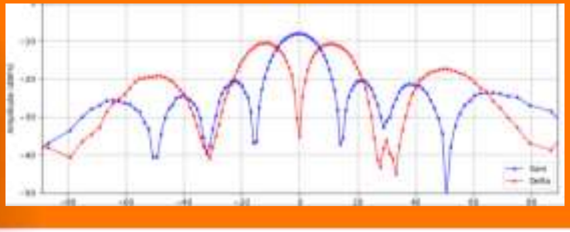
Antenna Patterns



Antenna Impairments



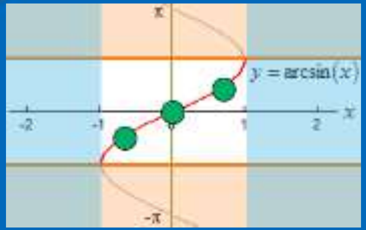
Monopulse Tracking



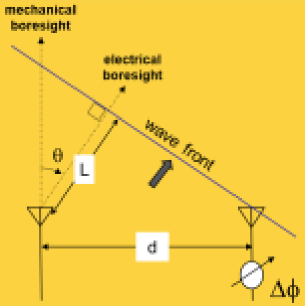
Overview of the Phased Array Workshop

Digitizer

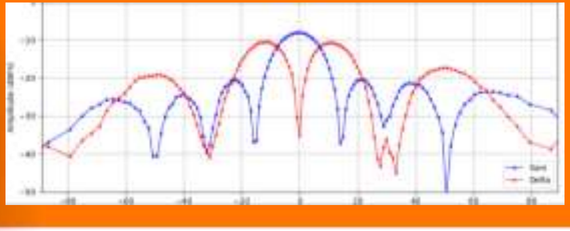
Antenna Impairments



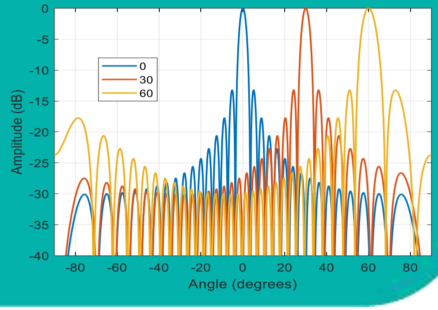
Steering Angle



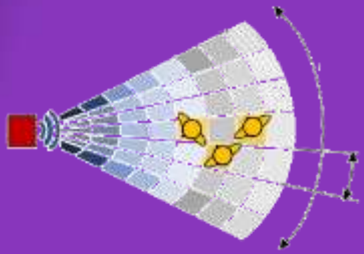
Monopulse Tracking



Antenna Patterns



Radar



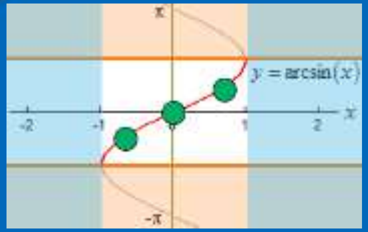
AHEAD OF WHAT'S POSSIBLE™

Session 1:
Hardware Design and Frequency Planning

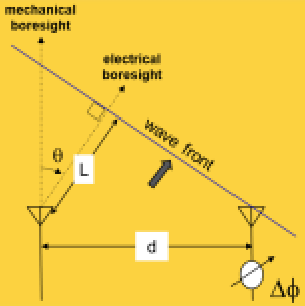
Phased Array Workshop: Hardware Design

Digitizer

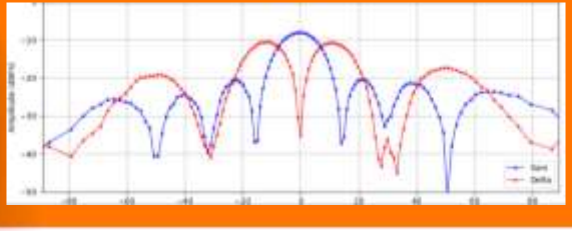
Antenna Impairments



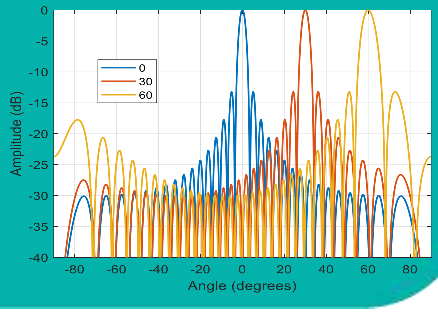
Steering Angle



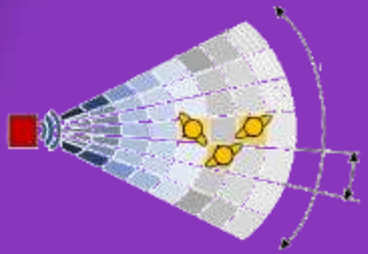
Monopulse Tracking



Antenna Patterns

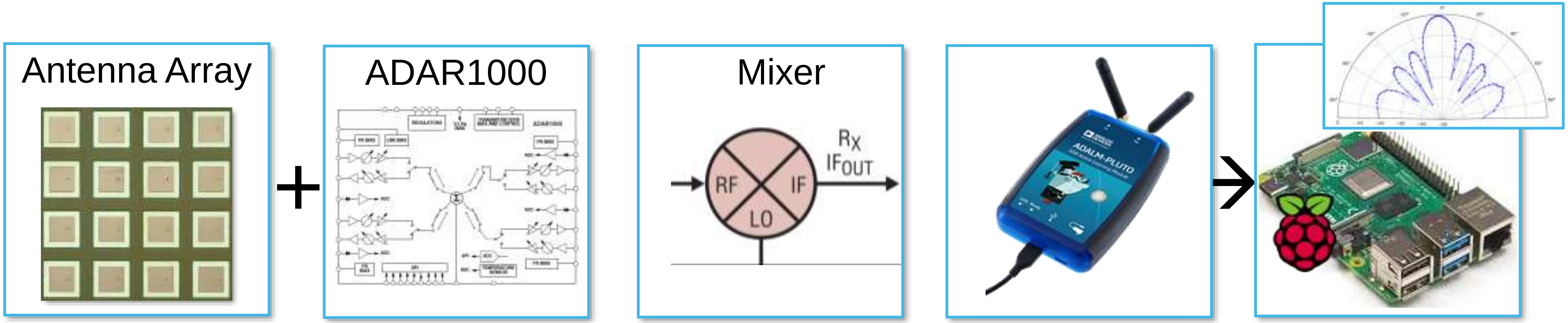


Radar

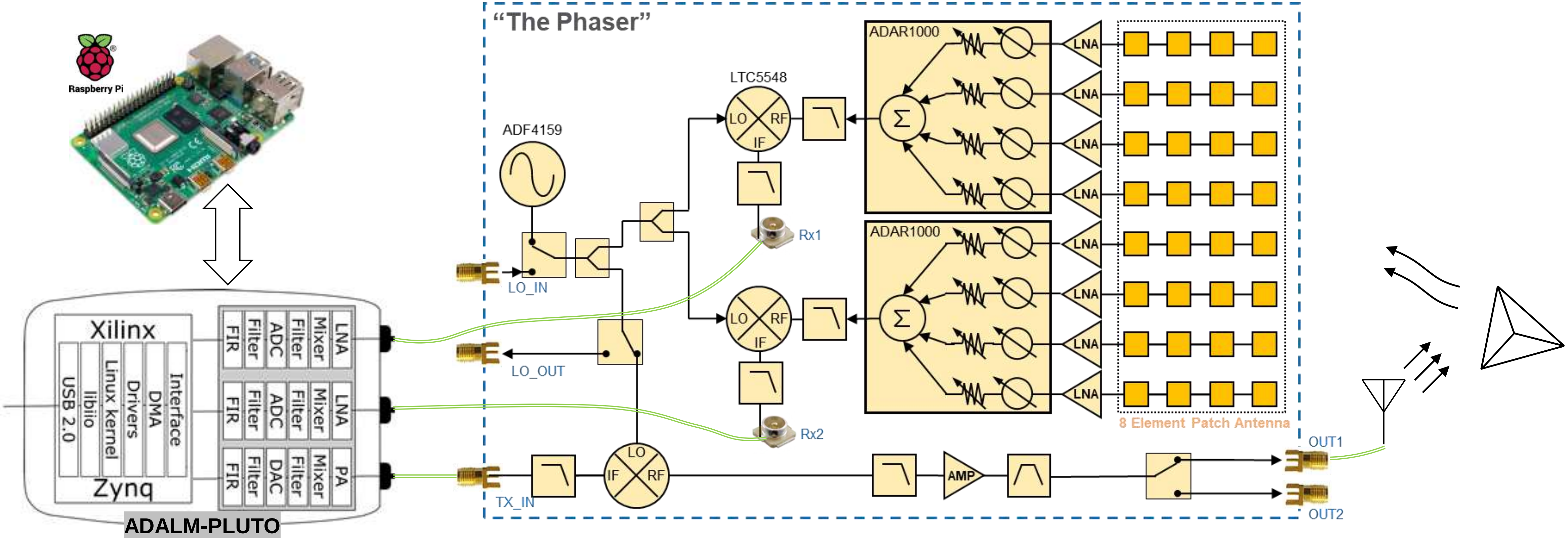


How to Build a Simple Phased Array Radar

- Can we build our own simple beamformer?
- How would we do that?
  - Antenna Array
  - Phase Shifter
  - Mixer (for higher frequencies)
  - Digitizer (data converter or transceiver)
  - And don't forget SOFTWARE!



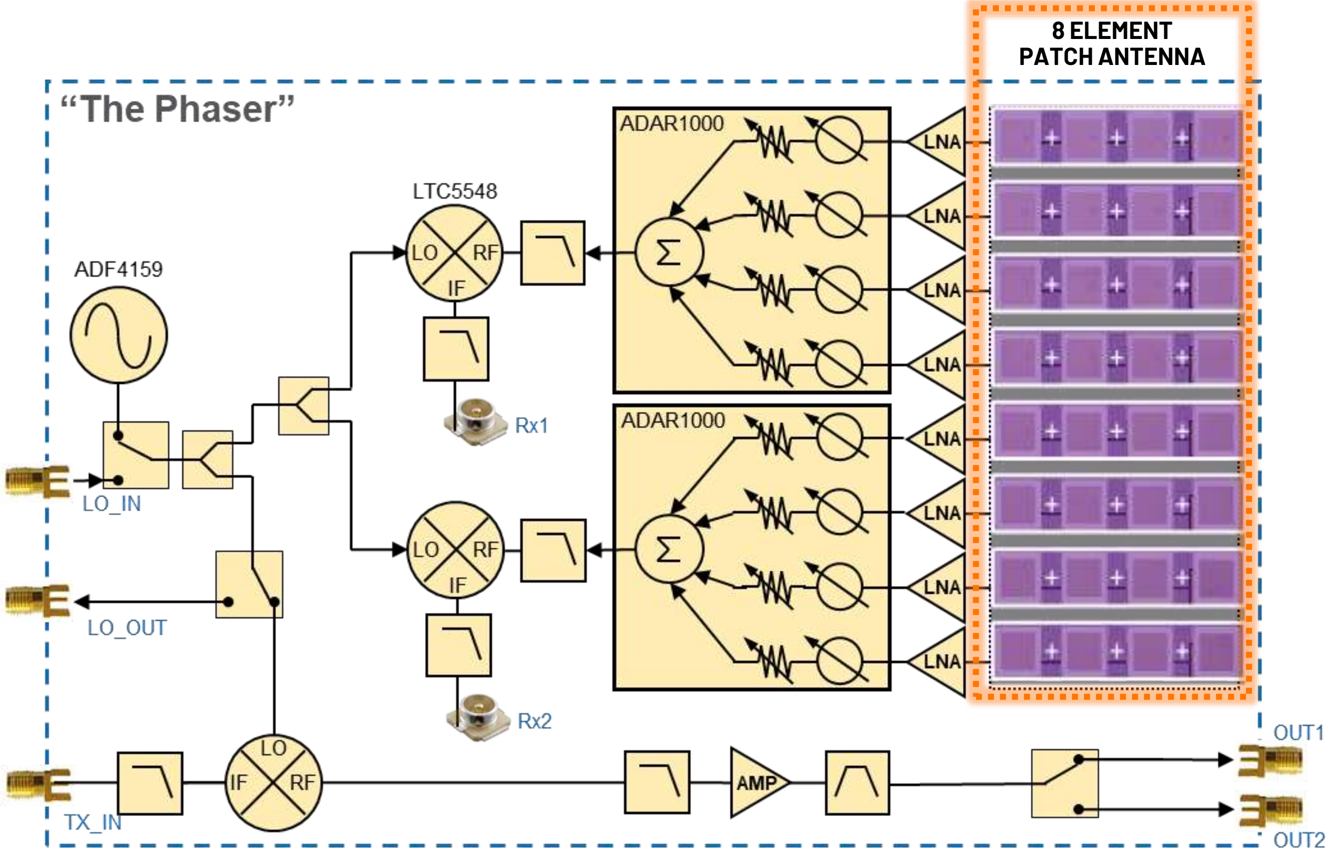
ADALM-PHASER



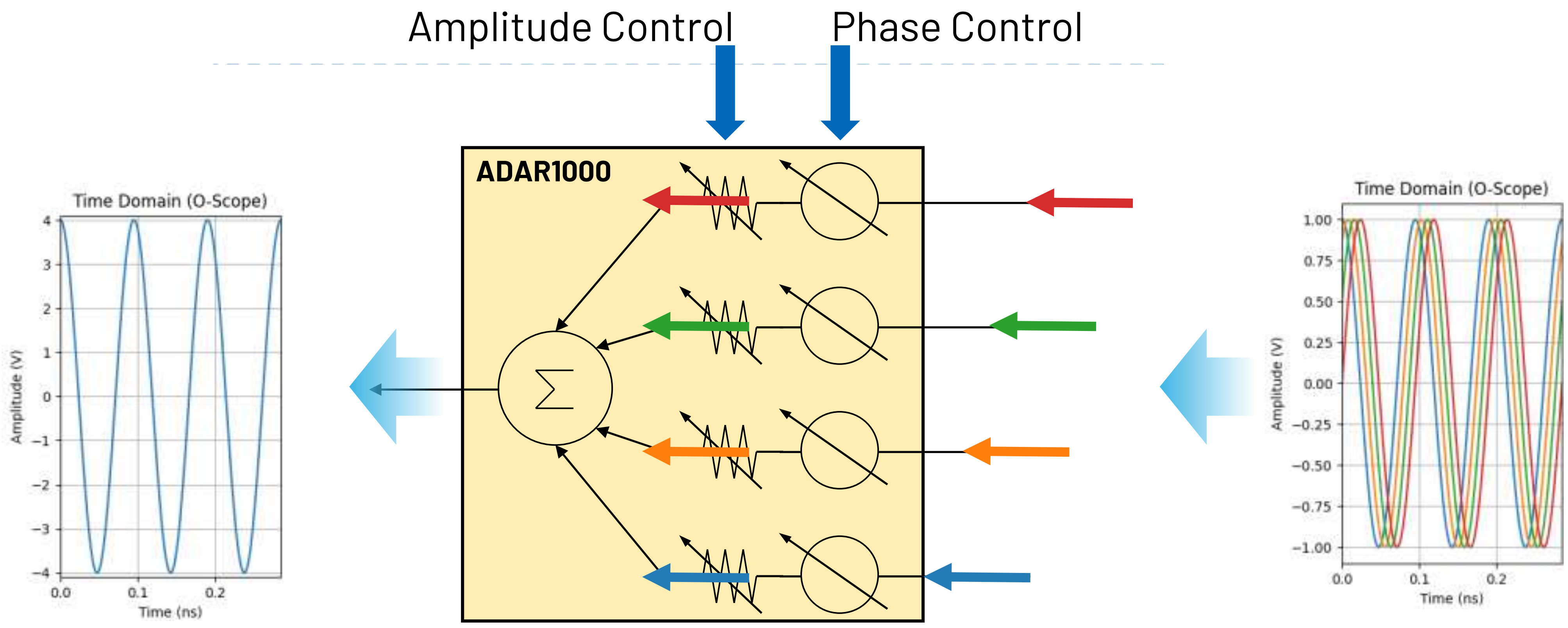
https://wiki.analog.com/phaser

Antenna Array

8 Element Uniform Linear Array



ADAR1000: 4 Channel Analog Beamformer

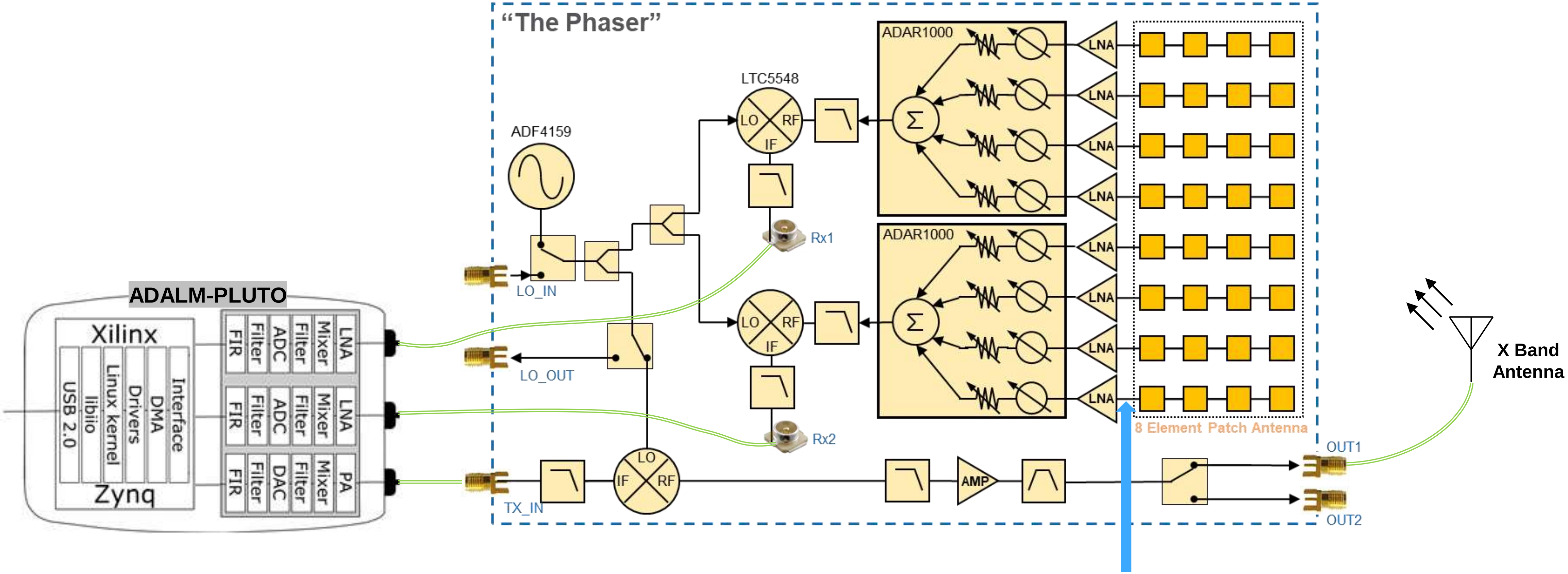


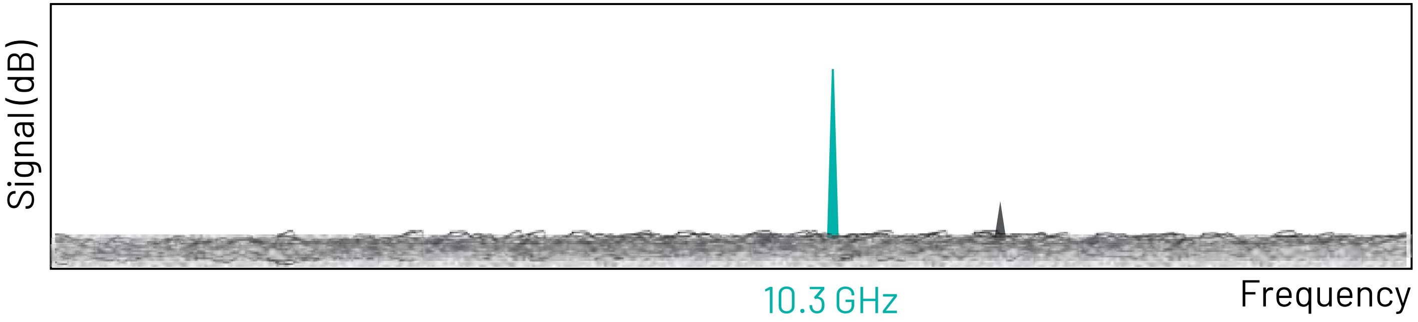
Signals combined in phase

Phase Shift and Adjust Amplitude

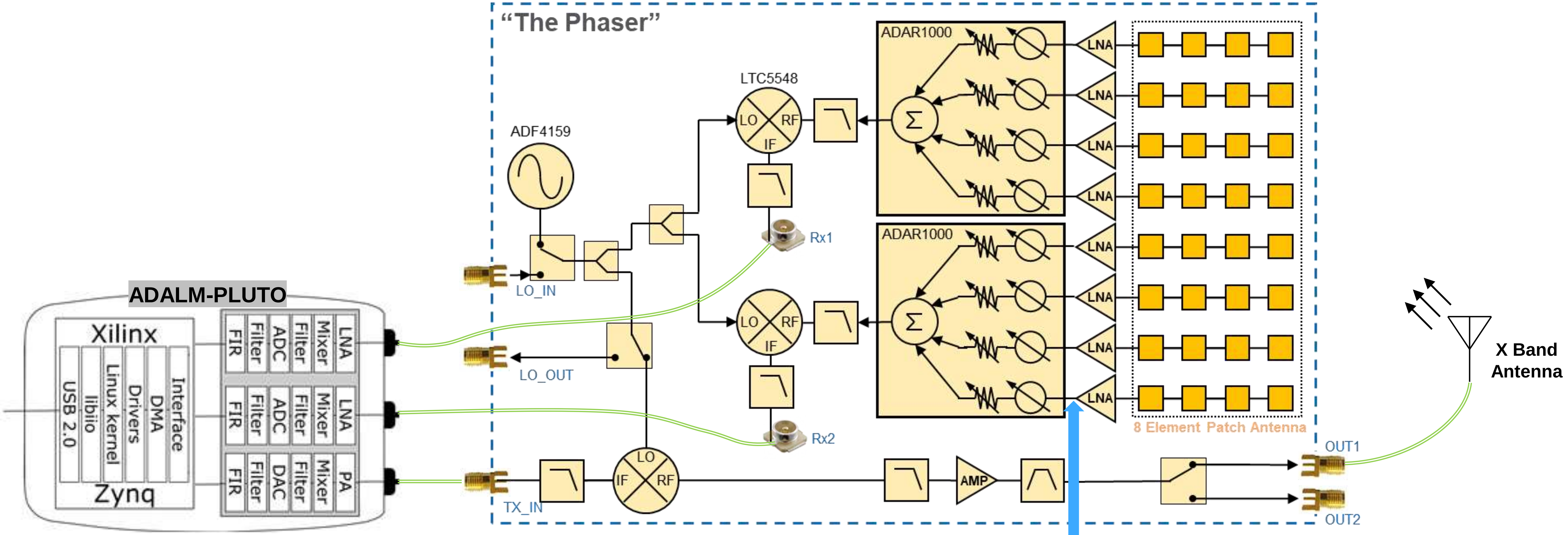
Signals arrive based on angle

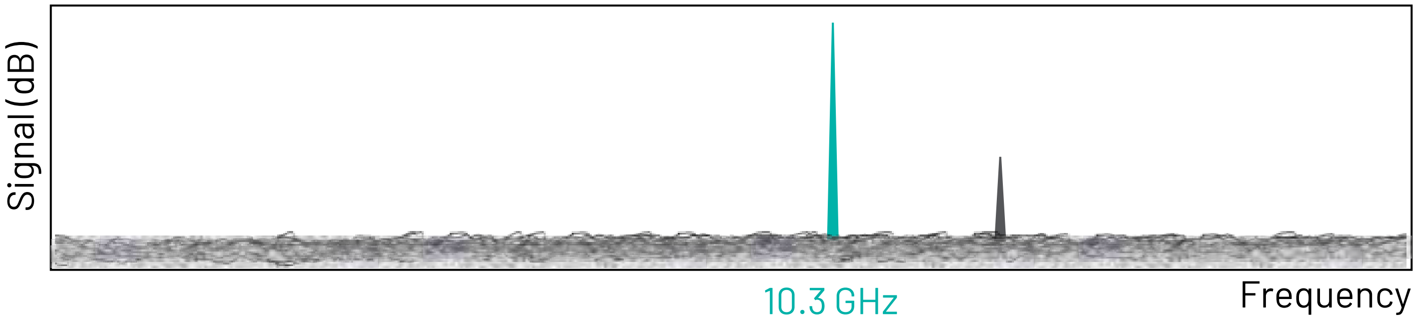
Input from Antenna Array



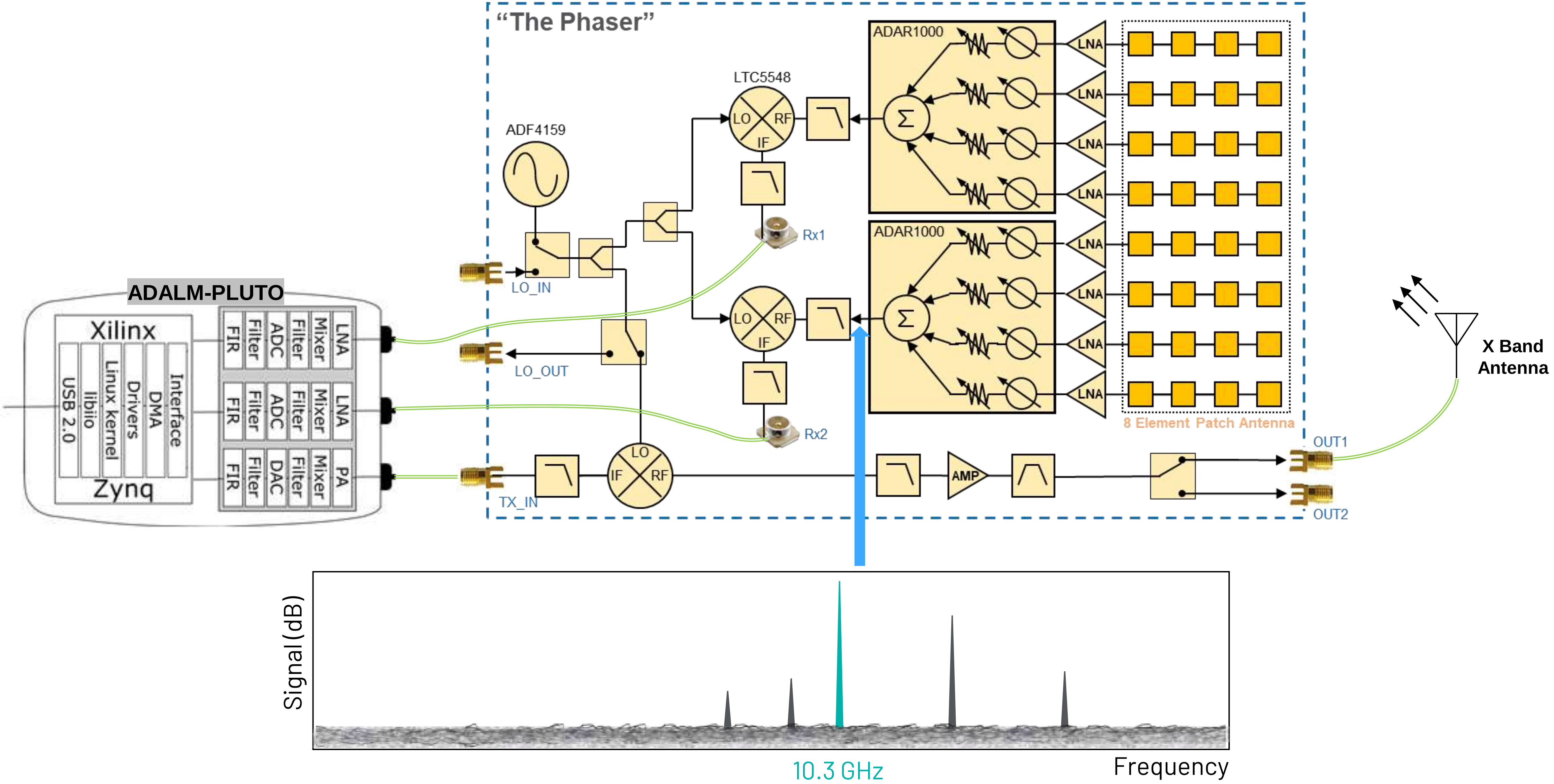


Low Noise Amplifier (LNA)

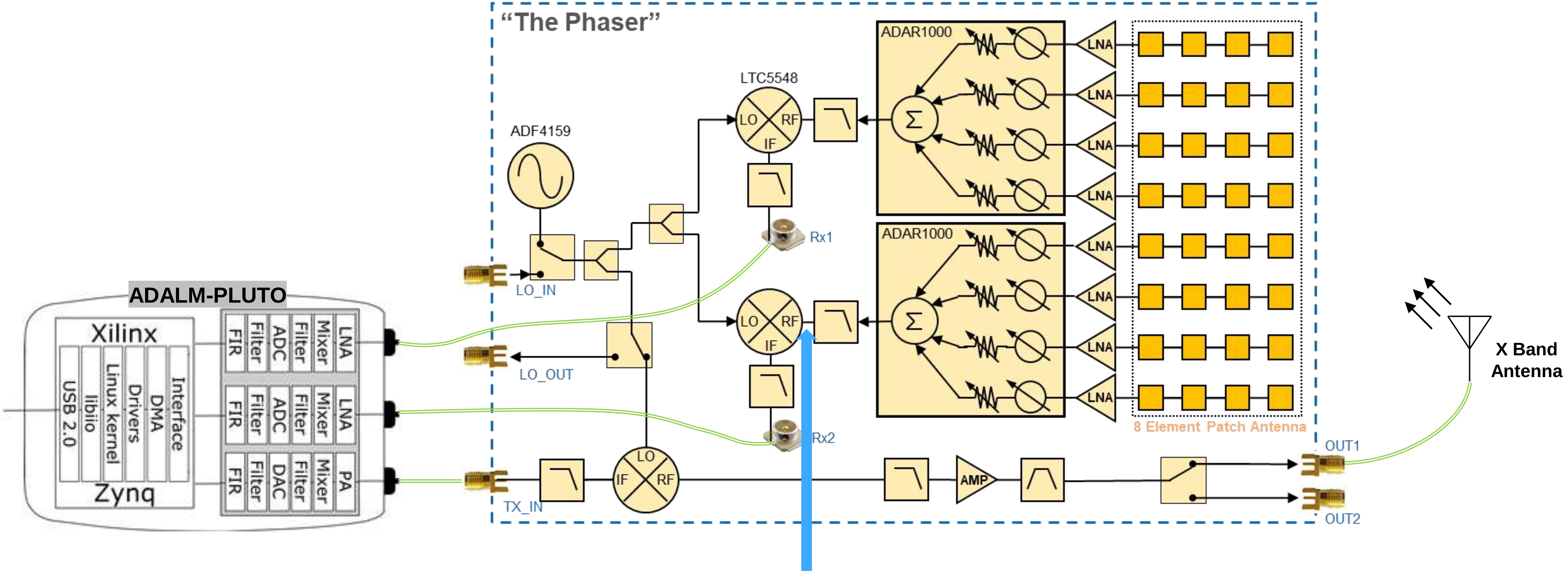


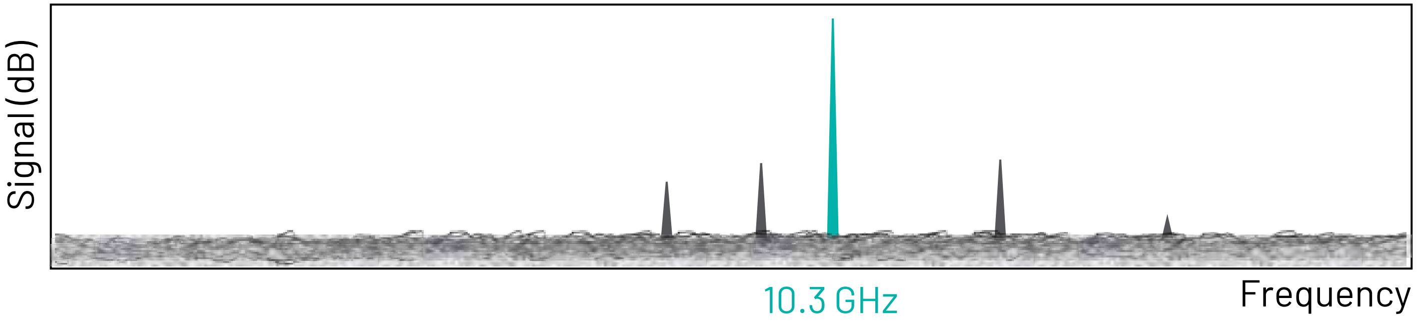


Beamforming

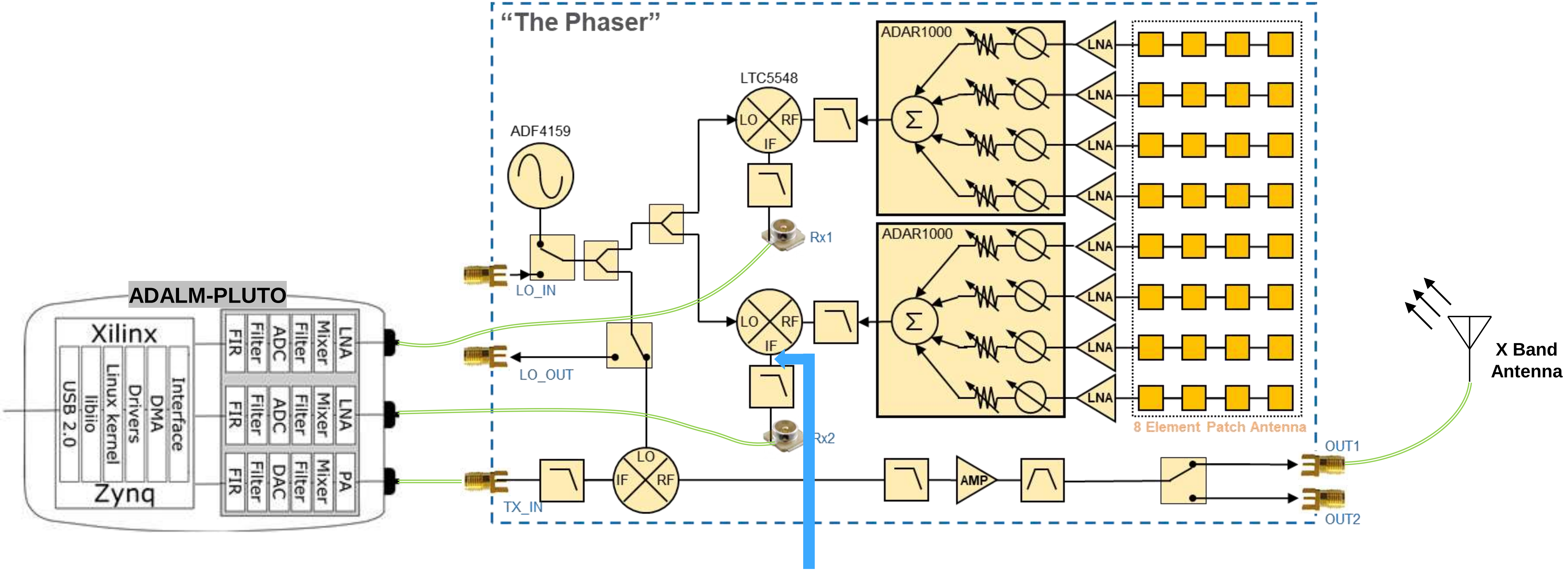


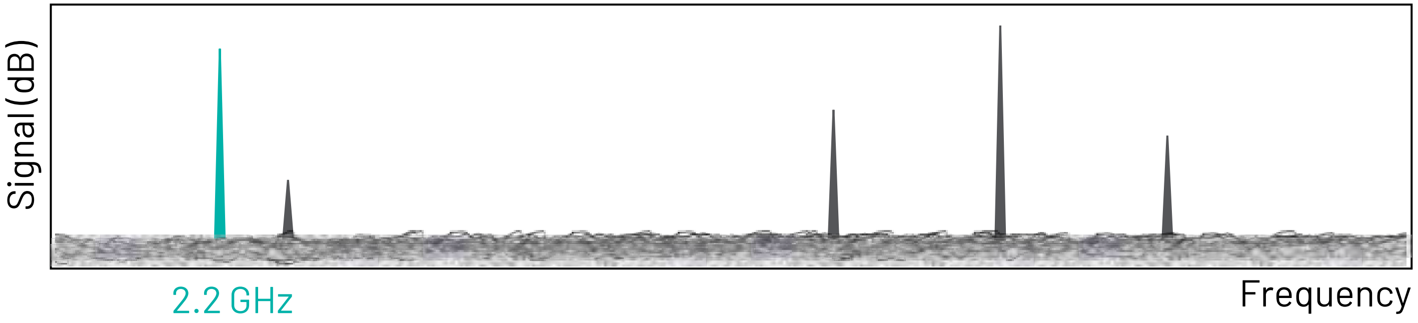
Low Pass Filter to Remove Spurs



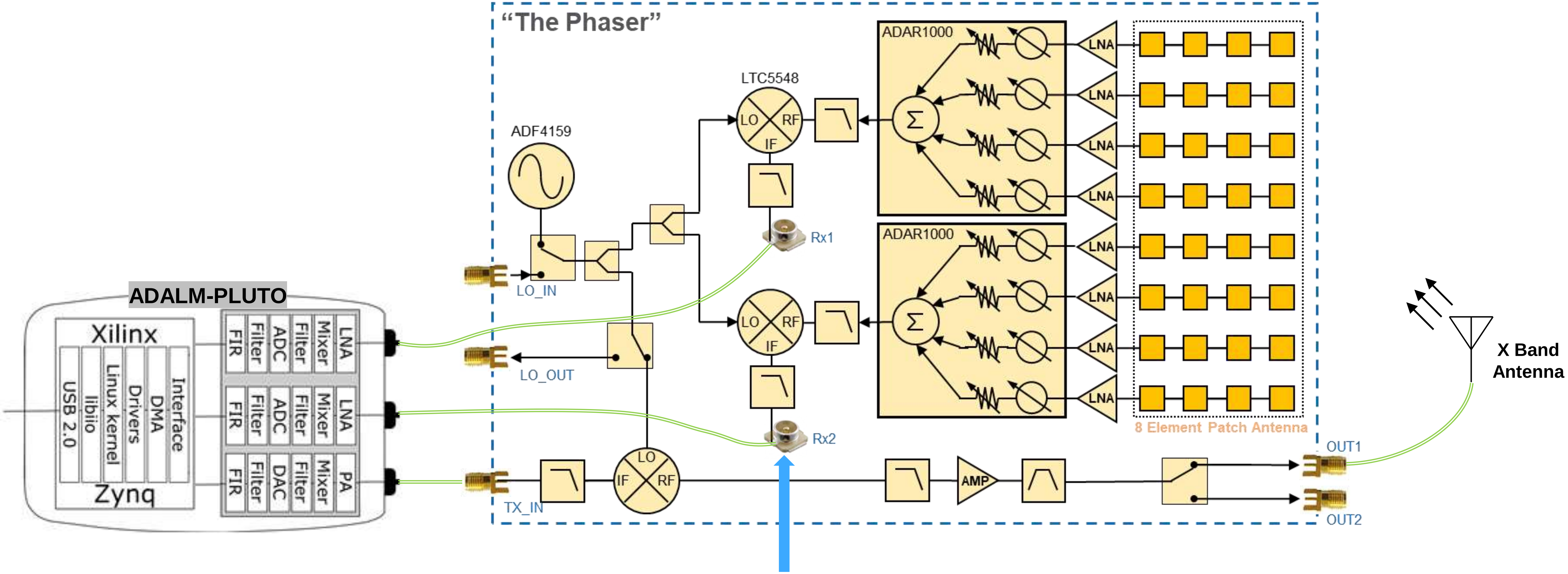


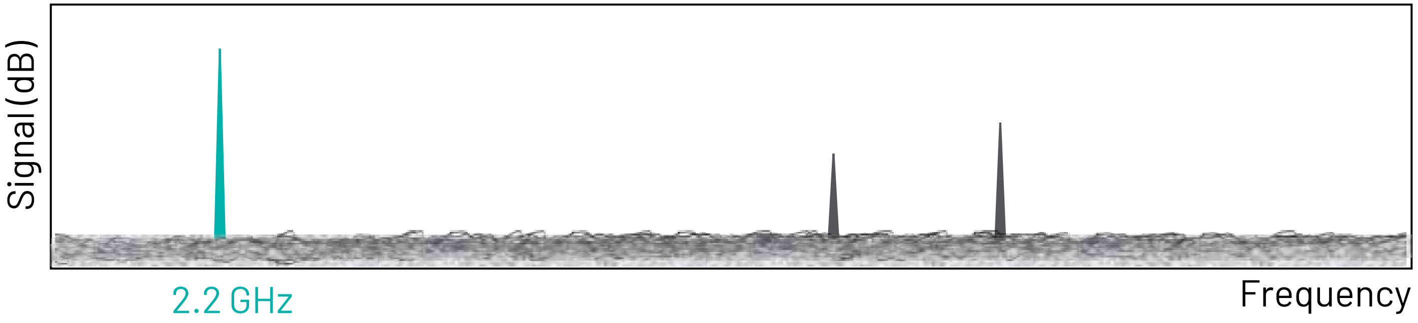
Downconvert with a Mixer



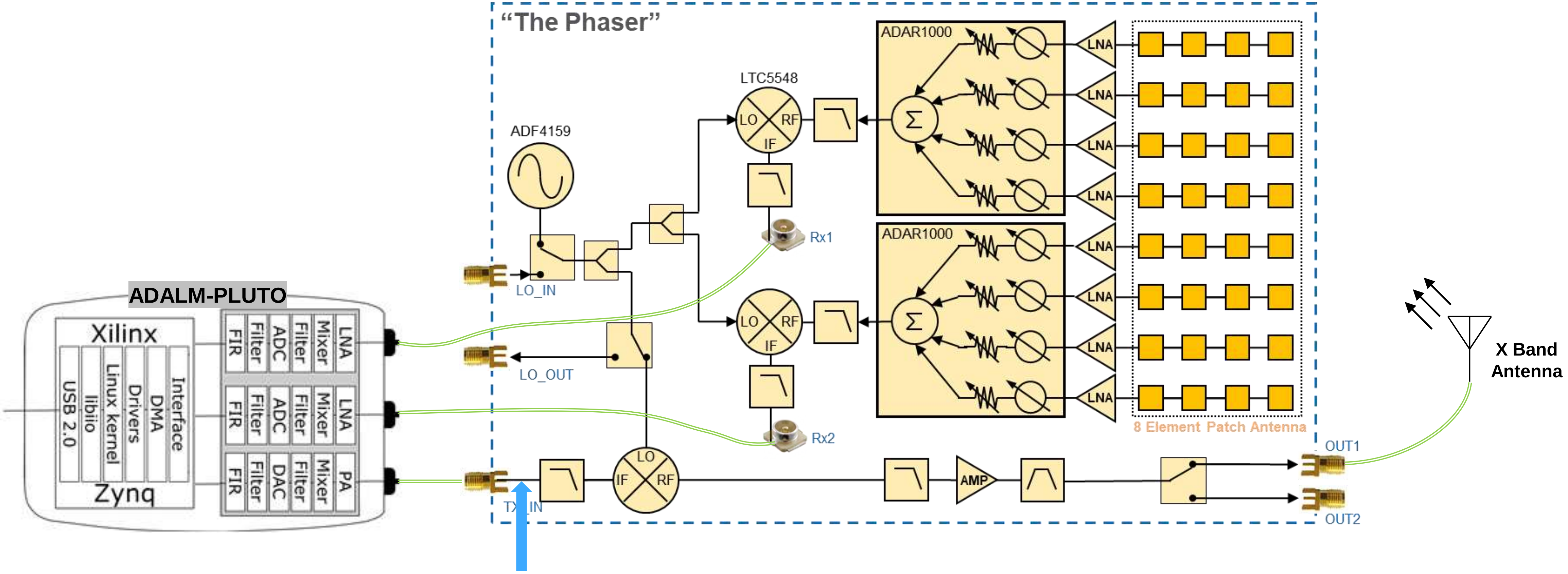


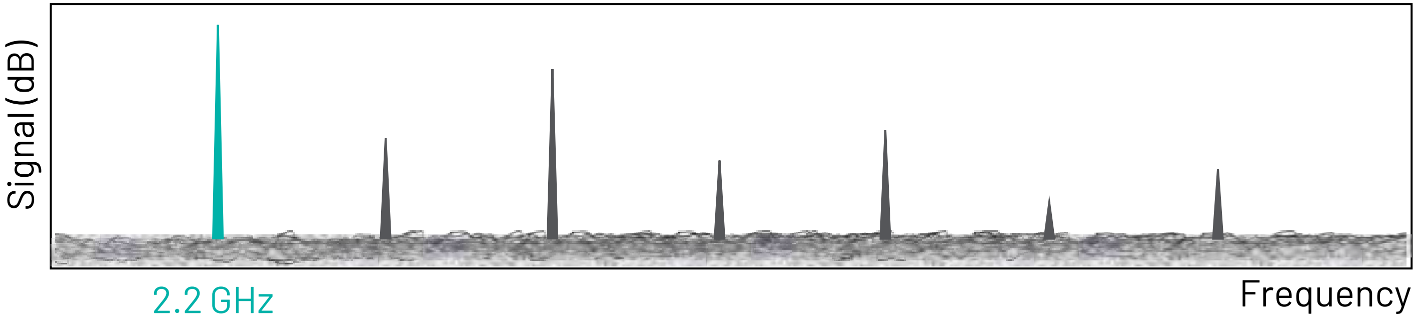
Low Pass Filter, Send to Pluto



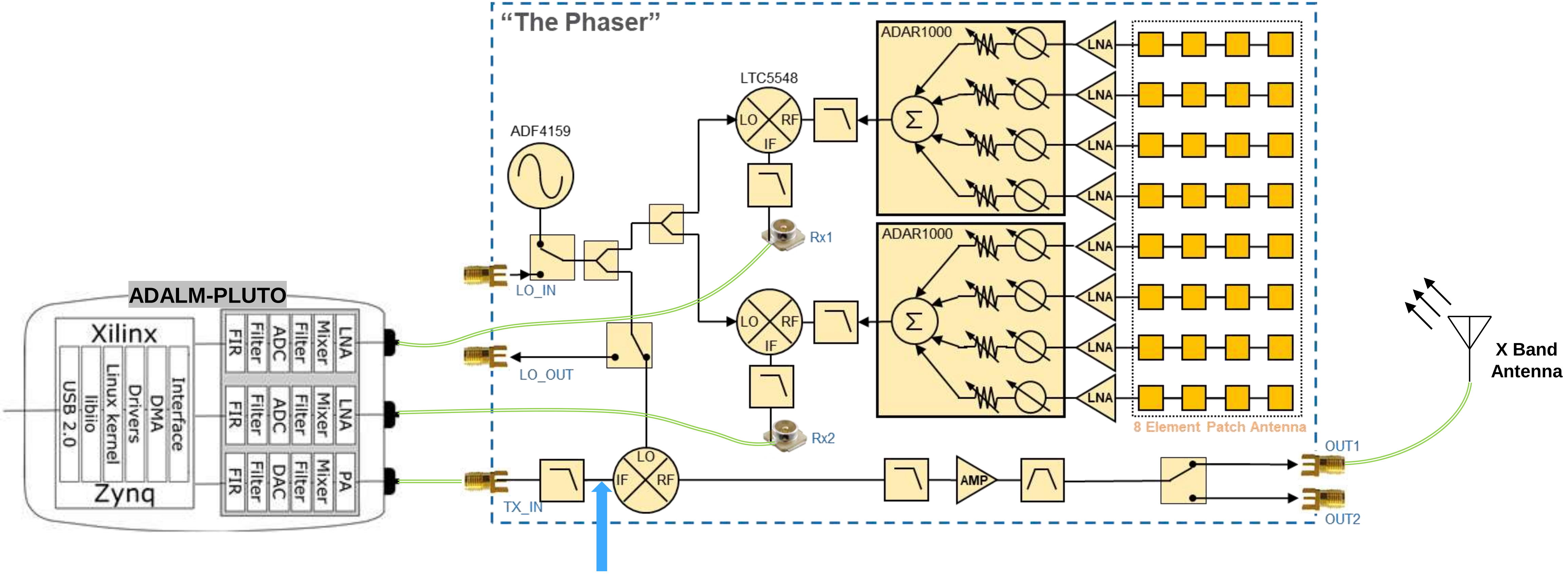


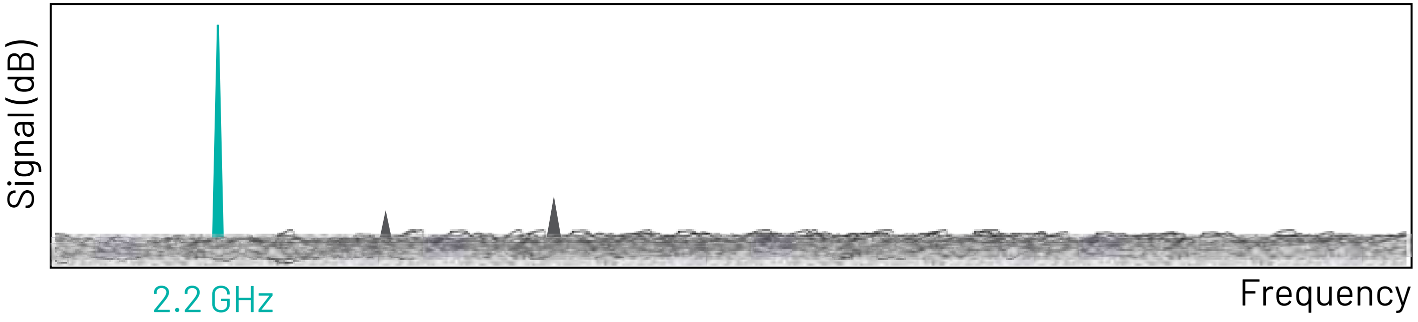
Transmit


"The Phaser"
ADALM-PLUTO
Xilinx
Zynq
USB 2.0
libiio
Linux kernel
Drivers
DMA
Interface
FIR
Filter
ADC
Filter
Mixer
LNA
FIR
Filter
ADC
Filter
Mixer
LNA
FIR
Filter
DAC
Filter
Mixer
PA
ADF4159
LO_IN
LO_OUT
TX_IN
LTC5548
LO
RF
IF
Rx1
Rx2
ADAR1000
ADAR1000
Σ
LNA
AMP
8 Element Patch Antenna
OUT1
OUT2
X Band
Antenna

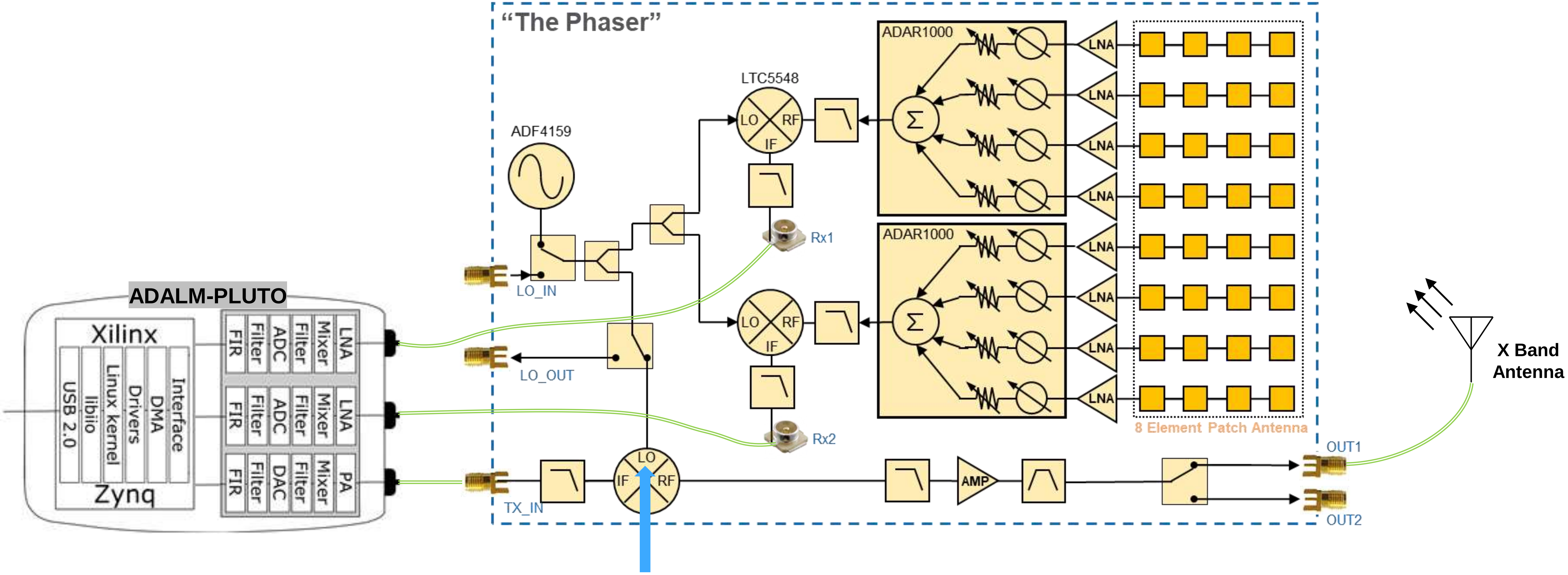

Signal (dB)
2.2 GHz
Frequency

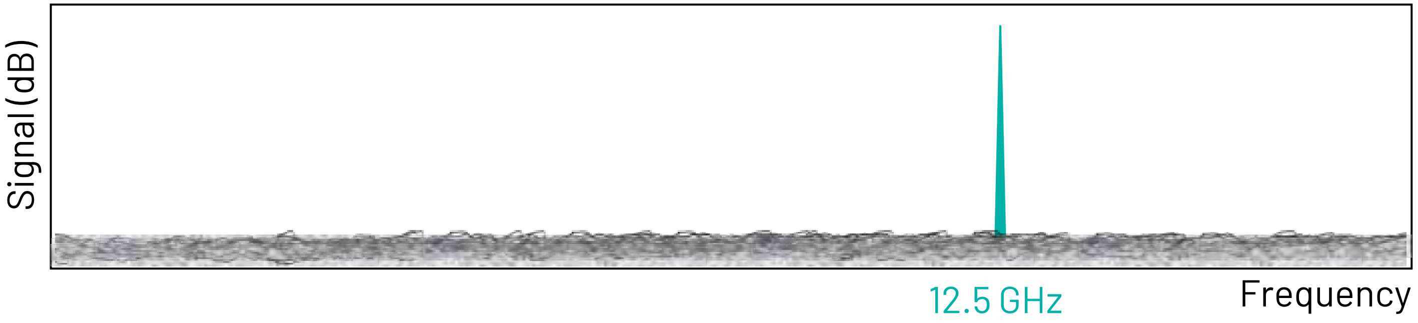
Low Pass Filter



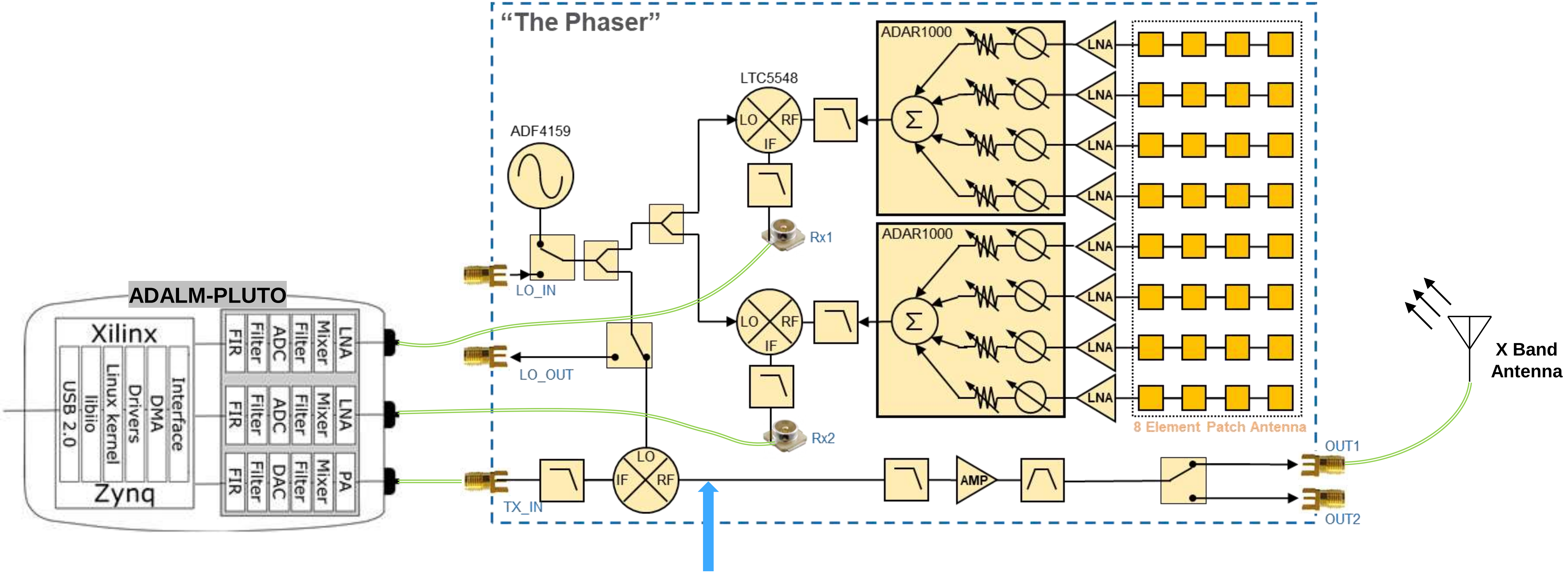


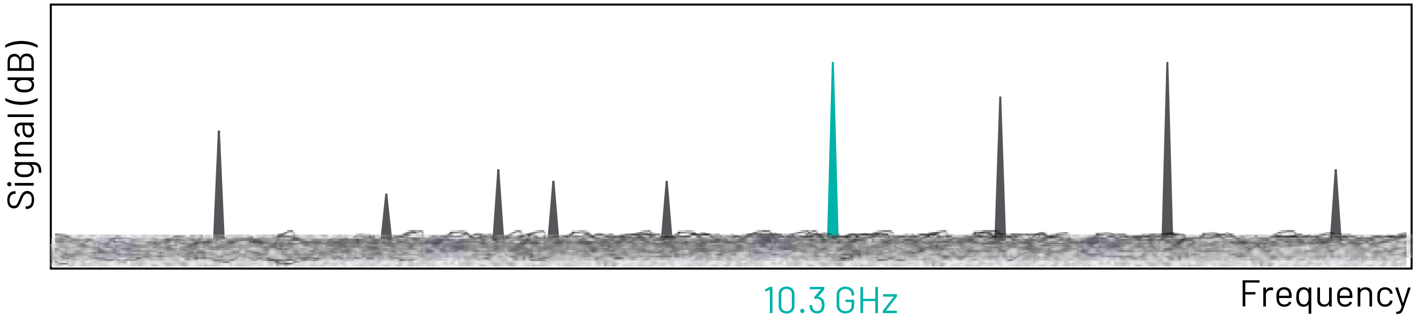
Local Oscillator (LO)



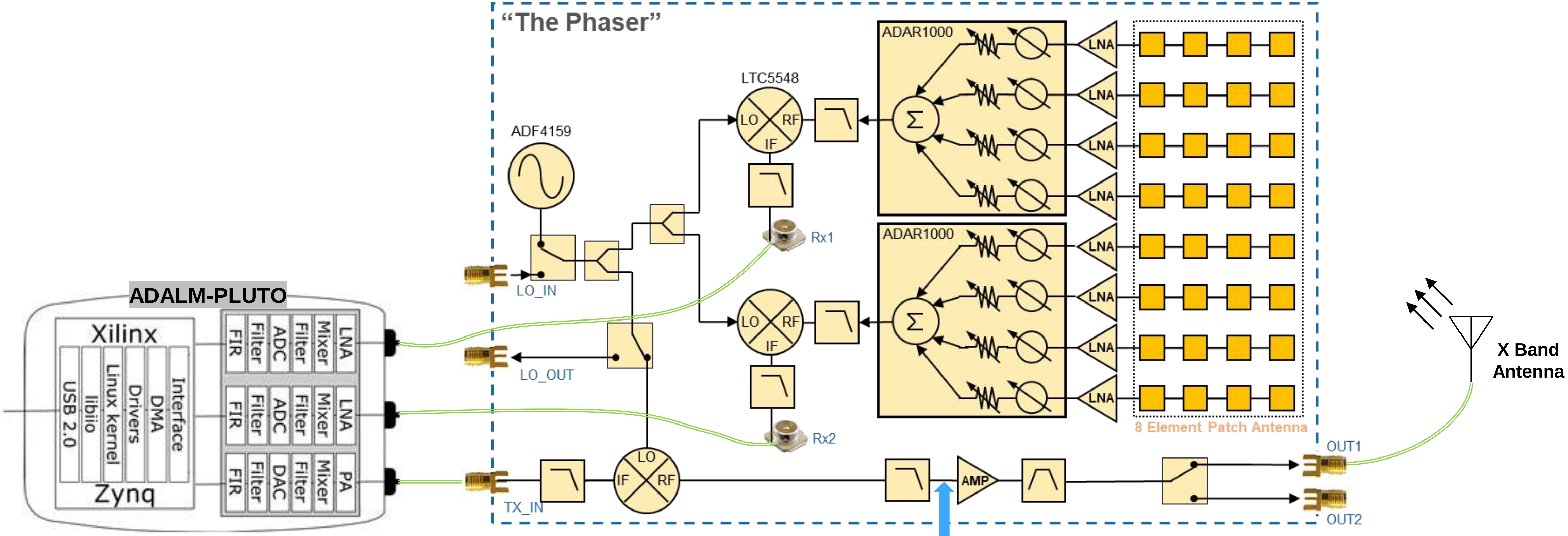


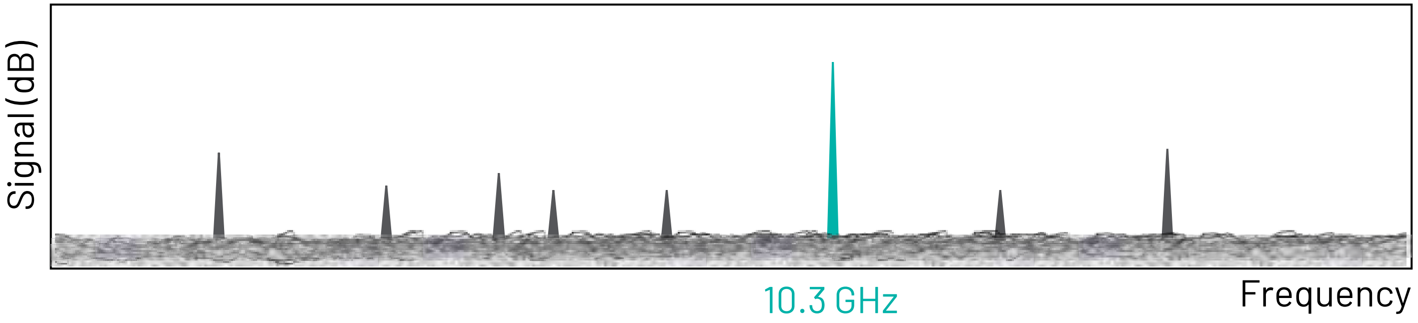
RF Output of the Mixer



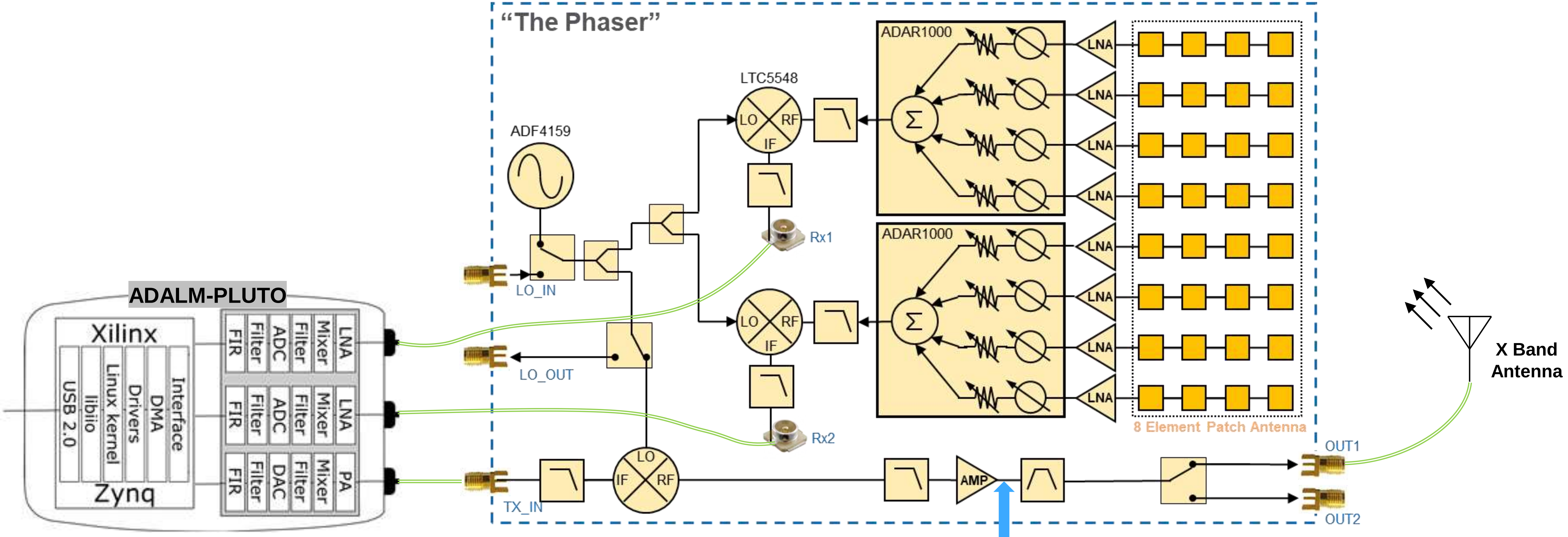


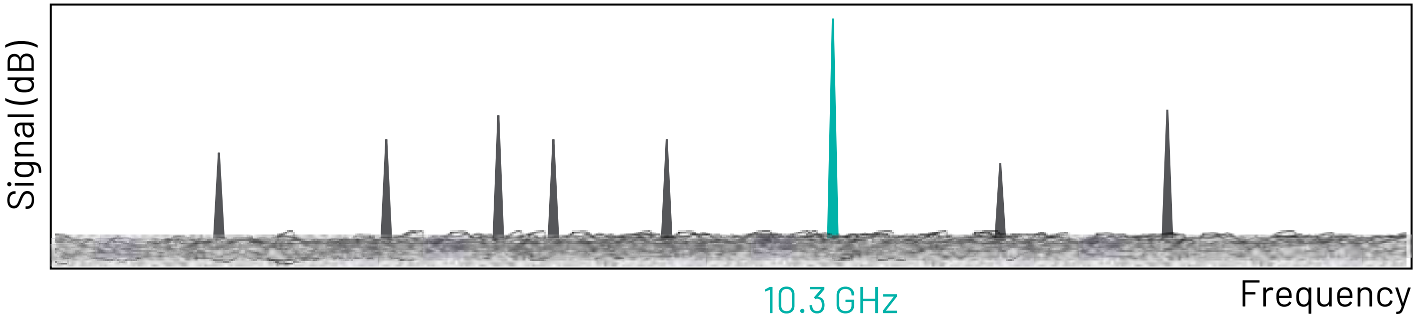
Low Pass Filter 10.3 GHz



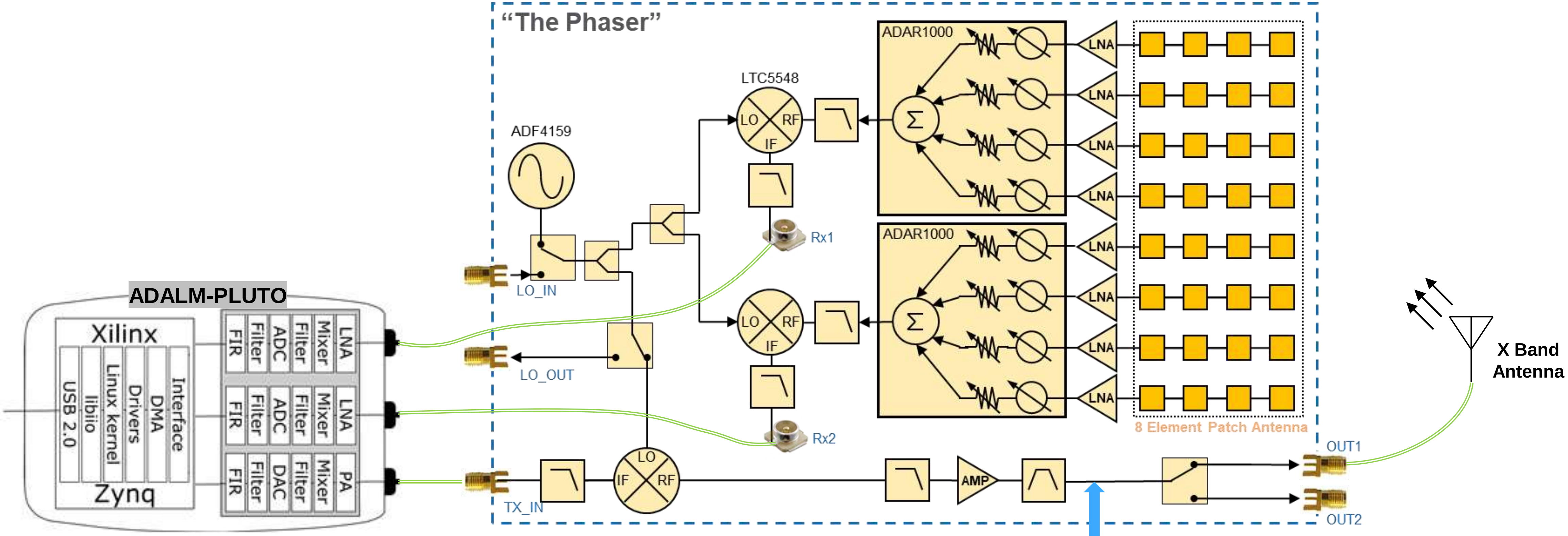


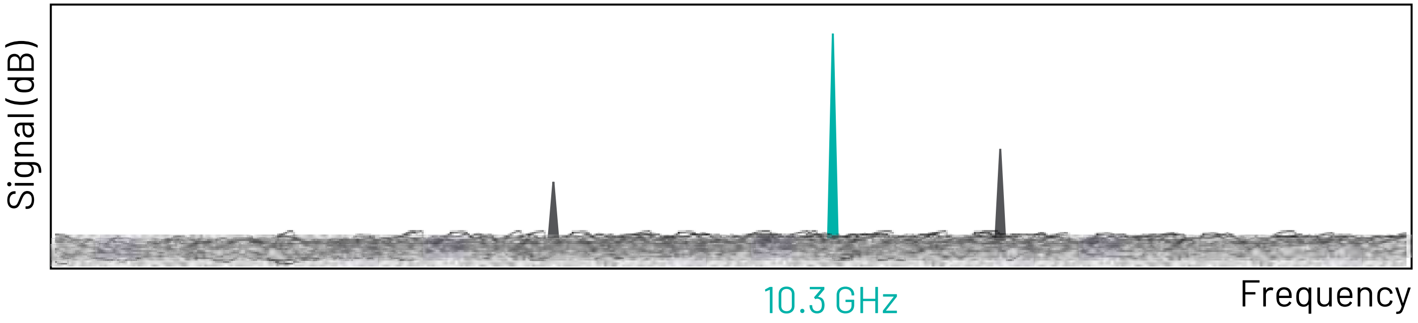
Amplify the Transmit Signal



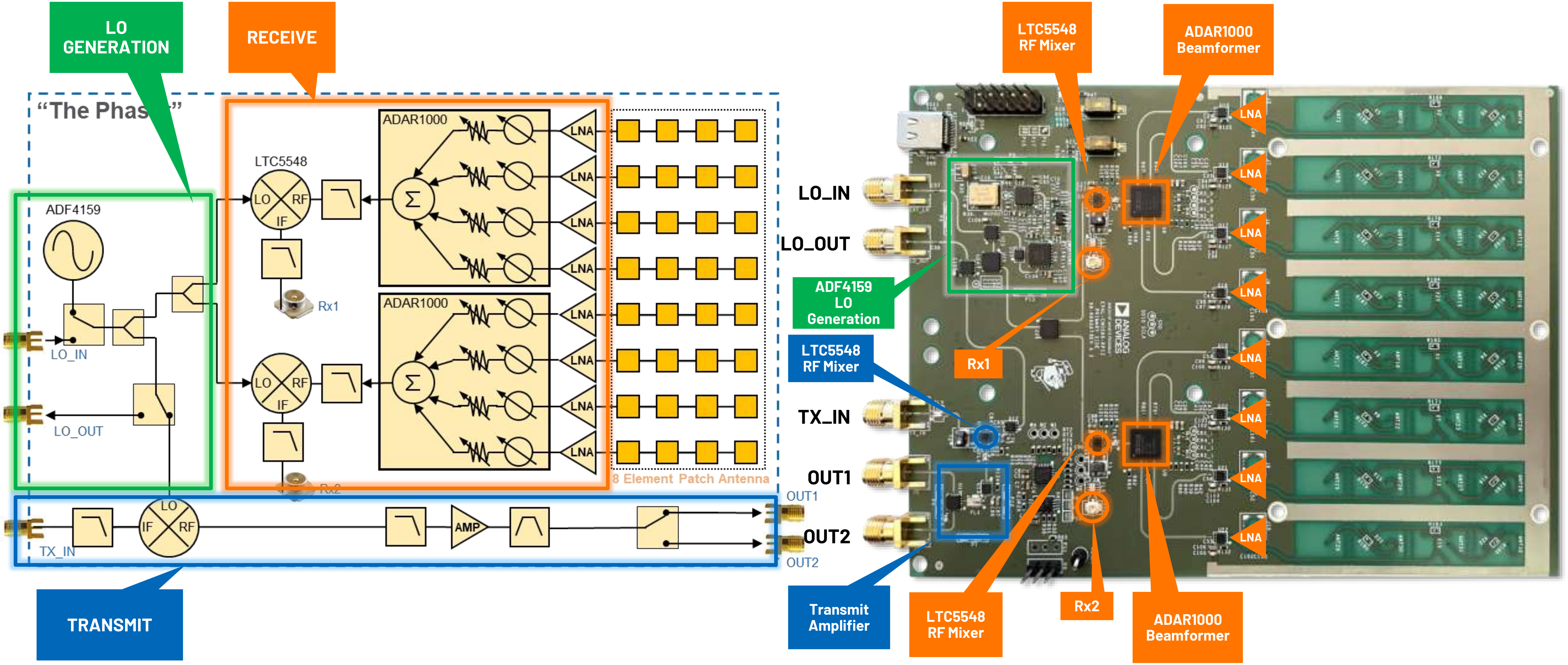


Bandpass Filter to 10 – 11 GHz





Block Diagram to Hardware

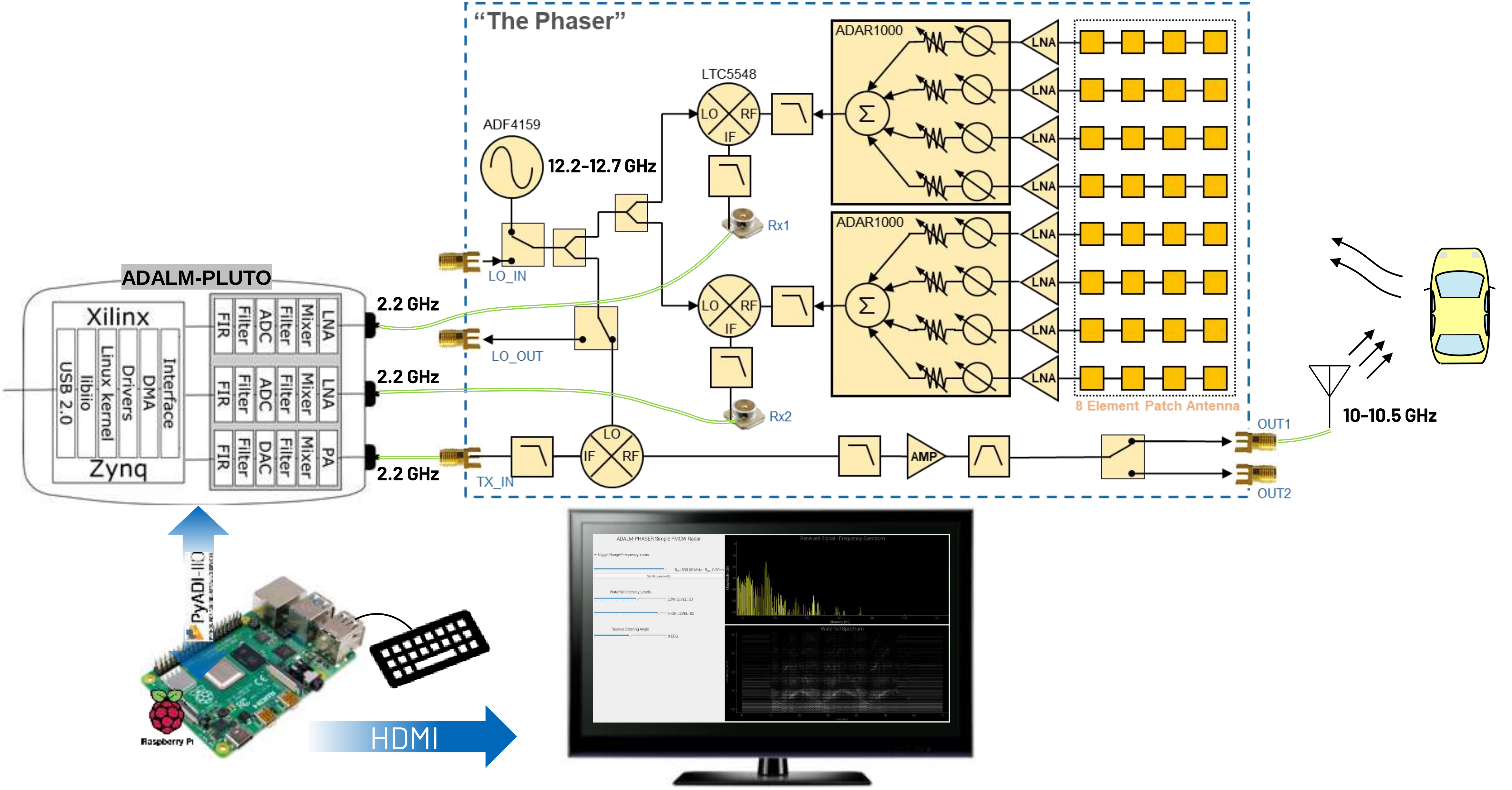


RECEIVE

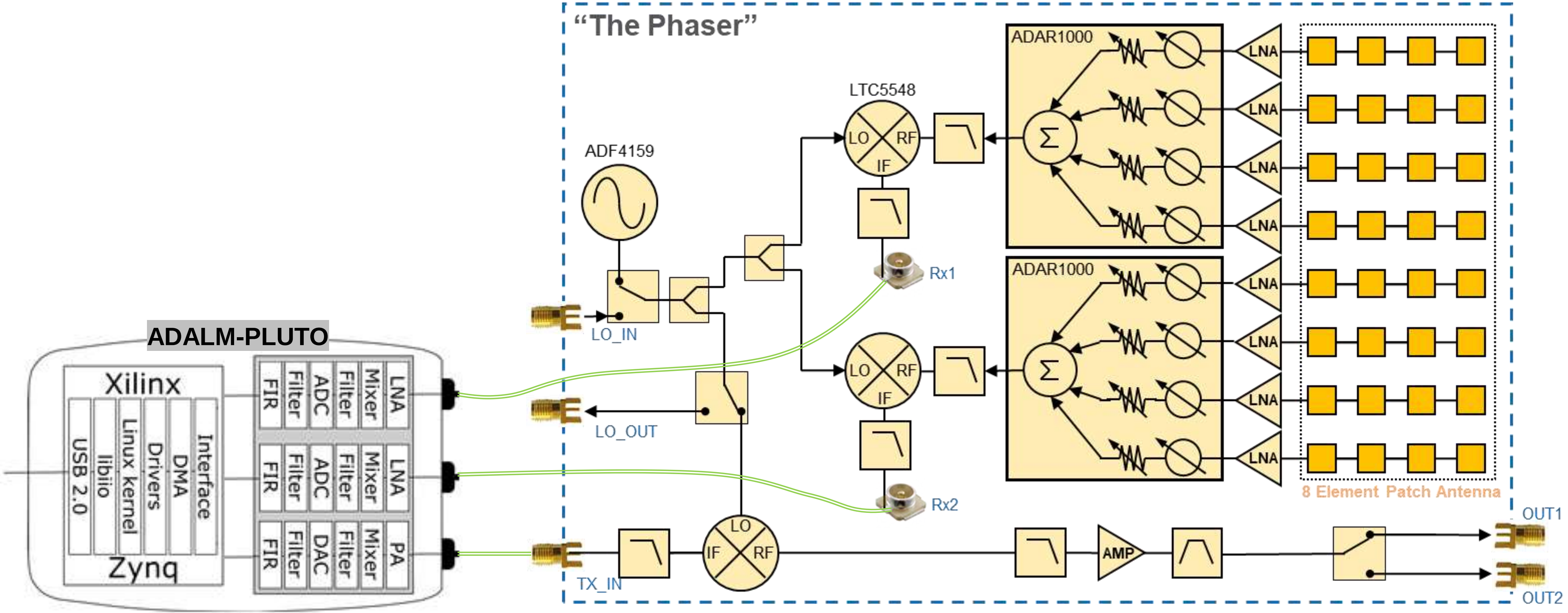
LO GENERATION

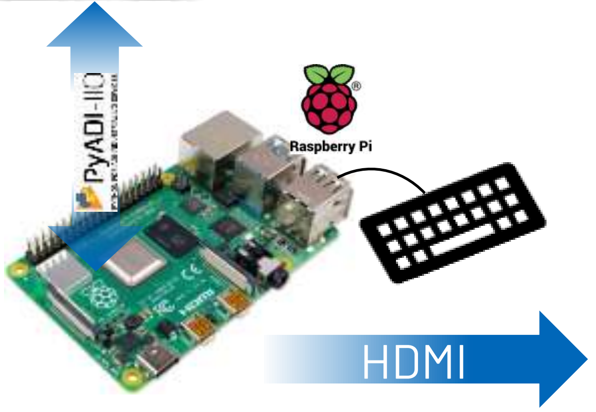
TRANSMIT

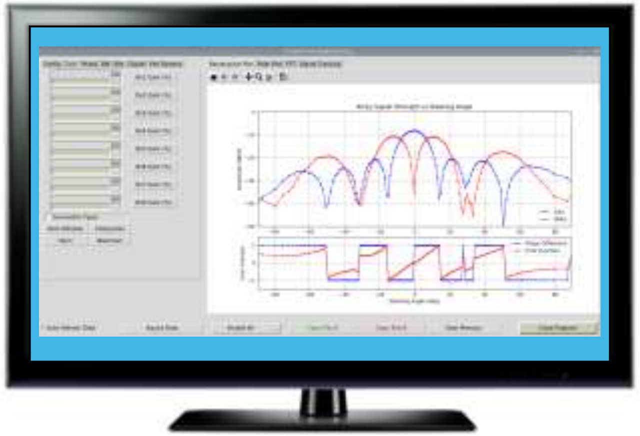
Standard RADAR Configuration



Standard Configuration for Most of the Labs Today





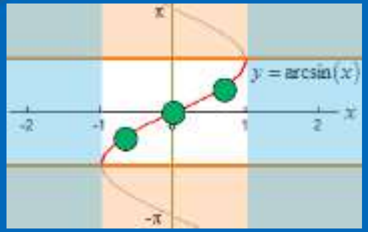


Session 2: SDR and System Level Control

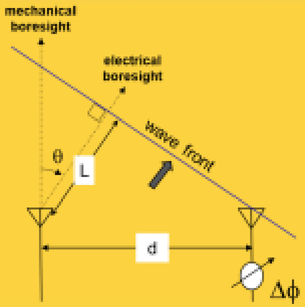
Phased Array Workshop: Software Control

Digitizer

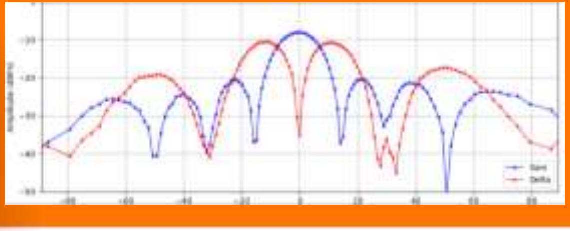
Antenna Impairments



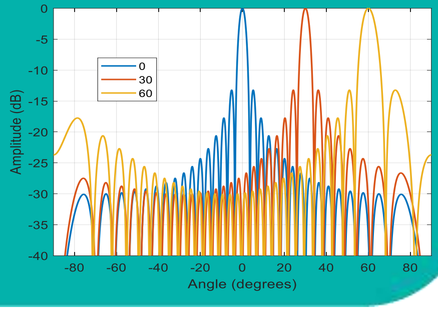
Steering Angle



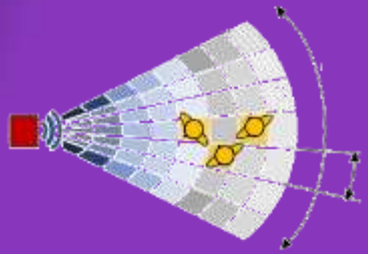
Monopulse Tracking



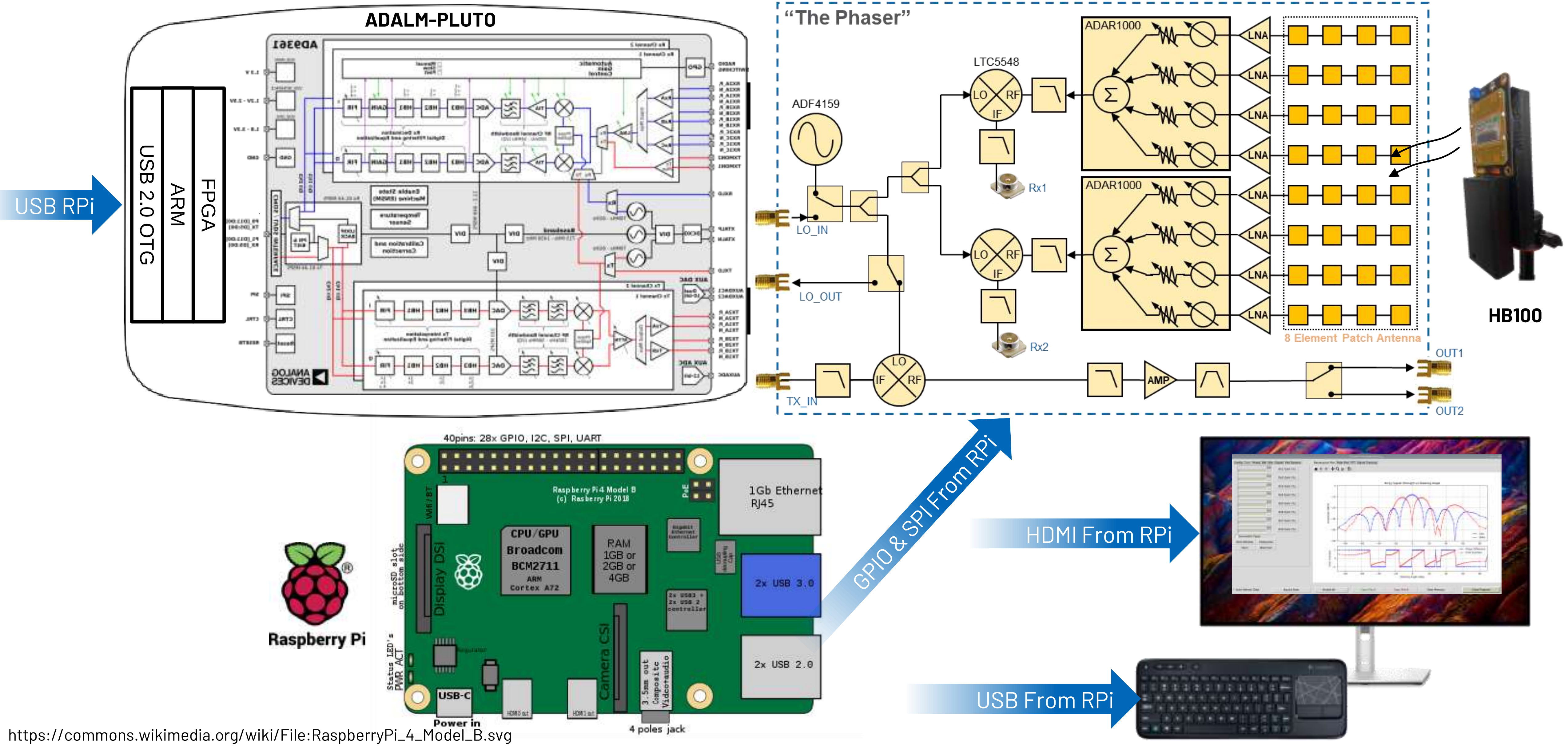
Antenna Patterns



Radar



System Level Diagram



https://commons.wikimedia.org/wiki/File:RaspberryPi_4_Model_B.svg

ADALM-PLUTO (PlutoSDR)

- 2 Rx, 2 Tx SDR
- $200
- Captures I/Q Samples
  - 12-bits
  - 65.1 kSPS to 61.44 MSPS
  - 200kHz to 20 MHz signal bandwidth
- Tuning range;
  - 325 MHz to 3.8 GHz
    - Guaranteed performance
  - 70 MHz to 6.0 GHz
    - Unknown specs
- Sends data to PC for processing over USB2

How to Program and Control the ADALM-Phaser

- Two Easy Methods:
  - Matlab → use Analog Devices Board Support Package in Matlab
  - Python → use PyADI-IIO
- We are using Python (it runs nicely on the Raspberry Pi)
- So we use PyADI-IIO:
  - https://analogdevicesinc.github.io/pyadi-iio/
  - PyADI-IIO is a python abstraction module for ADI hardware with IIO drivers to make them easier to use."
  - "glue layer" between IIO (which has a bit of a learning curve) and doing something useful
  - Pre-installed on ADI Kuiper Linux (ADI's custom Raspberry Pi OS, with device drivers and utilities)
  - Under the Surface: Built on the industry-standard Linux Industrial I/O framework:
    - Cross platform API (Windows/Linux/Mac)
    - Multiple bindings (Python, MATLAB, C, C#)

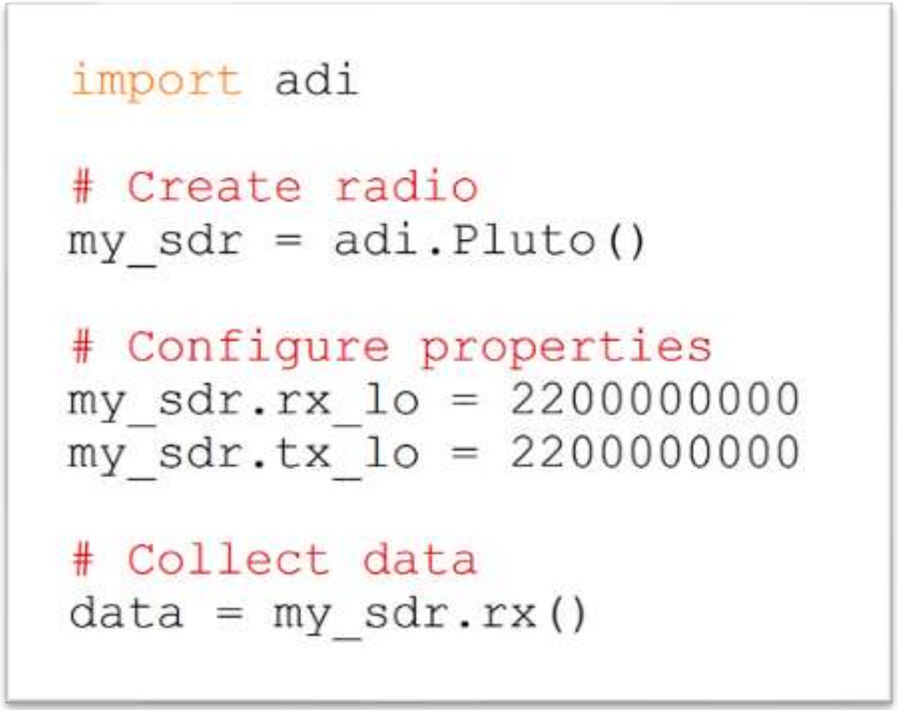
PyADI-IIO
PYTHON FOR ADI INDUSTRIAL I/O DEVICES

PYADI-IIO makes Python Control Easy!

PyADI-IIO

PYTHON FOR ADI INDUSTRIAL I/O DEVICES

- How easy is PYADI-IIO????
- Grab a chunk of data from Pluto a few lines of code:

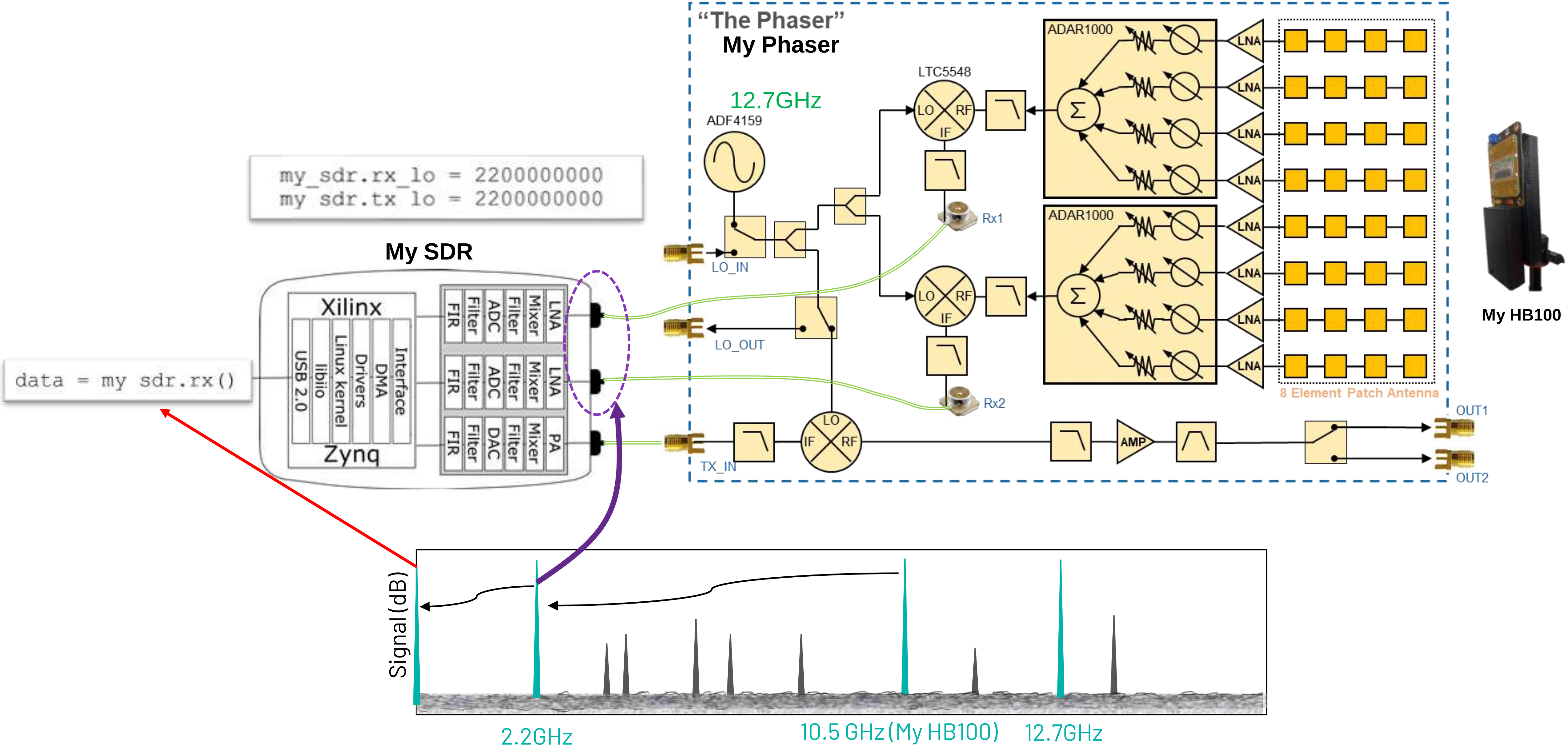


```
import adi

# Create radio
my_sdr = adi.Pluto()

# Configure properties
my_sdr.rx_lo = 2200000000
my_sdr.tx_lo = 2200000000

# Collect data
data = my_sdr.rx()
```

- Full example script here:

https://github.com/analogdevicesinc/pyadi-iio/blob/master/examples/pluto.py

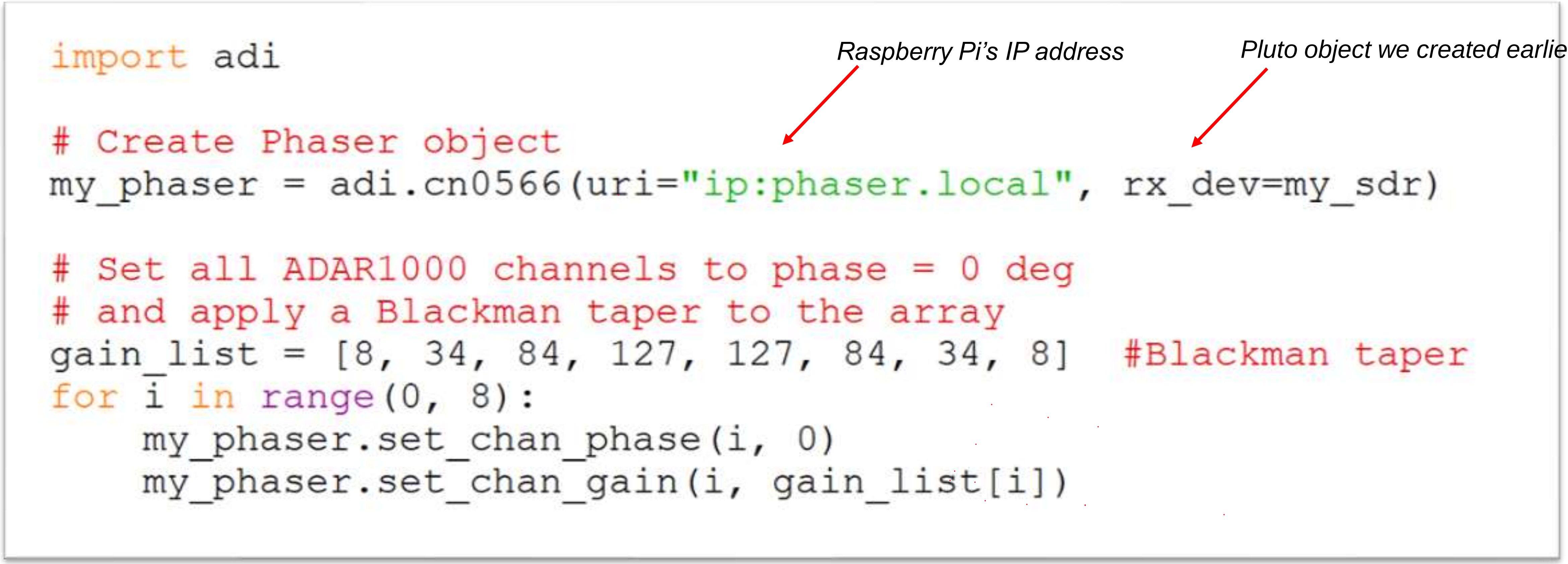
What can we do with Python and Pyadi-iio?



```
my_sdr.rx_lo = 2200000000
my_sdr.tx_lo = 2200000000
```

```
data = my_sdr.rx()
```

What does the Python look like to Control Phaser?



```
import adi

# Create Phaser object
my_phaser = adi.cn0566(uri="ip:phaser.local", rx_dev=my_sdr)

# Set all ADAR1000 channels to phase = 0 deg
# and apply a Blackman taper to the array
gain_list = [8, 34, 84, 127, 127, 84, 34, 8]  #Blackman taper
for i in range(0, 8):
    my_phaser.set_chan_phase(i, 0)
    my_phaser.set_chan_gain(i, gain_list[i])
```

Raspberry Pi's IP address

Pluto object we created earlier

- Full example script here:

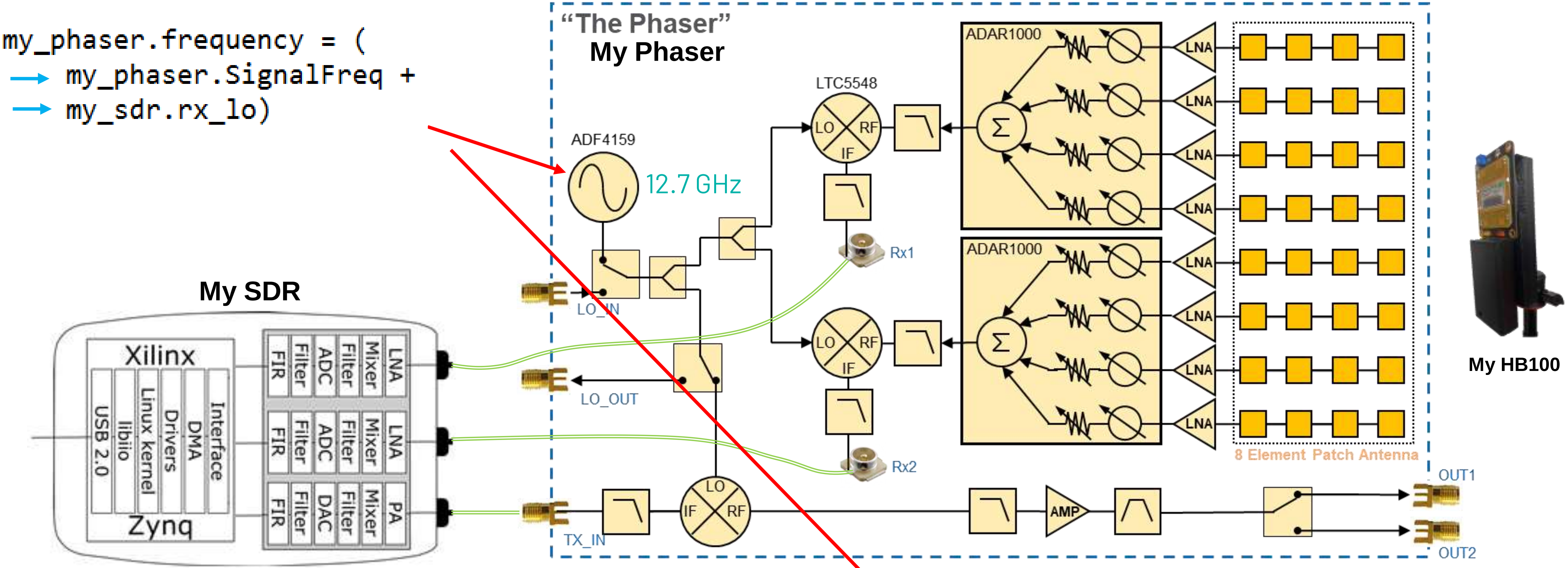
https://github.com/analogdevicesinc/pyadi-iio/blob/cn0566_dev/examples/cn0566/cn0566_minimal_example.py

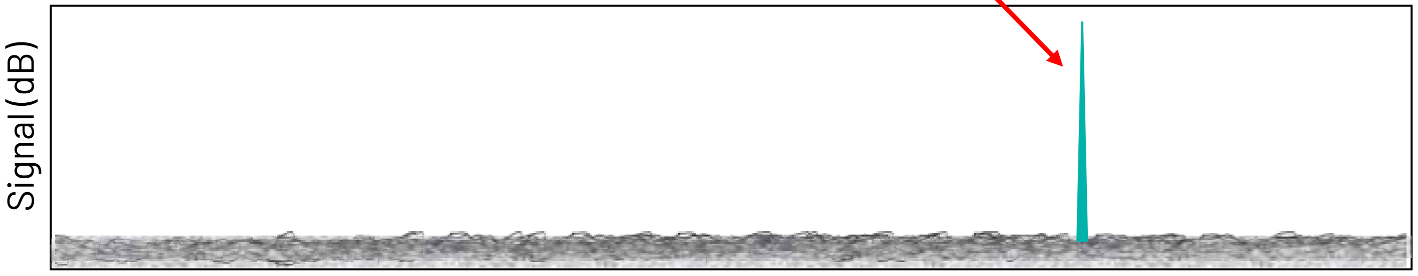
What can we do with Python and Pyadi-iio?

```
my_phaser.frequency = (
    my_phaser.SignalFreq +
    my_sdr.rx_lo)
```

10.5 GHz →

2.2 GHz →





12.7 GHz (LO)

From Phaser → Prototype → Production

SOFTWARE-DEFINED RADIO for ENGINEERS

TRAVIS F. COLLINS
ROBIN GETZ
DI PU
ALEXANDER M. WYGLINSKI

pysdr.org

PySDR: A Guide to SDR and DSP using Python

By Dr. Marc Lichtman

- More information on the software can be found online
  - wiki.analog.com/linux
  - SDR for Engineers – free textbook
  - PySDR.org
- Same infrastructure(PYADI-IIO, IIO) ALSO applies to most ADI products.
- All drivers are pre-loaded on our Linux distribution “ADI-KUIPER-LINUX”

ADI-KUIPER-LINUX

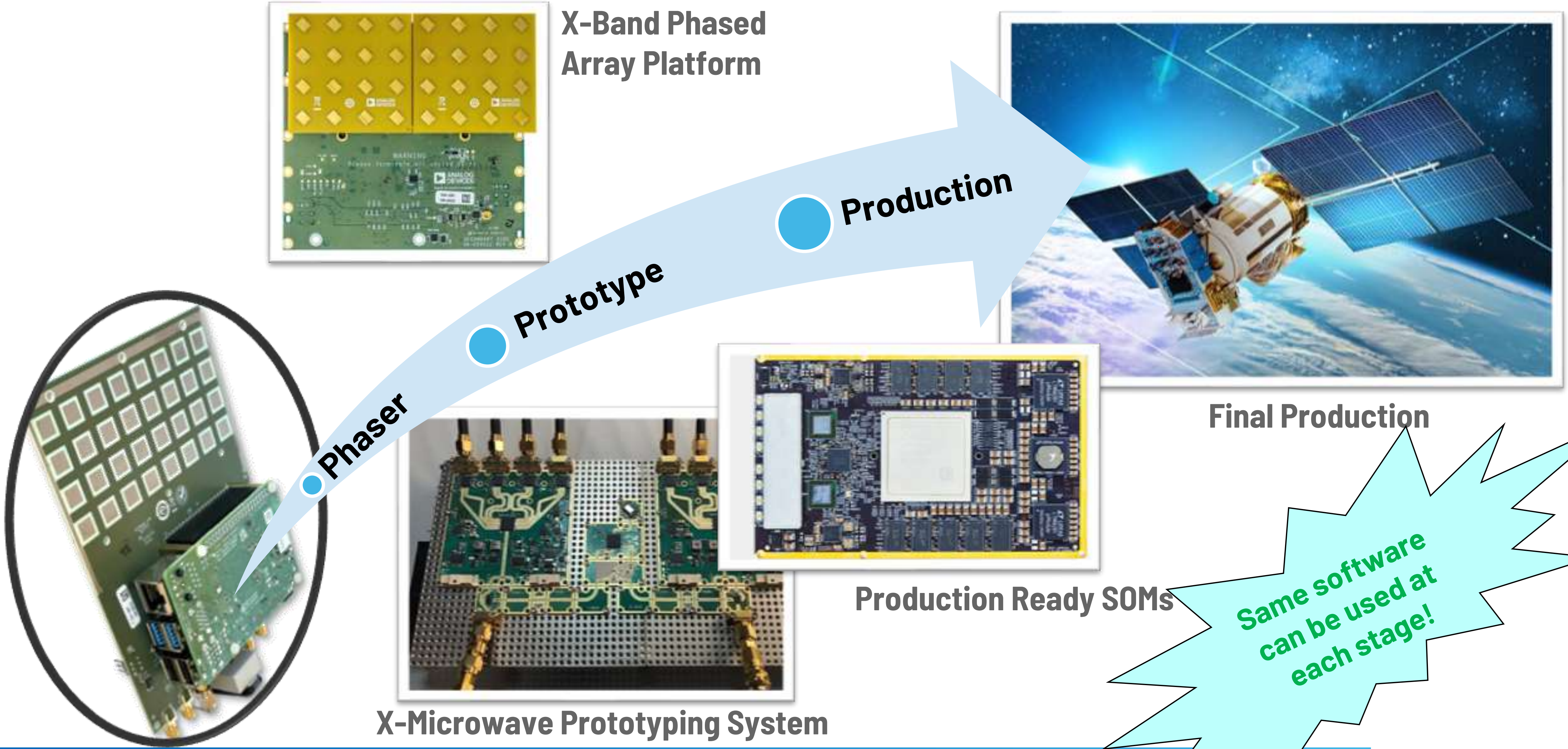
LINUX DEVICE DRIVERS FOR ADI PERIPHERALS

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Amplifiers & Linear
Analog-to-Digital Converters (ADC)
Audio and Video Products
Clock & Timing Products
Digital-to-Analog Converters (DAC)
High Speed Logic & Data Path Management
Industrial Ethernet
Interface and Isolation
Optical Communication & Sensing
Power Management
Power Monitor, Control & Protection
Processors & DSP
RF / IF & Microwave
Sensors & MEMS
Switches & Multiplexers
and many other products

Info: www.analog.com
Doc: wiki.analog.com/linux
Help: ez.analog.com/linux-device-drivers

From Phaser → Prototype → Production



X-Band Phased Array Platform

Phaser

Prototype

Production

Final Production

Production Ready SOMs

X-Microwave Prototyping System

Same software can be used at each stage!

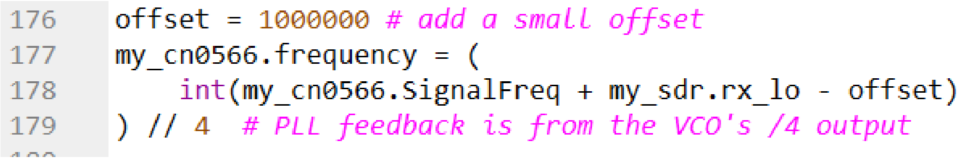
Lab 1-1: SDR and Software Control

Workshop Lab Guide

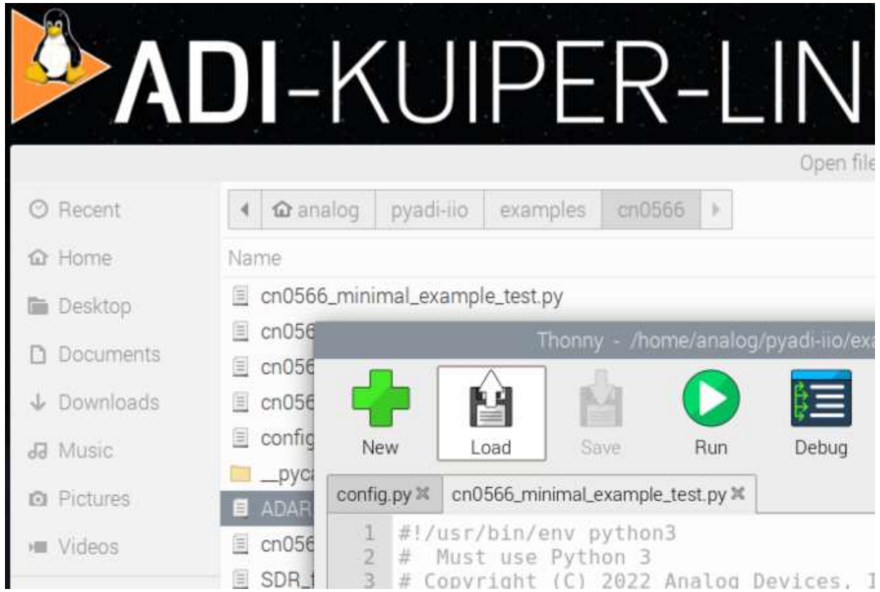
Lab: Aim phaser at HB100, downconvert, digitize, plot!

Instructions:

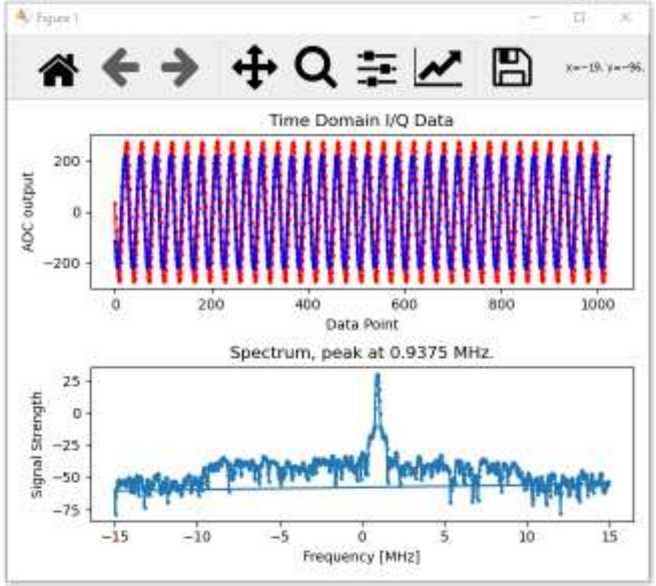
1. Open Thonny (World's Best Python IDE!) Start -> Programming -> Thonny
2. Load **`cn0566_minimal_example.py`** (at path **`pyadi-iio/examples/cn0566`**)
3. Click "Run"
4. Success!
5. Change line 176 to something between -10e6 and +10e6 (your choice!)



```
176  offset = 1000000 # add a small offset
177  my_cn0566.frequency = (
178      int(my_cn0566.SignalFreq + my_sdr.rx_lo - offset)
179  ) // 4  # PLL feedback is from the VCO's /4 output
```



```
1  #!/usr/bin/env python3
2  #  Must use Python 3
3  # Copyright (C) 2022 Analog Devices, I
```

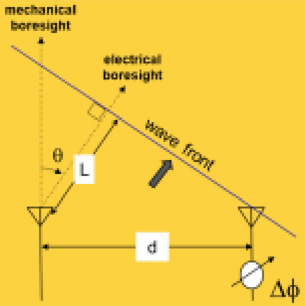


Session 3:
Basics of Phased Arrays and Steering Angle

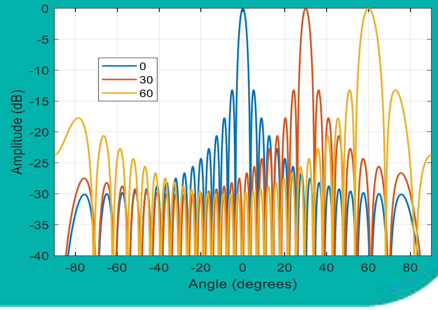
Phased Array Workshop: Steering Angle

Digitizer

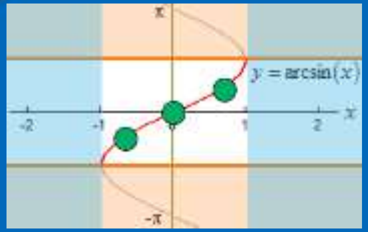
Steering Angle



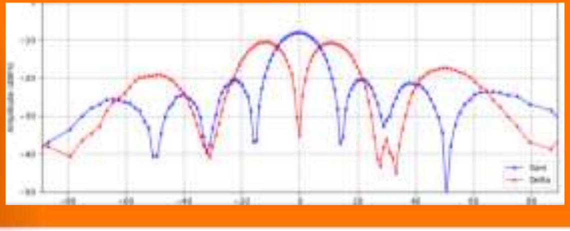
Antenna Patterns



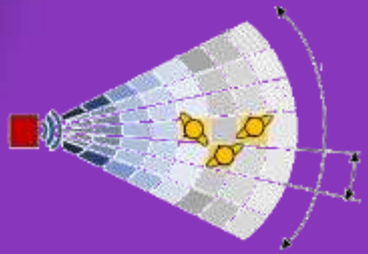
Antenna Impairments



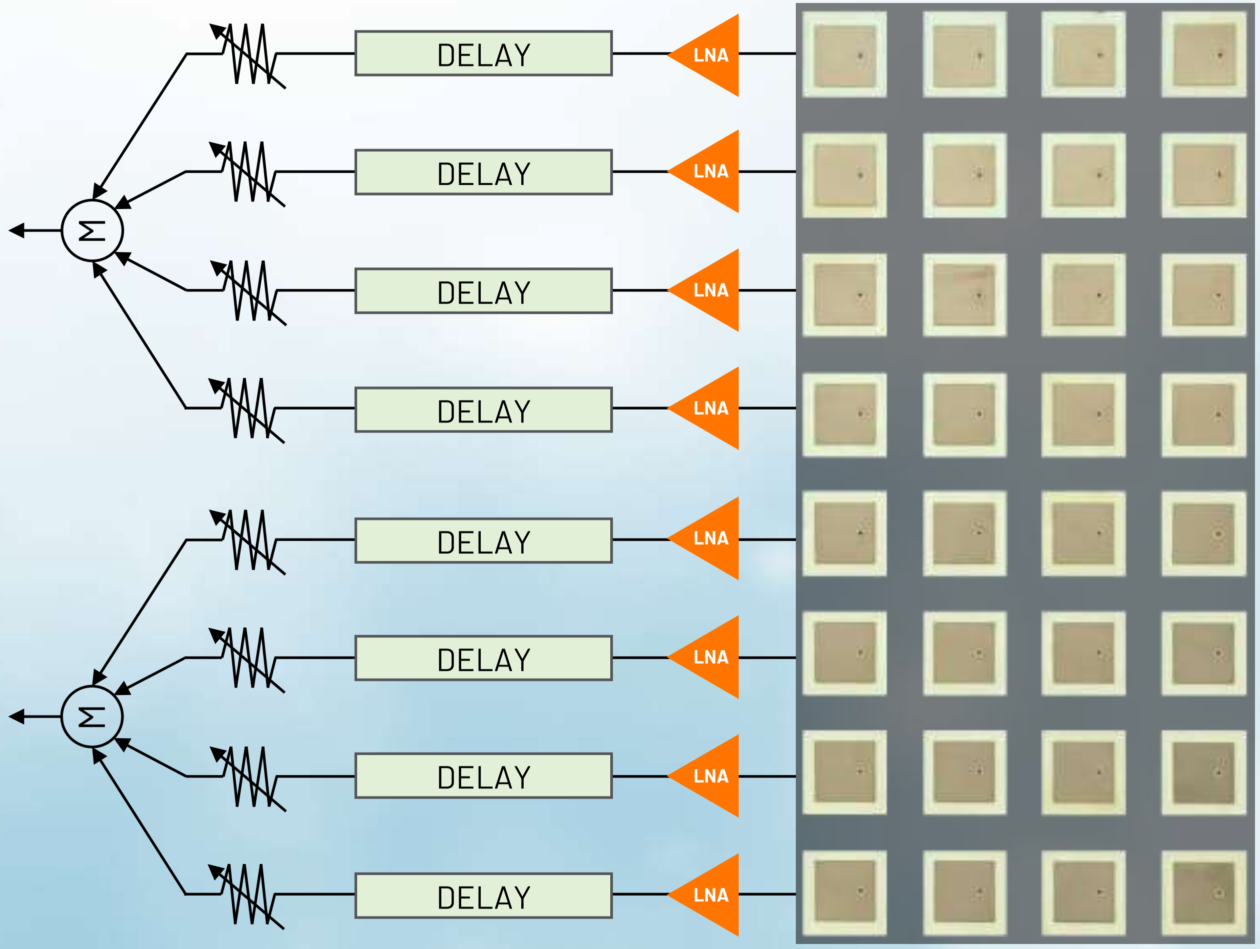
Monopulse Tracking

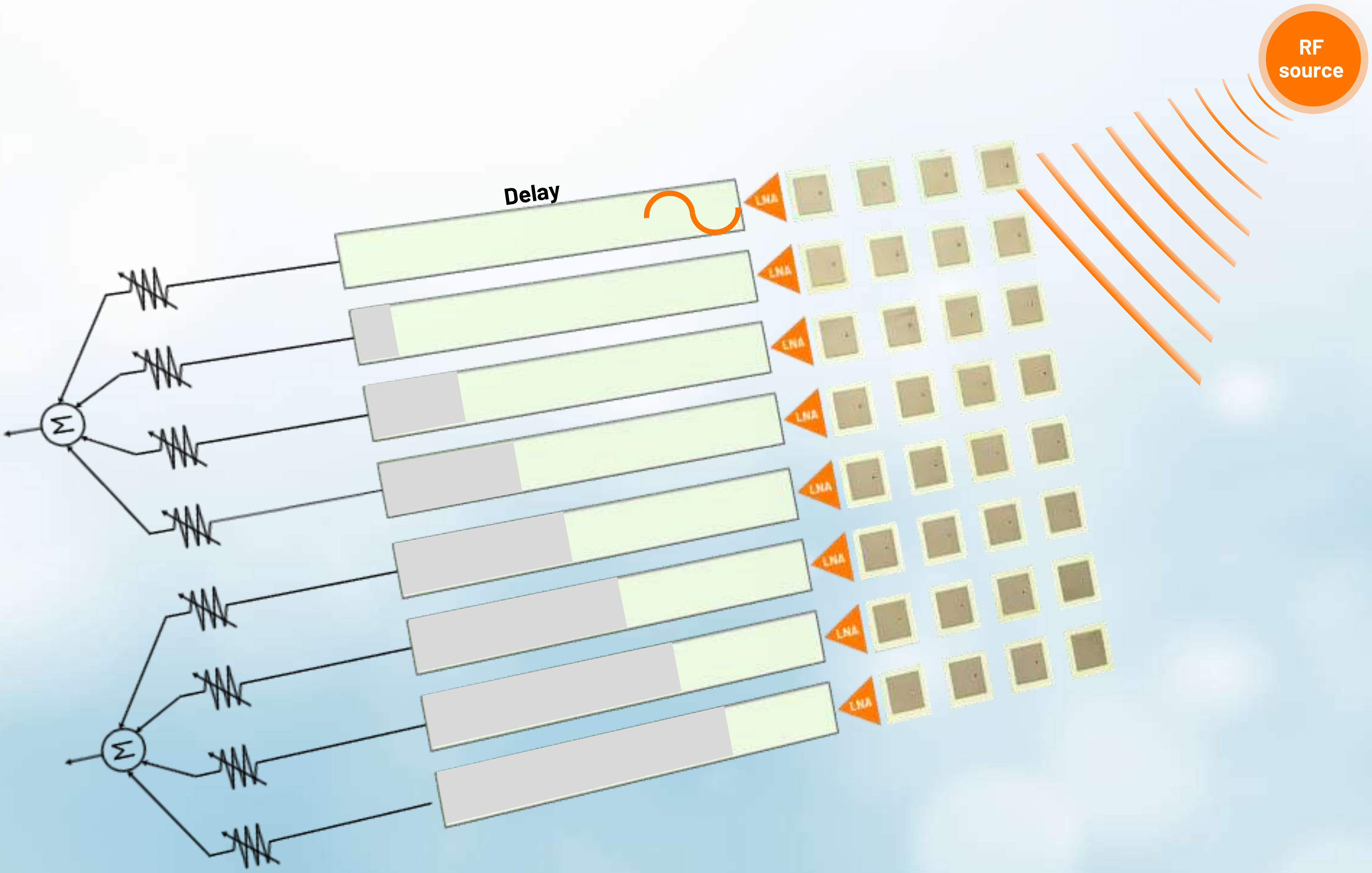


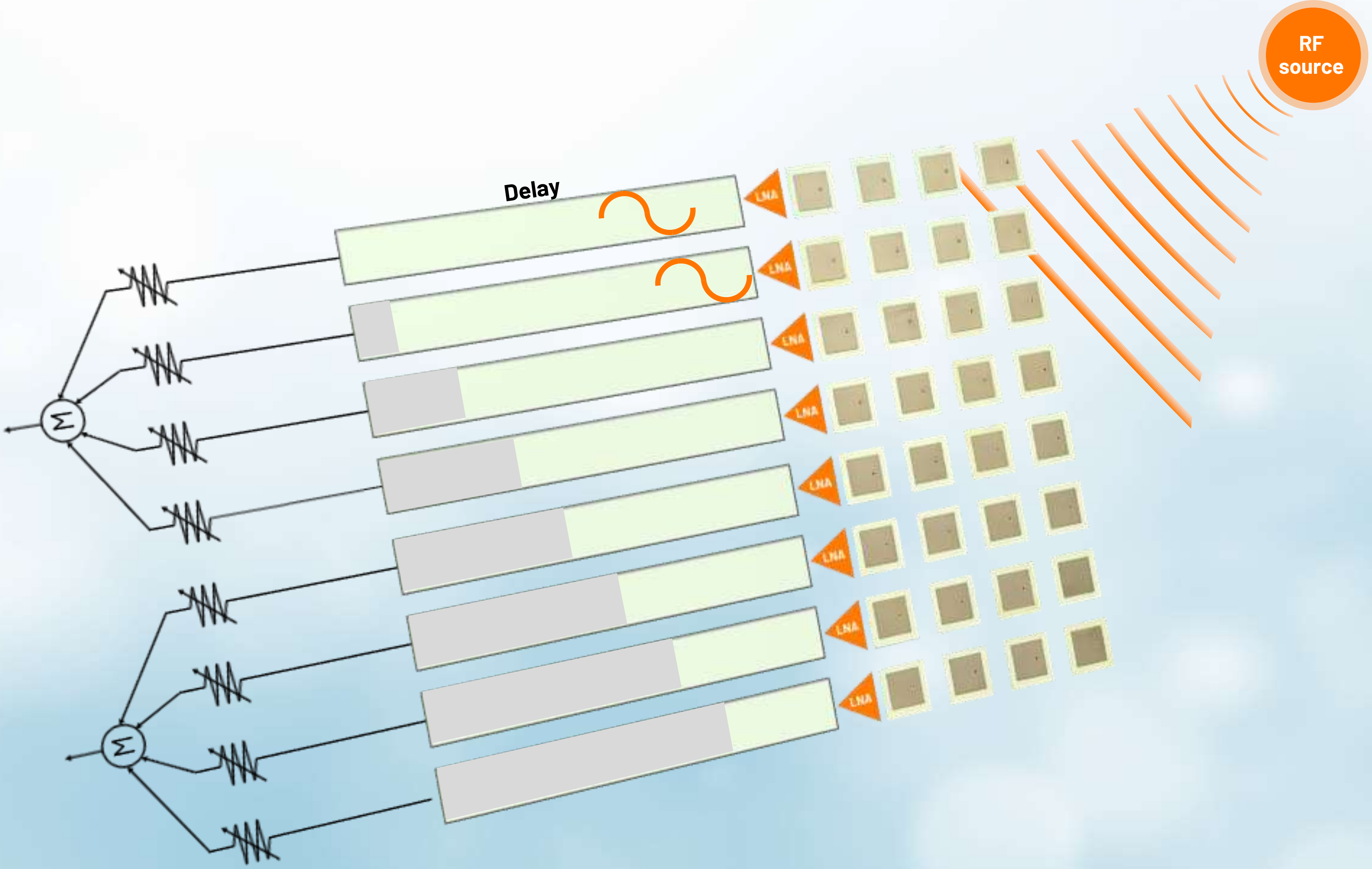
Radar

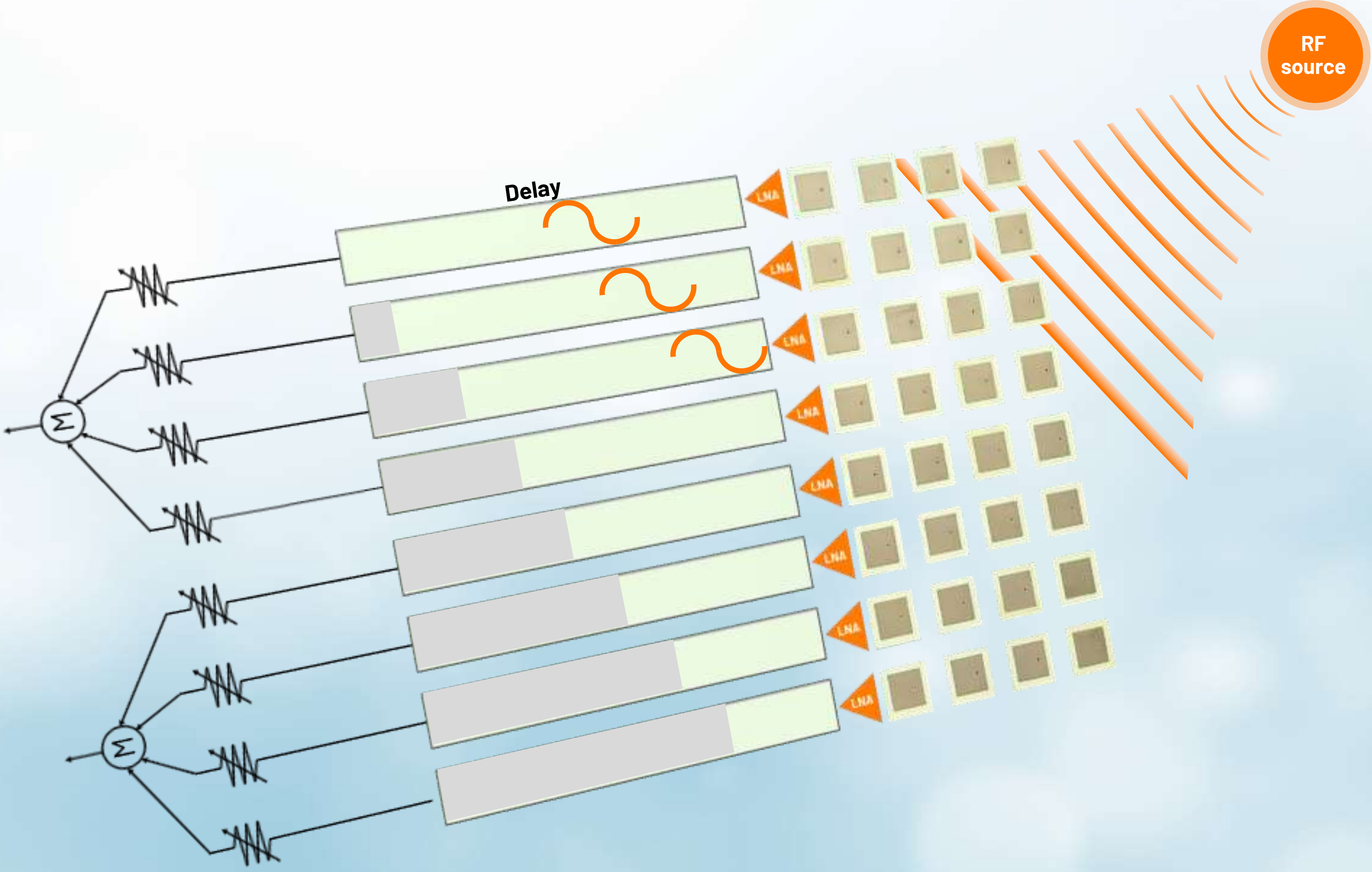


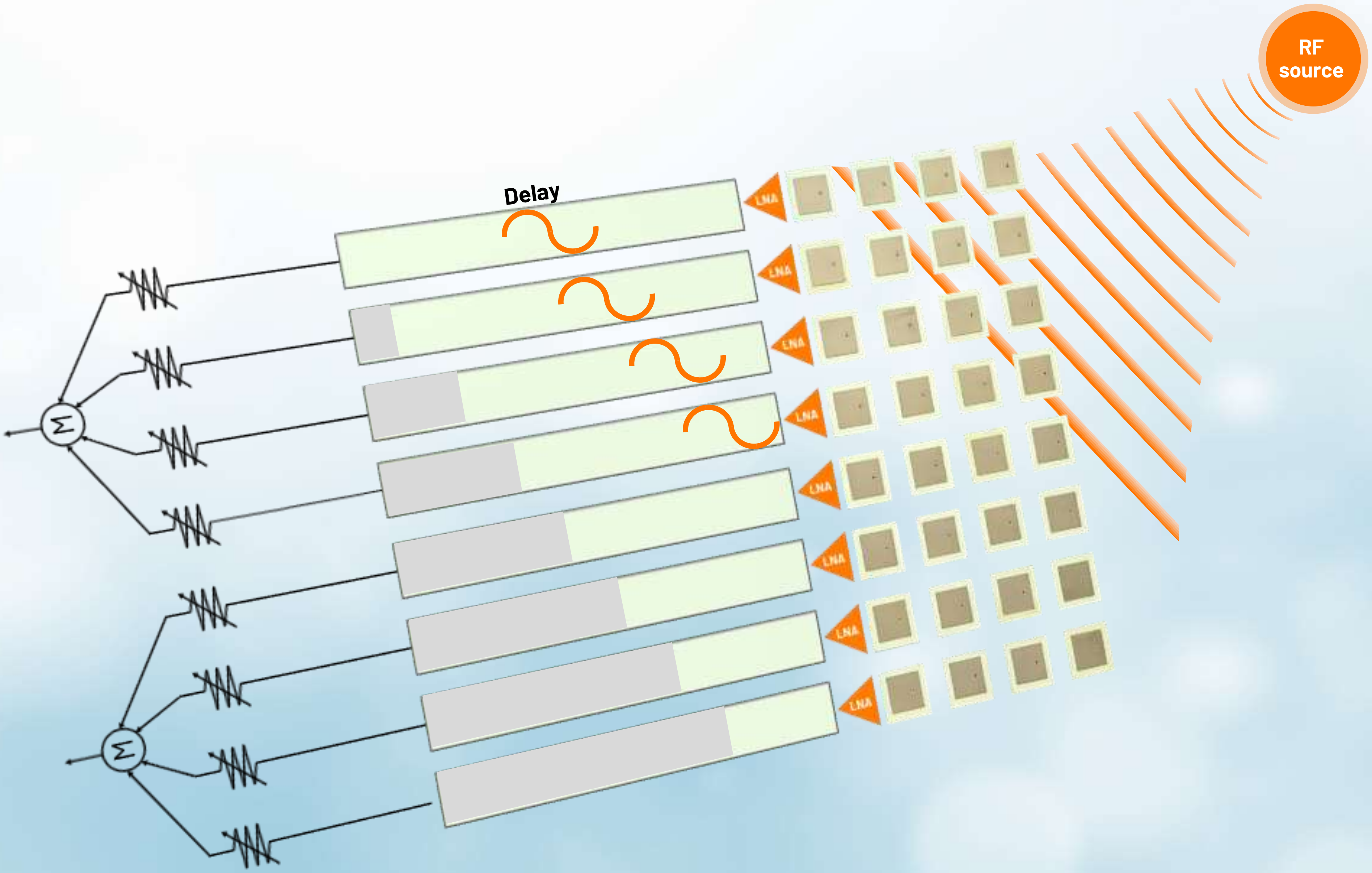
Basics of Phased Arrays




RF source
Delay
LNA
Σ


RF source
Delay
LNA
Σ


RF source
Delay
LNA
Σ


RF source
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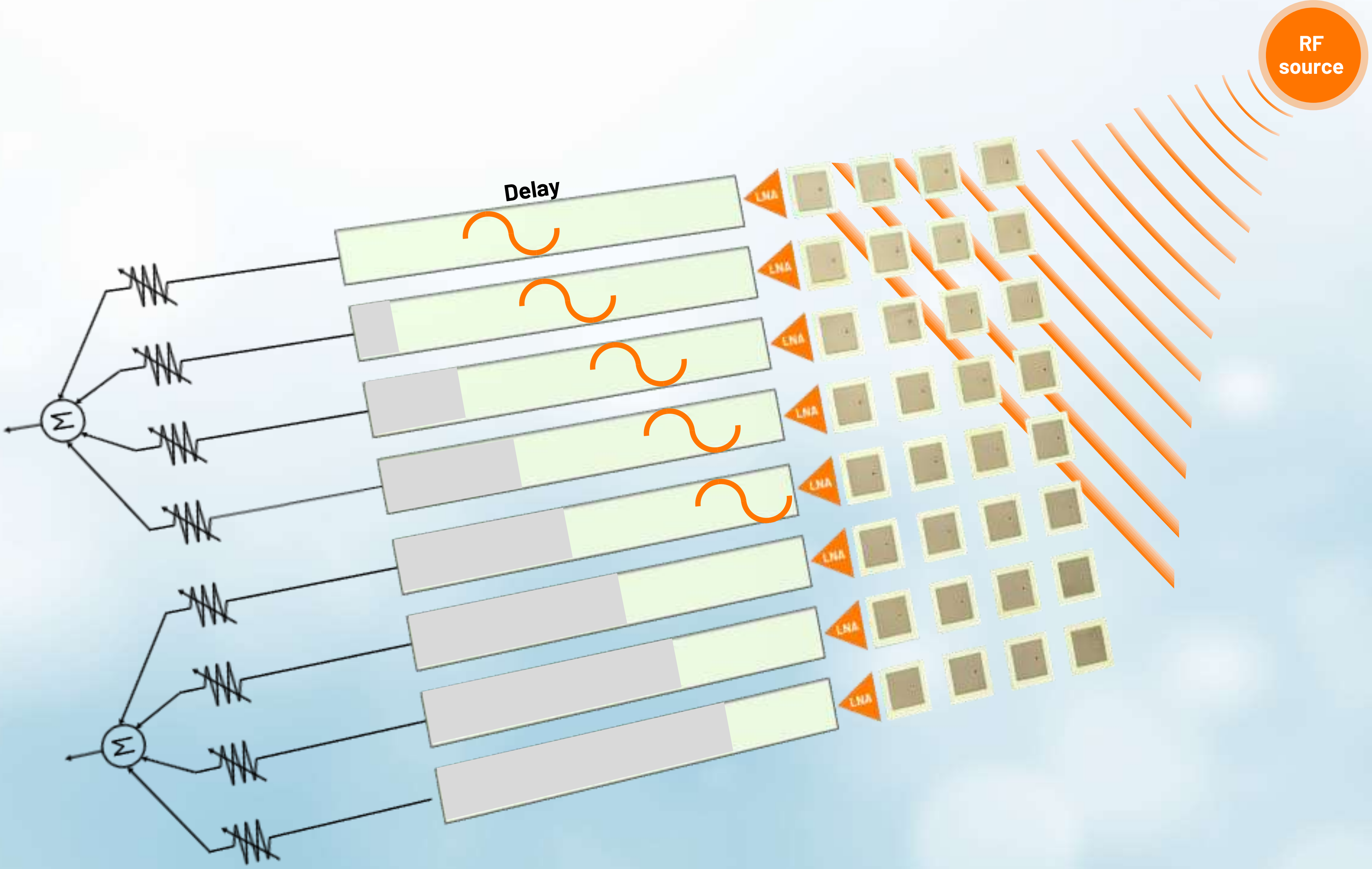
RF source
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LNA
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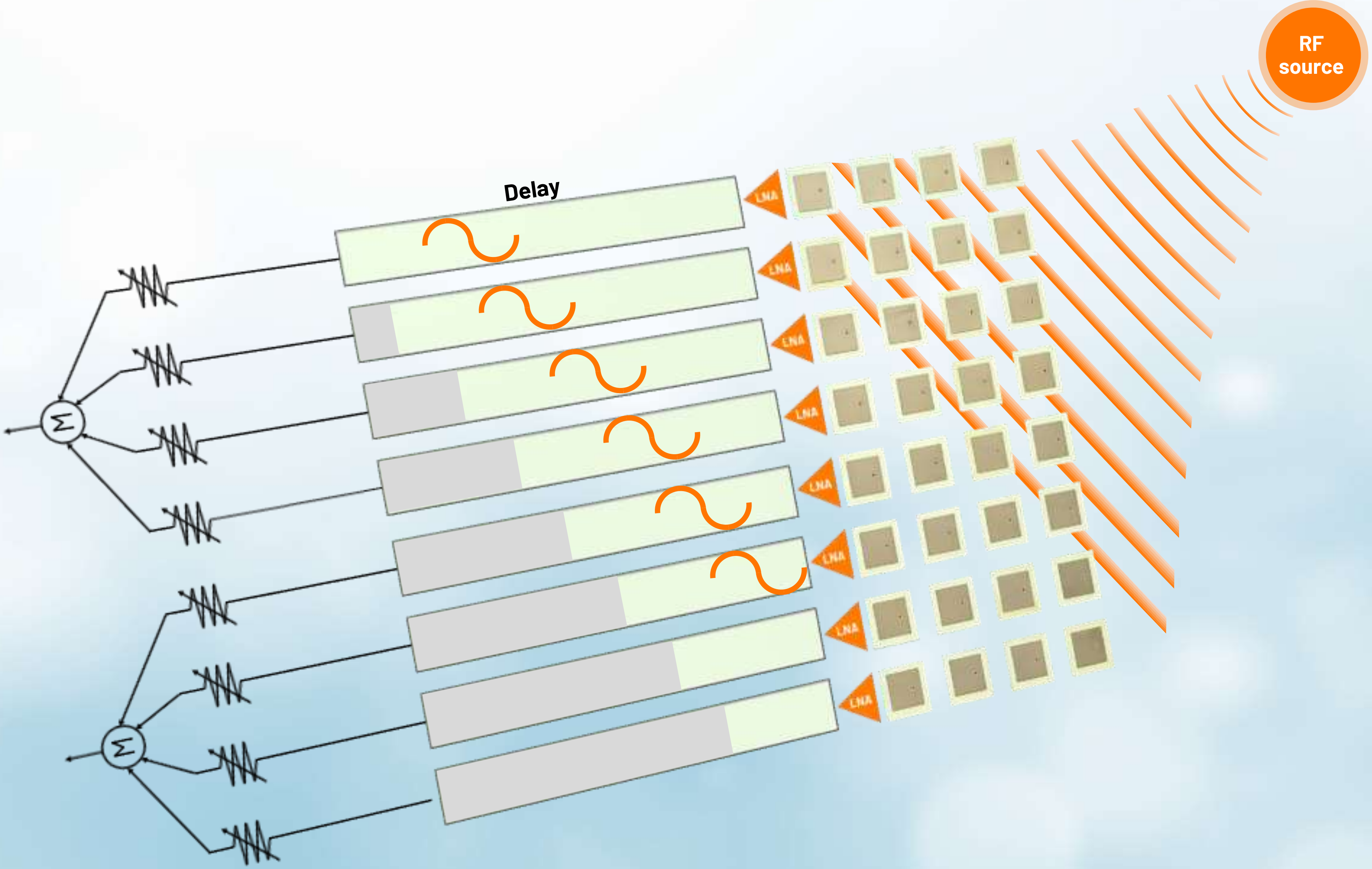
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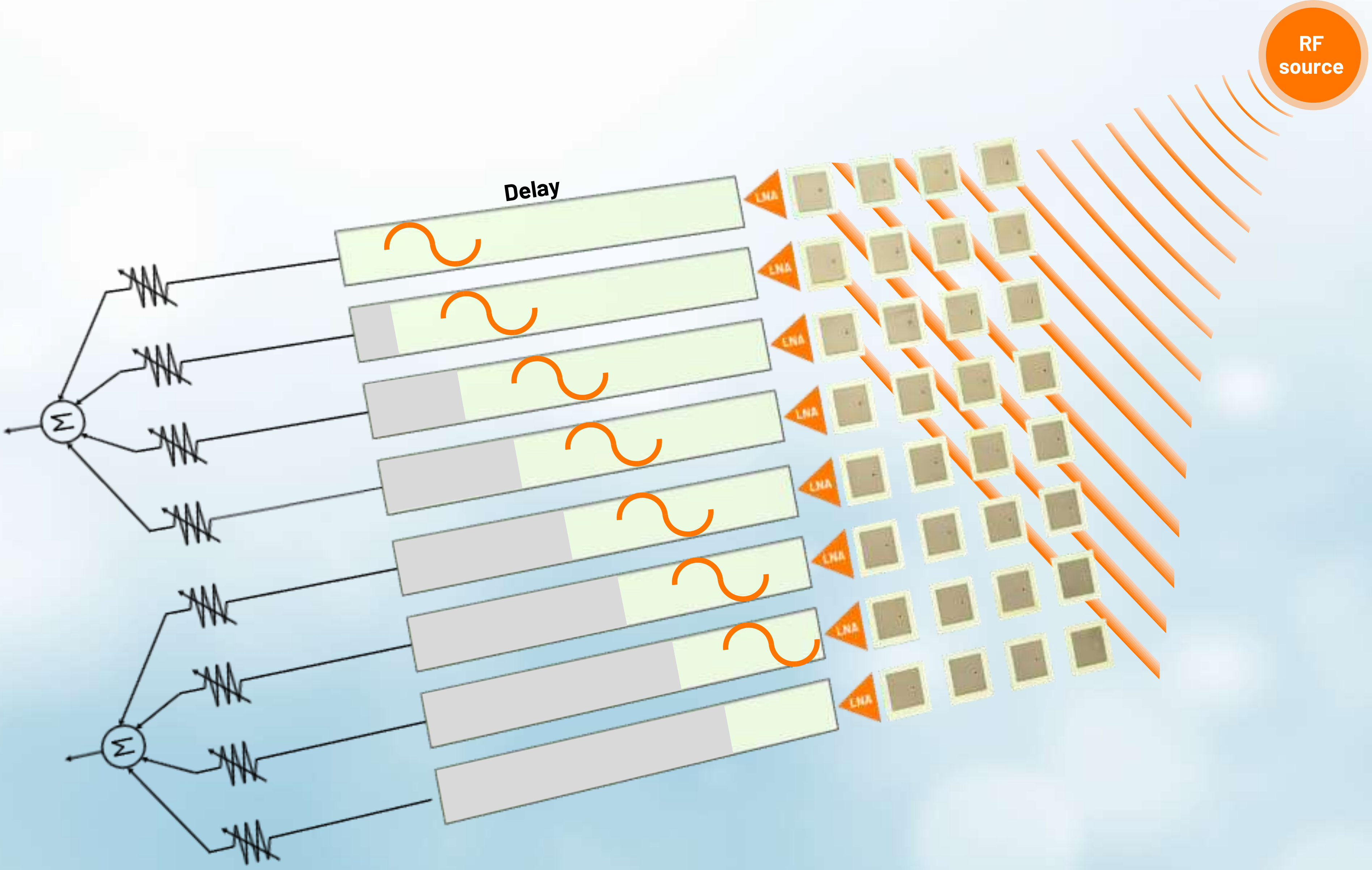
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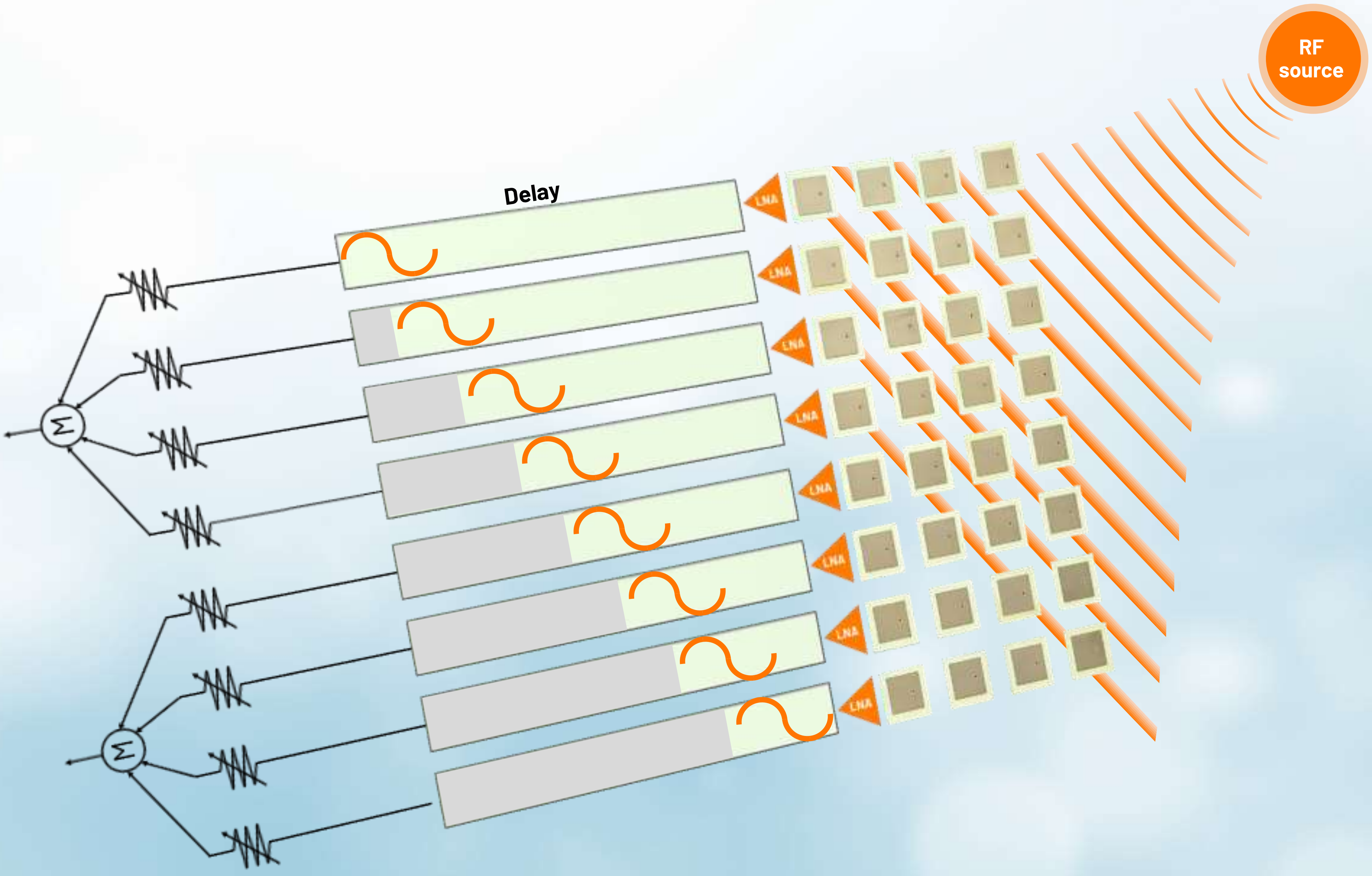
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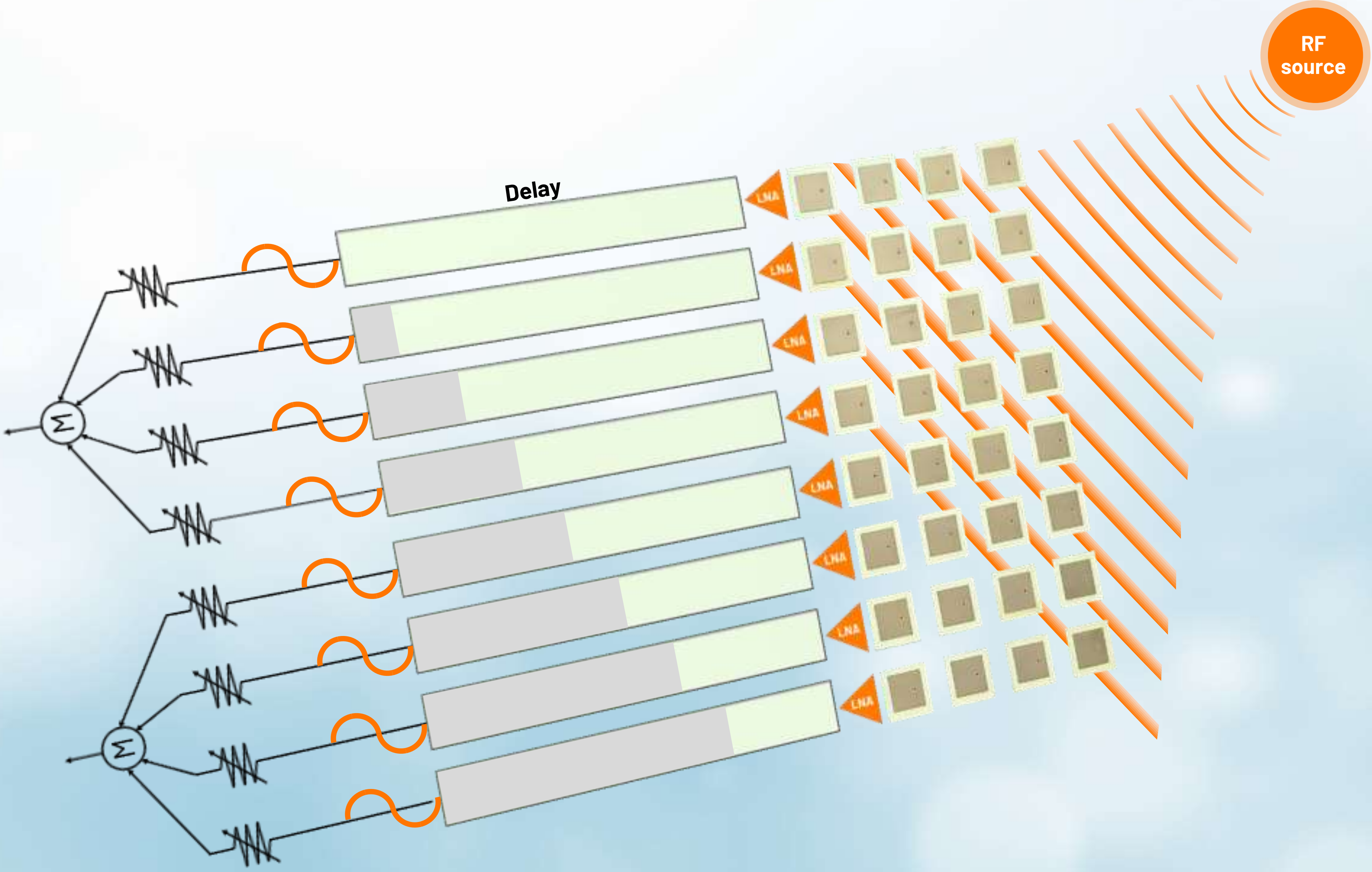
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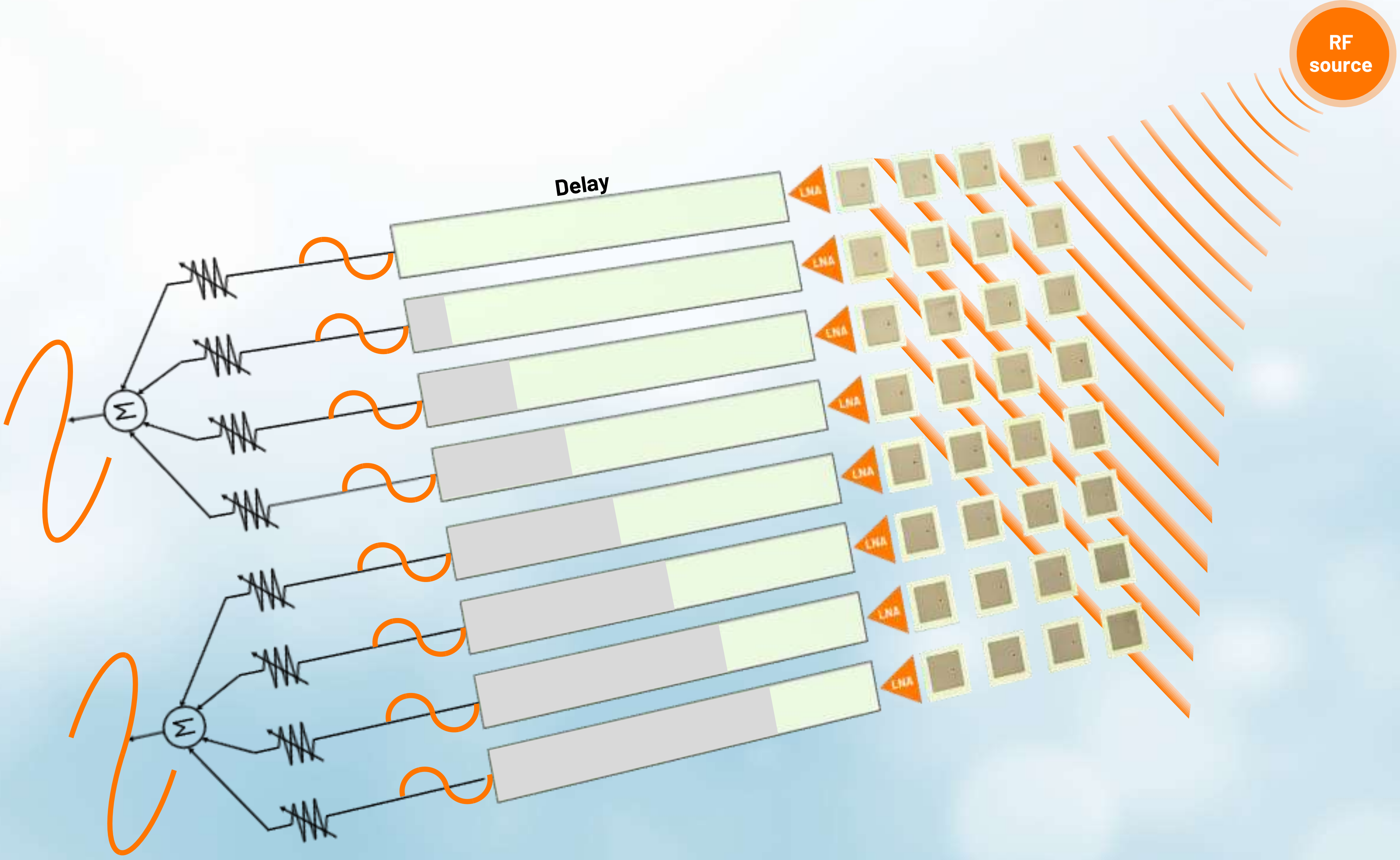
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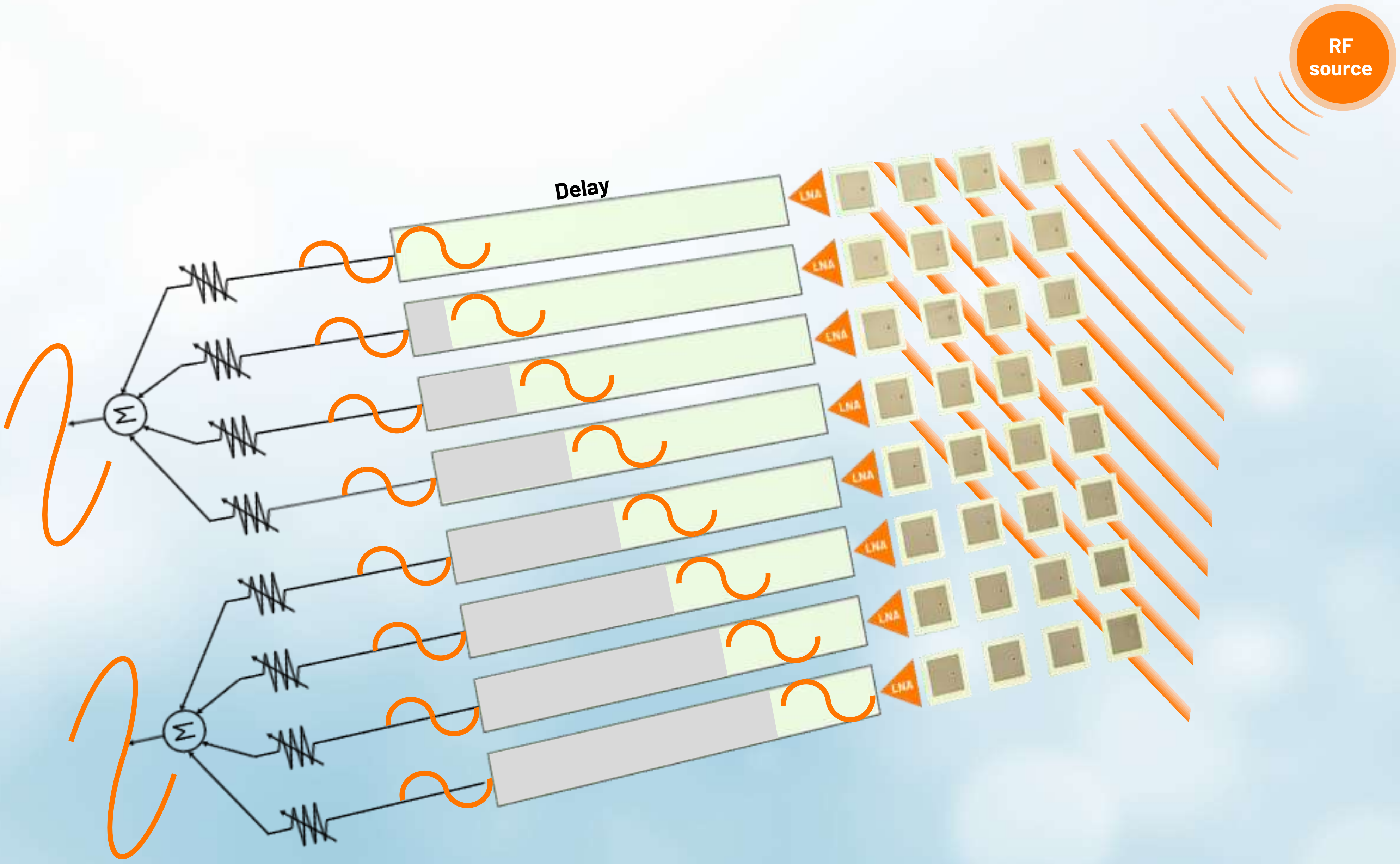
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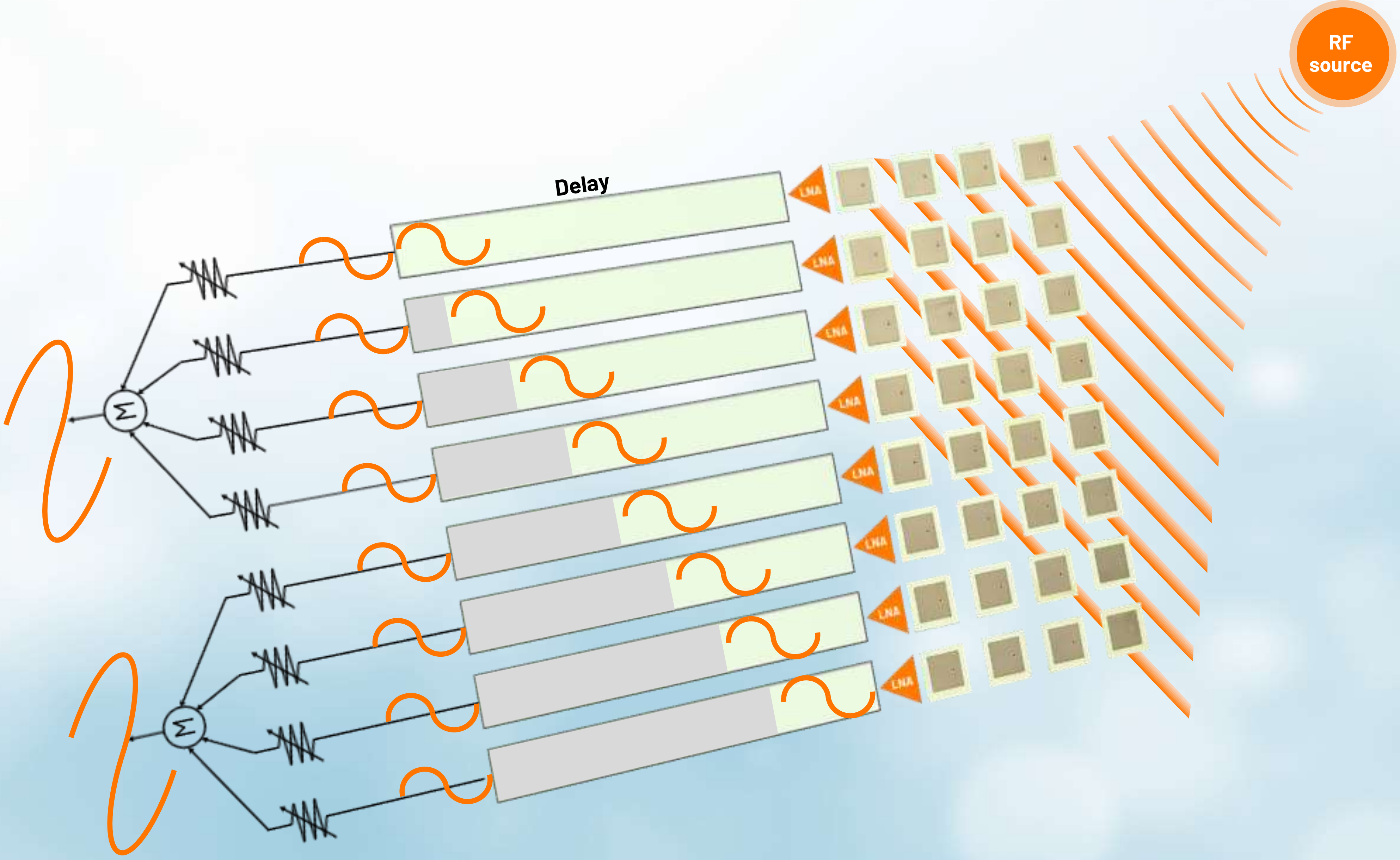
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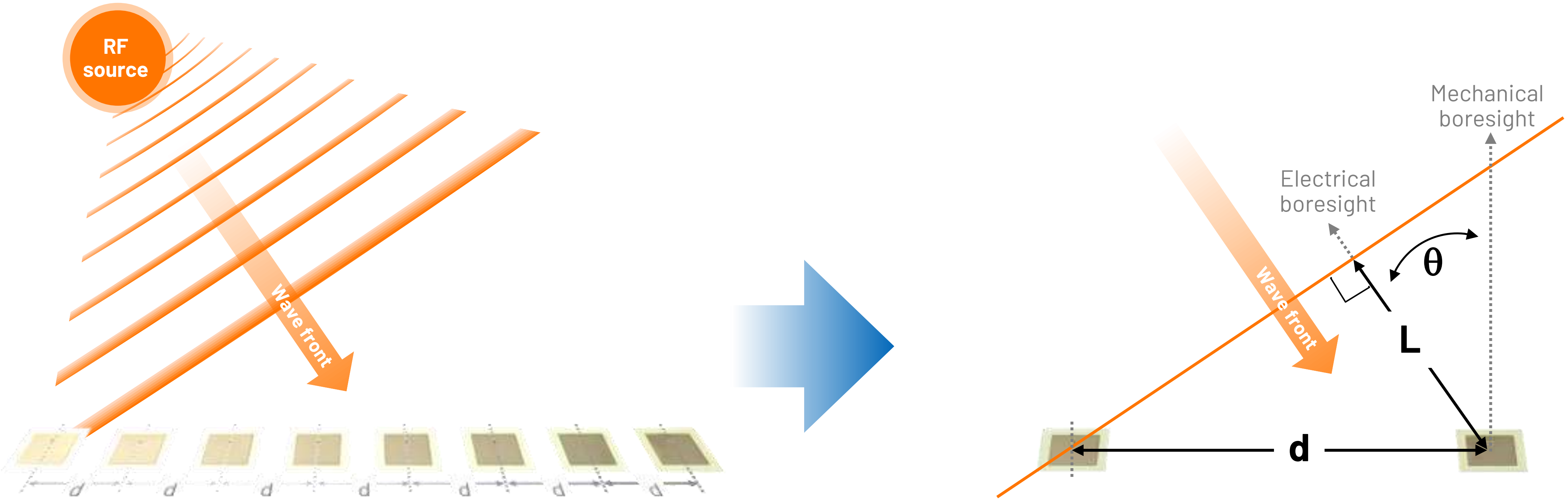
Understanding Steering Angle



θ - Beam electrical angle
L - Incremental propagation distance between elements
d - Distance between elements

Understanding Steering Angle

There are 3 ways to describe this delay:

1. An incremental distance to travel:

$L = d \sin \theta$

2. A time delay between elements:

$\Delta t = L / c = d \sin \theta / c$

$\rightarrow \theta = \sin^{-1}(\Delta t\, c / d)$

3. A phase shift between elements:

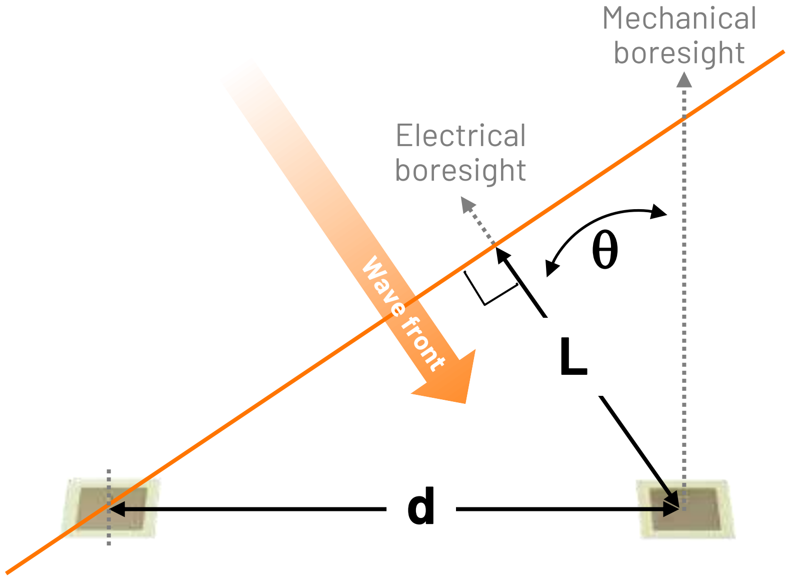
$\Delta\phi = 2\pi L / \lambda = 2\pi f L / c$

$\rightarrow \Delta\phi = 2 \pi f d \sin \theta / c$

$\rightarrow \theta = \sin^{-1}(\Delta\phi\, c / (2 \pi f d))$

Rewrite $\Delta\phi$ relative to wavelength

$$\Delta\phi = \frac{2\pi d \sin\theta}{\lambda}$$



θ - Beam electrical angle

L - Incremental propagation distance between elements

d - Distance between elements

Δt - Incremental time delay between elements

$\Delta\phi$ - Incremental phase shift between elements

What Phase Delta will Produce a 30° Steering Angle?

$\theta = 30^\circ = 0.52$ rad

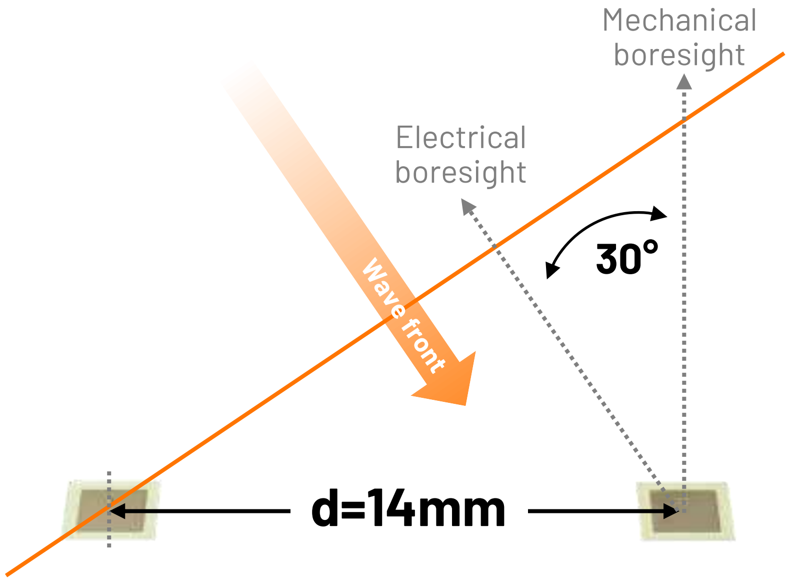
$d = 0.014$ m

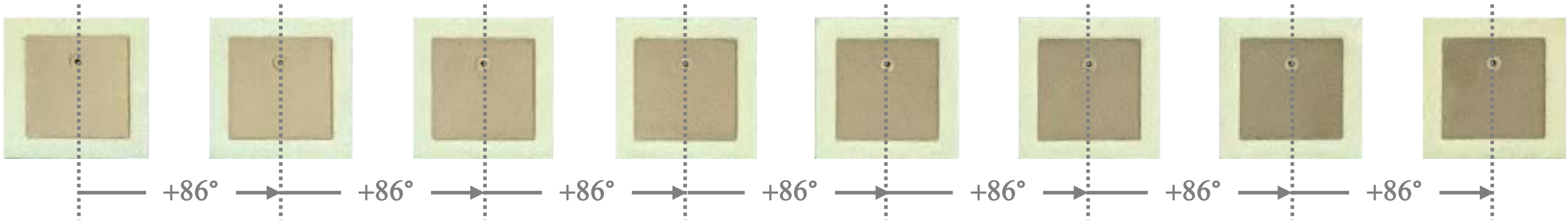
$f = 10.3$ GHz

$$\Delta\phi = 2\pi\, f\, d \sin\theta / c$$

$$= 2\pi * 10.3\text{x}10^9 * 0.014 * \sin(0.52) / 3\text{x}10^8$$

$$= 1.5 \text{ rad} = 86^\circ$$



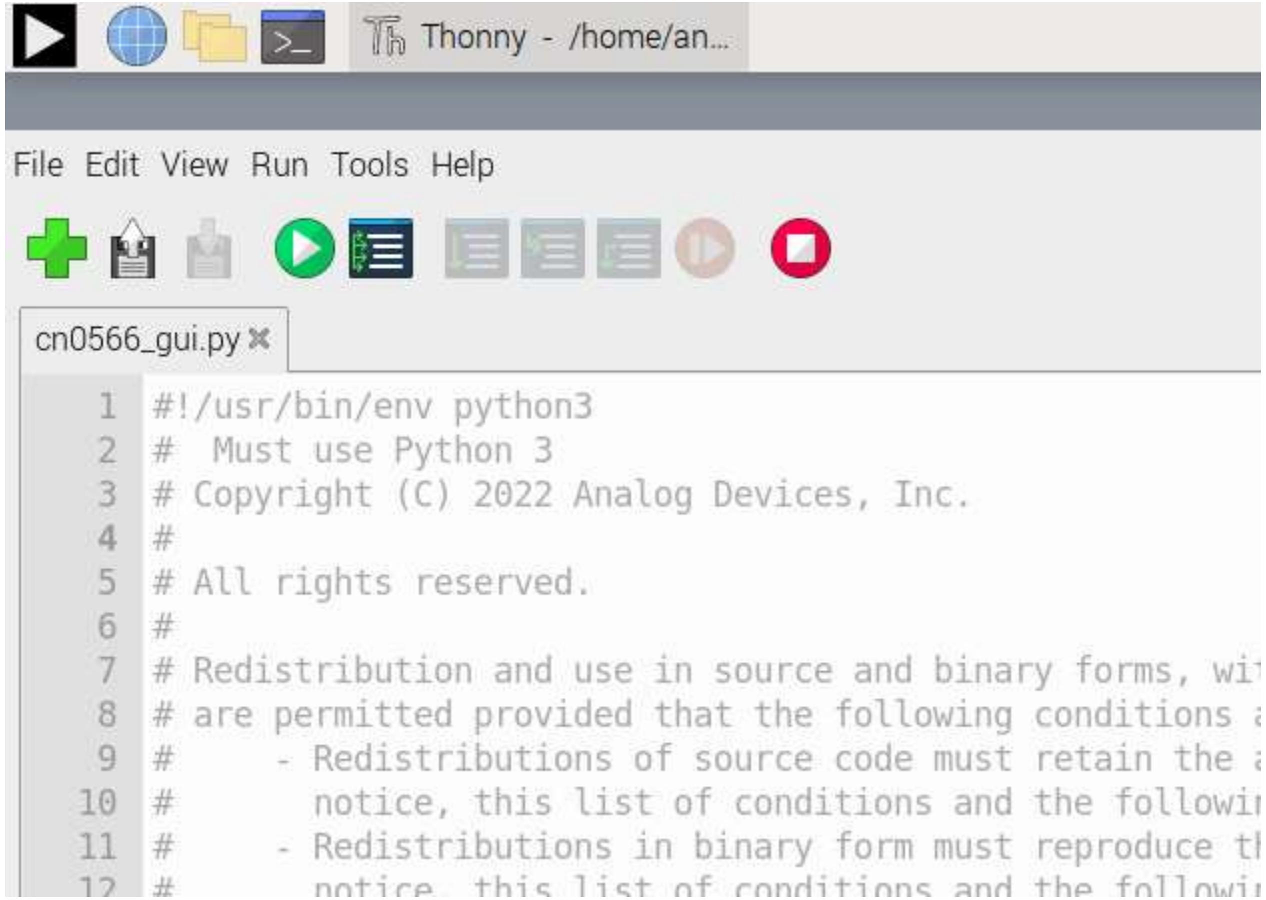


$\Delta\phi \rightarrow$ 0° 86° 172° 258° 344° 70° 156° 242°

Lab 3-1: Steering Angle

Workshop Lab Guide

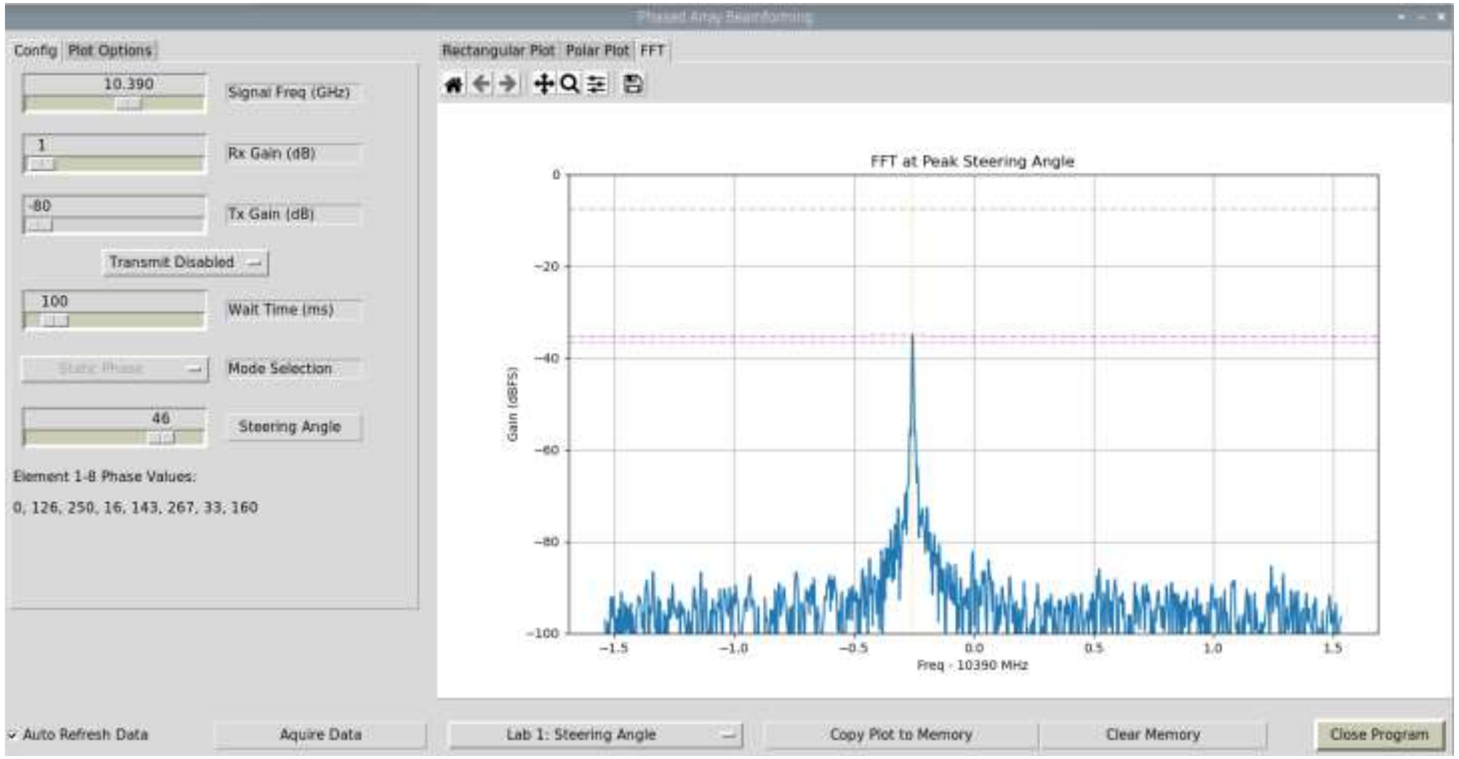
Lab 3-1: Steering Angle



```
#!/usr/bin/env python3
#  Must use Python 3
# Copyright (C) 2022 Analog Devices, Inc.
#
# All rights reserved.
#
# Redistribution and use in source and binary forms, wi
# are permitted provided that the following conditions a
#     - Redistributions of source code must retain the a
#       notice, this list of conditions and the followi
#     - Redistributions in binary form must reproduce th
#       notice, this list of conditions and the followi
```

- To start the Phaser GUI:
  - Find the “cn0566_gui.py” tab
  - Press the green play button

Lab 3-1: Steering Angle



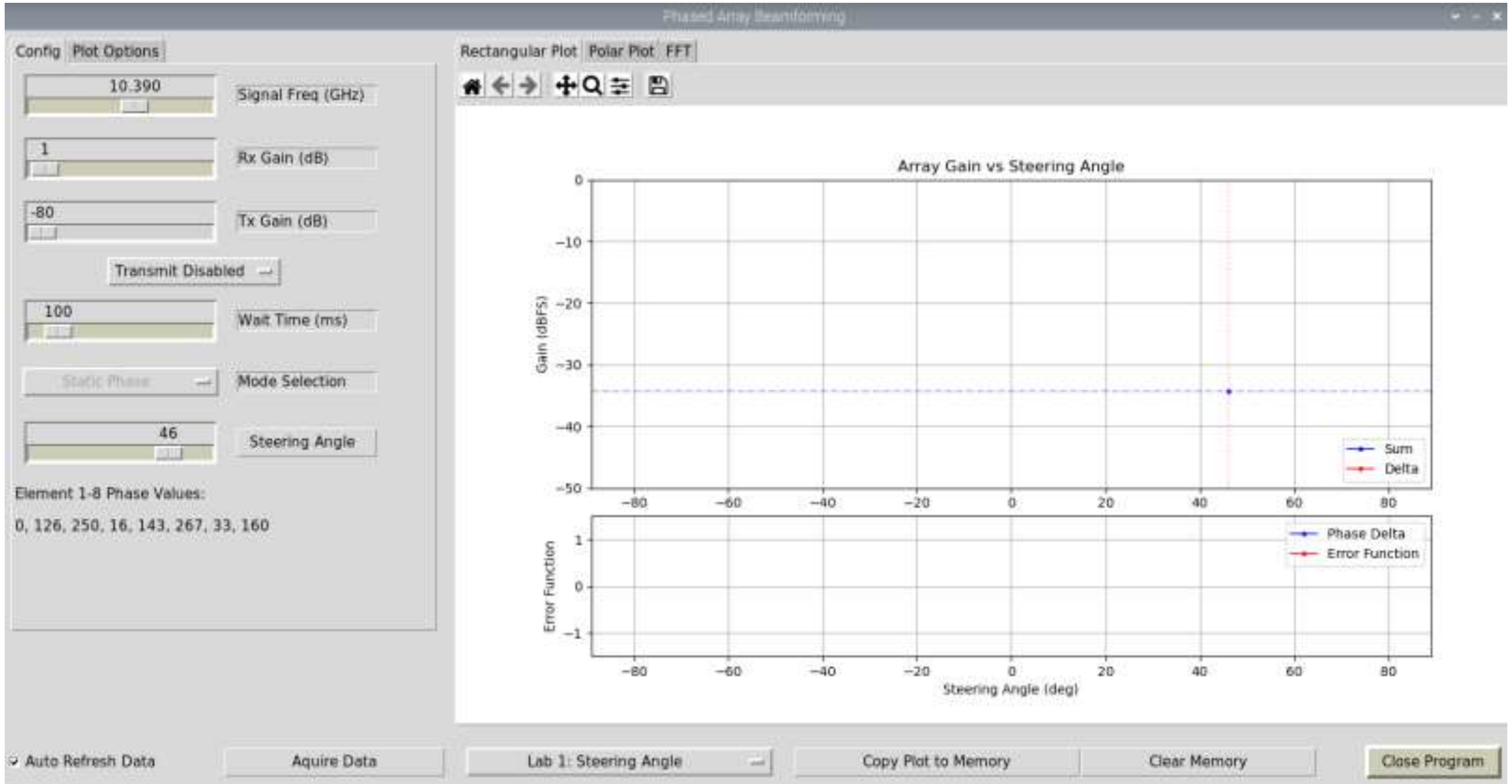
Signal Freq (GHz): 10.390
Rx Gain (dB): 1
Tx Gain (dB): -80
Transmit Disabled
Wait Time (ms): 100
Mode Selection: Static Phase
Steering Angle: 46

Element 1-8 Phase Values:
0, 126, 250, 16, 143, 267, 33, 160

✓ Auto Refresh Data
Lab 1: Steering Angle

- This is the FFT (amplitude vs frequency) of the HB100 source as received by the Phaser's array
- By adjusting the "Steering Angle" slider bar, you can change the phase values of each element.
- Move the HB100 to an angle of about 30 deg
- Now slide the "Steering Angle" to find the phase delta that produces the maximum FFT amplitude.

Lab 3-1: Steering Angle



Signal Freq (GHz): 10.390

Rx Gain (dB): 1

Tx Gain (dB): -80

Wait Time (ms): 100

Mode Selection: Static Phase

Steering Angle: 46

Element 1-8 Phase Values:

0, 126, 250, 16, 143, 267, 33, 160

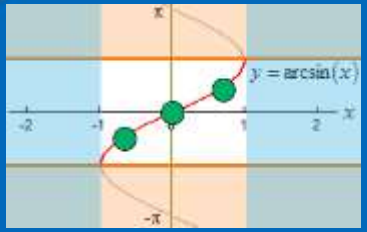
- Click on the “Rectangular Plot” tab
- This plots the peak FFT amplitude vs the selected steering angle
- Move the Steering Angle slider bar again.
- Does the amplitude move in a predictable way? What do you think is happening?

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Session 3: Array Factor and Element Factor

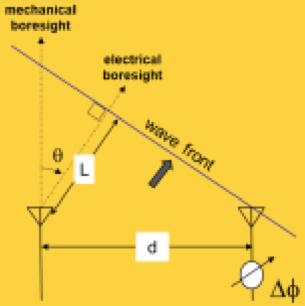
Phased Array Workshop: Antenna Patterns

Digitizer

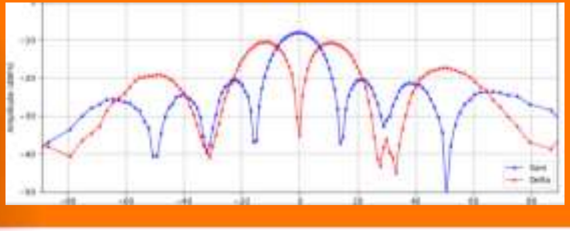


Antenna Impairments

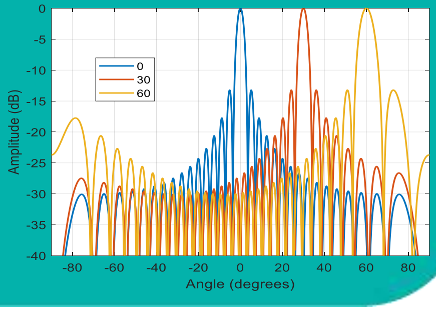
Steering Angle

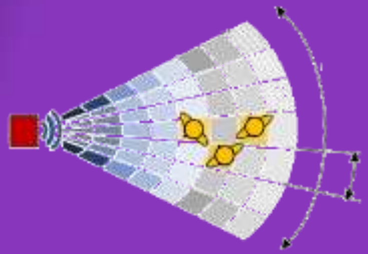


Monopulse Tracking



Antenna Patterns



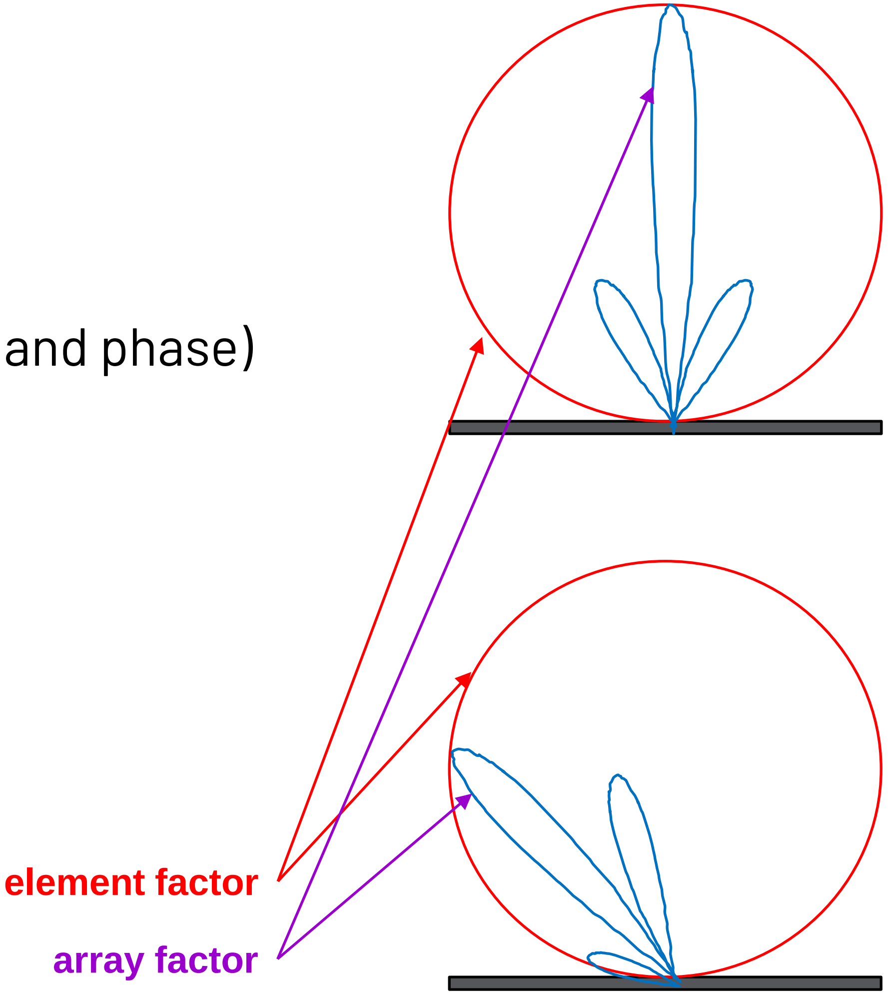


Radar

Understanding Antenna Patterns

- “Element Factor” - $G_E(\theta)$
  - the radiating pattern of a single element in the array
- “Array Factor” - $G_A(\theta)$
  - Determined by array geometry and beam weights (amplitude and phase)
- Antenna Gain (dB) ⟶ $G(\theta) = G_E(\theta) + G_A(\theta)$

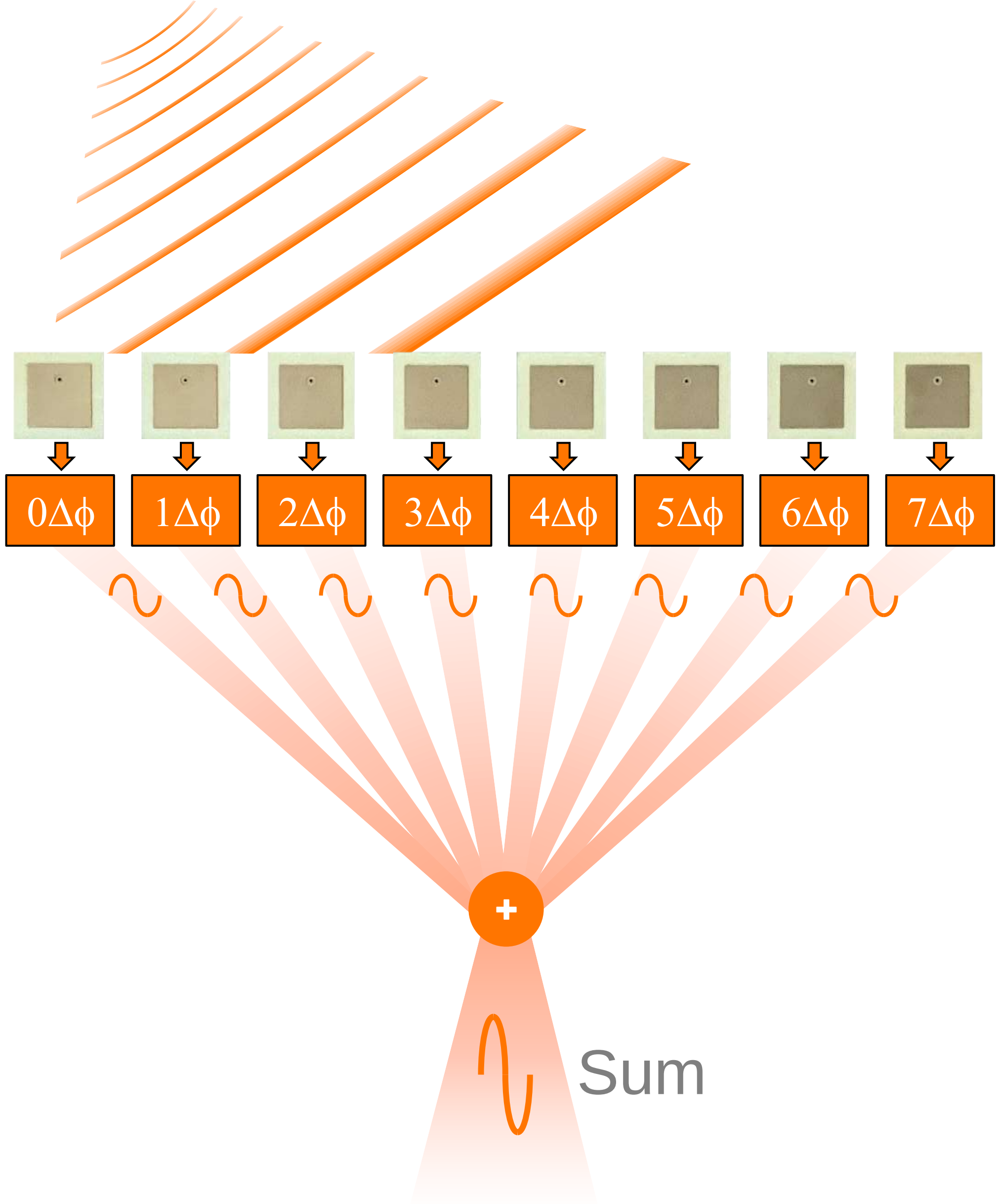
- Let’s focus on the Array Factor, $G_A(\theta)$

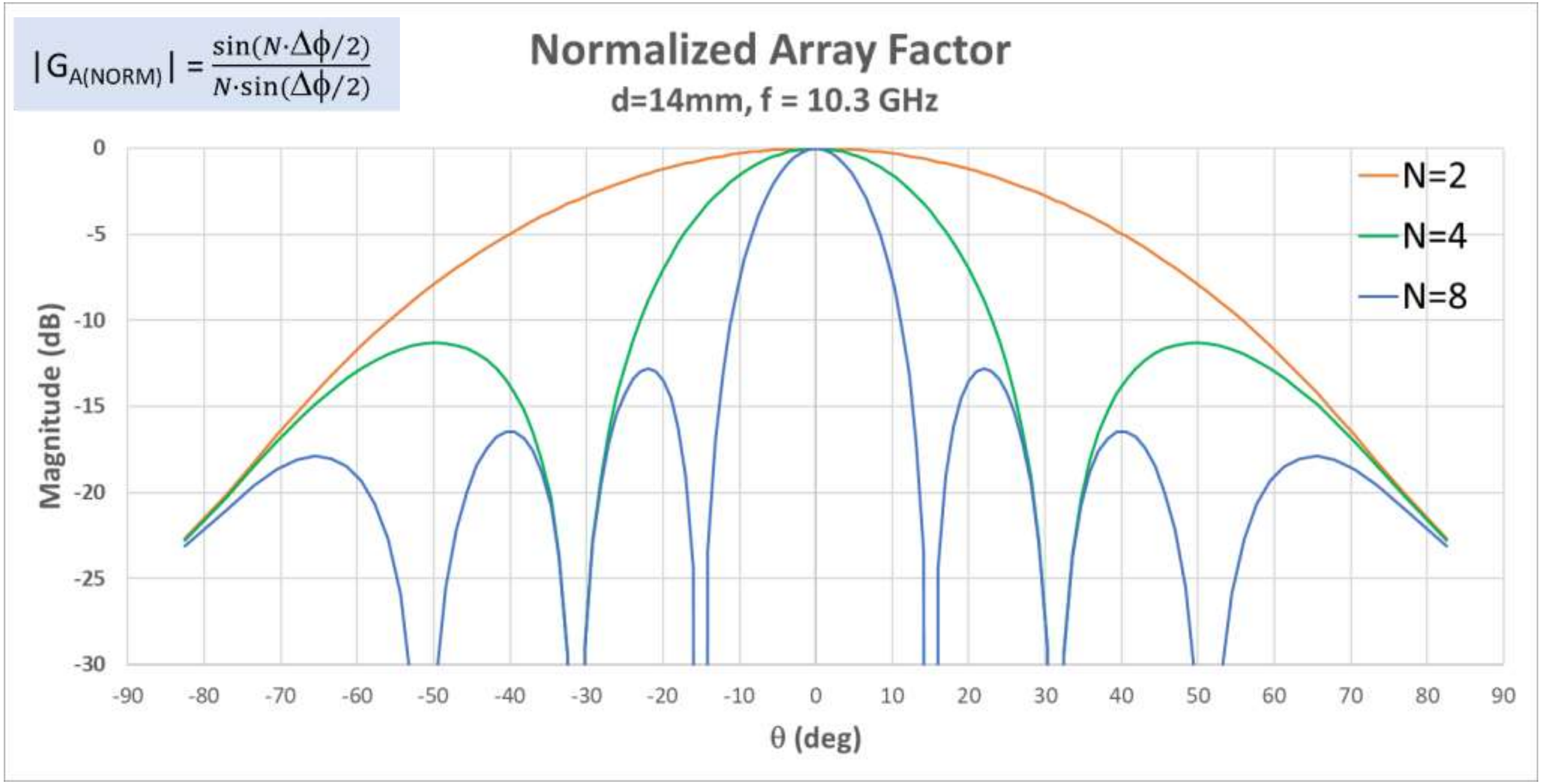


https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part1.html

Array Factor

- Recall that each element receives a signal that is delayed relative to the element next to it.
- And the array factor is the summation of all those signals:
  - $G_A = e^{j0\cdot\Delta\phi} + e^{j1\cdot\Delta\phi} + e^{j2\cdot\Delta\phi} \ldots + e^{j7\cdot\Delta\phi}$
- Simplifying, and normalizing, gives:
  - $\boxed{|G_{A(NORM)}| = \frac{\sin(N\cdot\Delta\phi/2)}{N\cdot\sin(\Delta\phi/2)}}$





$$|G_{A(NORM)}| = \frac{\sin(N\cdot\Delta\phi/2)}{N\cdot\sin(\Delta\phi/2)}$$

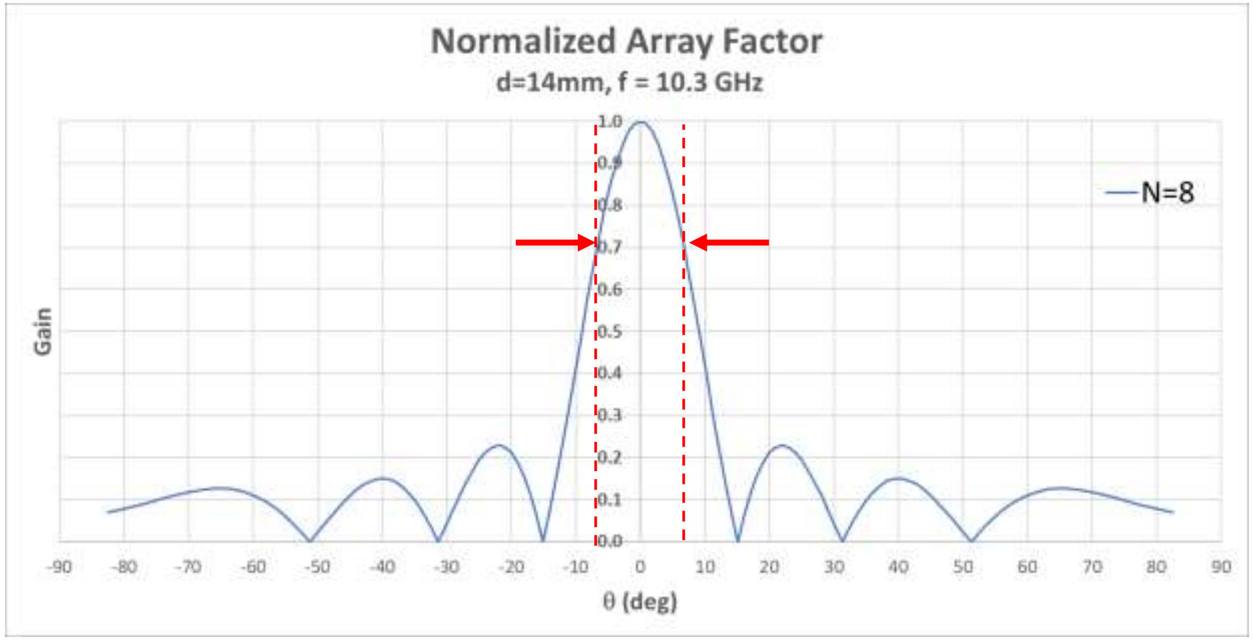
Normalized Array Factor

d=14mm, f = 10.3 GHz

Halfpower Beamwidth vs Number of Array Elements

- Halfpower Beam Width (HPBW)
  - Main lobe beamwidth, measured 3dB down from peak

$$\frac{\sin(N\cdot\Delta\phi/2)}{N\cdot\sin(\Delta\phi/2)} = 1/\sqrt{2} = 0.71$$



	f=10.3GHz
N=8	HPBW=13°
N=4	HPBW=27°
N=2	HPBW=62°

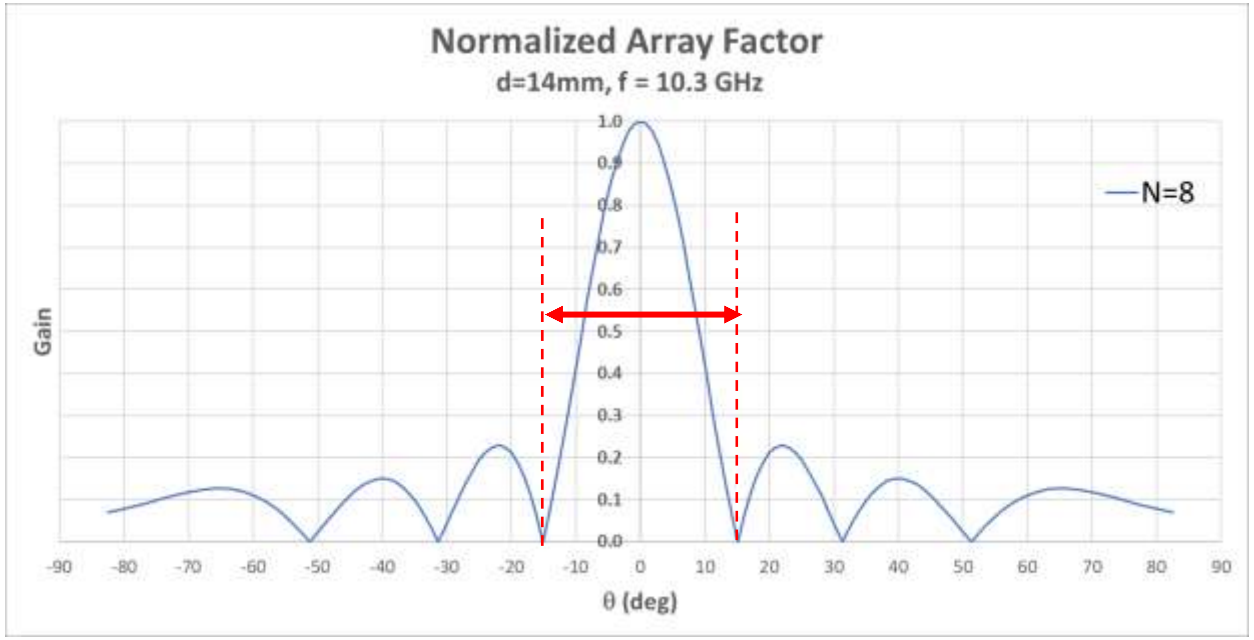
d = 14 mm

First Null Beamwidth vs Number of Array Elements

▸ First Null Beam Width (FNBW)

- Spacing between main lobe nulls

$$\frac{\sin(N\cdot\Delta\phi/2)}{N\cdot\sin(\Delta\phi/2)} = 0$$



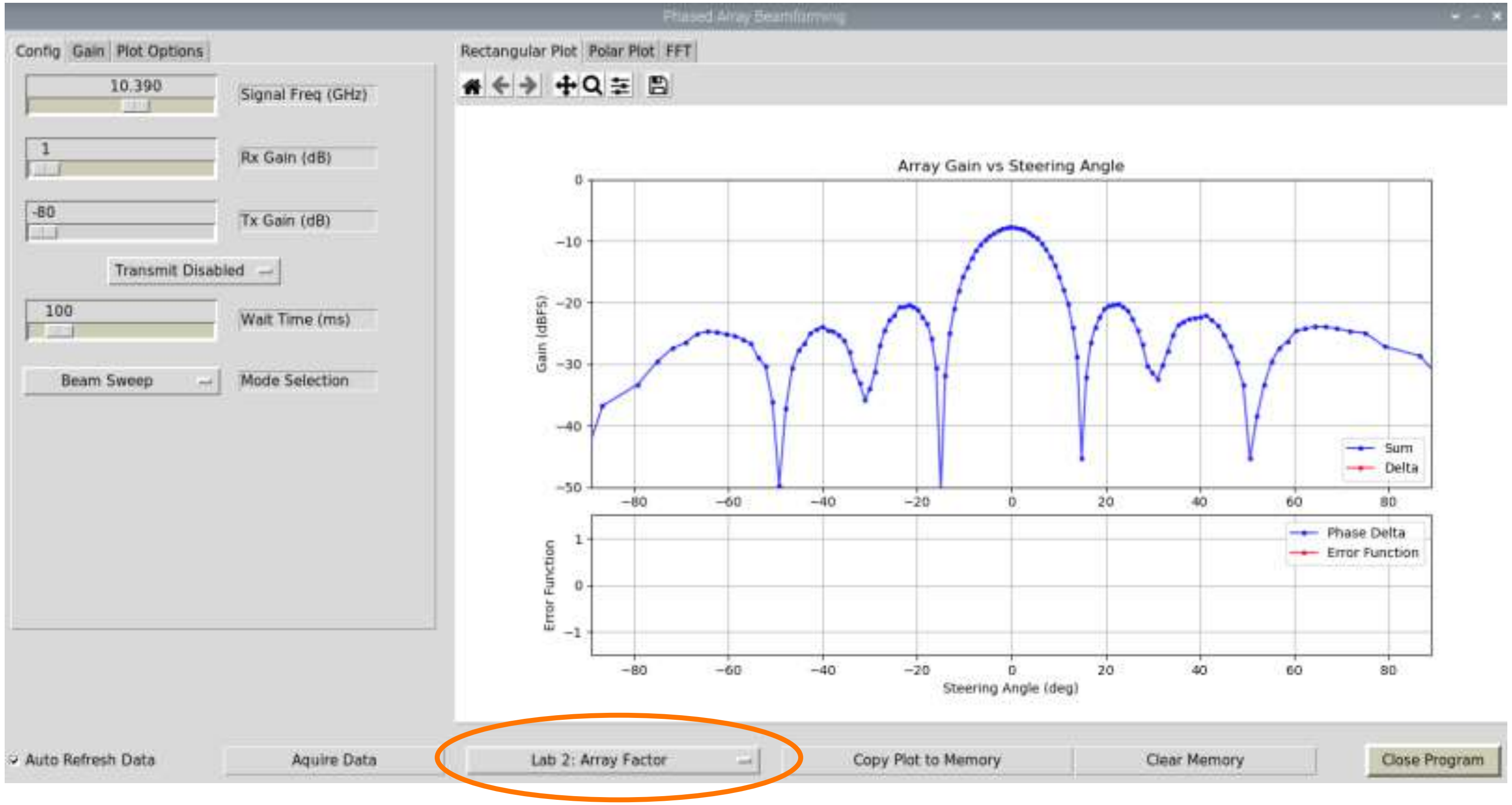
	f=10.3GHz
N=8	FNBW=30°
N=4	FNBW=62°
N=2	FNBW=180°

d = 14 mm

Lab 3-2: Array Factor and Beamwidth

Workshop Lab Guide

Lab 3-2: Array Factor and Beamwidth



10.390 Signal Freq (GHz)

1 Rx Gain (dB)

-80 Tx Gain (dB)

Transmit Disabled

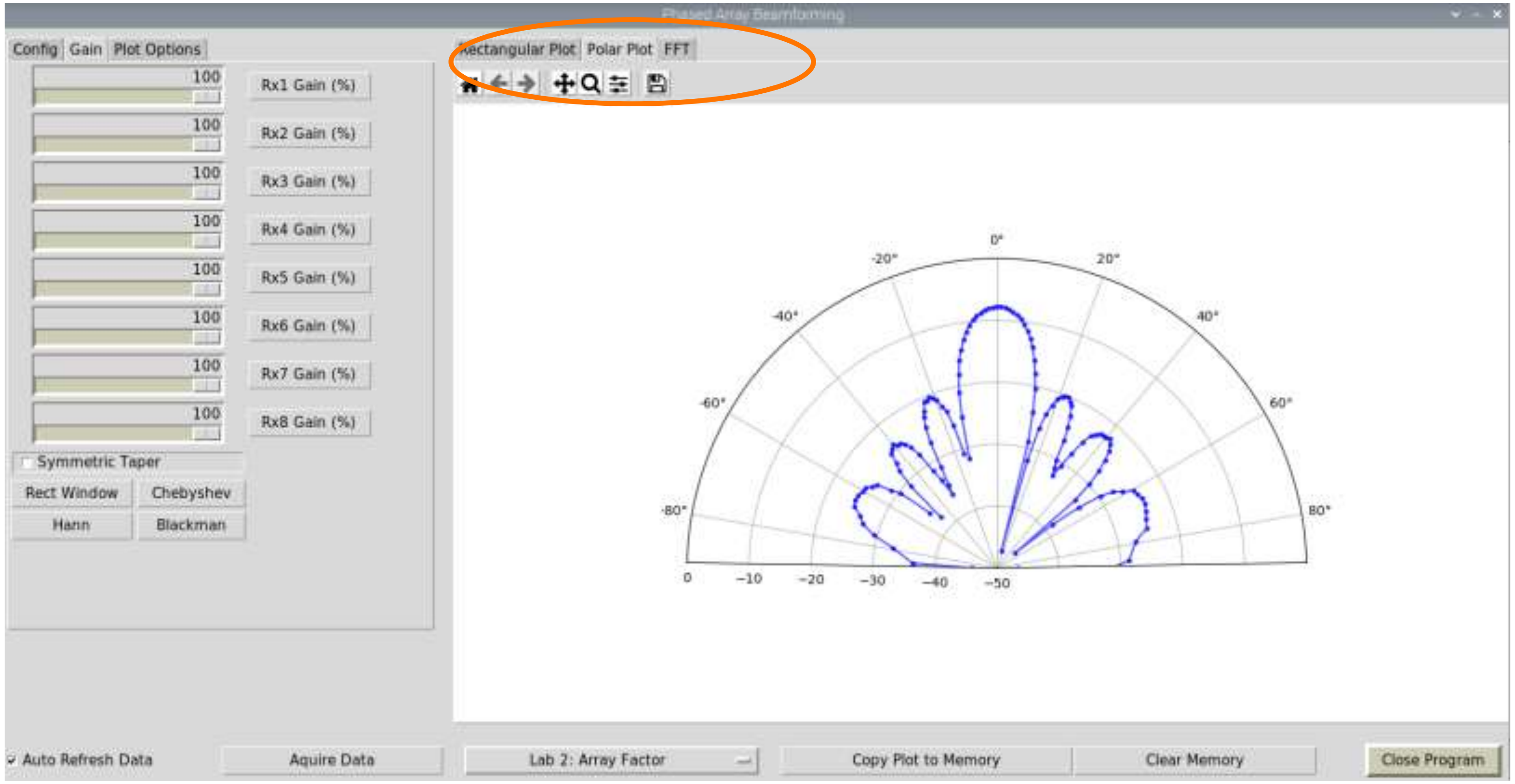
100 Wait Time (ms)

Beam Sweep Mode Selection

Lab 2: Array Factor

- ▶ In the Phaser GUI, select “Lab 2: Array Factor”
- ▶ Slowly move the HB100 in a half-circle around the array and observe the changes
- ▶ Does the main lobe’s beamwidth remain constant as you move the RF source?

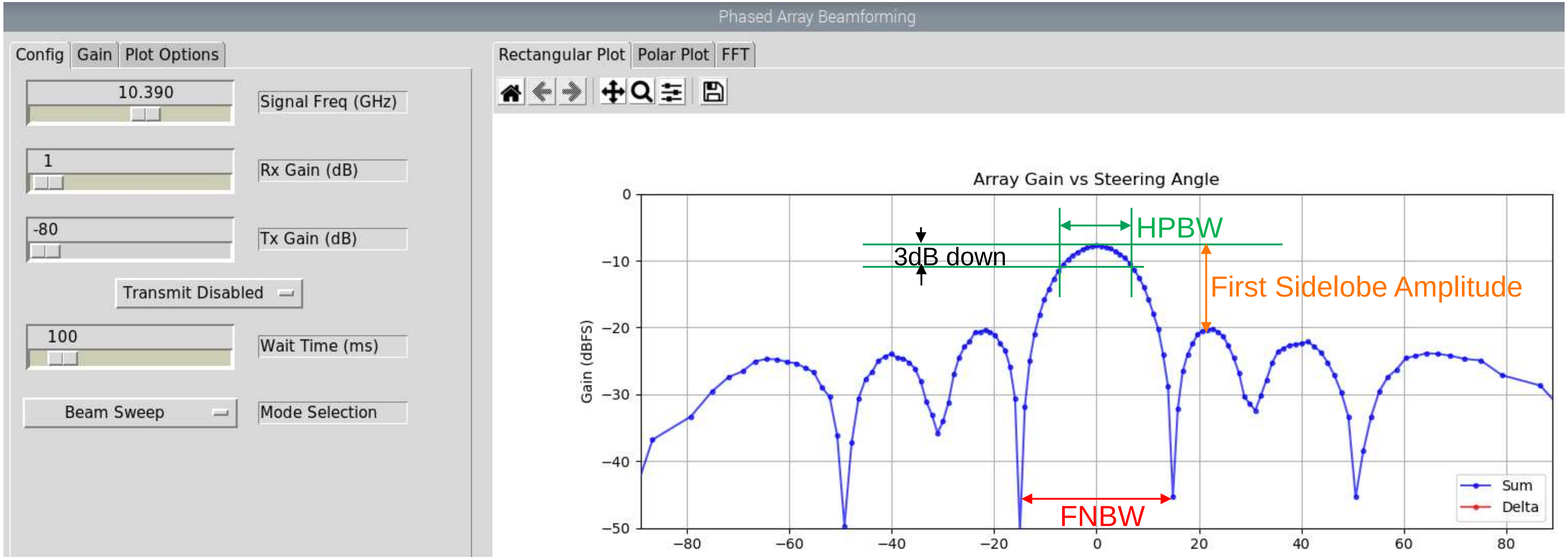
Lab 3-2: Array Factor and Beamwidth



Rx1 Gain (%) 100
Rx2 Gain (%) 100
Rx3 Gain (%) 100
Rx4 Gain (%) 100
Rx5 Gain (%) 100
Rx6 Gain (%) 100
Rx7 Gain (%) 100
Rx8 Gain (%) 100
☐ Symmetric Taper
☑ Auto Refresh Data

- In the Phaser GUI, select "Polar Plot"
- This is the same data, just displayed on a polar grid
- Slowly move the HB100 in a half-circle around the array and observe the changes again

Lab 3-2: Array Factor and Beamwidth



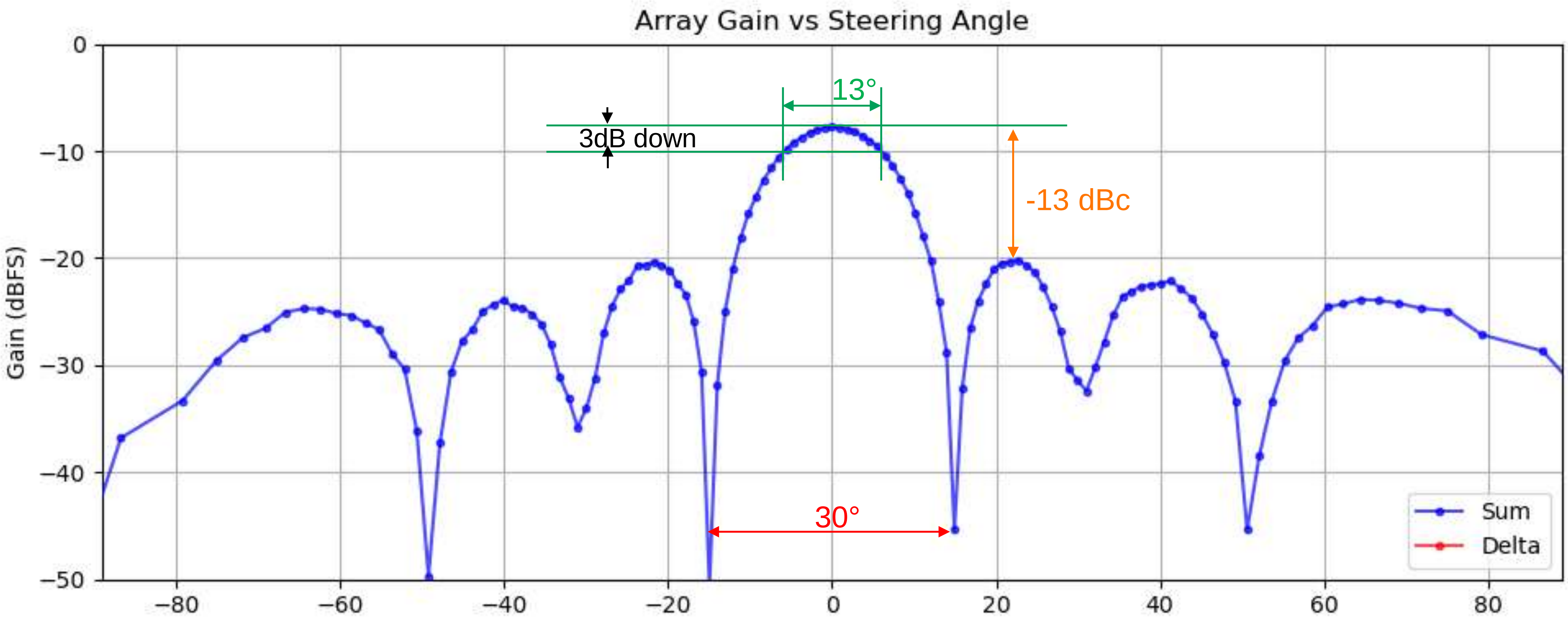
Signal Freq (GHz): 10.390
Rx Gain (dB): 1
Tx Gain (dB): -80
Transmit Disabled
Wait Time (ms): 100
Mode Selection: Beam Sweep

- Move the HB100 to the mechanical boresight location (i.e. directly facing the array)
- Record the following:

Peak Amplitude	Half Power Width	First Null Width	First Sidelobe Amplitude
_____ dBFS	_____ °	_____ °	_____ dBc

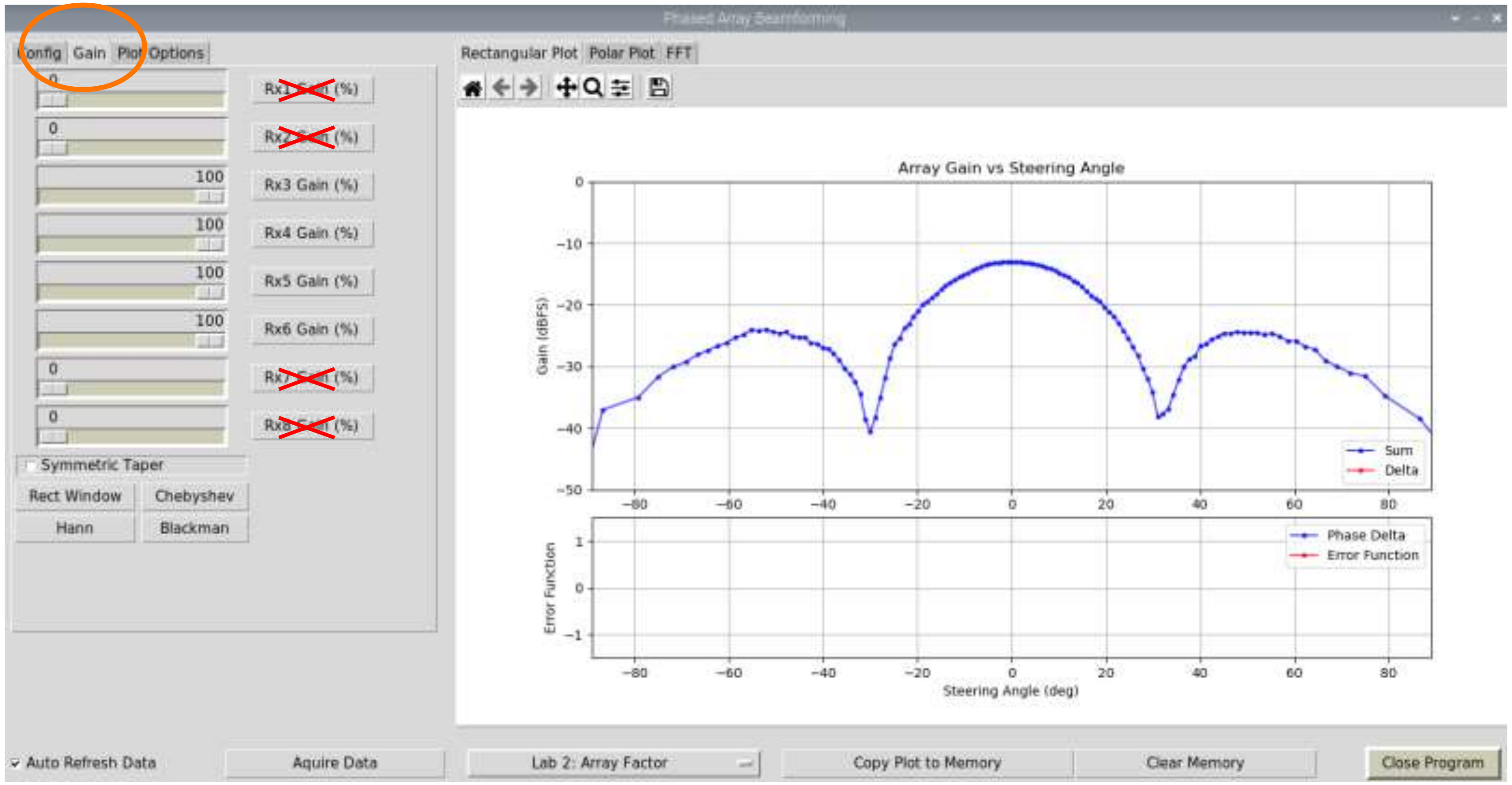
Lab 3-2: Array Factor and Beamwidth

Example of Measured Results:



- ▶ How do your results compare to the calculated values from the lecture?

Lab 3-2: Array Factor and Beamwidth



- In the Phaser GUI, select the “Gain” tab
- Click the Rx1_Gain button to disable that channel.
- Do the same for Rx2, Rx7, and Rx8. We now have a 4 element array!
- Repeat the beamwidth measurements and compare to the calculated values

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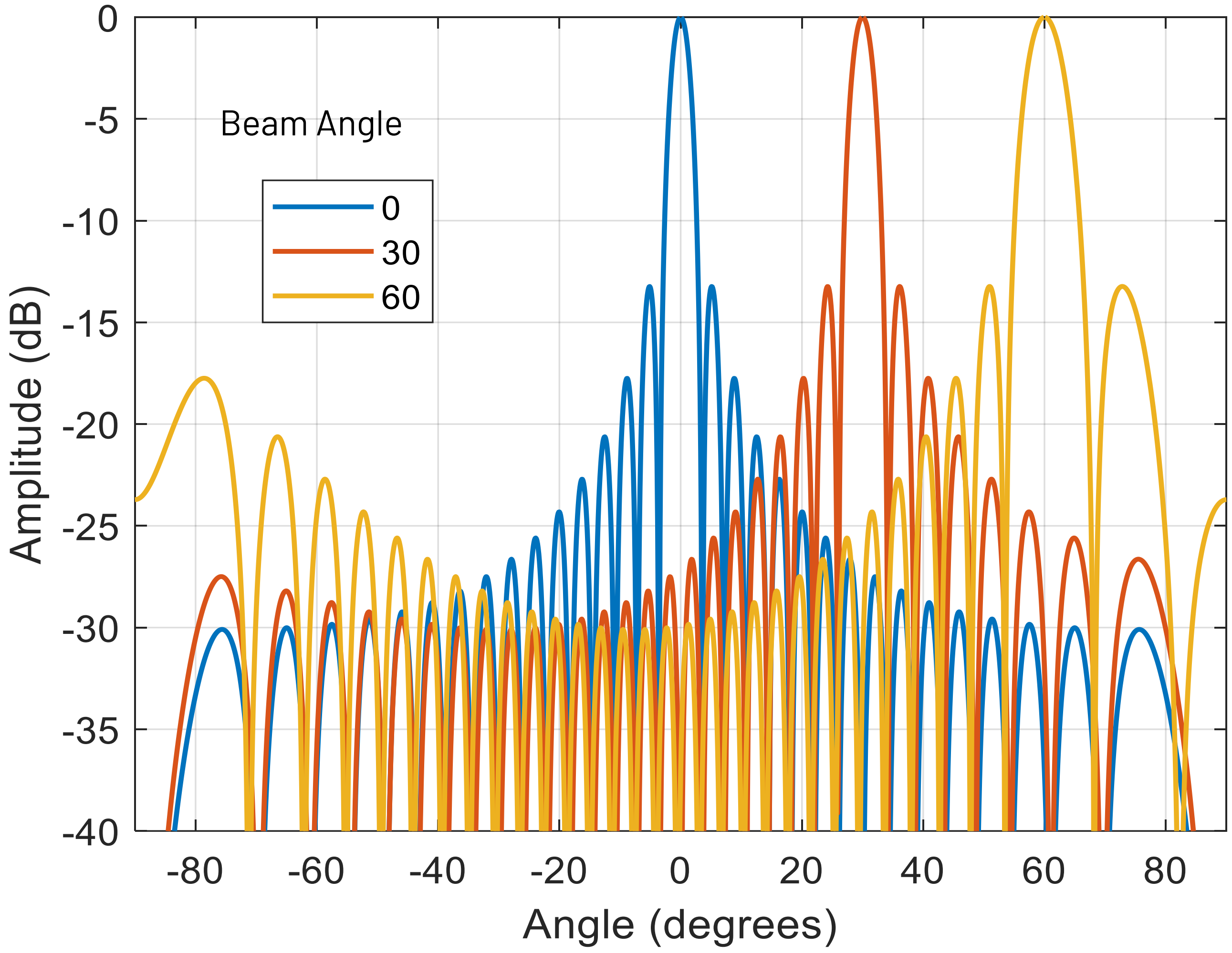
Session 3-3: Element Factor

Beam Width vs Angle

$$AF[\theta,\Delta\phi]=\frac{\sin\left(N\left[\frac{\pi d}{\lambda}\sin(\theta)-\frac{\Delta\phi}{2}\right]\right)}{N\sin\left(\frac{\pi d}{\lambda}\sin(\theta)-\frac{\Delta\phi}{2}\right)}$$

Normalized array factor of a 32 element linear array at several beam angles, d=λ/2



https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part1.html

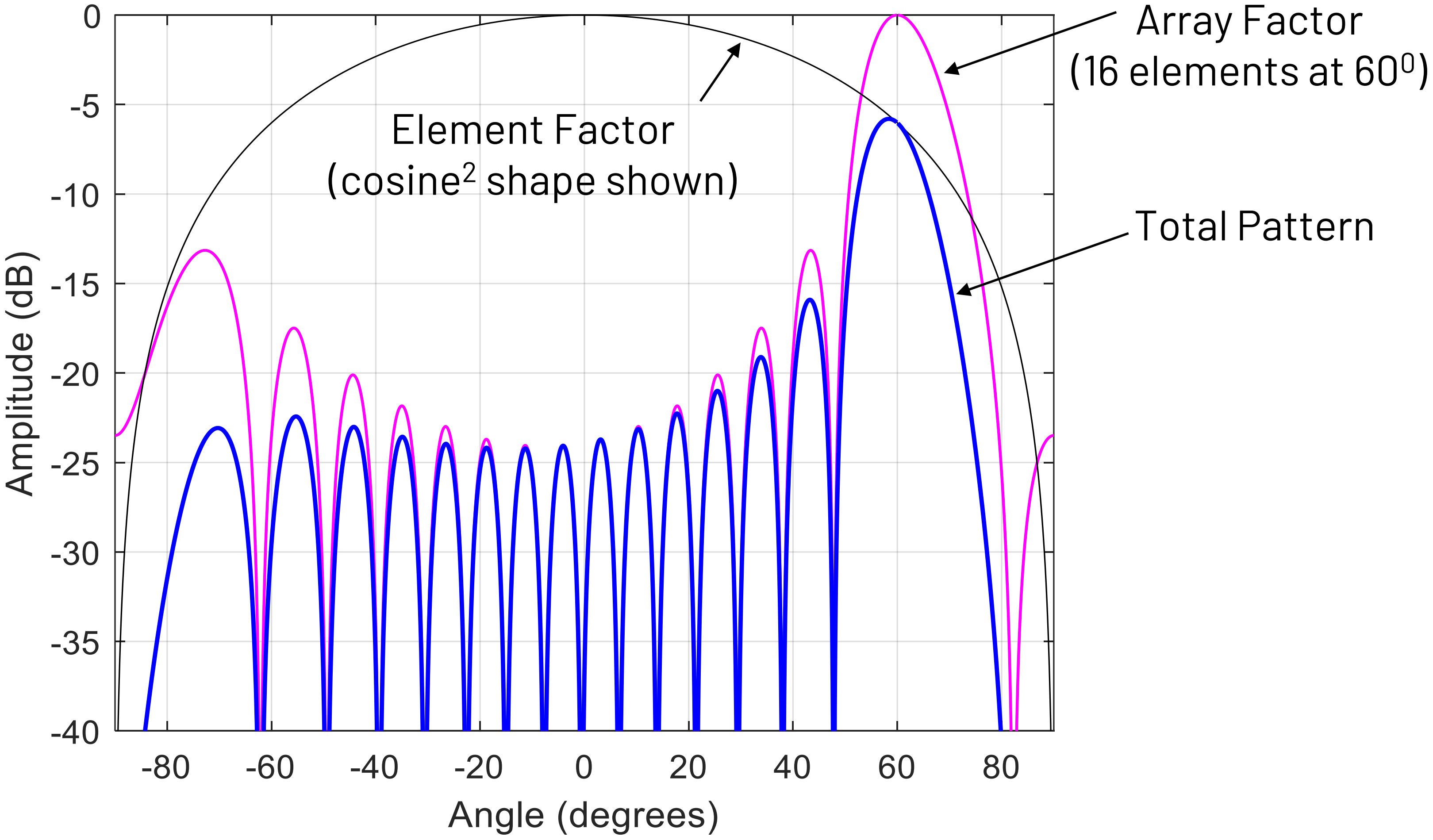
Array Factor + Element Factor

The Phased Array Gain (dB)

$G(\theta) = G_E(\theta) + G_A(\theta)$

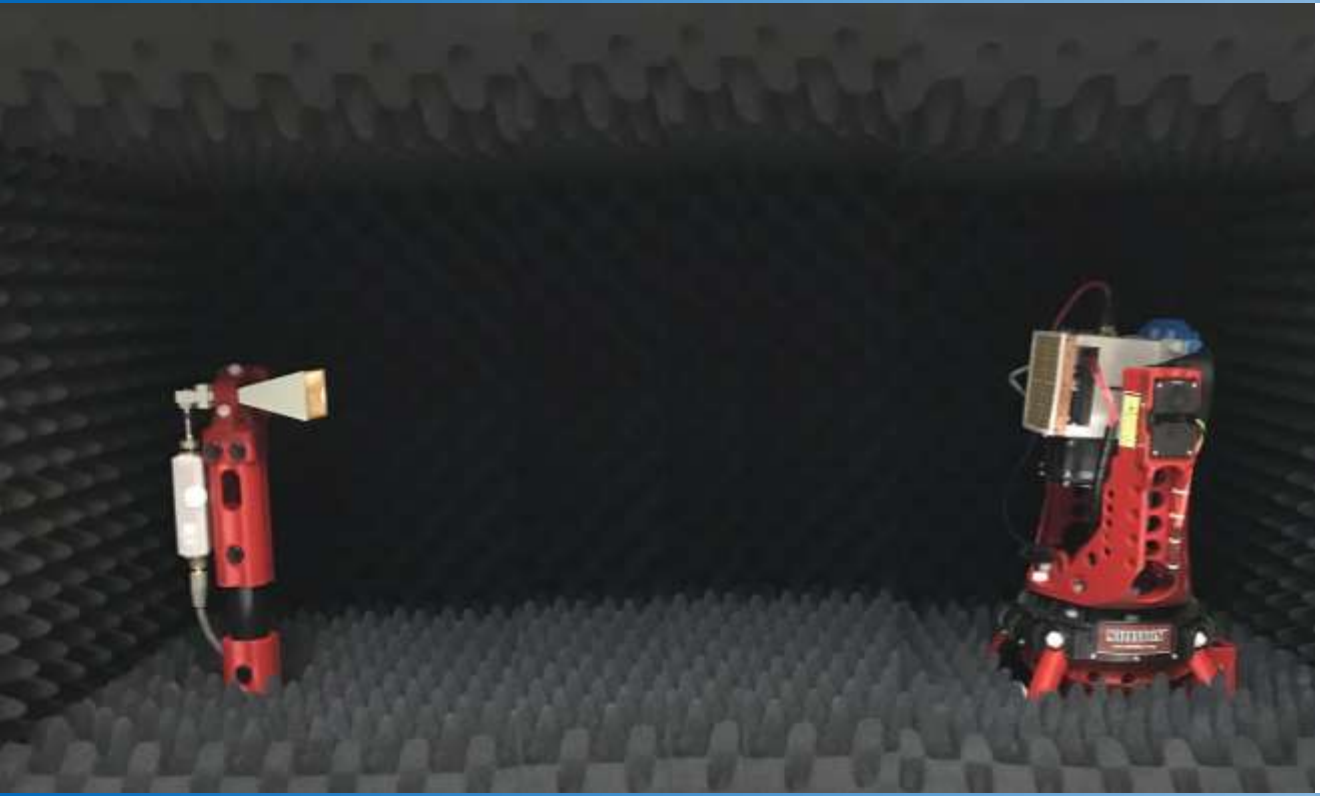
- Observations

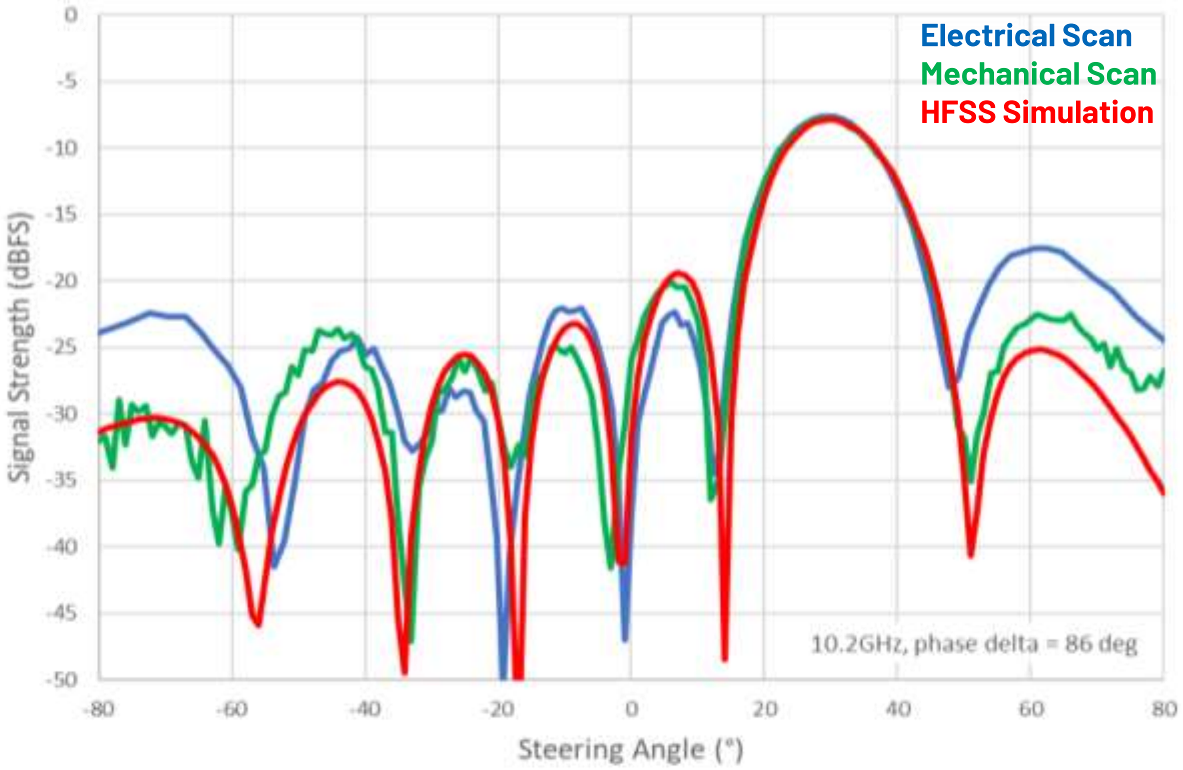
1) The main beam loses amplitude at the rate of the element factor
2) The sidelobes on boresight have no amplitude loss.
3) The result is the sidelobe performance of the overall array degraded off boresight



https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part1.html

Electrical Scan vs Antenna Chamber





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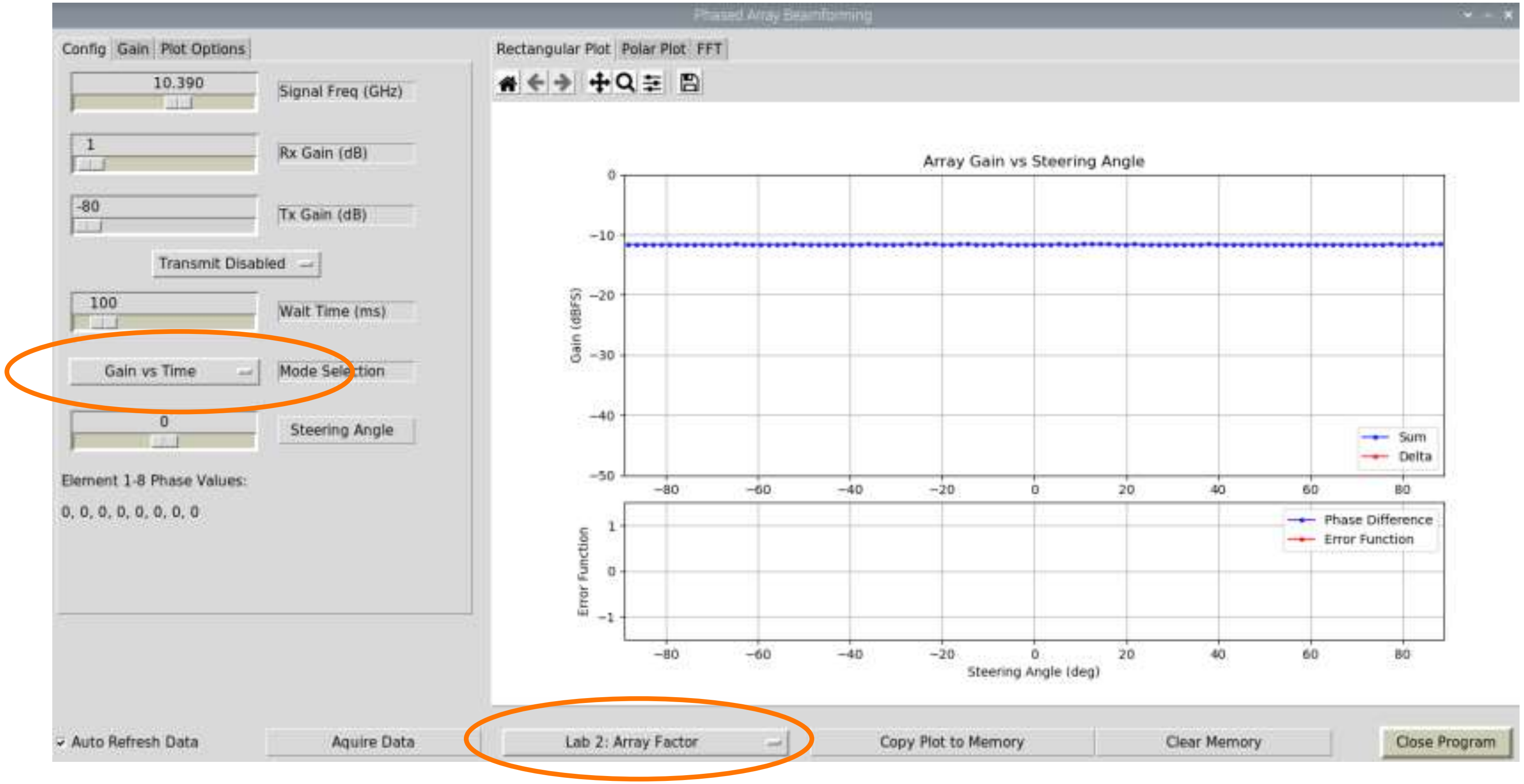
Lab 3-3: Measuring the Actual Antenna Pattern

Workshop Lab Guide

Lab 3-3: Measuring the Actual Antenna Pattern



Signal Freq (GHz): 10.390

Rx Gain (dB): 1

Tx Gain (dB): -80

Transmit Disabled

Wait Time (ms): 100

Mode Selection: Gain vs Time

Steering Angle: 0

Element 1-8 Phase Values:
0, 0, 0, 0, 0, 0, 0, 0

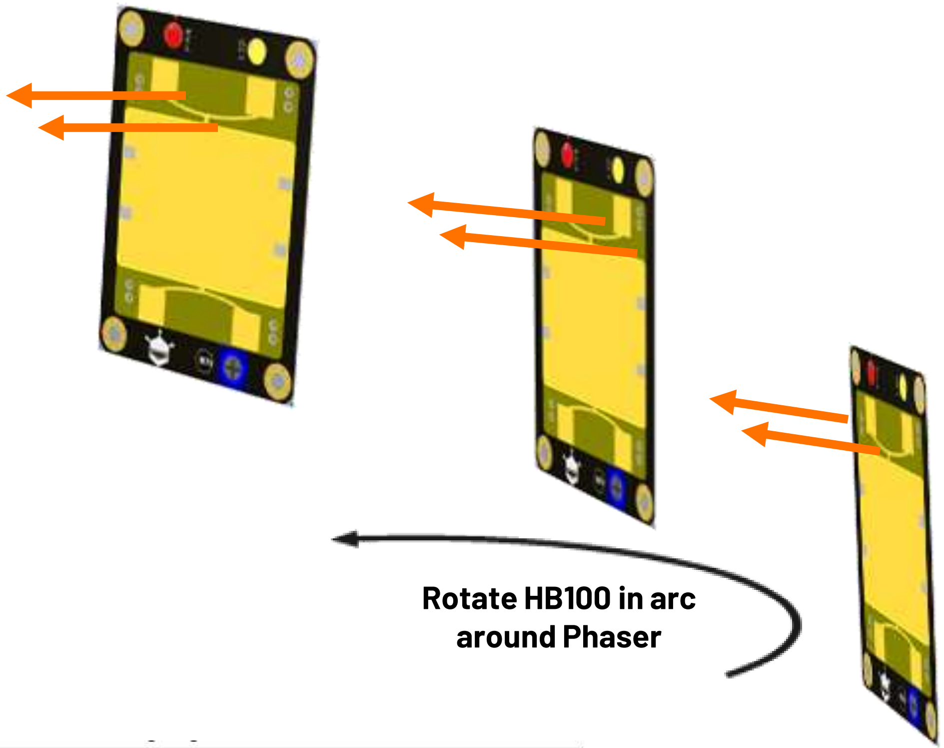
☑ Auto Refresh Data

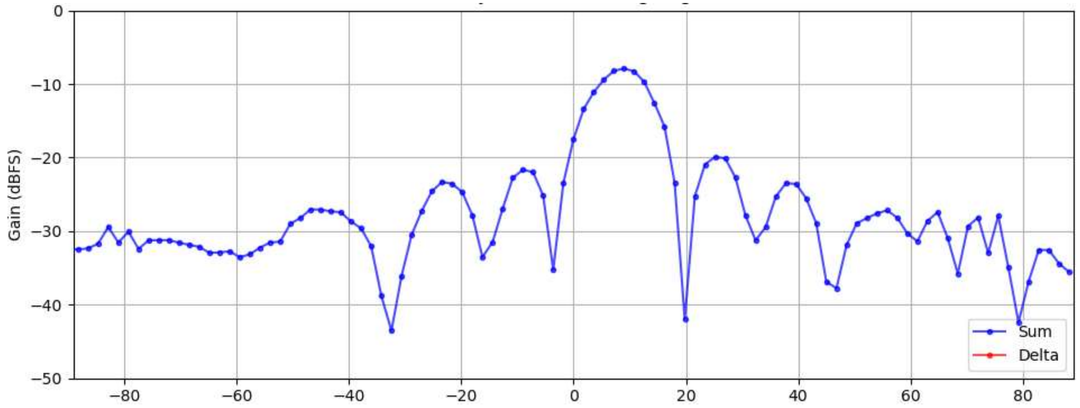
Lab 2: Array Factor

- In the Phaser GUI, select “Lab 2: Array Factor”
- In the “Config” tab, select “Signal vs Time” from “Mode Selection”
- This plots peak amplitude vs time (ignore the x-axis!)

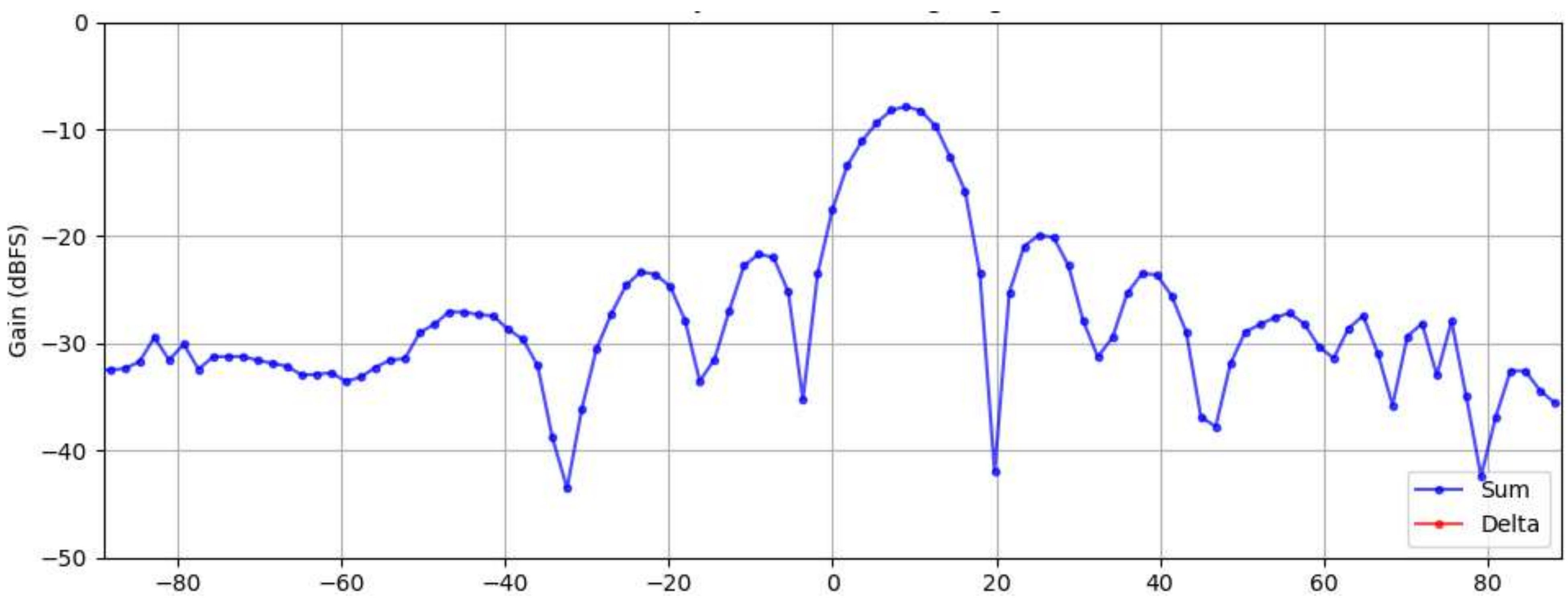
Lab 3-3: Measuring the Actual Antenna Pattern

- Now rotate the HB100 in a radius around the Phaser board –keep the HB100 pointed at Phaser!
- Start at the left position (-90 deg), and move around to the right position (+90 deg)
- Keep a smooth, consistent speed!
- Practice a few times, then try time it so that one smooth rotation covers the entire graph span
- With practice, it may look like this:


Rotate HB100 in arc around Phaser



Lab 3-3: Measuring the Actual Antenna Pattern



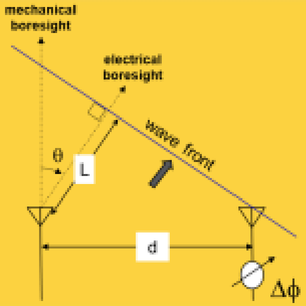
- ▶ Ok, so we can't really get angular measurements from this (we can never rotate it perfectly)
- ▶ But we can get accurate lobe amplitudes:
  - ▶ Compare these amplitudes to your earlier measurements. How close are they?
- ▶ Repeat the process, but change the "Steering Angle" from 0 deg to 30 deg.

Session 4:
Antenna Impairments

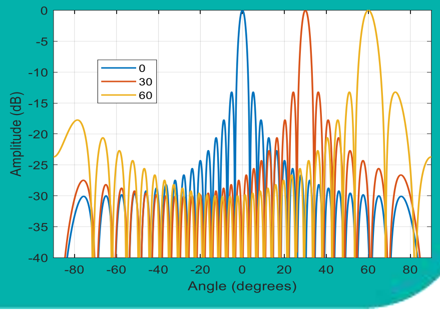
Phased Array Workshop: Antenna Impairments

Digitizer

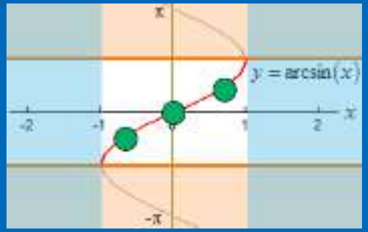
Steering Angle



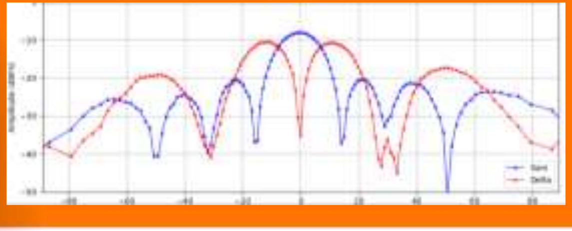
Antenna Patterns



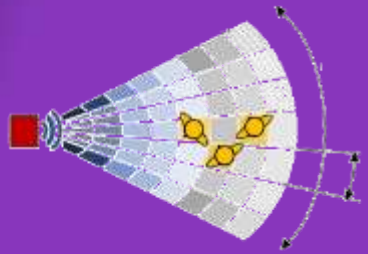
Antenna Impairments



Monopulse Tracking



Radar

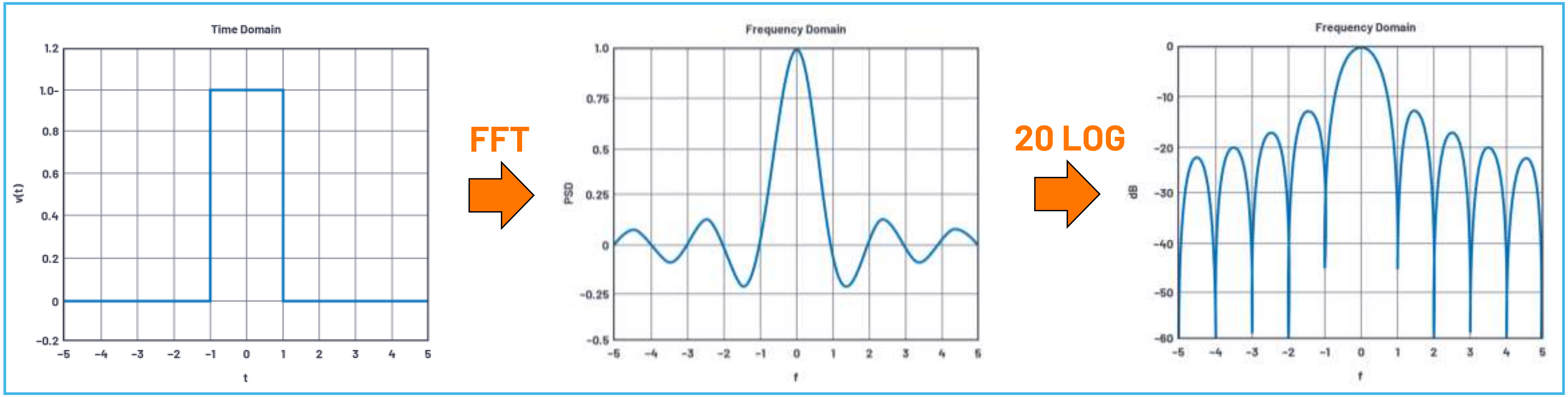


Session 4: Antenna Impairments

Sidelobes and Tapering

Sidelobes

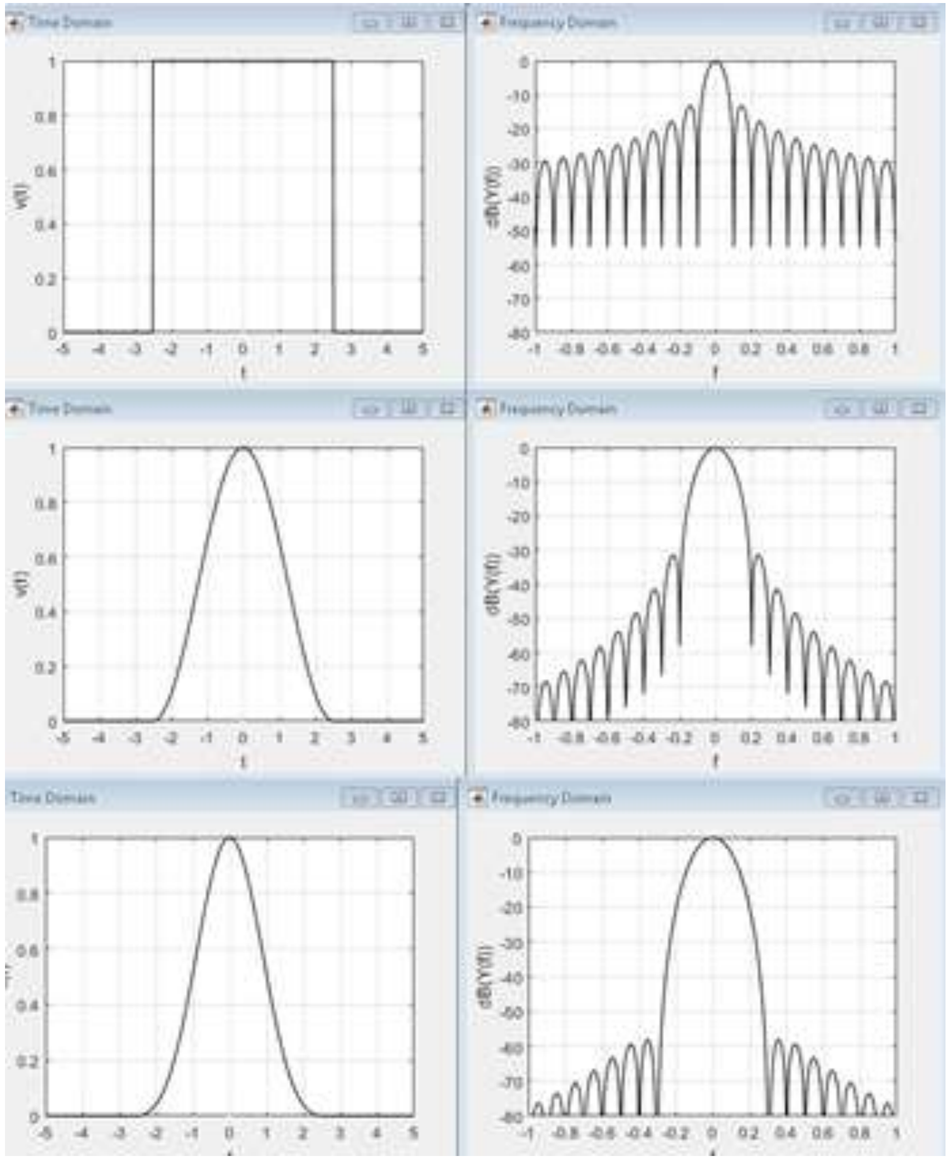
- With all elements at the same gain, we effectively have a box car window.
  - This is analogous to rectangular window FFT



- Time domain pulse → frequency domain sin(x)/x → first sidelobe -13dBc, etc.
- As pulse becomes wider…
  - Main lobe narrows
  - Sidelobes move in
  - Sidelobe levels remain unchanged

https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part3.html

Understanding Beam Tapering: Window Functions



Boxcar – 1st sidelobe @ -13dBc Narrowest main lobe

Hanning – 1st sidelobe < -30dBc Main lobe broadens

Blackman – Lowest sidelobes Broadest main lobe

Note: windowing losses not shown in these examples

Sidelobe Control: Beam Tapering

Field Domain
(Element Amplitude)

Spatial Domain
(Radiated Pattern Weighting)

Uniform Weighting

Hamming Weighting

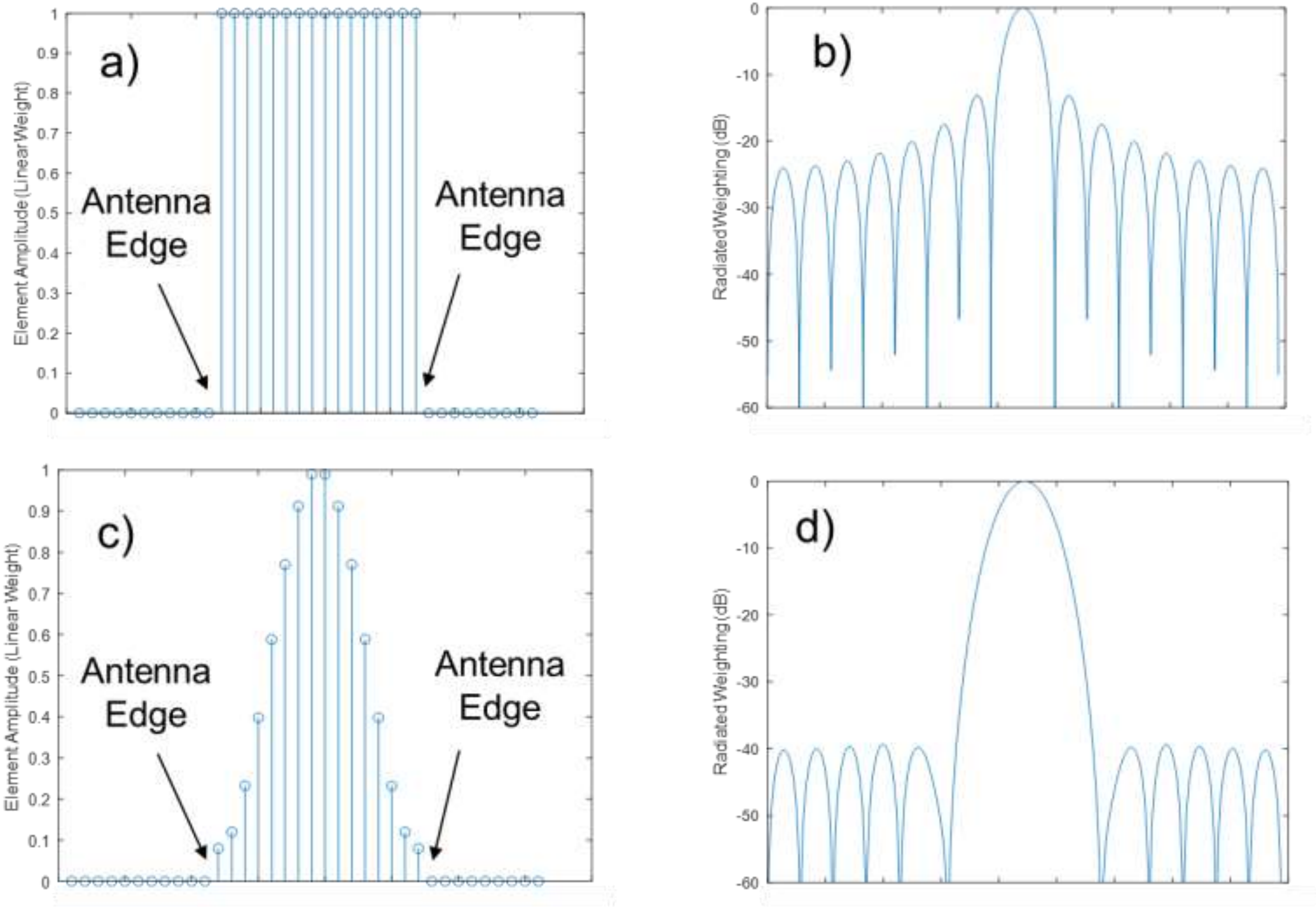
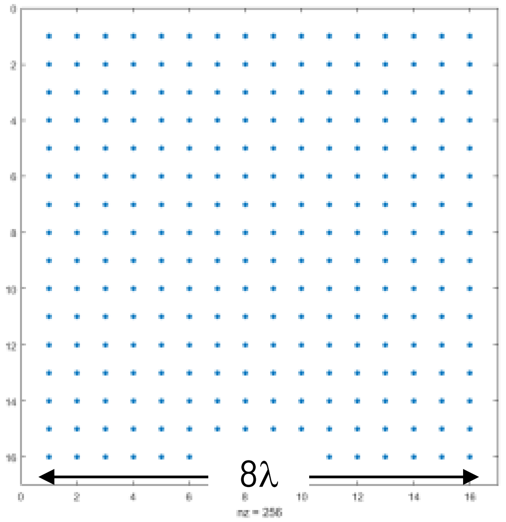
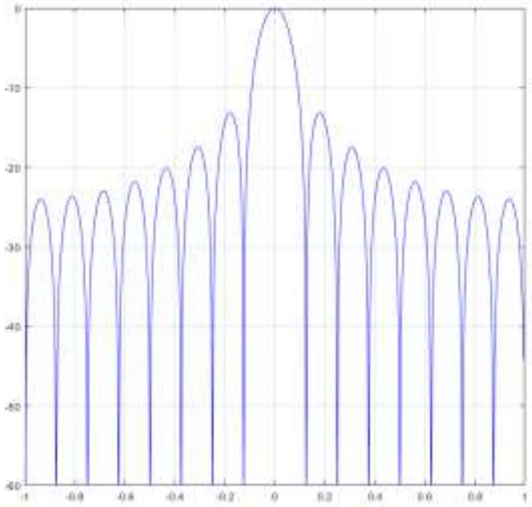


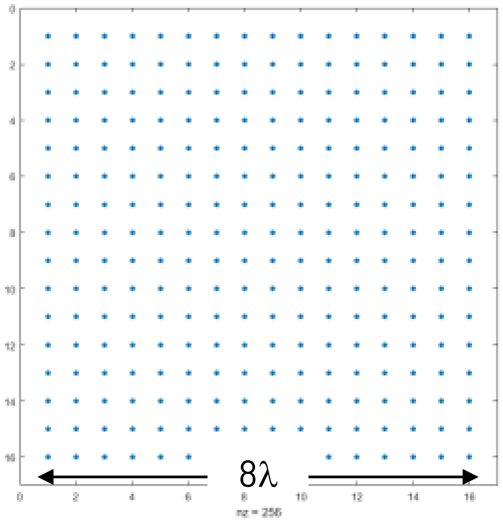
Figure from "Phased Array Antenna Patterns—Part 3: Sidelobes and Tapering"

Sidelobe Control: Comparison of Tapering Methods

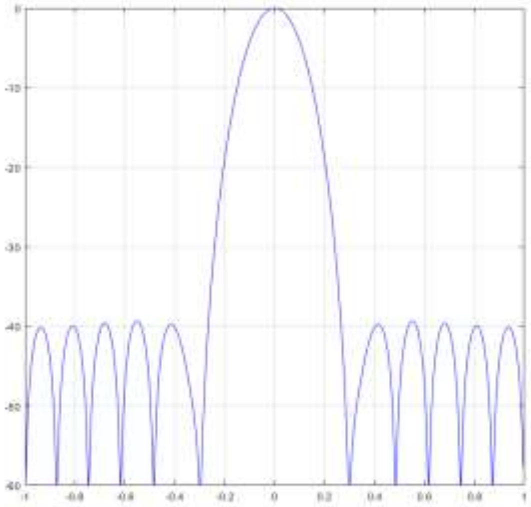


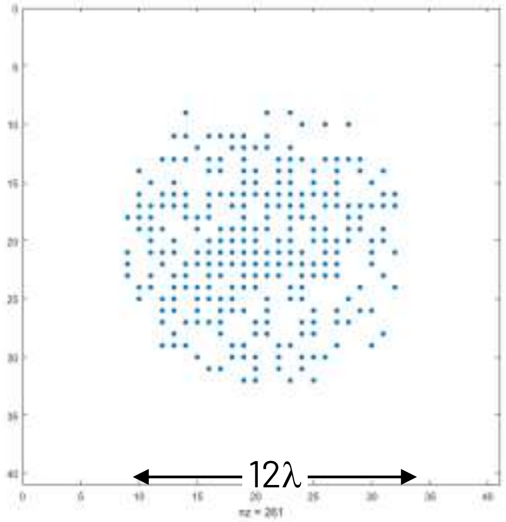
Uniform Illumination



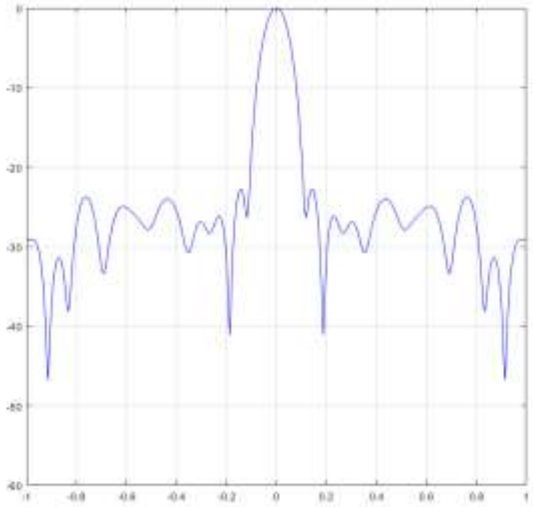


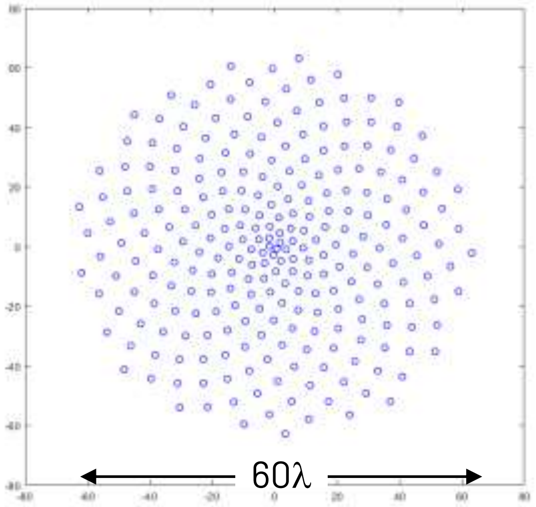
Hamming Amplitude



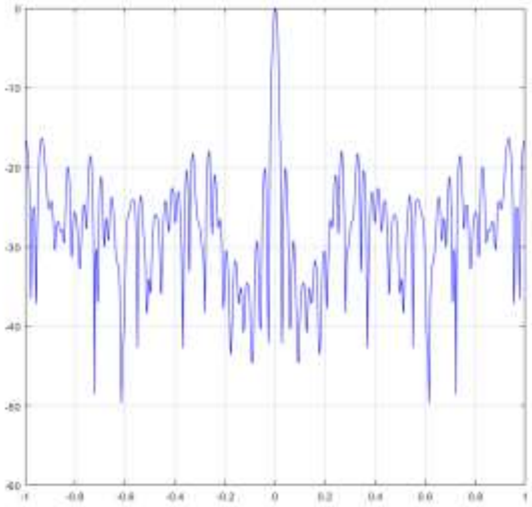


Hamming Thinned





Spiral



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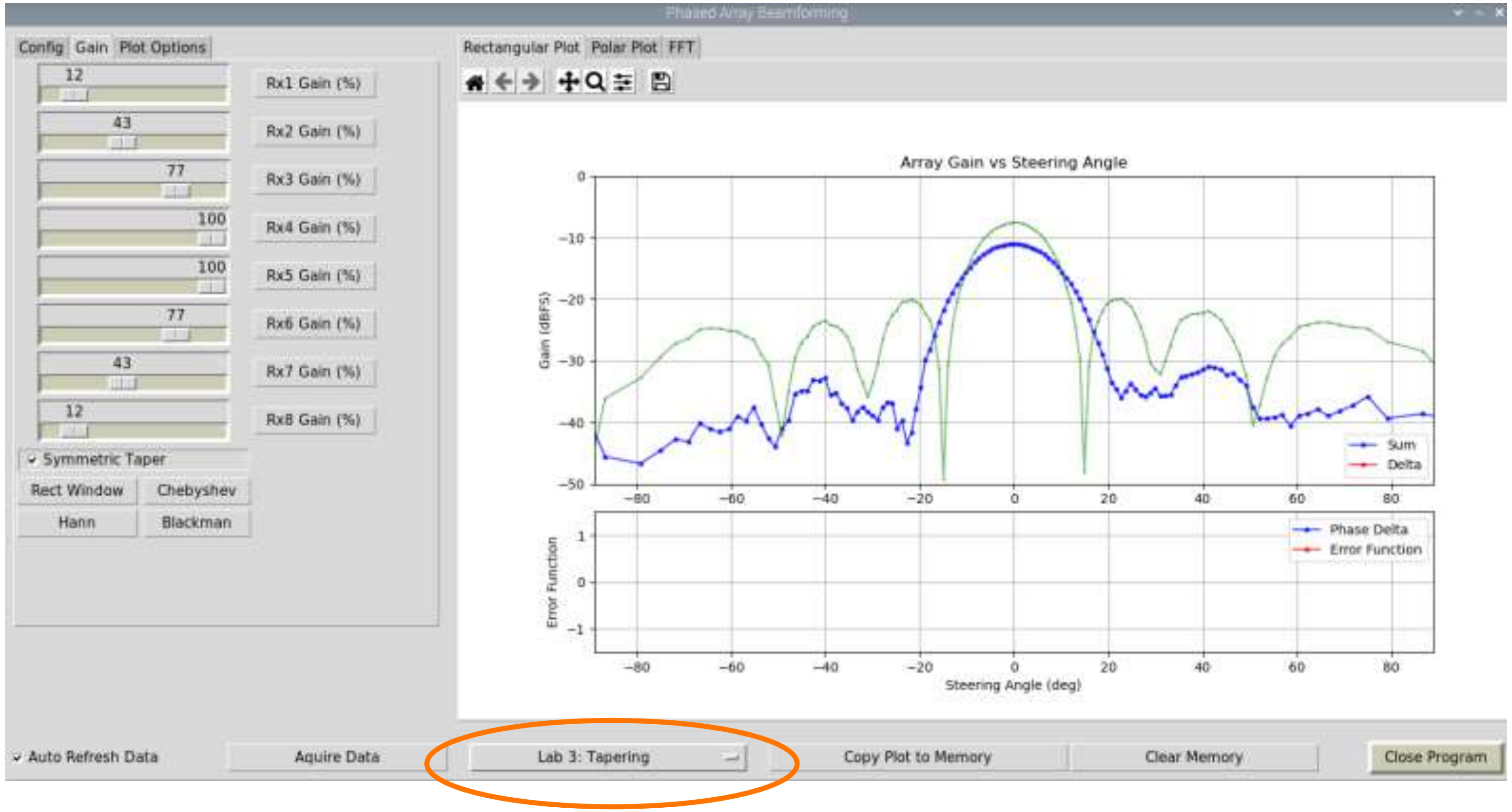
Lab 4-1: Sidelobes and Tapering

Workshop Lab Guide

Lab 4-1: Sidelobes and Tapering



Rx1 Gain (%) 12
Rx2 Gain (%) 43
Rx3 Gain (%) 77
Rx4 Gain (%) 100
Rx5 Gain (%) 100
Rx6 Gain (%) 77
Rx7 Gain (%) 43
Rx8 Gain (%) 12
☑ Symmetric Taper
☑ Auto Refresh Data
Lab 3: Tapering

- In the Phaser GUI, select "Lab 3: Tapering"
- Press "Copy Plot to Memory", then try one of the tapering profile buttons.
- What is the impact to sidelobe level, beamwidth, and peak gain?
- Select "Symmetric Taper" and invent your own profile! Can you make a "better" taper?

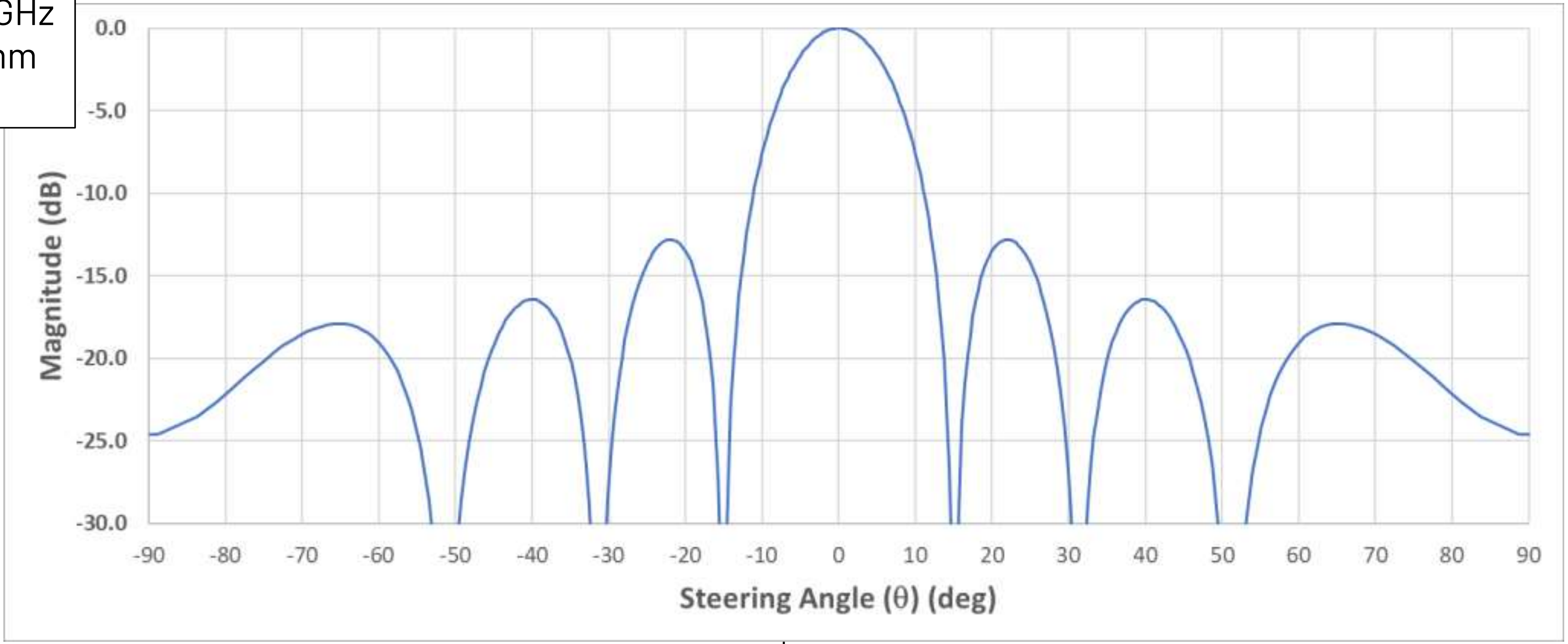
Session 4:
Antenna Impairments
Grating Lobes

Understanding Grating Lobes: Math and Theory

- Grating Lobes are analogous to aliasing on an ADC
  - From sampling theory, we need minimum sample rate of 2x frequency of interest
- Grating Lobes are "Spatial Aliasing"
  - Each antenna element is a spatial "sample"
  - Need two "samples" per wavelength to avoid spatial aliasing (aka Grating Lobes)
    - For $<\lambda/2$ element spacing, no grating lobes occur
    - For $>\lambda/2$ element spacing, grating lobes will appear at the opposite horizon

Understanding Grating Lobes

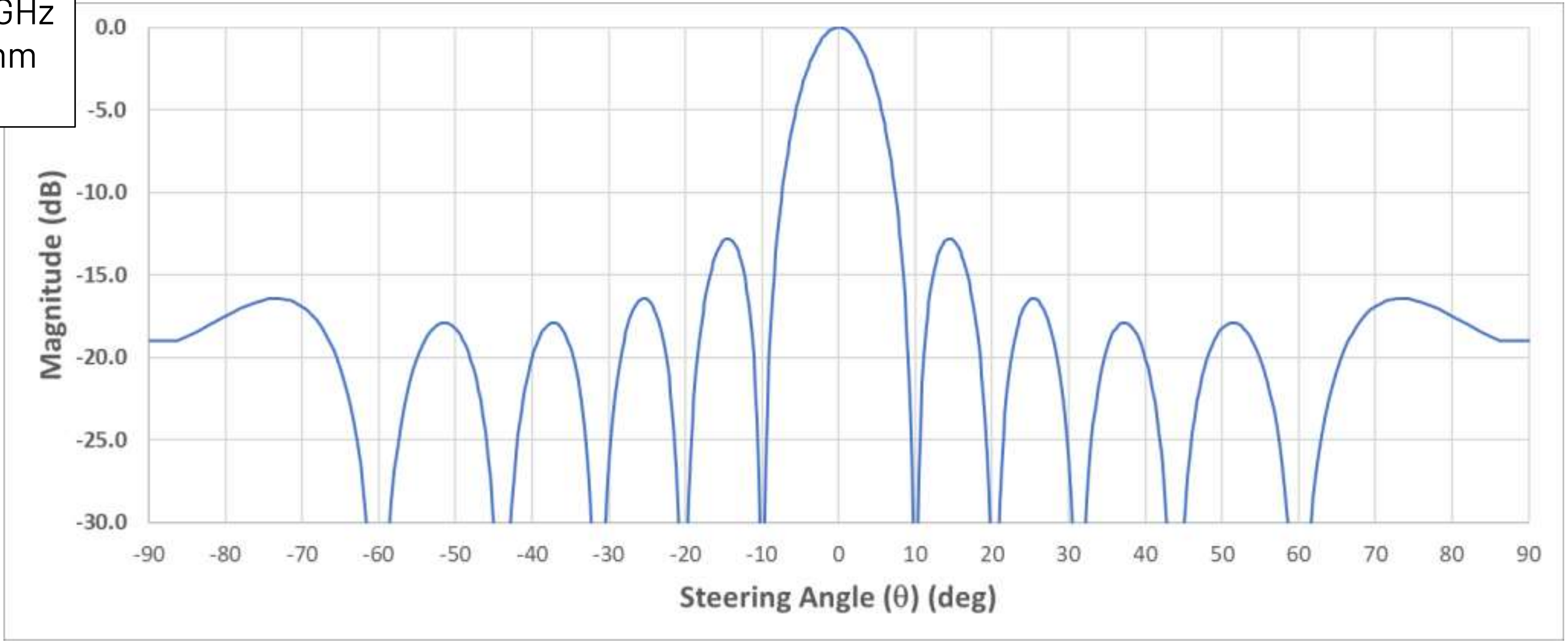
f = 10.7 GHz
λ = 28 mm
N = 8



d = 0.5 λ = 14 mm

Understanding Grating Lobes

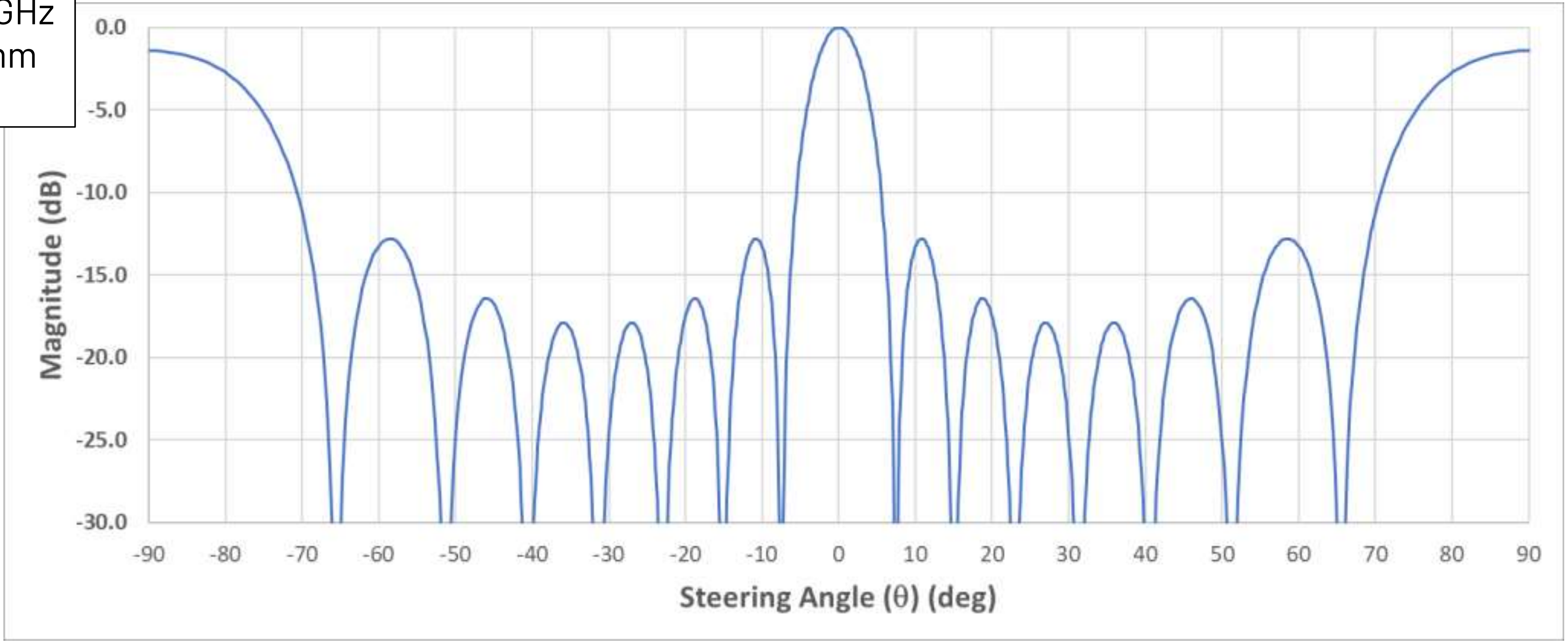
f = 10.7 GHz
λ = 28 mm
N = 8



d = 0.75 λ = 21 mm

Understanding Grating Lobes

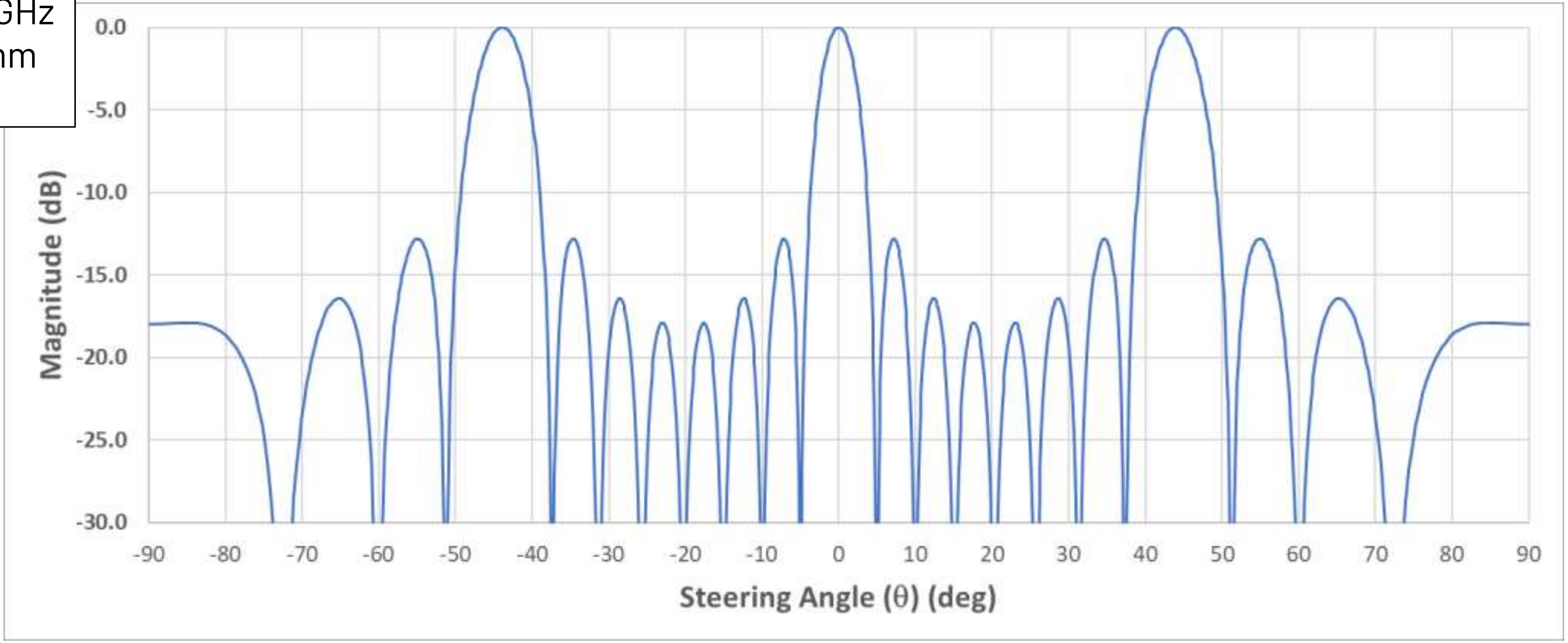
f = 10.7 GHz
λ = 28 mm
N = 8



d = 1.0 λ = 28 mm

Understanding Grating Lobes

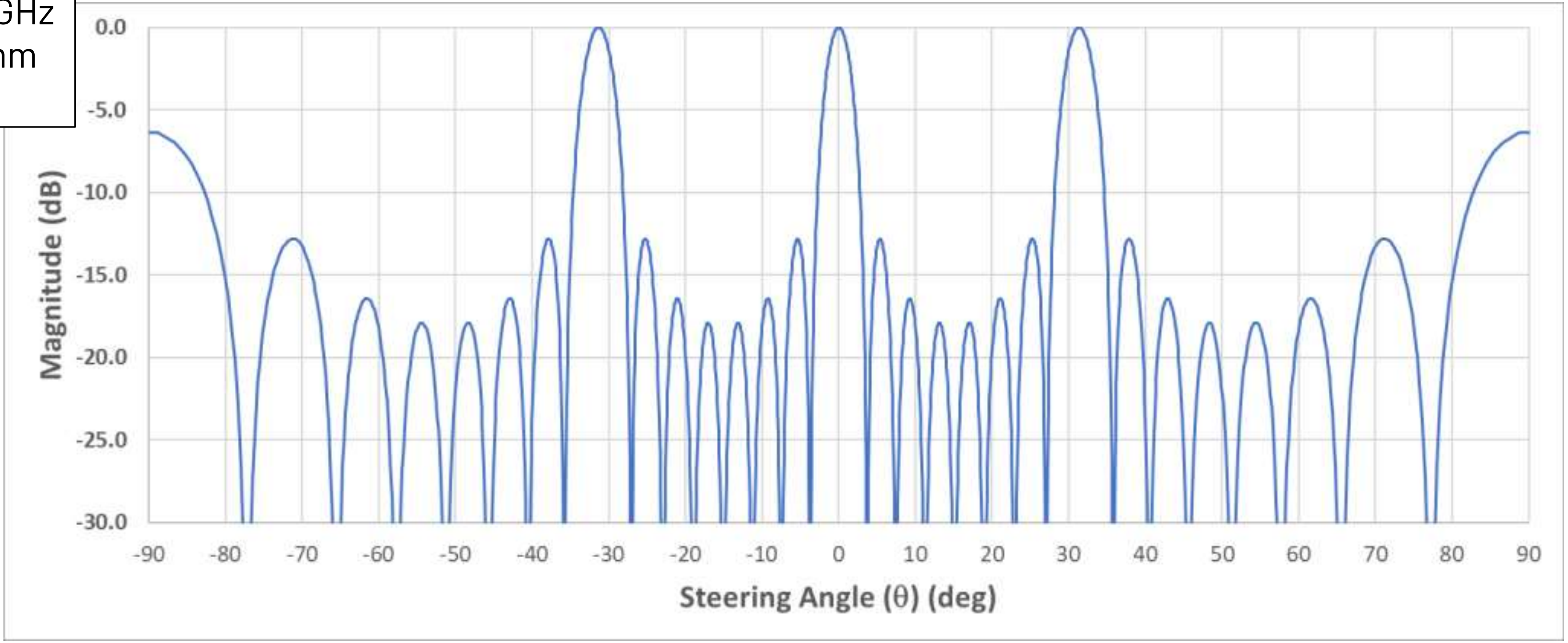
f = 10.7 GHz
λ = 28 mm
N = 8



d = 1.5 λ = 42 mm

Understanding Grating Lobes

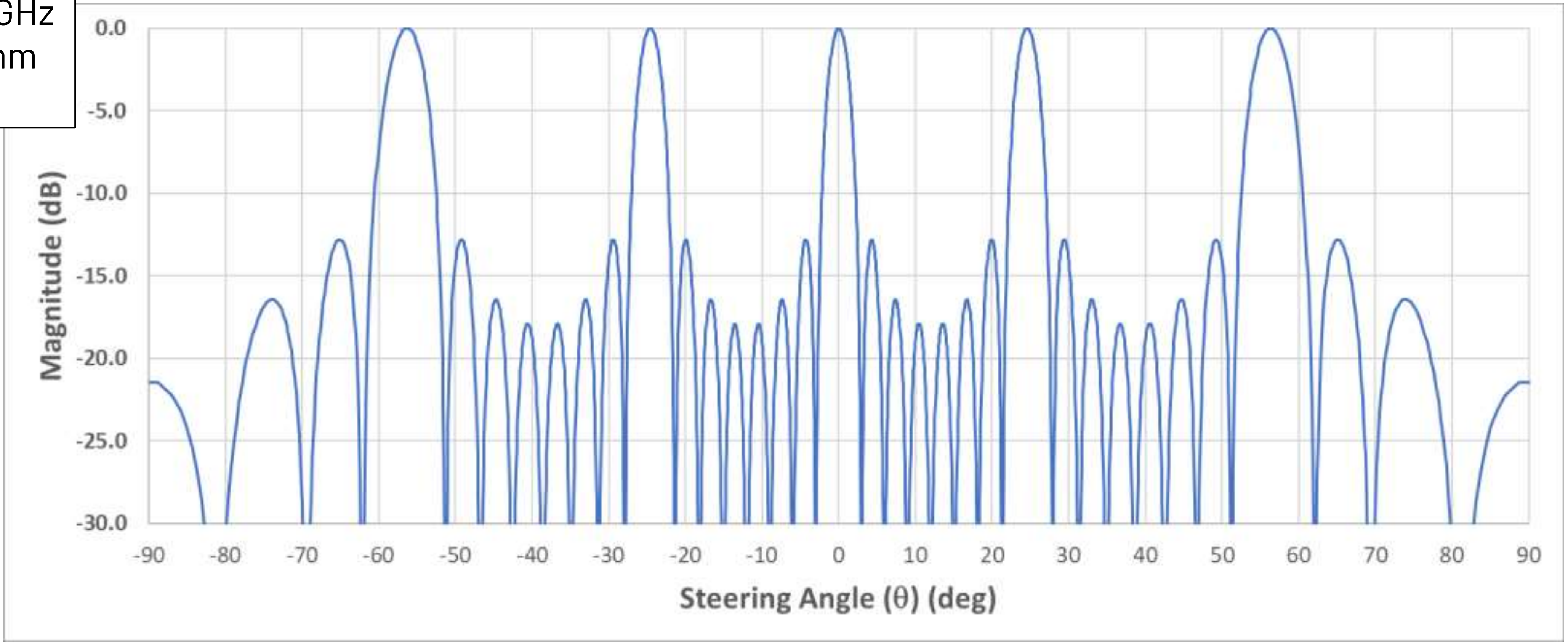
f = 10.7 GHz
λ = 28 mm
N = 8



d = 2.0 λ = 56 mm

Understanding Grating Lobes

f = 10.7 GHz
λ = 28 mm
N = 8



d = 2.5 λ = 70 mm

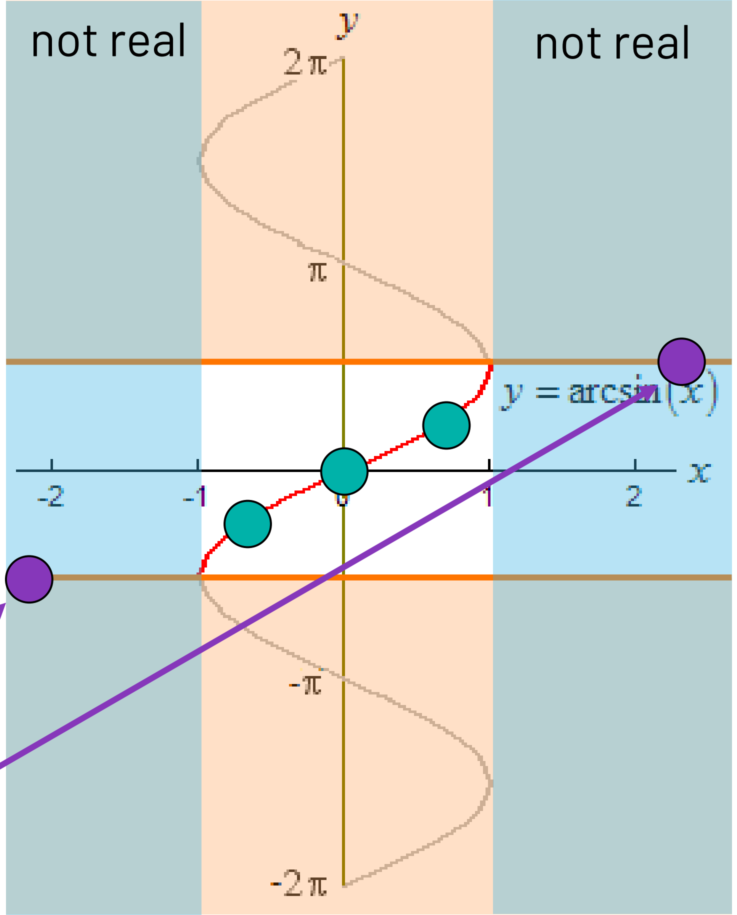
Understanding Grating Lobes: Math and Theory

For Broadside (i.e. steering angle = 0°)

θ_{MAIN} **= $\mathbf{\sin^{-1}(m\,\lambda/d)}$**, for m=0, ±1, ±2, etc.

- Case 1: λ =28mm, and d=14mm (λ/d = 2)
  - This yields only one real solution (only m=0 gives valid solution)

- Case 2: λ =28mm, and d=42mm (λ/d = 0.66)
  - θ(main lobe) = $\sin^{-1}$(m * 0.66), is valid for m=0 AND ±1
  - We will see 3 main lobes!
    - Located at θ = 0, θ = ±0.72 rad (±41°)
  - FYI, m= ± 2 gives π/2- i*0.78, which we ignore



https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part2.html

Understanding Grating Lobes: Math and Theory

- We can tolerate wider element spacing if the max beam angle is constrained:

$$d_{max} = \frac{\lambda}{1+|sin\theta_{max}|}$$

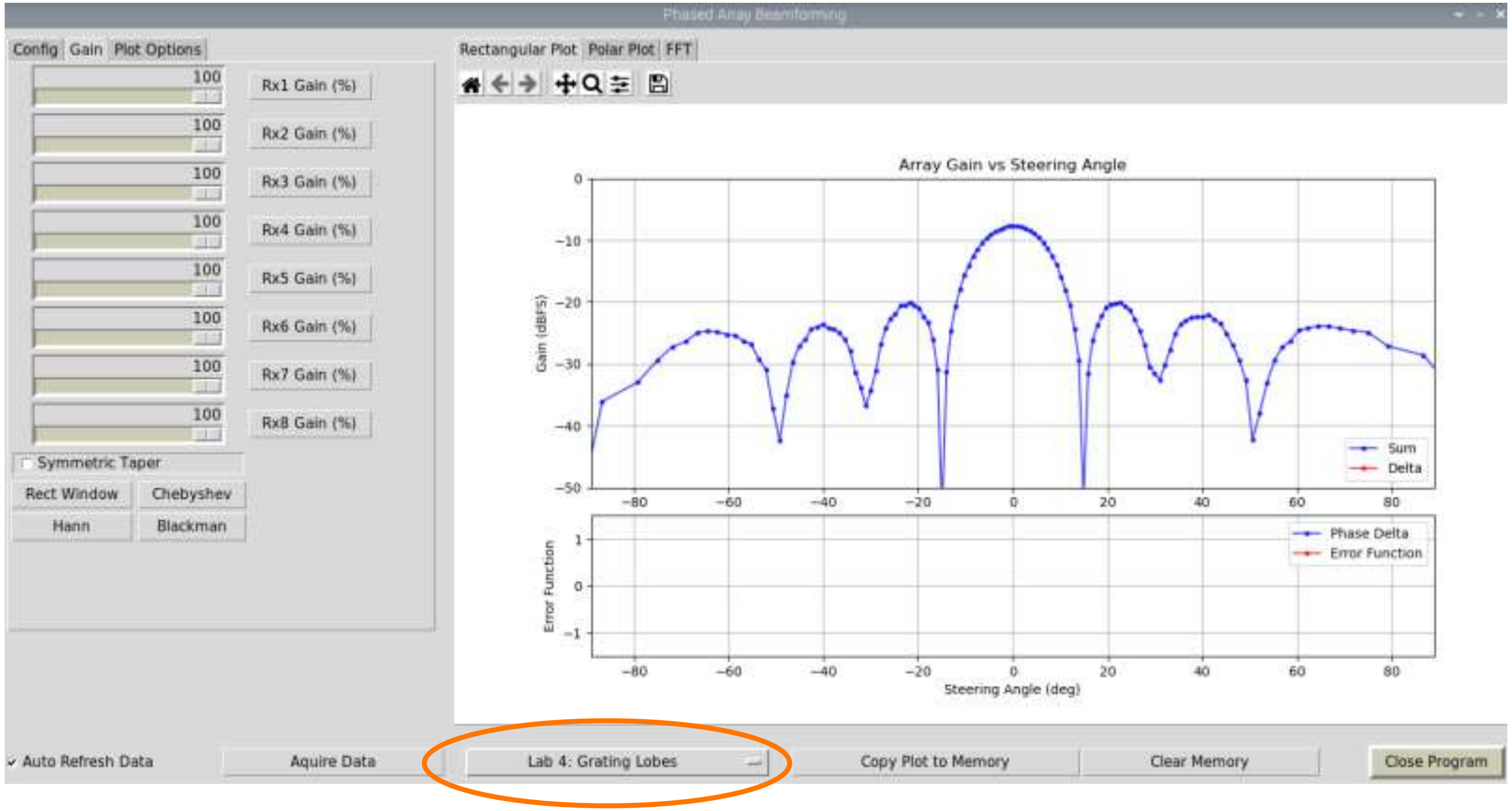
Derivation in "Phased Array Antenna Patterns—
Part 2: Grating Lobes and Beam Squint"

- Let's say our array spacing is d=14mm (this is Phaser's array spacing)
- But our signal is at 11.5 GHz
- 11.5 GHz wavelength (λ) is 26mm →spacing is **0.54 λ**
- So if f=11.5GHz, and d=14mm, then:
  - θ_{max} = arcsin(3E8/(11.5E9*0.014)-1) = 60 deg
  - We expect to see a grating lobe, on the opposite horizon, as we steer the beam to **60 deg**

Lab 4-2: Grating Lobes

Workshop Lab Guide

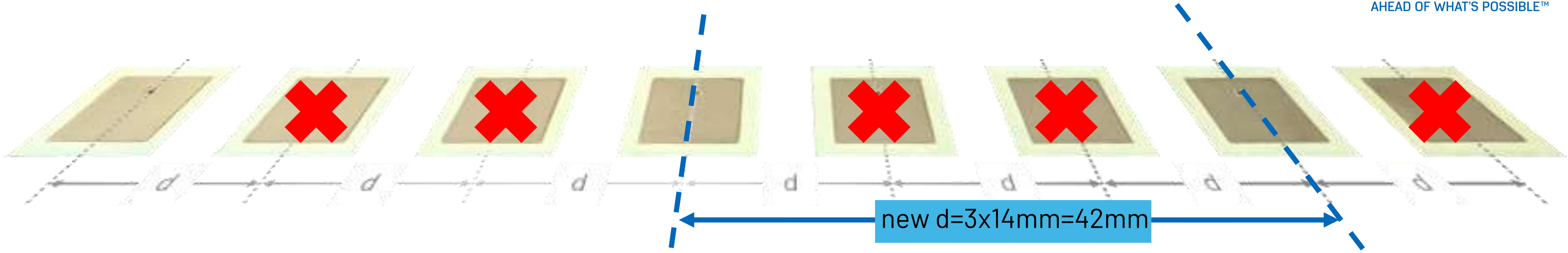
Lab 4-2: Grating Lobes



Rx1 Gain (%) 100
Rx2 Gain (%) 100
Rx3 Gain (%) 100
Rx4 Gain (%) 100
Rx5 Gain (%) 100
Rx6 Gain (%) 100
Rx7 Gain (%) 100
Rx8 Gain (%) 100
☐ Symmetric Taper
☑ Auto Refresh Data
Lab 4: Grating Lobes

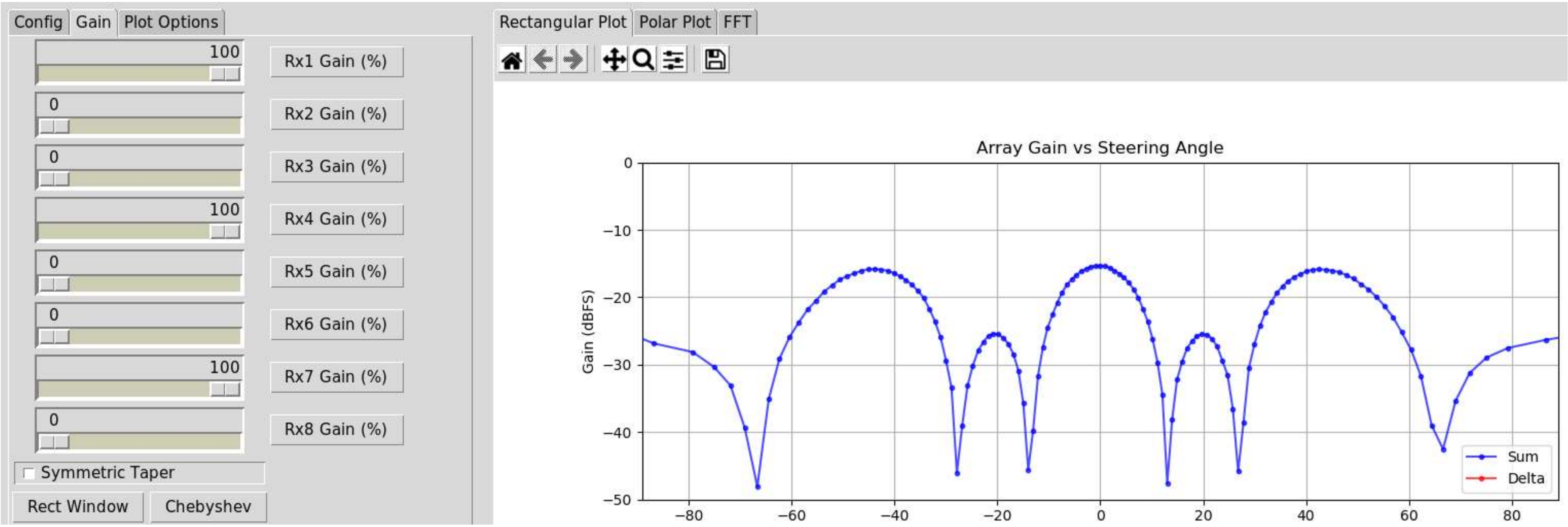
- In the Phaser GUI, select “Lab 4: Grating Lobes”
- Set the RF source (HB100) to be directly in front of the array (full broadside)

Grating Lobes: Case 2



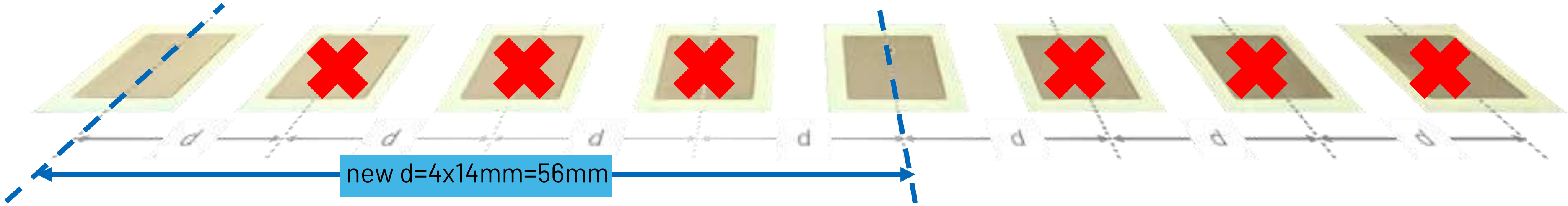
  - Set Rx2, Rx3, Rx5, Rx6, and Rx8 to 0: now our d = 3 * 14 mm = 42 mm

- For f=10.3GHz (λ=0.29), we expect to see main lobes at:
  - $\sin^{-1}(\pm 0 \cdot 0.029/0.042)$ **and** $\sin^{-1}(\pm 1 \cdot 0.029/0.042)$ which is 0° and ±44°



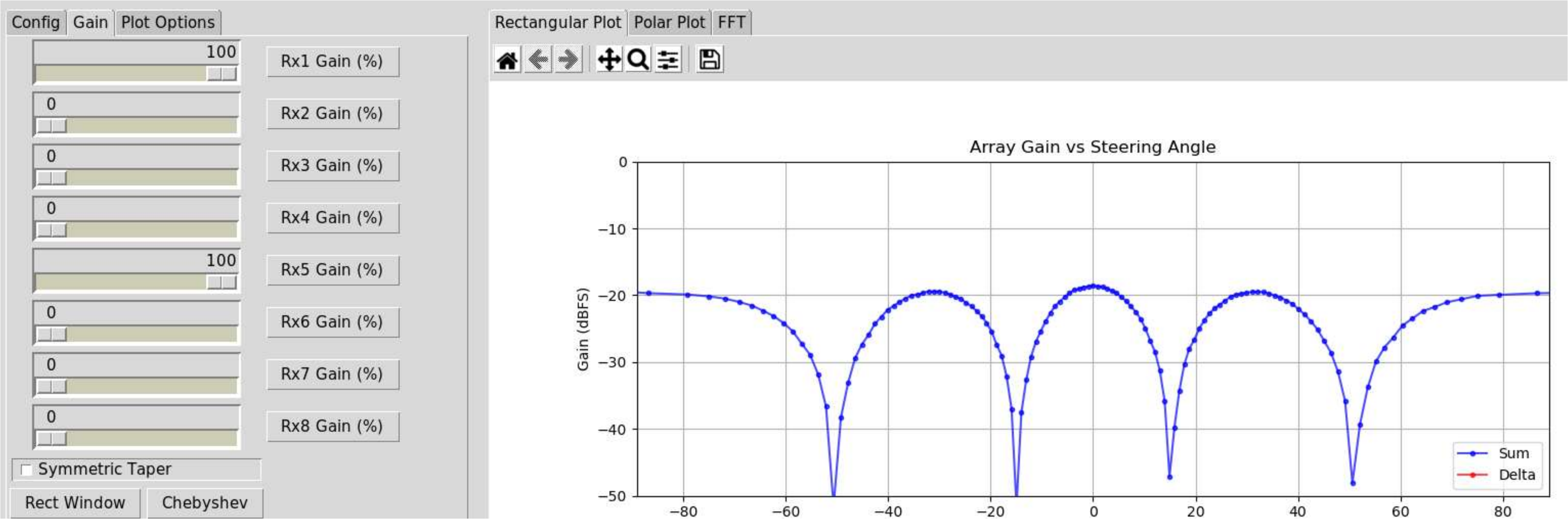
Rx1 Gain (%): 100
Rx2 Gain (%): 0
Rx3 Gain (%): 0
Rx4 Gain (%): 100
Rx5 Gain (%): 0
Rx6 Gain (%): 0
Rx7 Gain (%): 100
Rx8 Gain (%): 0
☐ Symmetric Taper

Grating Lobes: Case 3



- – Set Rx2, Rx3, Rx4, Rx6, Rx7, and Rx8 to 0: now our d = 4 * 14 mm = 56 mm

- For f=10.3GHz (λ=0.29), we expect to see main lobes at:
  - – $\sin^{-1}(\pm 0 \cdot 0.029/0.056)$ **and** $\sin^{-1}(\pm 1 \cdot 0.029/0.056)$ **and** $\sin^{-1}(\pm 2 \cdot 0.029/0.056)$ which is 0° and ±31° and ±90°



Rx1 Gain (%) 100
Rx2 Gain (%) 0
Rx3 Gain (%) 0
Rx4 Gain (%) 0
Rx5 Gain (%) 100
Rx6 Gain (%) 0
Rx7 Gain (%) 0
Rx8 Gain (%) 0
☐ Symmetric Taper

Session 4:
Antenna Impairments
Beam Squint

Understanding Beam Squint: Math and Theory

- Remember that the same delay can be solved for in two ways:
  1. As a time delay:

     $\theta = \sin^{-1}(\Delta t\ c / d)$

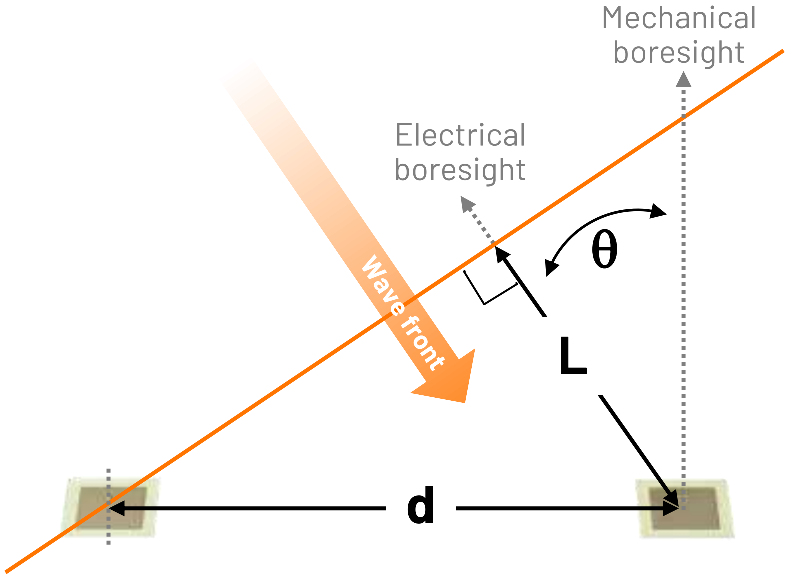
     This **is not** a function of frequency

  2. As a phase delay:

     $\theta = \sin^{-1}(\Delta \phi\ c / (2\pi\ f\ d))$

     This **is** a function of frequency

     If we change frequency, the steering angle “changes”



- That is beam squint:
  - The beam angle changing as a function of frequency.
  - A true time delay beamformer doesn’t have that problem because it doesn’t have that frequency dependence.
  - Mechanical boresight also does not have beam squint – as the phase shift is 0, and so there is no frequency component.

Understanding Beam Squint: Math and Theory

- Beam deviation (beam squint) vs frequency can be calculated as:

$$\Delta\theta = arcsin\left(\frac{f_0}{f} sin\,\theta_0\right) - \theta_0$$

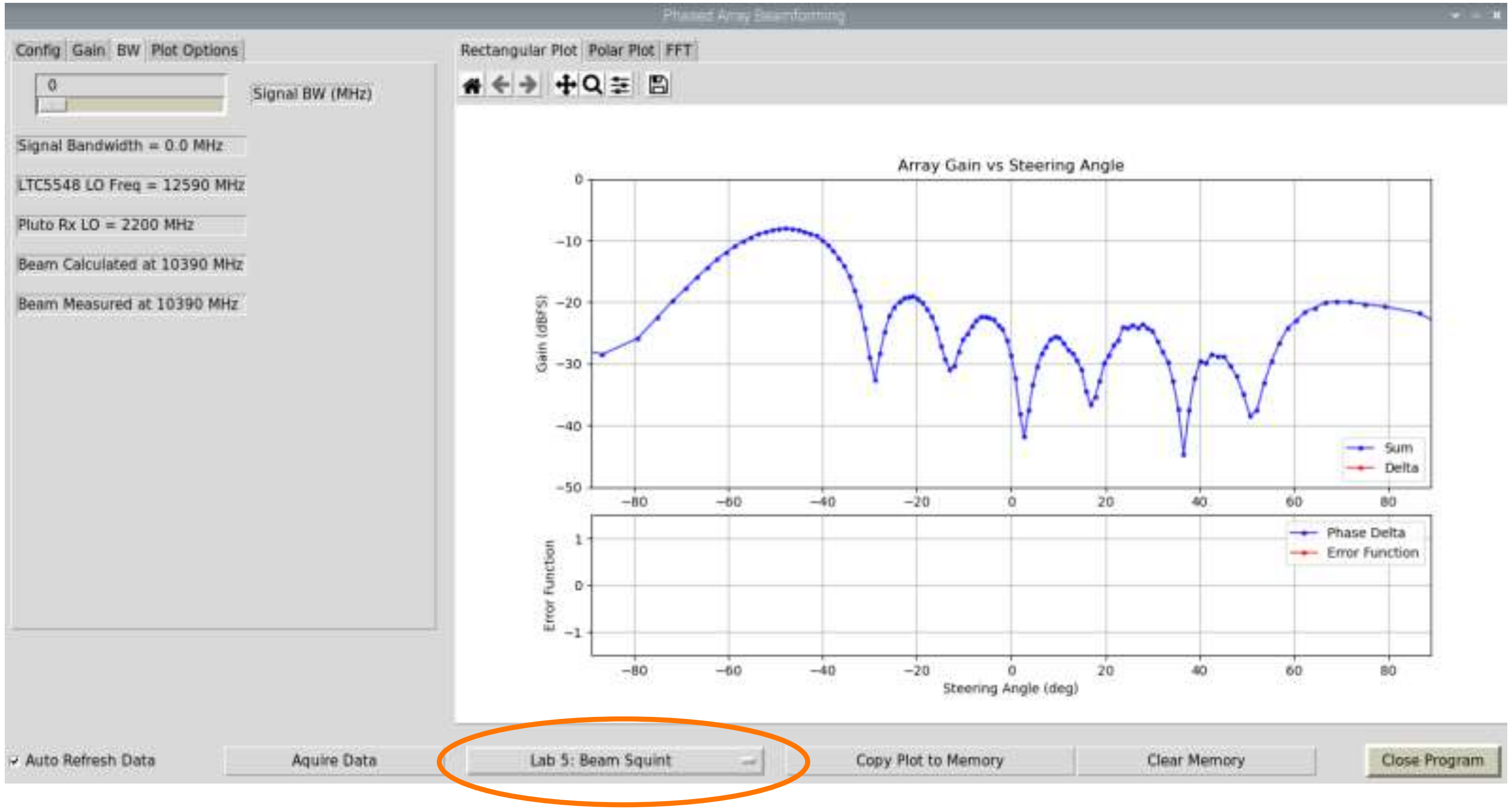
- For example
  - Let's set our carrier frequency to be 10.5 GHz, and f_0 = 10 GHz (500 MHz of BW)
  - We want to steer the beam to +/- 45° from mechanical boresight
  - $\Delta\theta$ = arcsin(10.5/10 * sin(45°)) - 45°= 3°
  - The beam will shift 3° at 10.5 GHz vs 10 GHz

https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part2.html

Lab 4-3: Beam Squint

Workshop Lab Guide

Lab 4-3: Beam Squint



Signal Bandwidth = 0.0 MHz

LTC5548 LO Freq = 12590 MHz

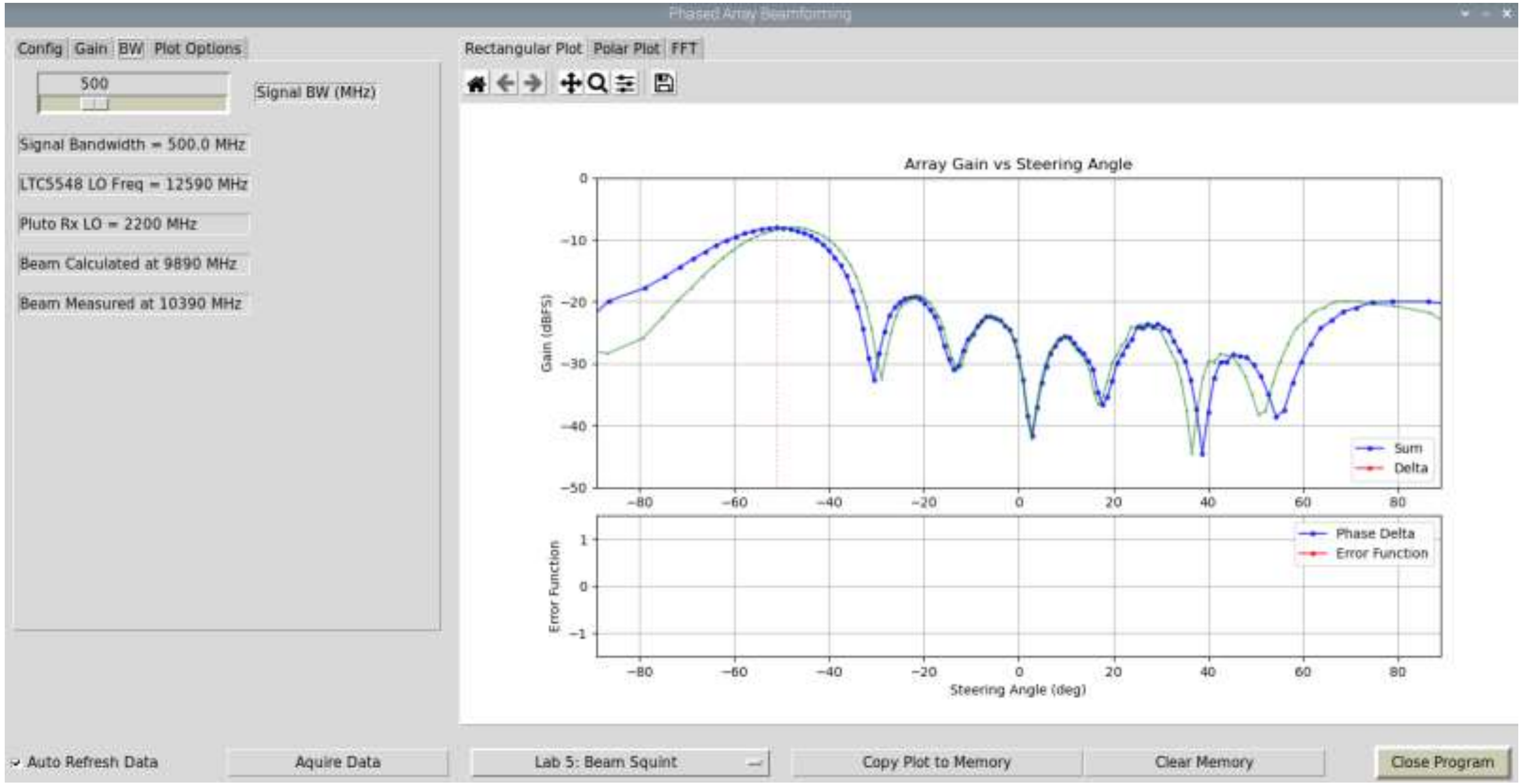
Pluto Rx LO = 2200 MHz

Beam Calculated at 10390 MHz

Beam Measured at 10390 MHz

- ▶ In the Phaser GUI, select “Lab 5: Beam Squint”
- ▶ Set the RF source (HB100) to an angle of about 50 deg
- ▶ Click “Copy Plot to Memory”
- ▶ Record the peak angle (you can also turn on “Show Peak Angle” under “Plot Options” tab)

Lab 4-3: Beam Squint



Signal Bandwidth = 500.0 MHz

LTC5548 LO Freq = 12590 MHz

Pluto Rx LO = 2200 MHz

Beam Calculated at 9890 MHz

Beam Measured at 10390 MHz

- Change the “Signal BW” slider bar to 500 MHz
- Record the new peak angle. Did it match our ~3° calculation?
- Try other signal bandwidths and observe the effect.
- Try other steering angles and observe the effect.

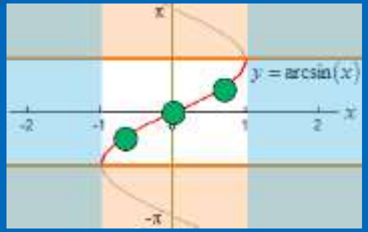
- *Note: since our HB100 frequency source is fixed, we instead change the frequency at which the steering angle is calculated. i..e the “Beam Calculated at” frequency. Both methods are equivalent. Its just easier to change the calculated frequency in our lab. It also avoids other changes in the antenna pattern that would come from a new frequency—which let’s us do a more straightforward comparison.*

Session 5:
Hybrid Beamforming

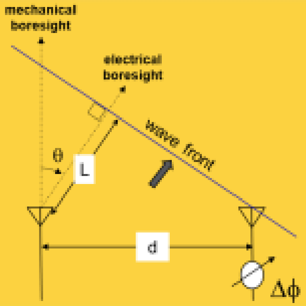
Phased Array Workshop: Hybrid Beamforming

Digitizer

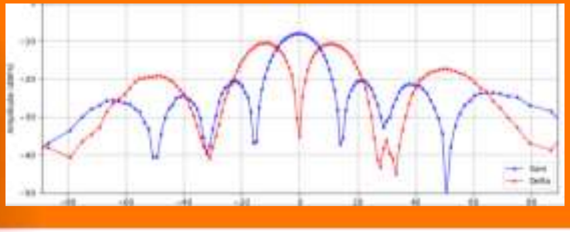
Antenna Impairments



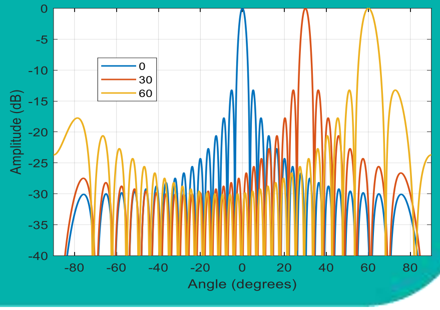
Steering Angle



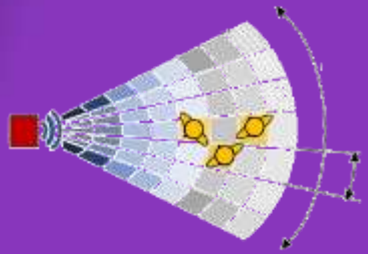
Monopulse Tracking



Antenna Patterns



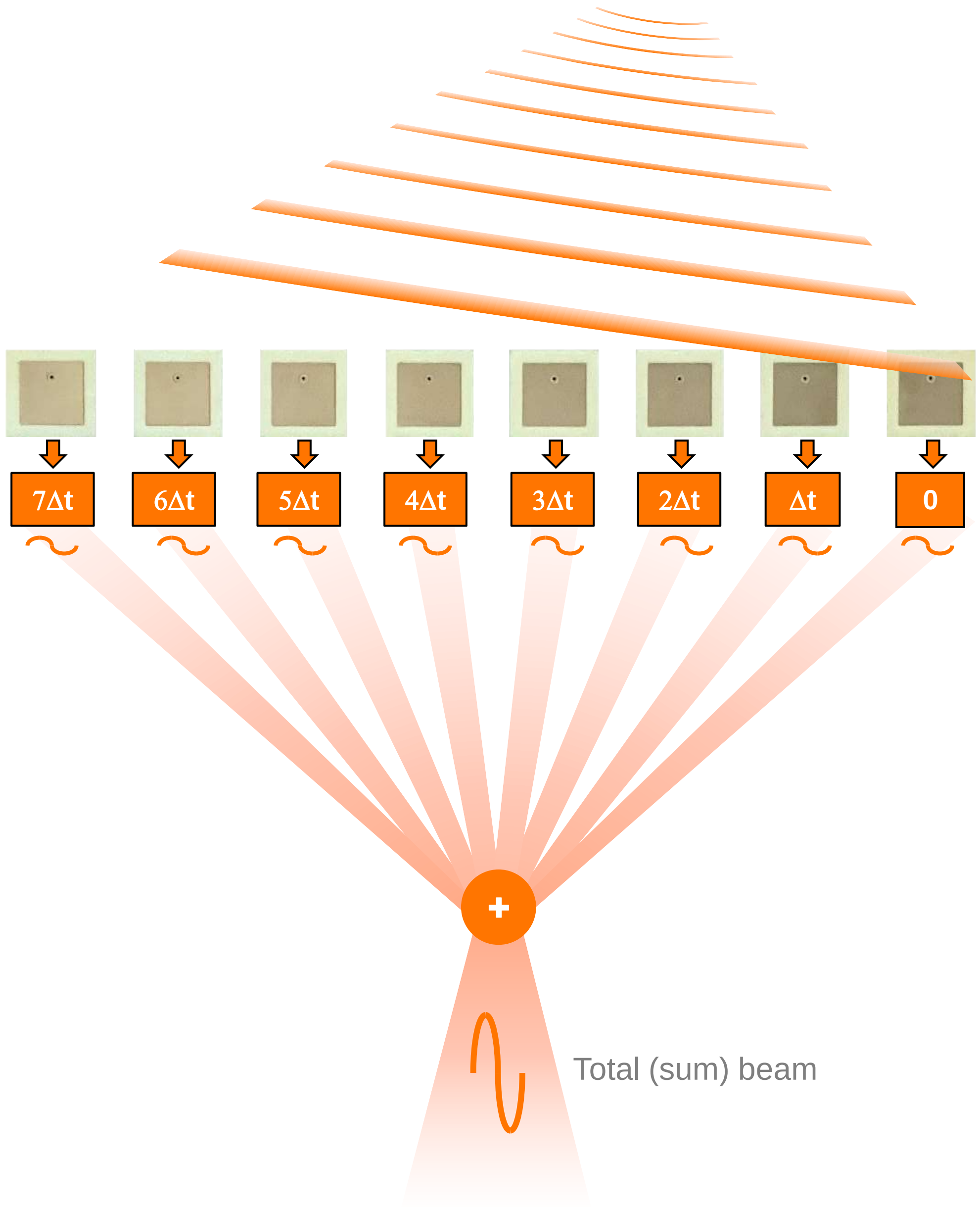
Radar



Analog vs Digital Beamforming

- Right now, we have one beam

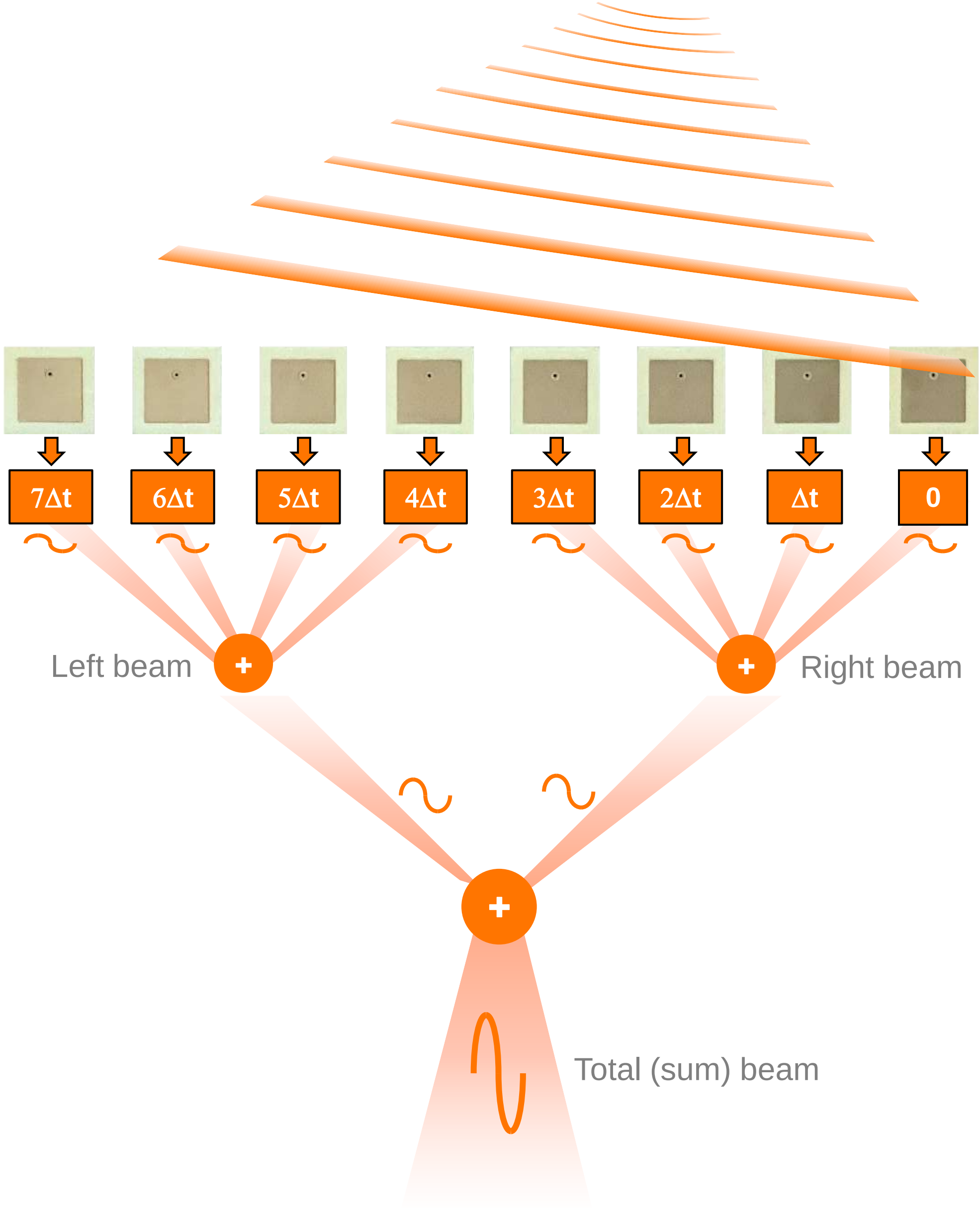
Analog Beamforming



Analog vs Digital Beamforming

- But we can break our beam into two sides:
  - "Left beam"
  - "Right beam"
- Summing the Left beam with the Right beam would give us the same total beam

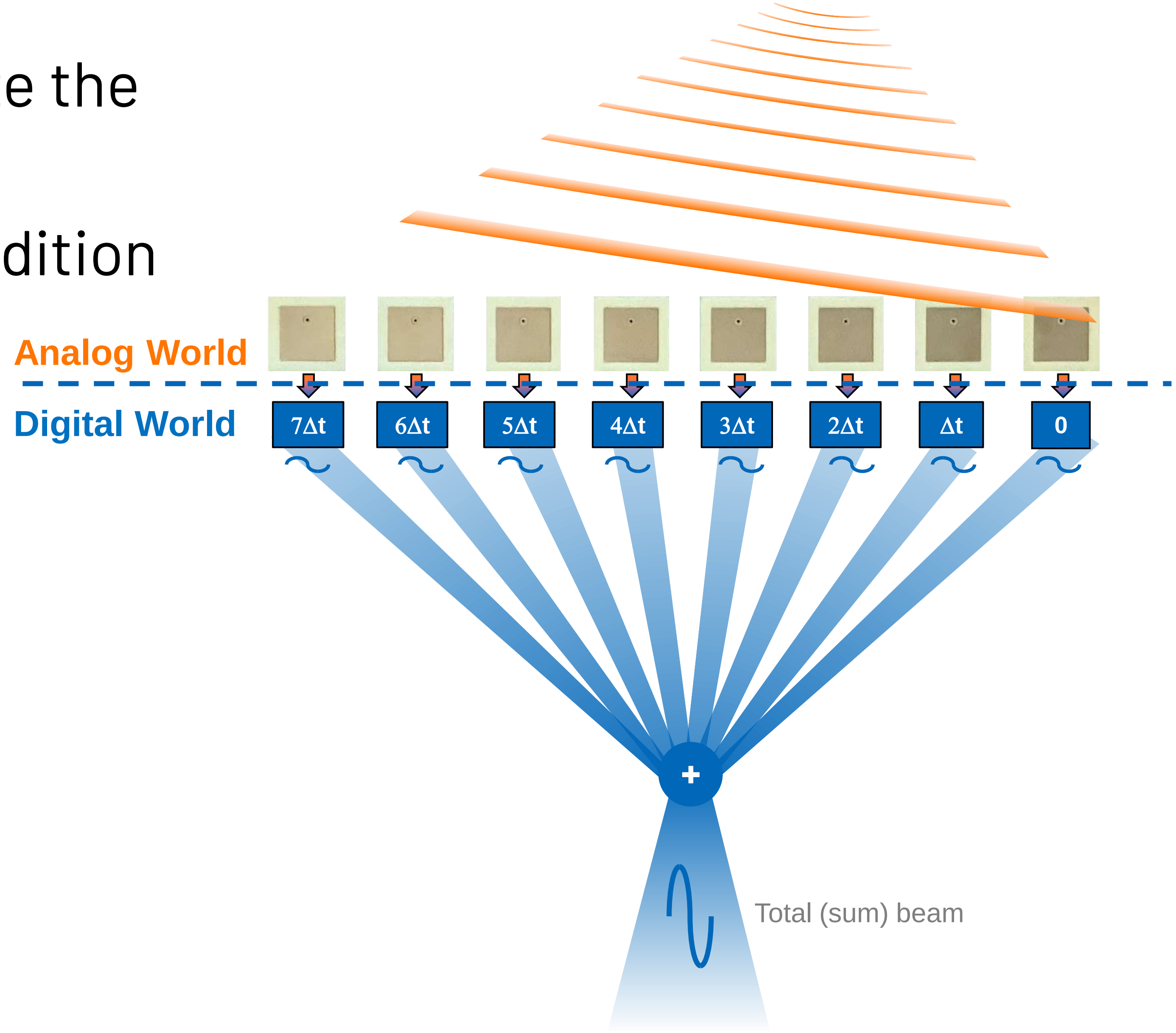
Analog Beamforming



Analog vs Digital Beamforming

- Alternatively, we can digitize the signal at each element
- Then compute the beam addition in the digital world

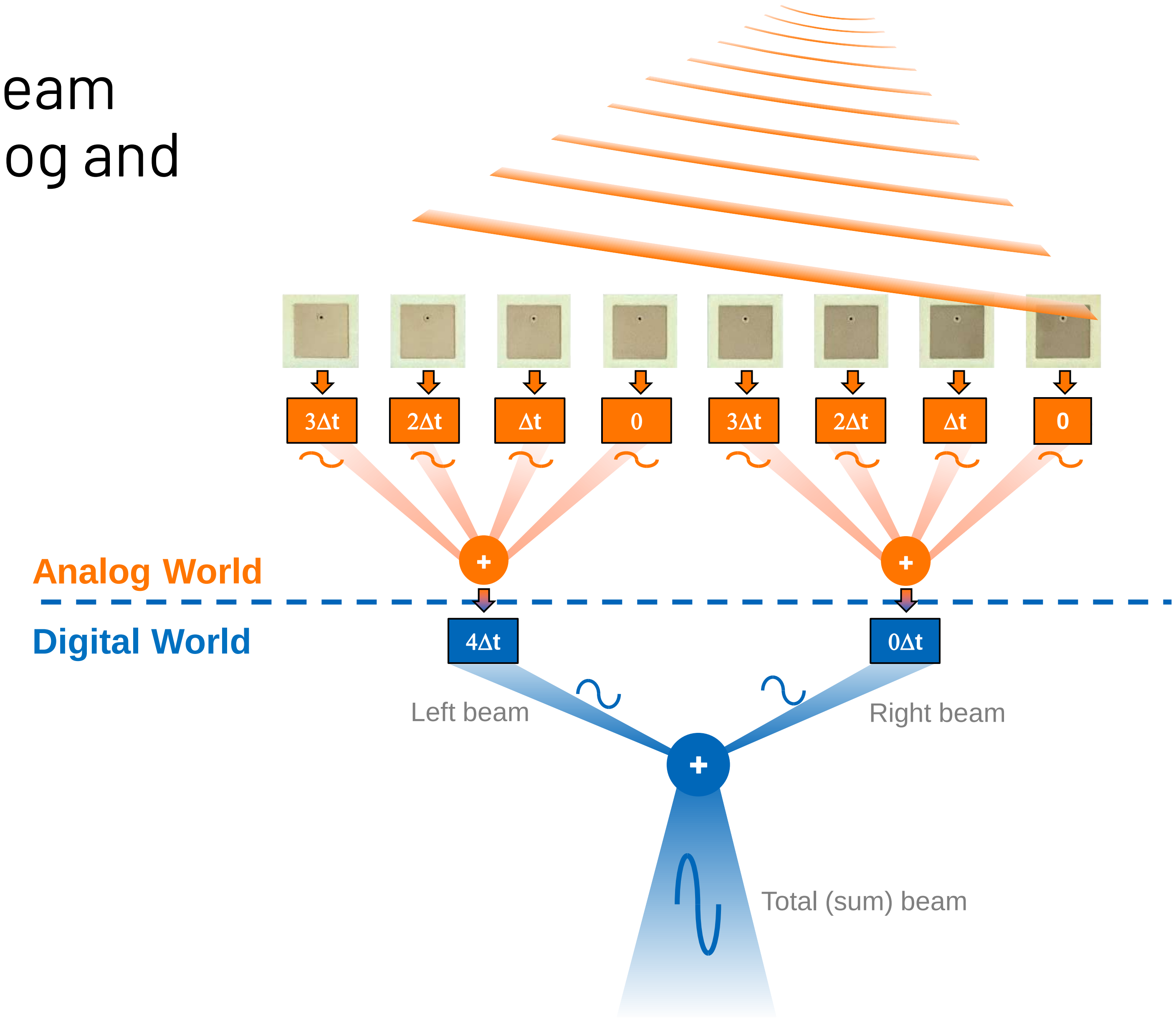
Digital Beamforming



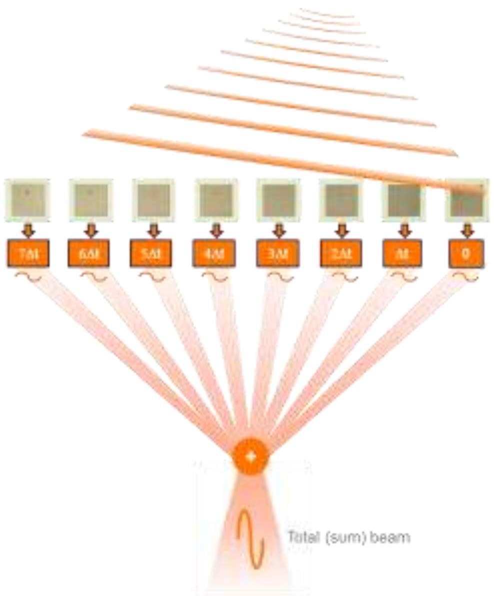
Hybrid Beamforming

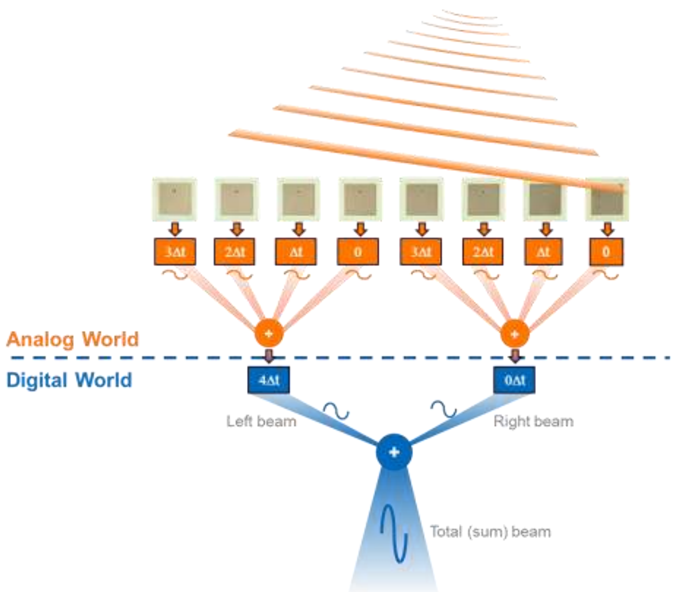
- We can also break up the beam addition into separate analog and digital sections
- The signal can be digitized anywhere in the RF chain

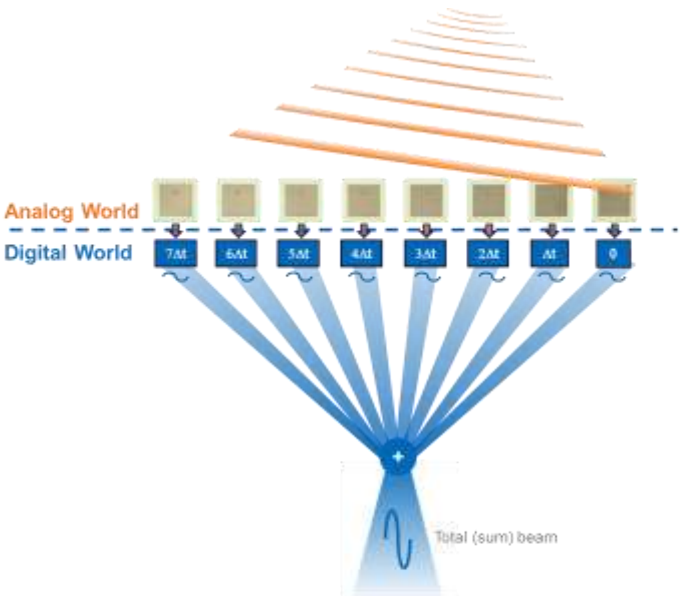
Hybrid Beamforming



Beamforming Architectures

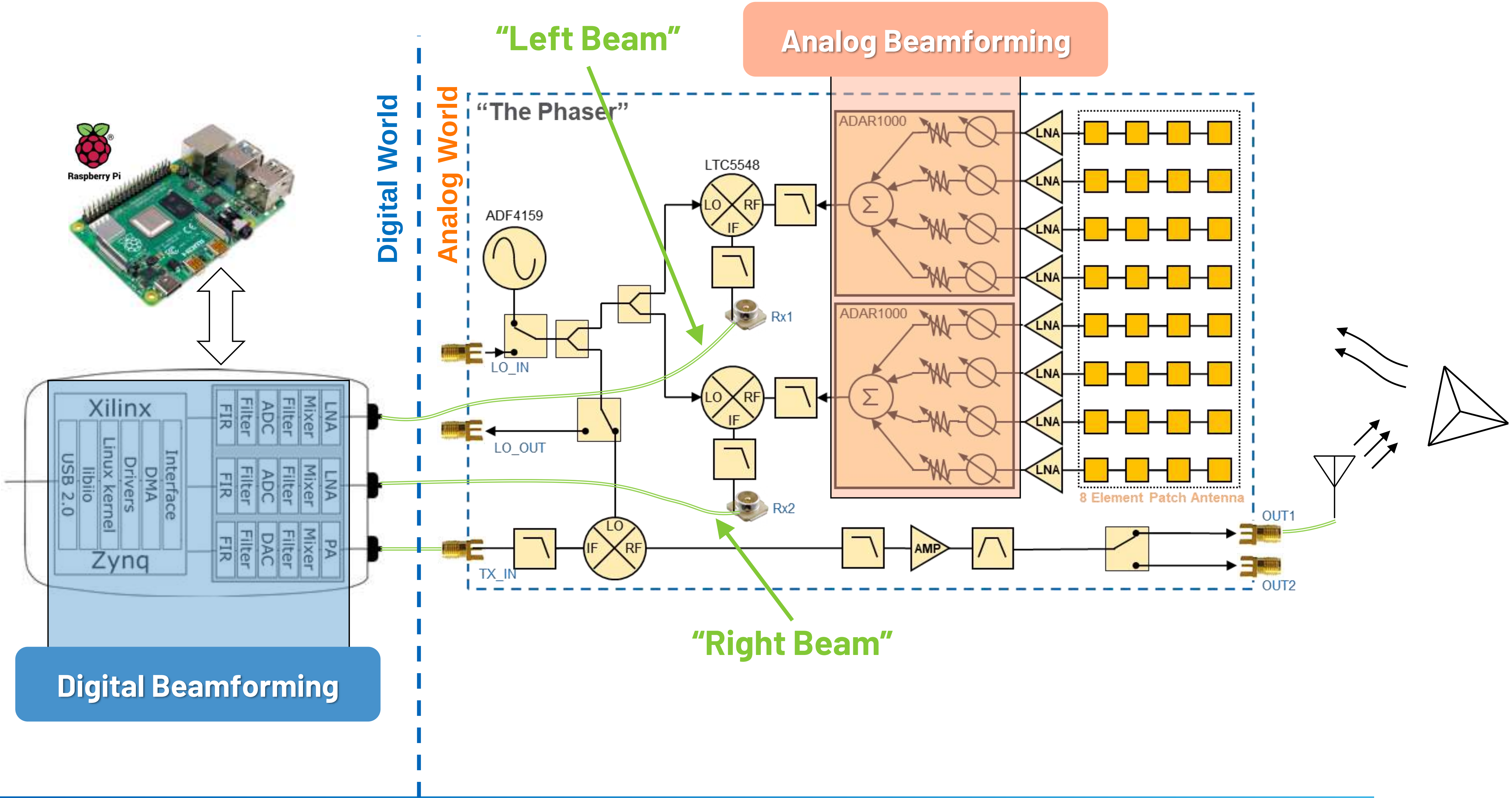






Analog Beamforming	Hybrid Beamforming	Digital Beamforming
Beam formed by weighting RF paths	Digital combining of multiple analog beams	Beam formed by weighting digital paths
Single set of data converters	1 < m < n sets of data converters	Separate data converters for each element
Low power/complexity	Moderate power/complexity	Highest power / complexity
Good for coverage	Compromise between analog and digital	Highest capacity / flexibility
Single narrow beam	Often the best choice with existing technology	Wide analog beamwidth, narrow digital beams

Hybrid Beamforming



"Left Beam"

Analog Beamforming

Digital World

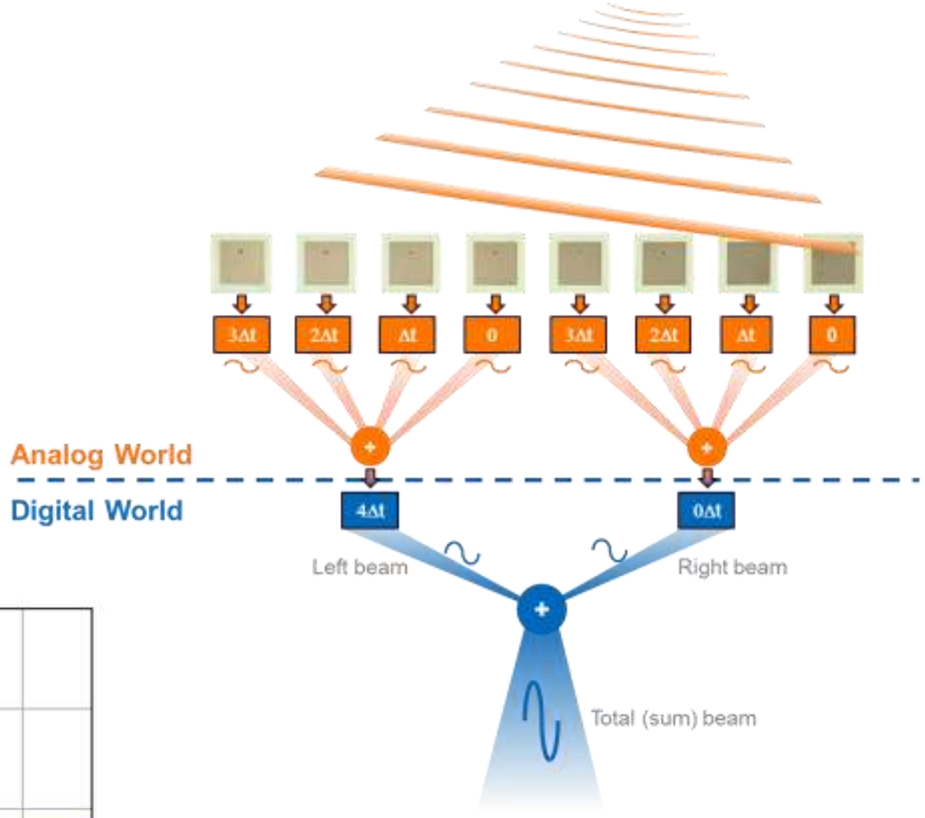
Analog World

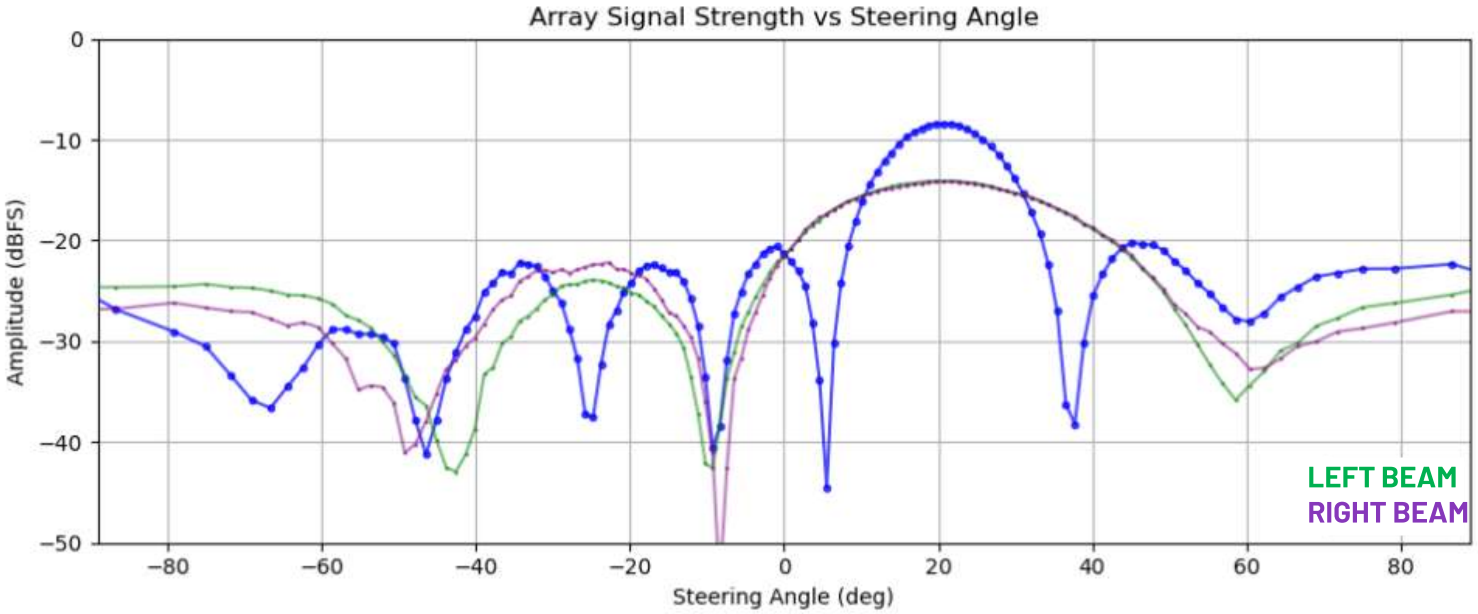
"Right Beam"

Digital Beamforming

Hybrid Beamforming

- ▶ The “Left” and “Right” beam each look like a N=4 array
- ▶ Their patterns are slightly offset—due to non-idealities of the hardware
- ▶ Adding them together gets us back to our N=8 Array

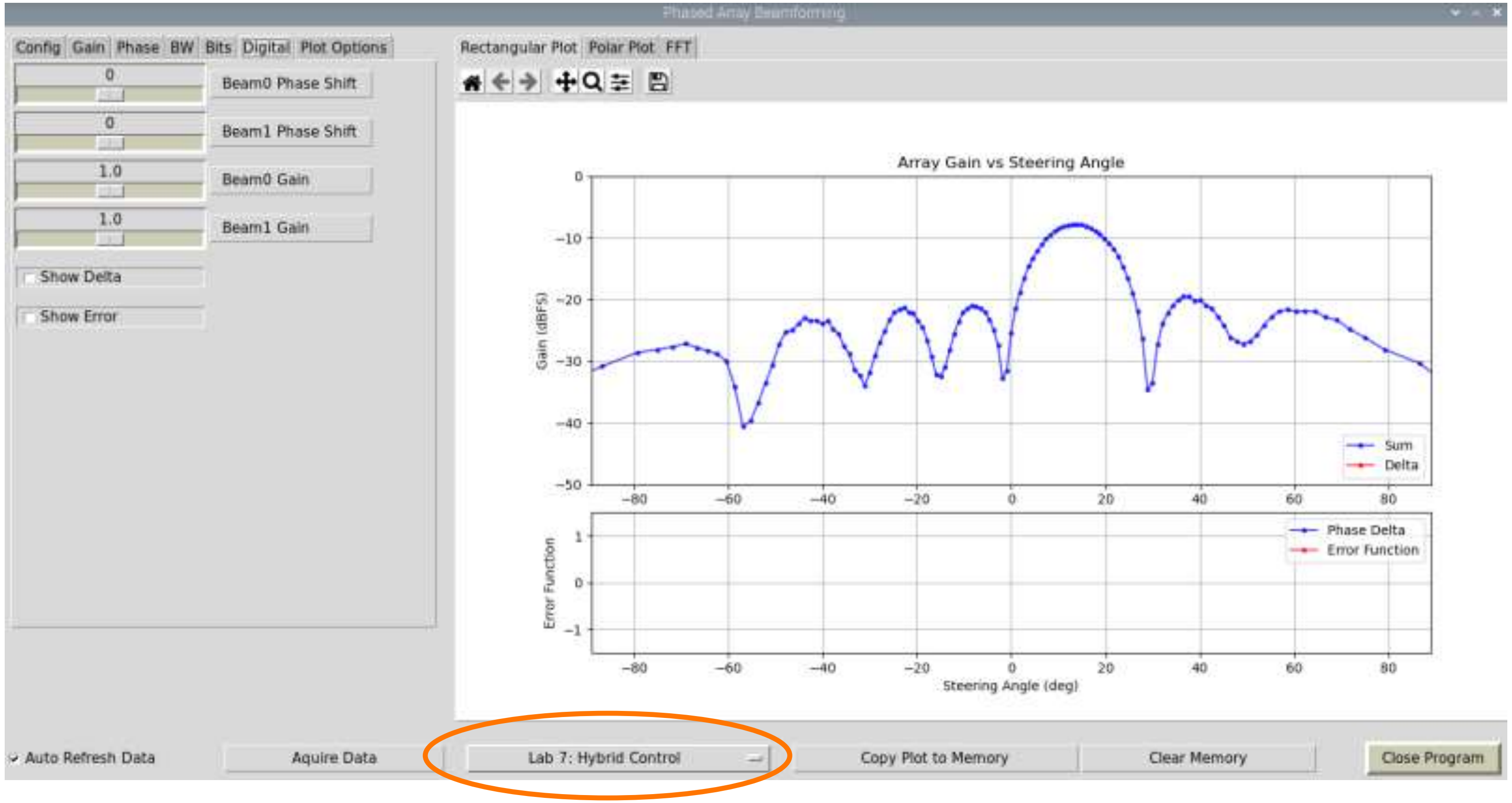




Lab 5-1: Hybrid Beamforming

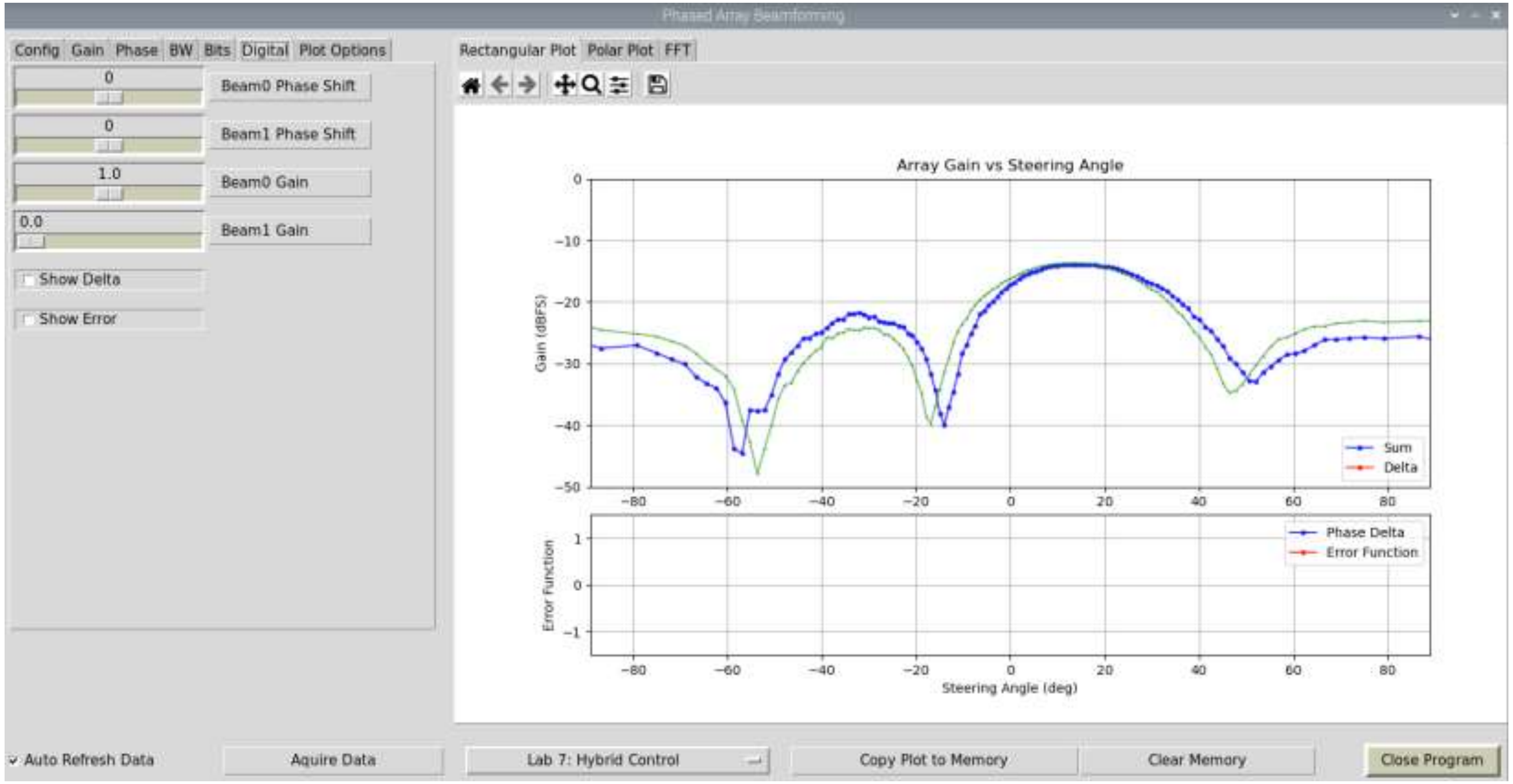
Workshop Lab Guide

Lab 5-1a: Hybrid Beamforming



- In the Phaser GUI, select "Lab 7: Hybrid Control"
- In the "Digital" tab, you can change the gain and phase of each ADAR1000 output:
  - Beam1 is elements 1-4 (the left 4 elements)
  - Beam0 is elements 5-8 (the right 4 elements)

Lab 5-1a: Hybrid Beamforming



Beam0 Phase Shift: 0

Beam1 Phase Shift: 0

Beam0 Gain: 1.0

Beam1 Gain: 0.0

☐ Show Delta

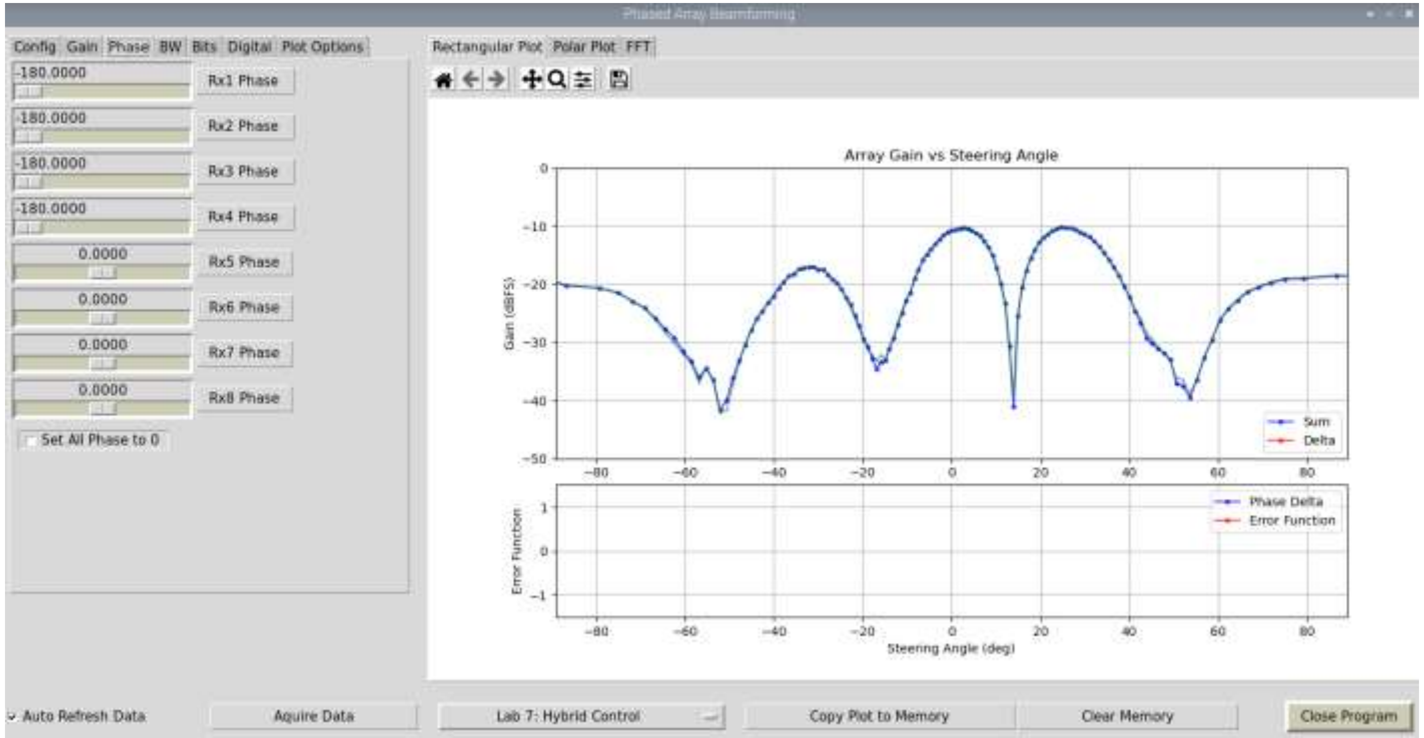
☐ Show Error

☑ Auto Refresh Data

Lab 7: Hybrid Control

- Set Beam0 gain to "0", and copy Plot to Memory
- Then set Beam0 gain back to "1" and set Beam1 gain to "0".
- Why do the two traces have a wider main lobe than when both gains were set to "1"?

Lab 5-1a: Hybrid Beamforming



Rx1 Phase: -180.0000
Rx2 Phase: -180.0000
Rx3 Phase: -180.0000
Rx4 Phase: -180.0000
Rx5 Phase: 0.0000
Rx6 Phase: 0.0000
Rx7 Phase: 0.0000
Rx8 Phase: 0.0000

- Select “Lab 7: Hybrid Control” again, to reset all the settings
- Set “Beam1 Phase Shift” to -180 deg
- Copy that Plot to Memory
- Then return “Beam1 Phase shift” to 0 deg, and set Rx1-Rx4 to -180 deg in the “Phase” tab
- Can you find any differences between controlling things analog (Phase/Gain tabs) or digitally?

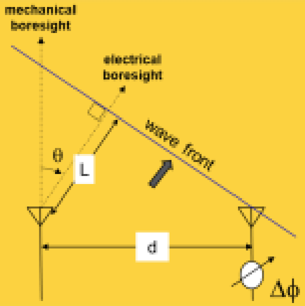
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Session 6:
Monopulse Tracking

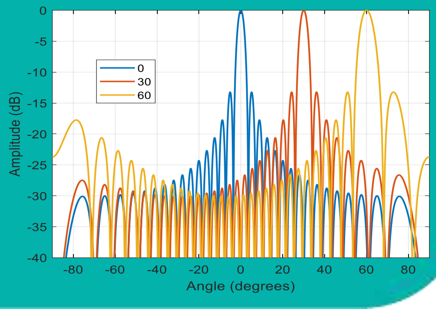
Phased Array Workshop: Monopulse Tracking

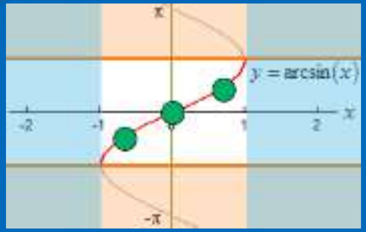
Digitizer

Steering Angle



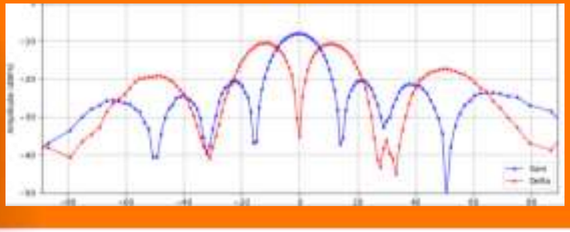
Antenna Patterns

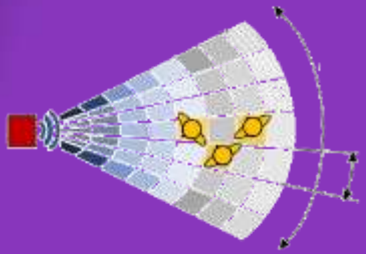




Antenna Impairments

Monopulse Tracking

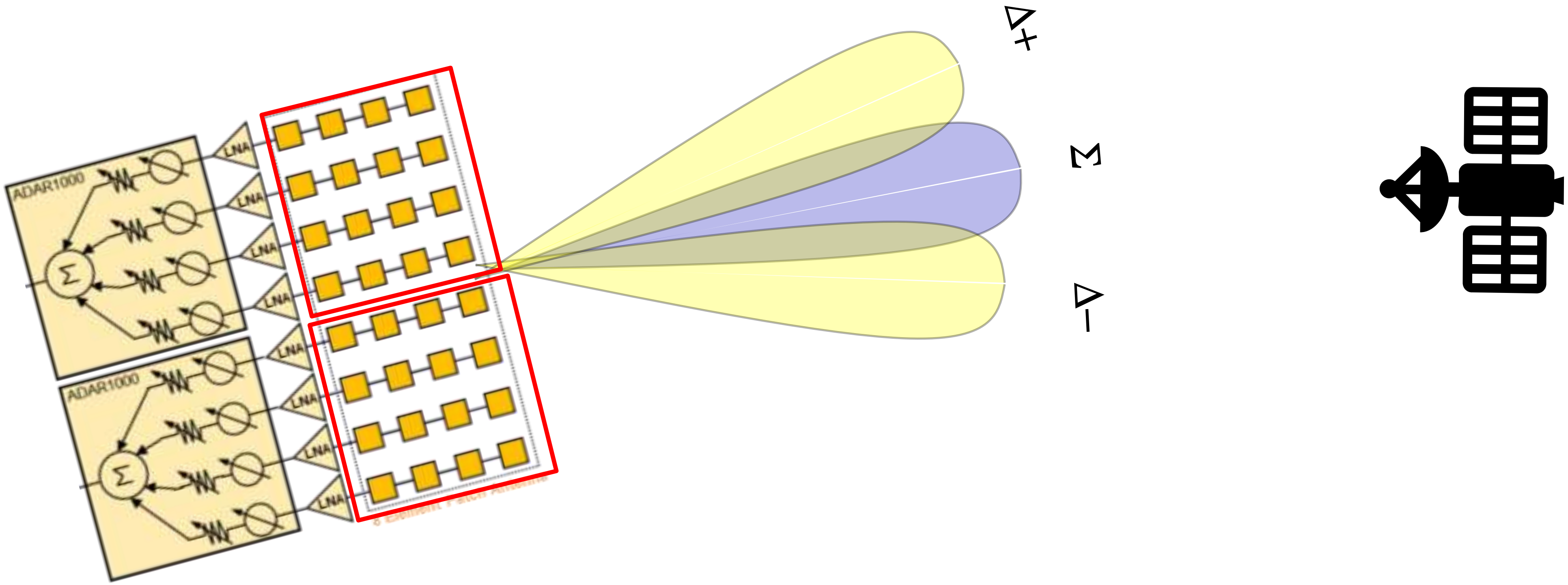




Radar

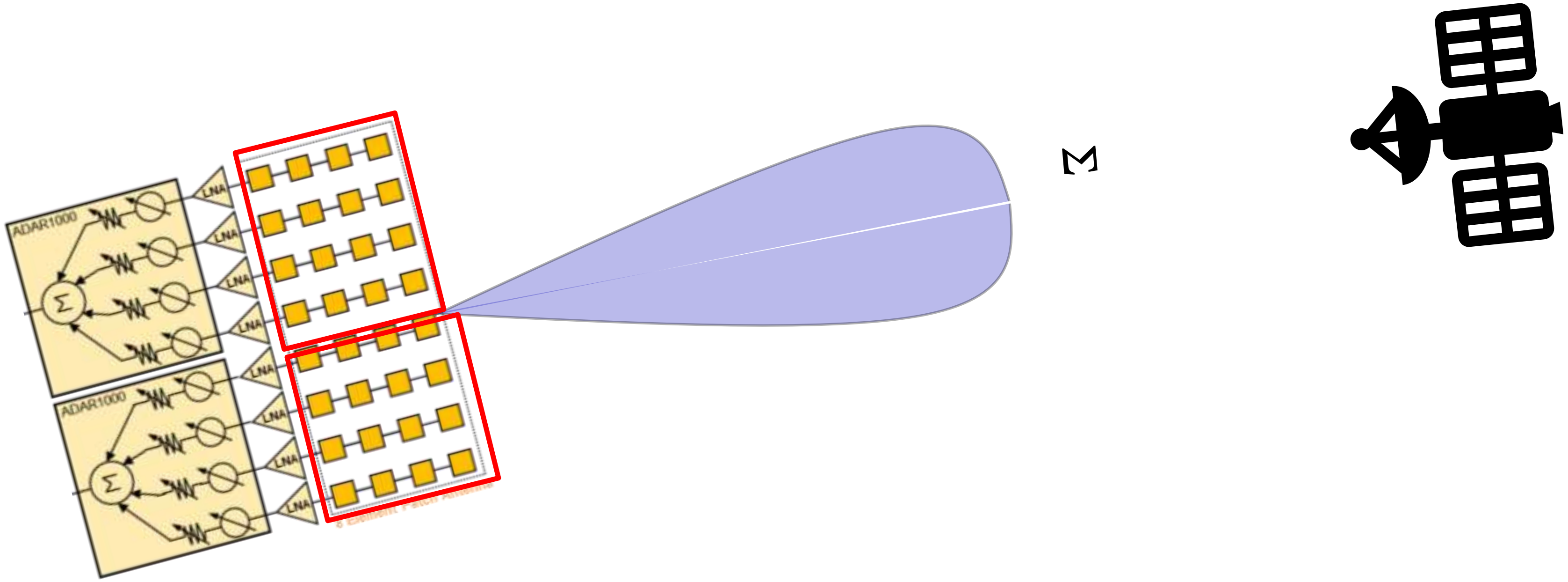
Monopulse Basics

- Robert M Page in 1943 first demonstrated Monopulse tracking for the Navy
- The array we are using can track in a single plane on the horizon
- The Sum beam and Delta Beam shown in the previous lab is used for Monopulse tracking.



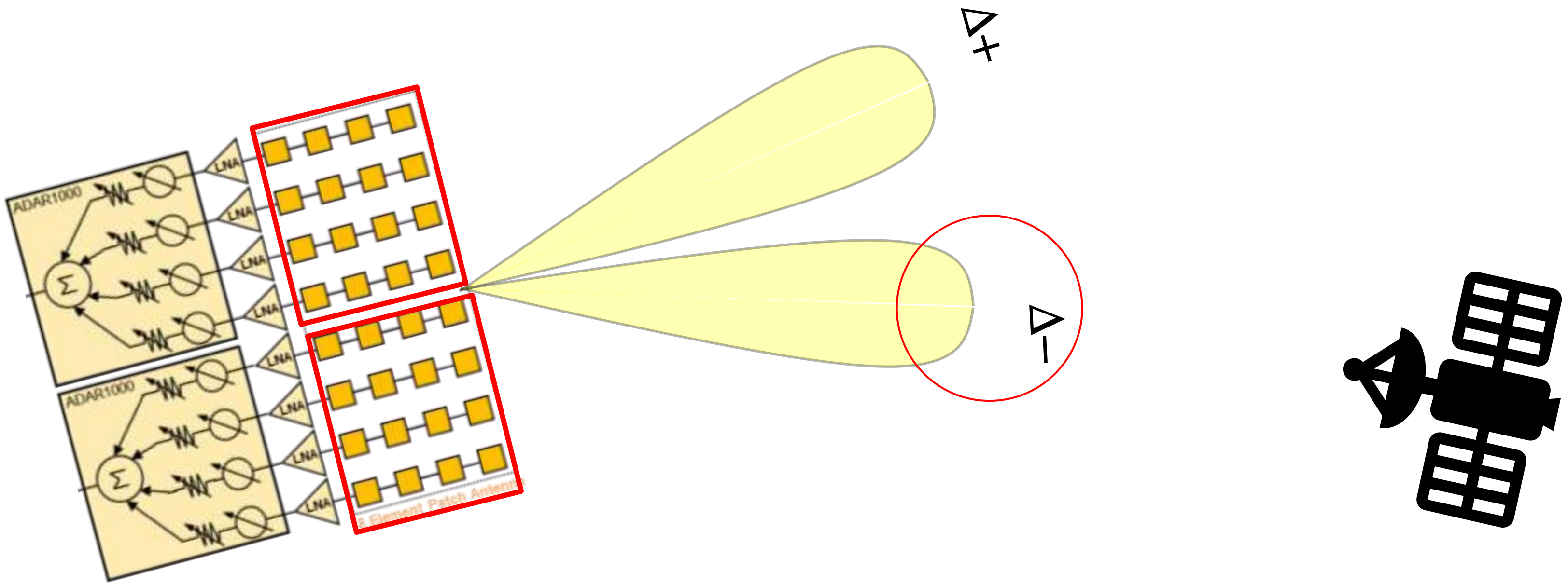
Monopulse Basics – Sum Channel

- The Sum Channel is the combination of both beams being added in phase

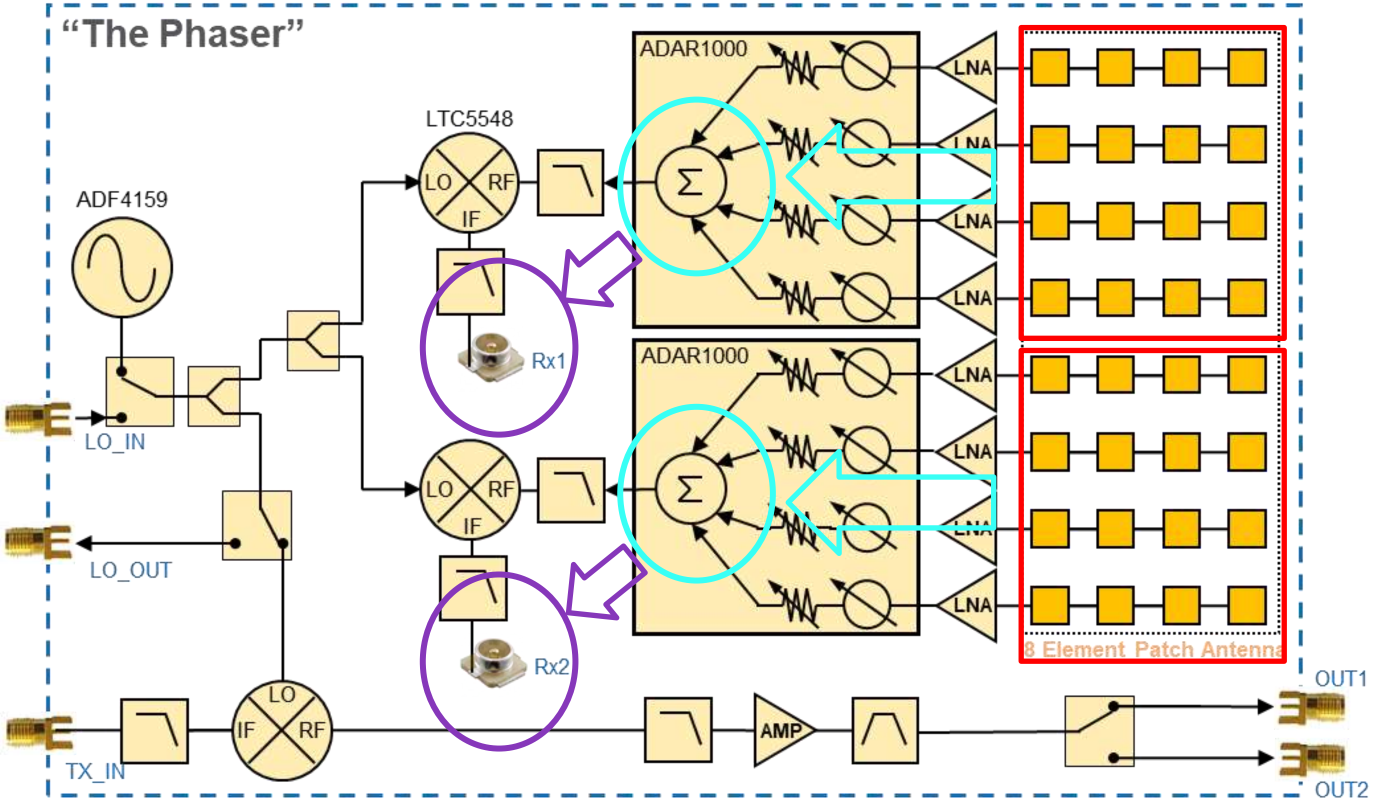


Monopulse Basics – Delta Channel

- The delta channel adds a 180 degree phase shift to one of the beams and then combines both beams together. Giving us that characteristic null
- Each side of the beam then can be corelated to a +1 or-1 value which tells us which side of the beam we are on when trying to track an object

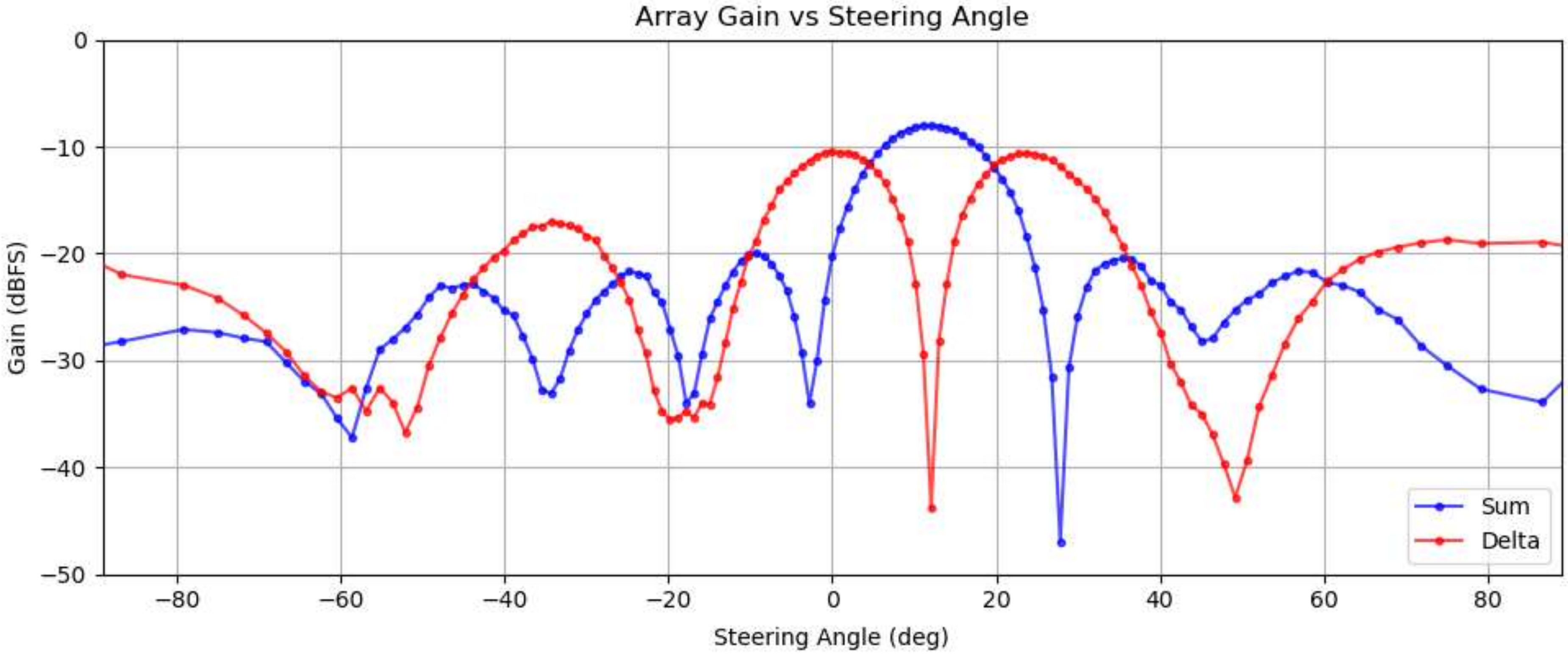


Monopulse Basics – Digital Receiver

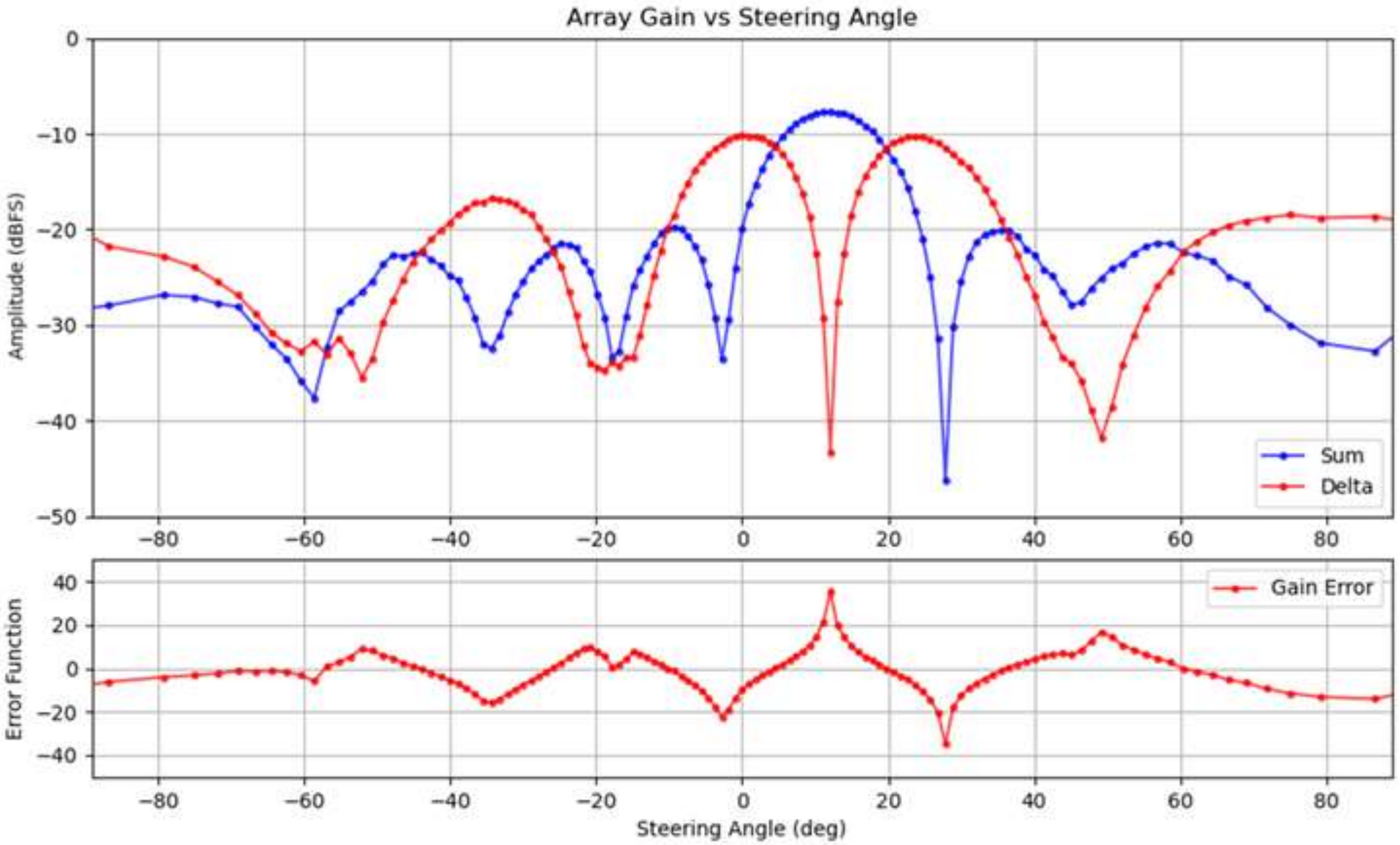


Understanding Monopulse Tracking

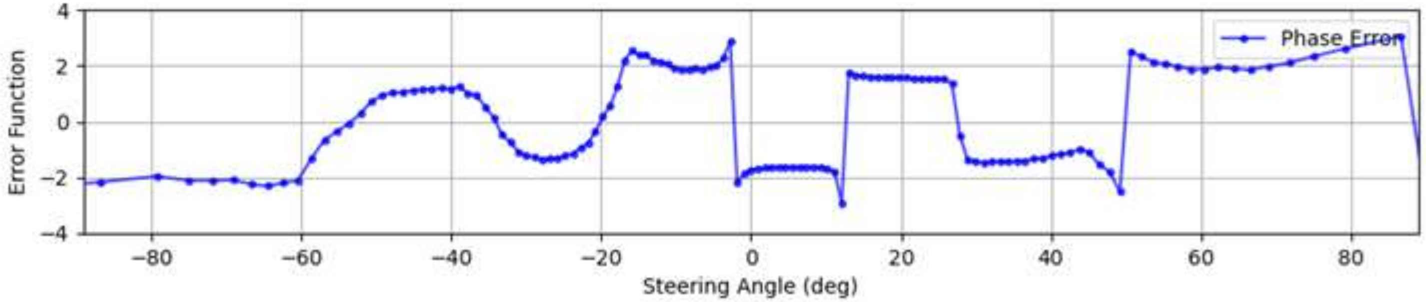
- Del and Sum Beam Overlayed



Understanding Monopulse Tracking

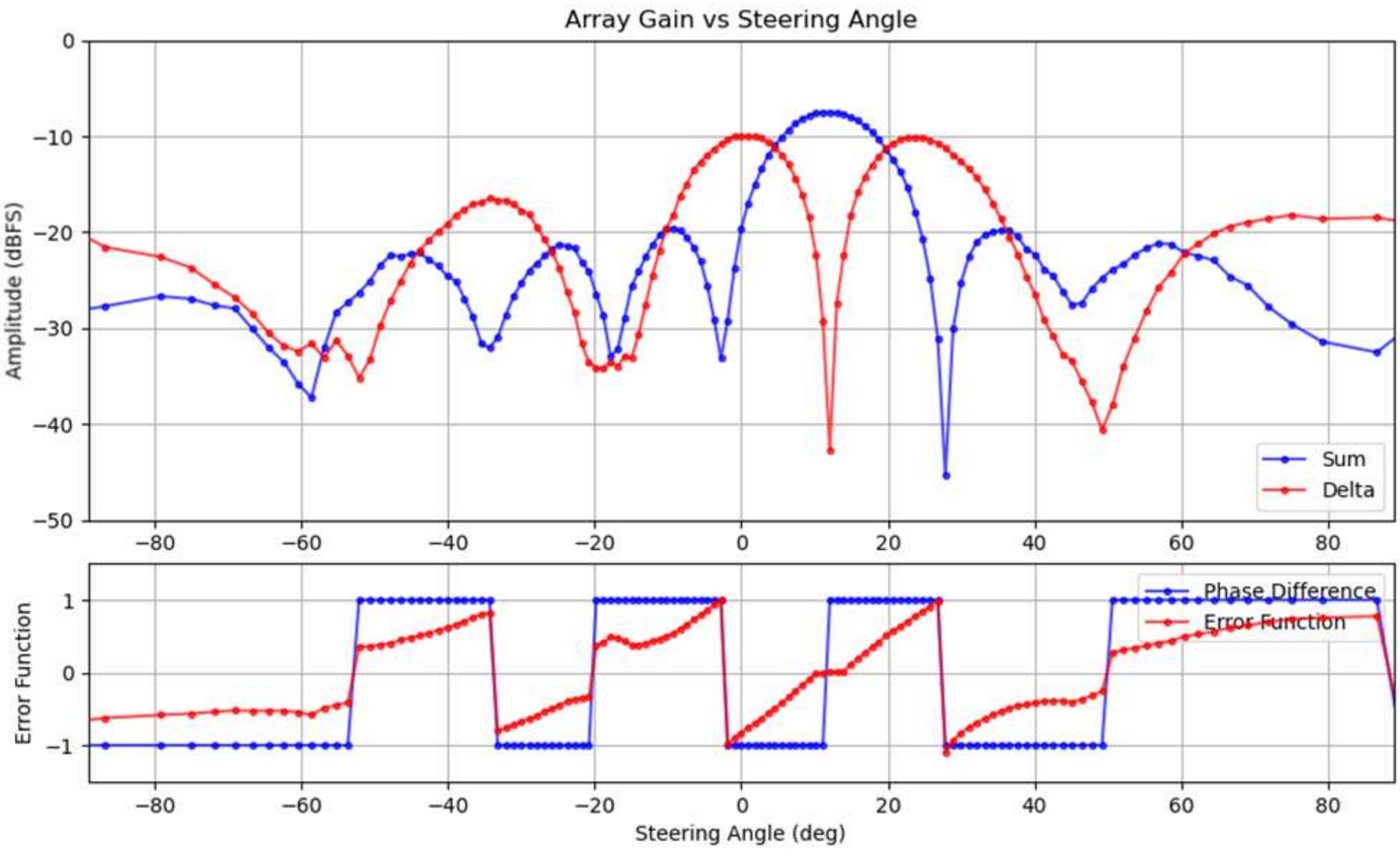


"Gain Error" = "Sum" – "Delta"



"Phase Error" = (phase(Sum) – phase(Delta))

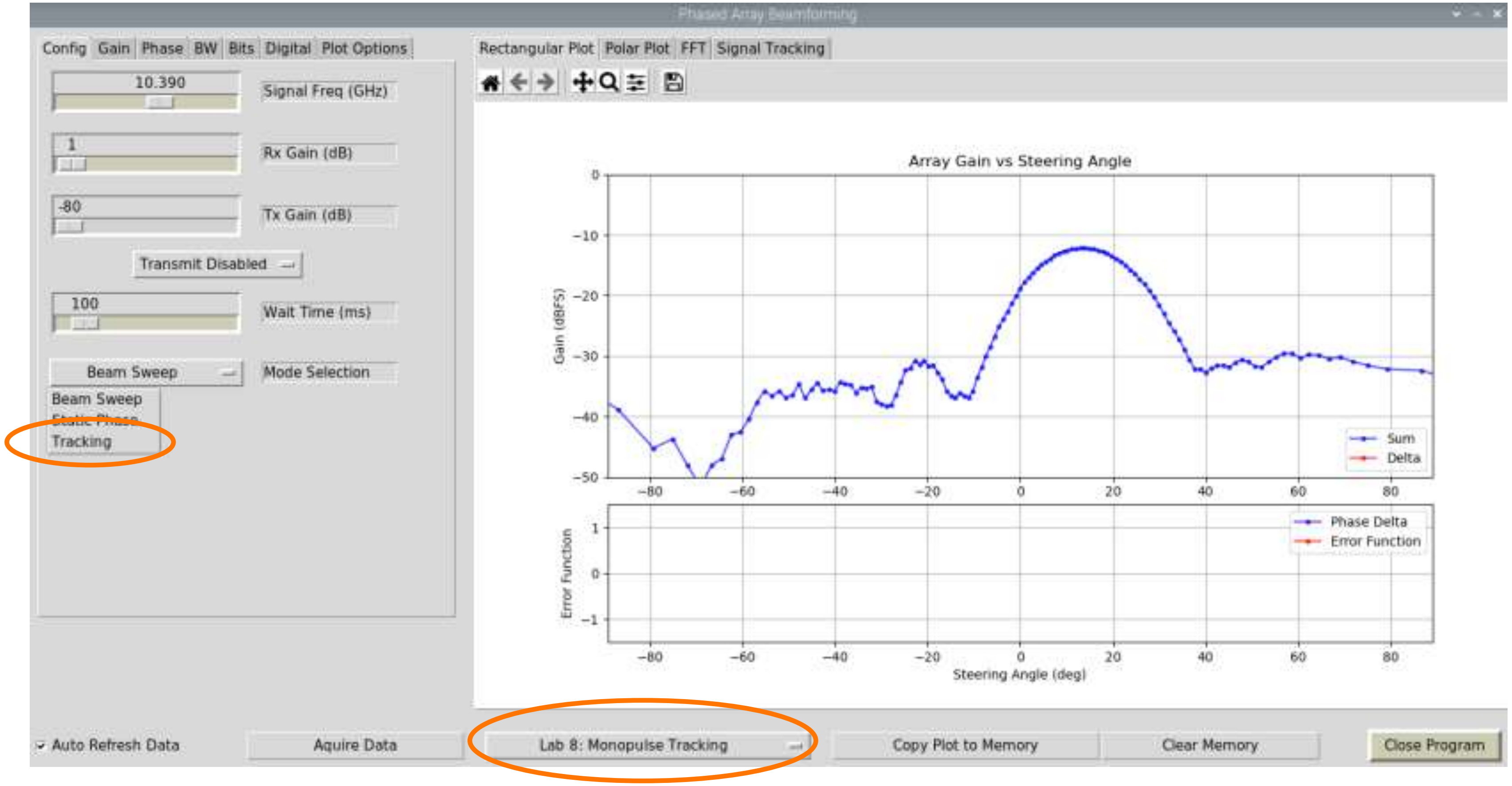
Understanding Monopulse Tracking



Lab 6-1: Monopulse Tracking

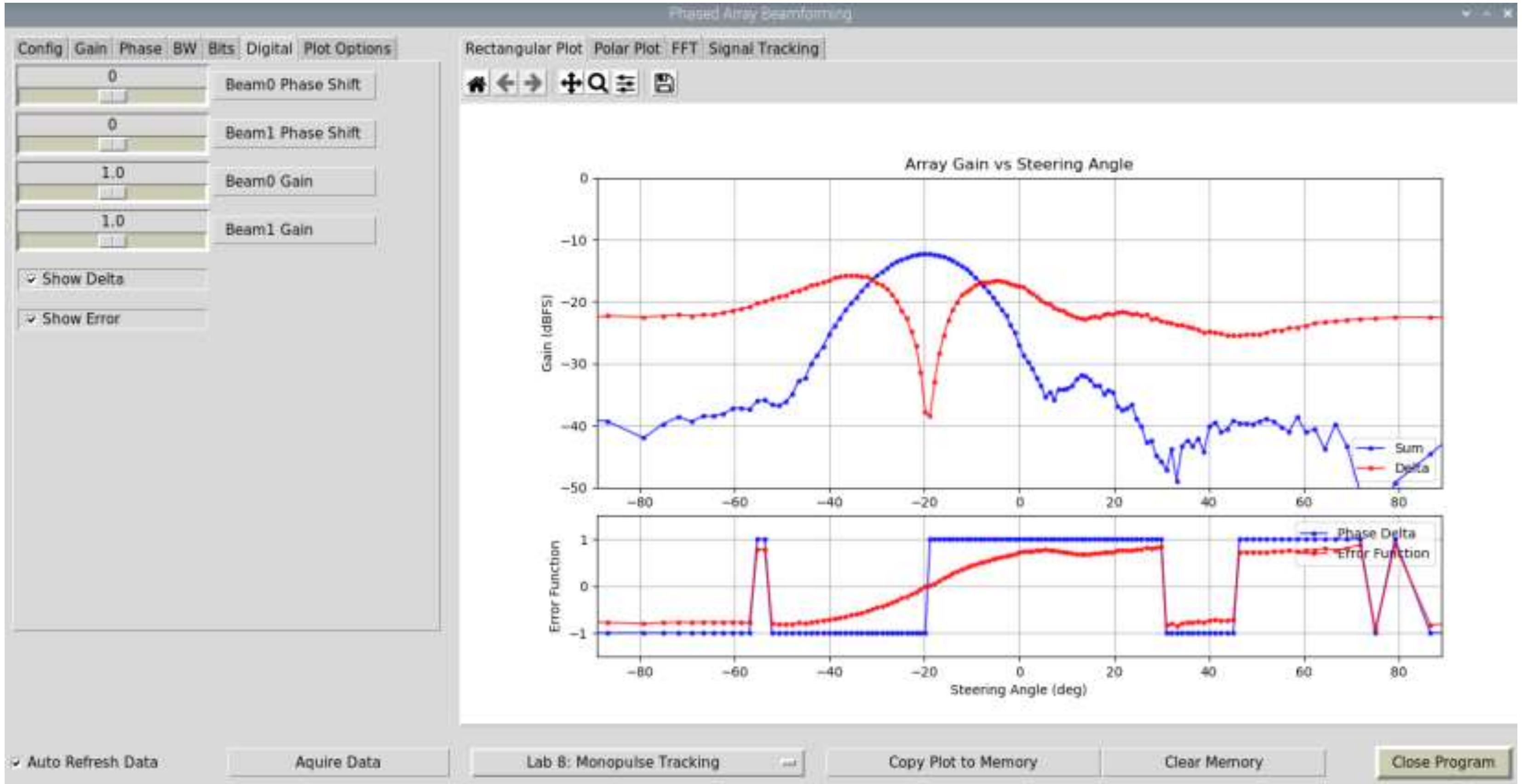
Workshop Lab Guide

Lab 6-1: Monopulse Tracking



- In the Phaser GUI, select “Lab 8: Monopulse Tracking”
- In the “Gain” tab, select “Blackmon” taper

Lab 6-1: Monopulse Tracking



Beam0 Phase Shift: 0

Beam1 Phase Shift: 0

Beam0 Gain: 1.0

Beam1 Gain: 1.0

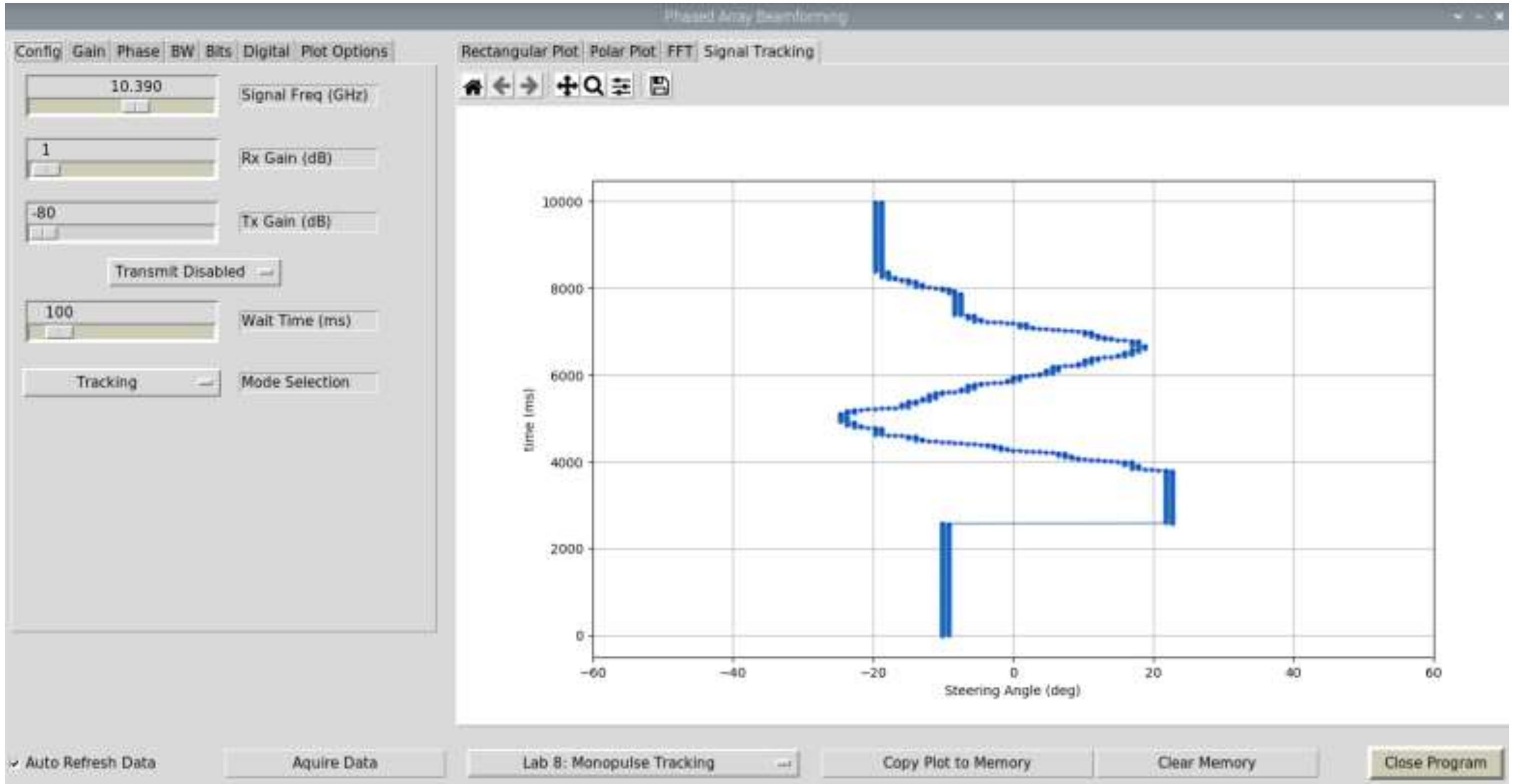
☑ Show Delta

☑ Show Error

☑ Auto Refresh Data

- ▶ In the “Digital” tab, select “Show Delta” and “Show Error”
- ▶ From the lecture, what do the “Delta”, “Phase Delta”, and “Error Function” bars represent?
- ▶ Rotate the array and observe the plots’ responses

Lab 6-1: Monopulse Tracking



Signal Freq (GHz): 10.390
Rx Gain (dB): 1
Tx Gain (dB): -80
Transmit Disabled
Wait Time (ms): 100
Mode Selection: Tracking

- ▶ In the “Config” tab, select “Tracking” from the “Mode Selection” pull down menu
- ▶ Rotate the Phaser antenna and observe the tracking function in action

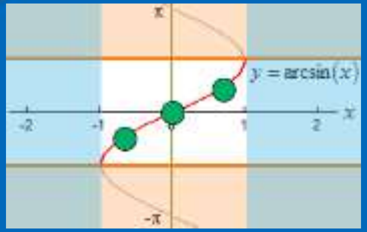
AHEAD OF WHAT'S POSSIBLE™

Session 7: Radar

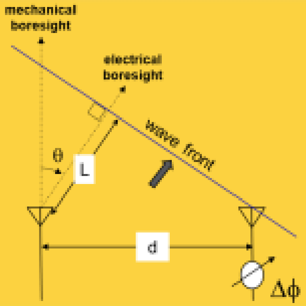
Phased Array Workshop: RADAR

Digitizer

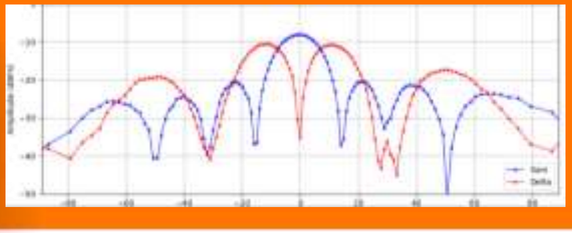
Antenna Impairments



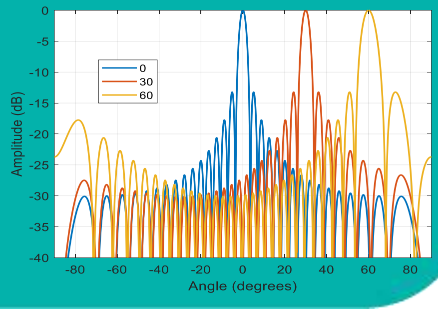
Steering Angle



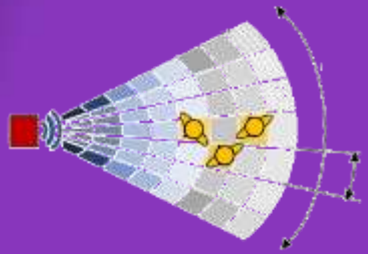
Monopulse Tracking



Antenna Patterns

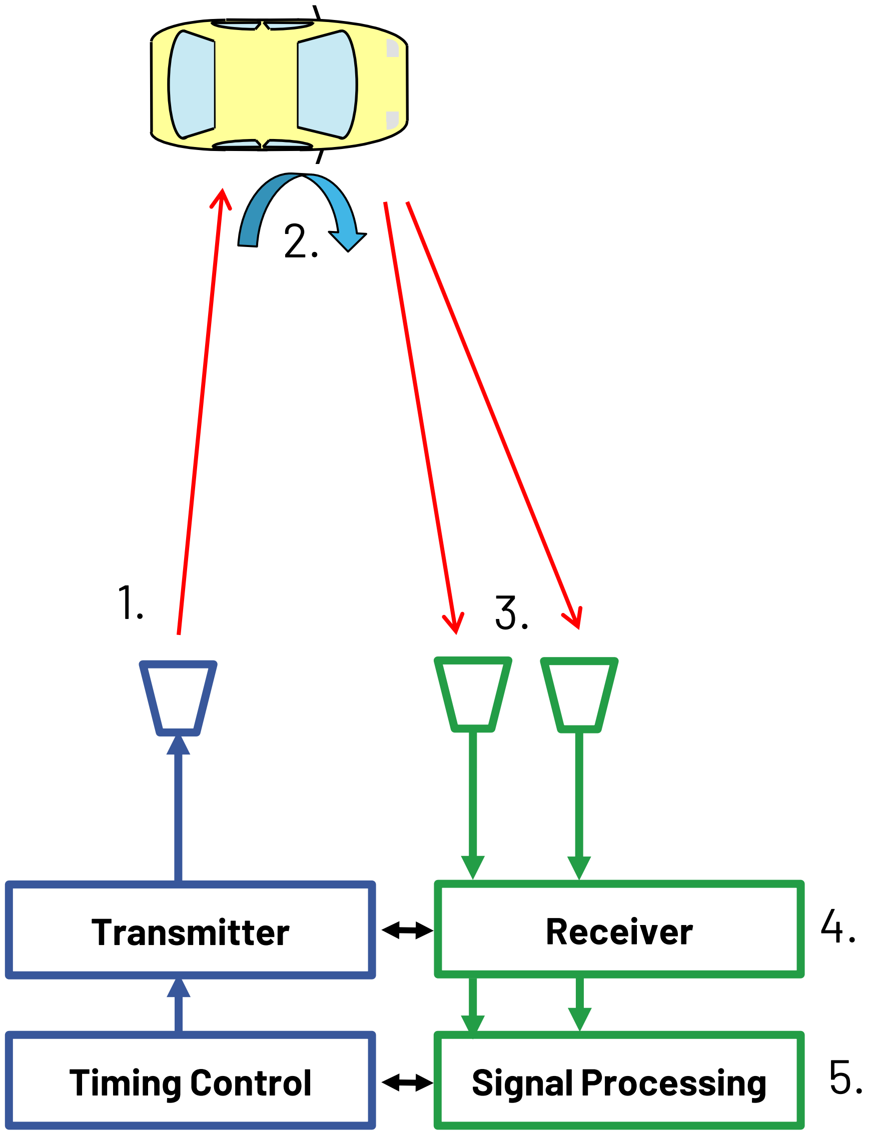


Radar



Radar Basics: Introduction

- **RADAR = Ra**dio **D**etection **A**nd **R**anging
  1. Radar transmits modulated EM-wave with an antenna
  2. Wave gets reflected at target
  3. Wave travels back to Radar receive antennas
  4. Receiver detects reflected wave
  5. Signal Processing estimates
     a) Distance (time delay)
     b) Angle of arrival (phase difference at multiple antenna elements)
     c) Velocity (Doppler shift)



Radar Range Equation

Antenna Gain

Transmit Power

λ = **wavelength** of carrier frequency

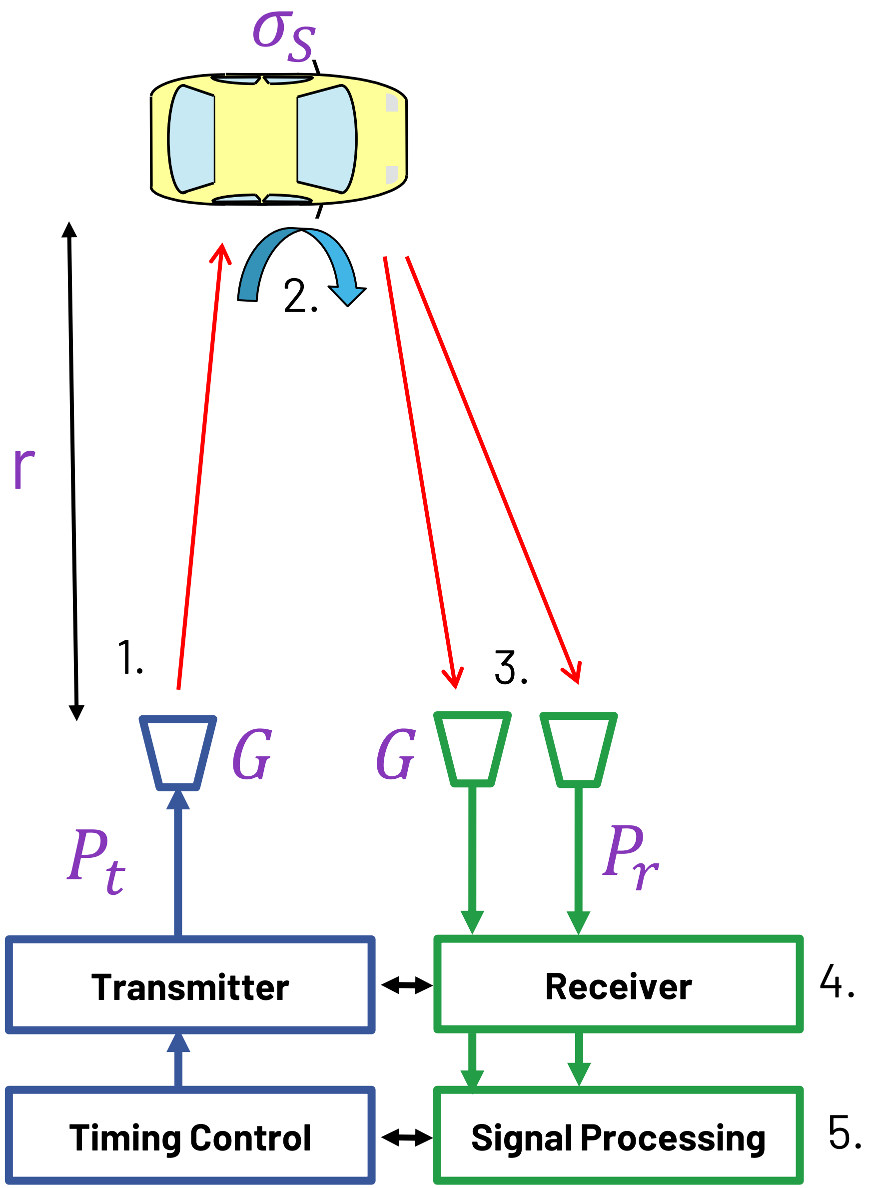
σ_S = **Radar Cross Section**

$$P_r = P_t \frac{G^2 \cdot \lambda^2 \cdot \sigma_S}{(4\pi)^3 \cdot r^4}$$

Receive Power

Range

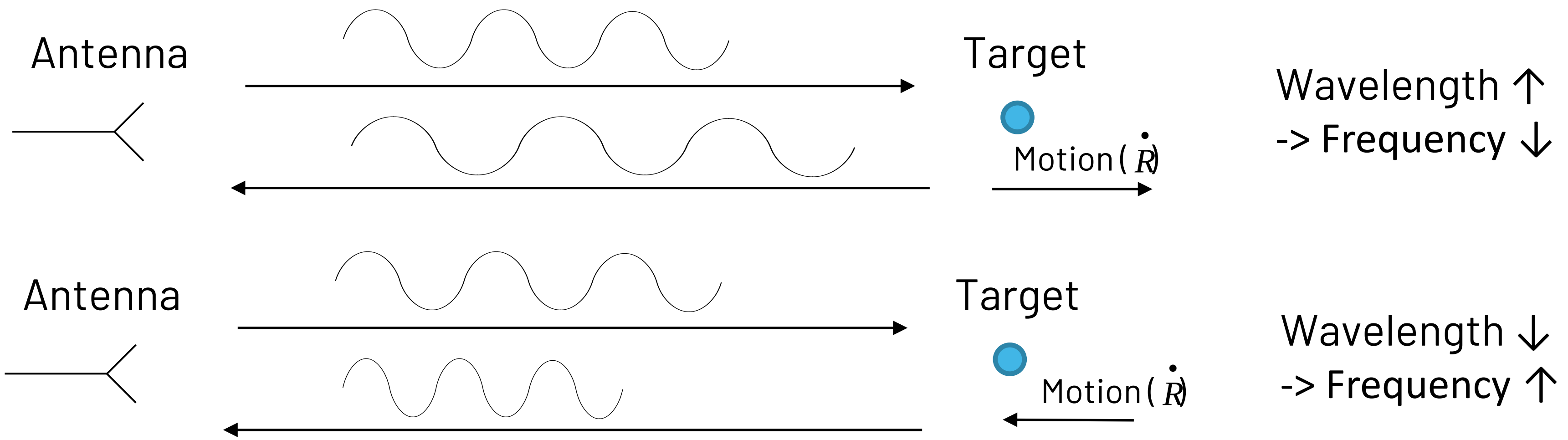
Key Points: Power Proportional to $\frac{1}{R^4}$



Doppler

- Doppler Frequency: Frequency change based on movement of the target in range
- Caused by wavelength expansion or contraction

Visual Explanation



Doppler Frequency $$f_d = \frac{-2\dot{R}}{\lambda}$$

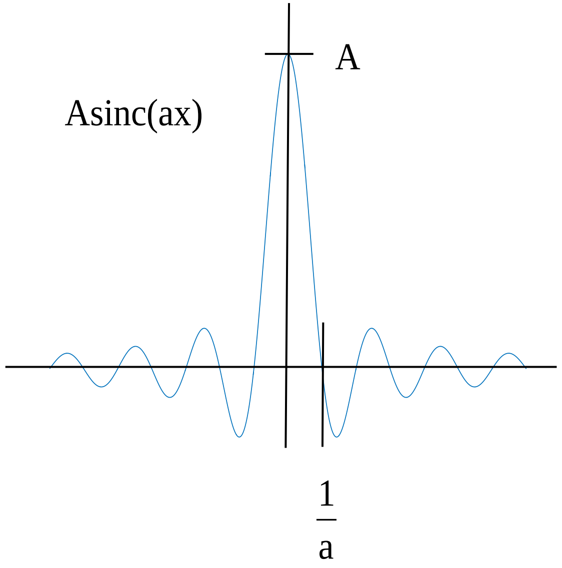
$\dot{R}$ = Range Rate

λ = wavelength

The Sinc Function at Work Again

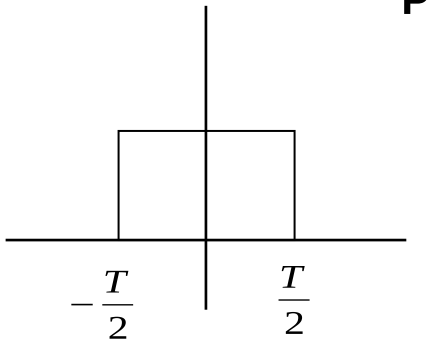
SINC Function

$$\mathrm{sinc}(x) = \frac{\sin \pi x}{\pi x}$$

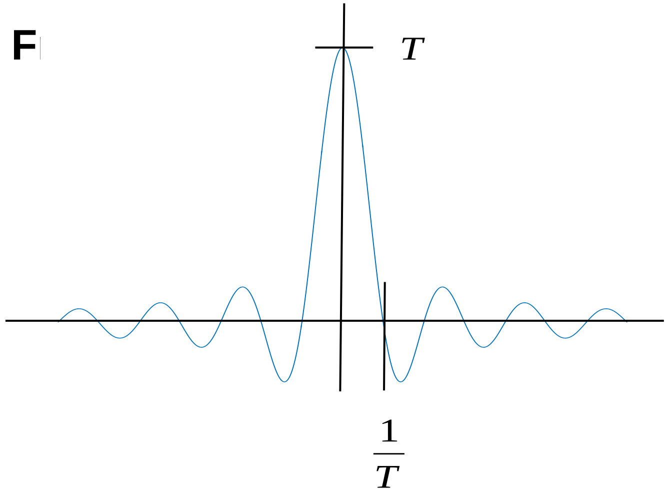


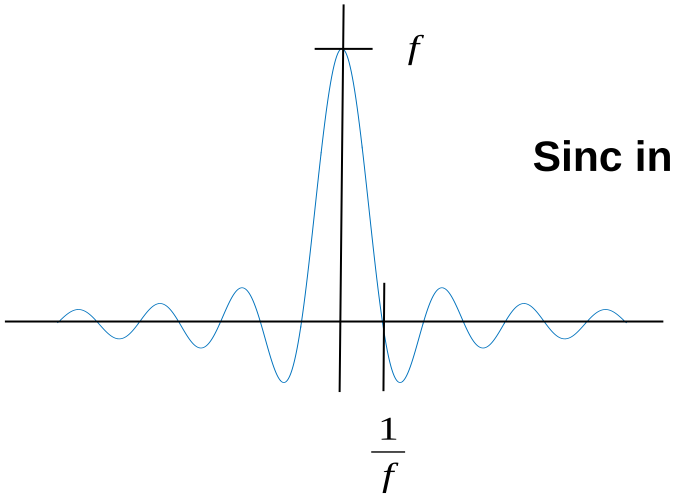
Time

Frequency

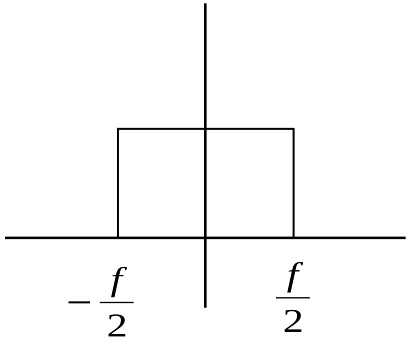


Pulse in Time ←→ Sinc in F





Sinc in Time ←→ Pulse in Freq



Key Point: Wider Bandwidth = Better Range Resolution

Two Basic Types of Radar: Pulsed and FMCW (2)

Pulsed

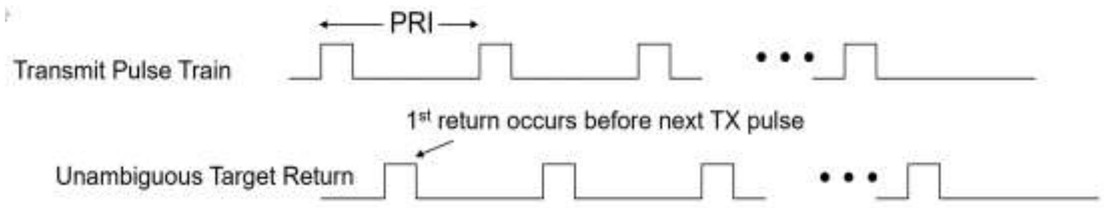
(Classical Radar Technique)

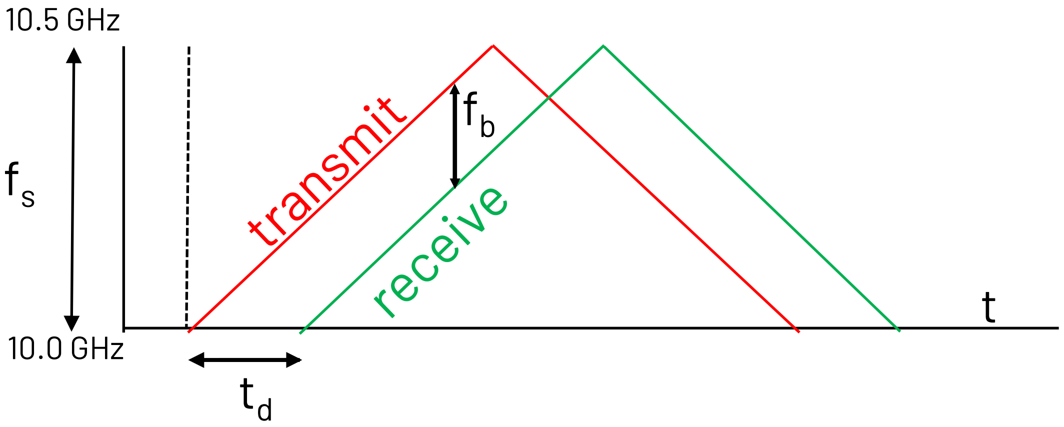
- Typical Applications
  - High Power Long Range Radars
  - Timeline: Transmit then Receive
- Energy = Power * Time
- Pulse Compression used for range resolution

FMCW

(Freq. Modulated Continuous Wave)

- Simpler Low Cost Implementation
- Simultaneous Transmit and Receive
- Close Range Applications
- Collision Avoidance,
  - Automotive Radar

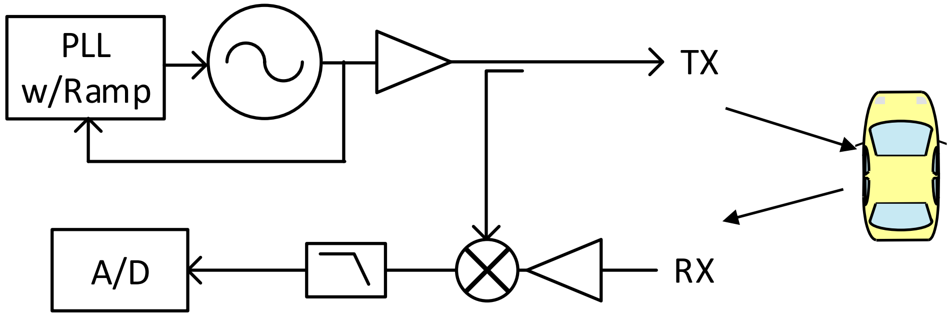


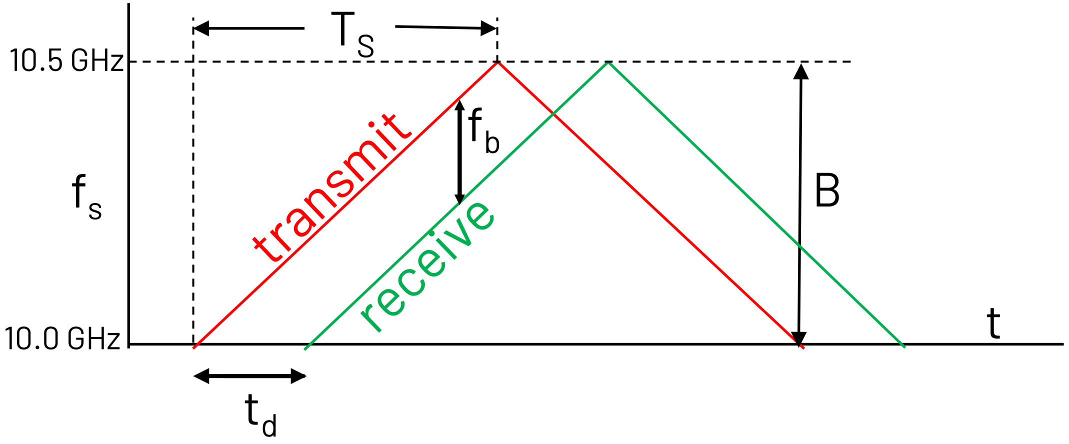


FMCW Radar

- **FMCW:** Frequency Modulated Continuous Wave
- Different Class than Pulsed Radars
- **Beat frequency** proportional to time delay -> FFT for range estimation
- Typically used for short range
  - Automotive, Seekers, Collision Avoidance, etc
- Separate TX and RX Antennas
- Benefits:
  - Simple Architectures
  - Low Frequency Sampling
  - Can be made low cost

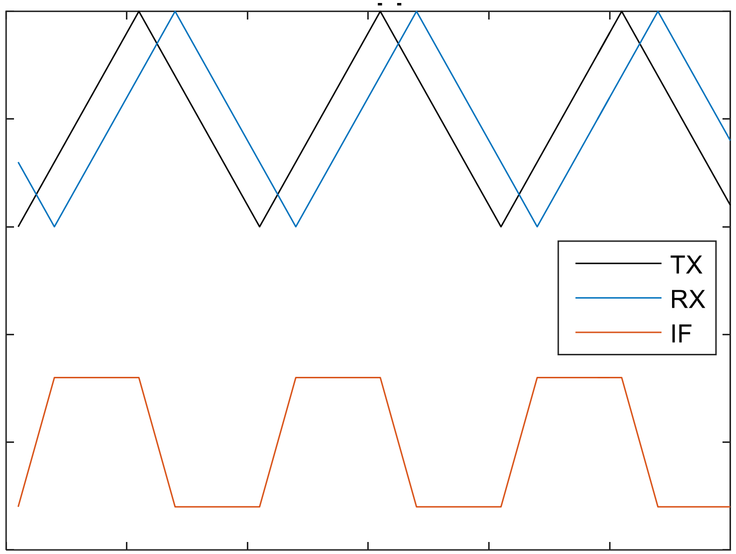
Basic Architecture

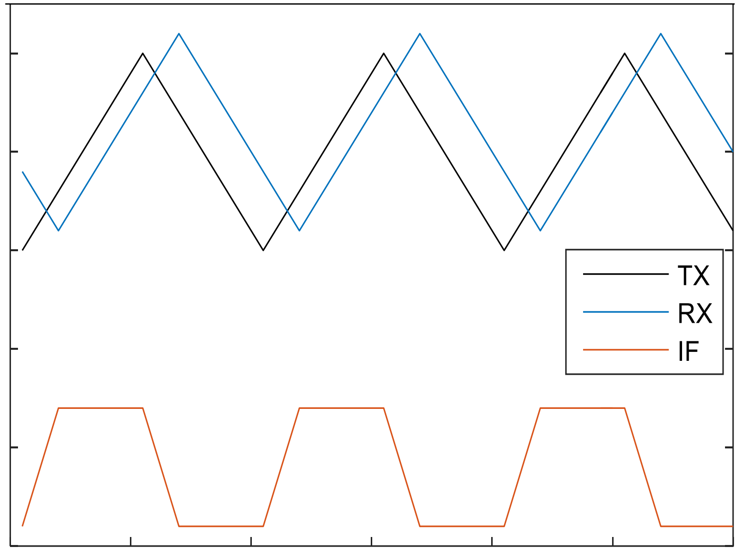




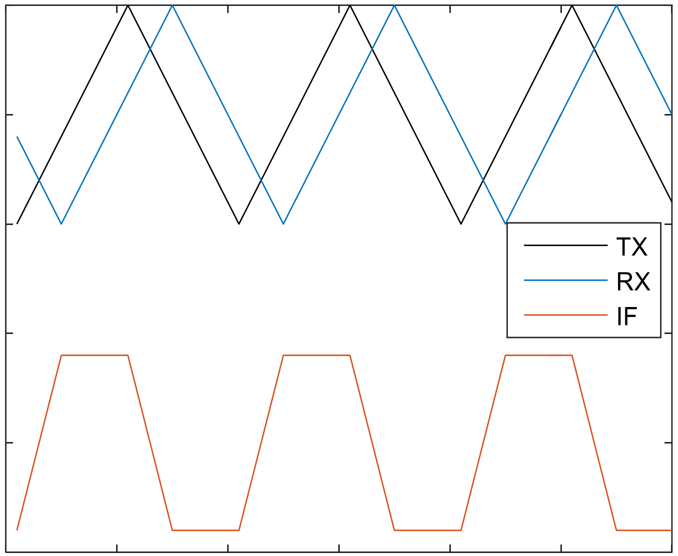
FMCW Radar

Example Frequency Plots


Baseline Range No Doppler


Doppler Shift

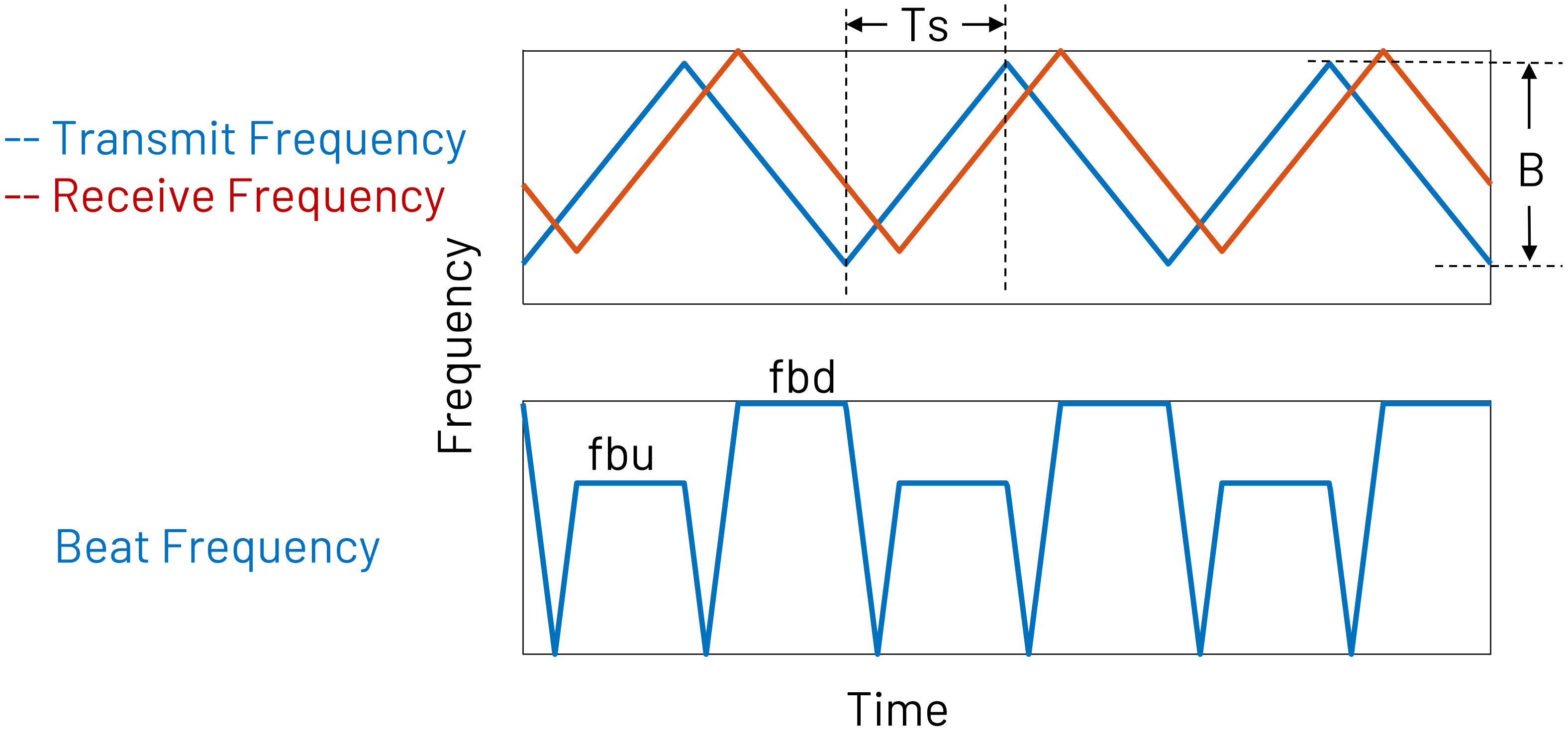
Doppler -> Frequency Offset


Range Shift

Range -> Frequency Spread

Both Range and Doppler Determined From IF

FMCW Key Calculations



$$R = \frac{cT_s}{4B}(fbd + fbu)$$

$$v = \frac{\lambda}{4}(fbd - fbu)$$

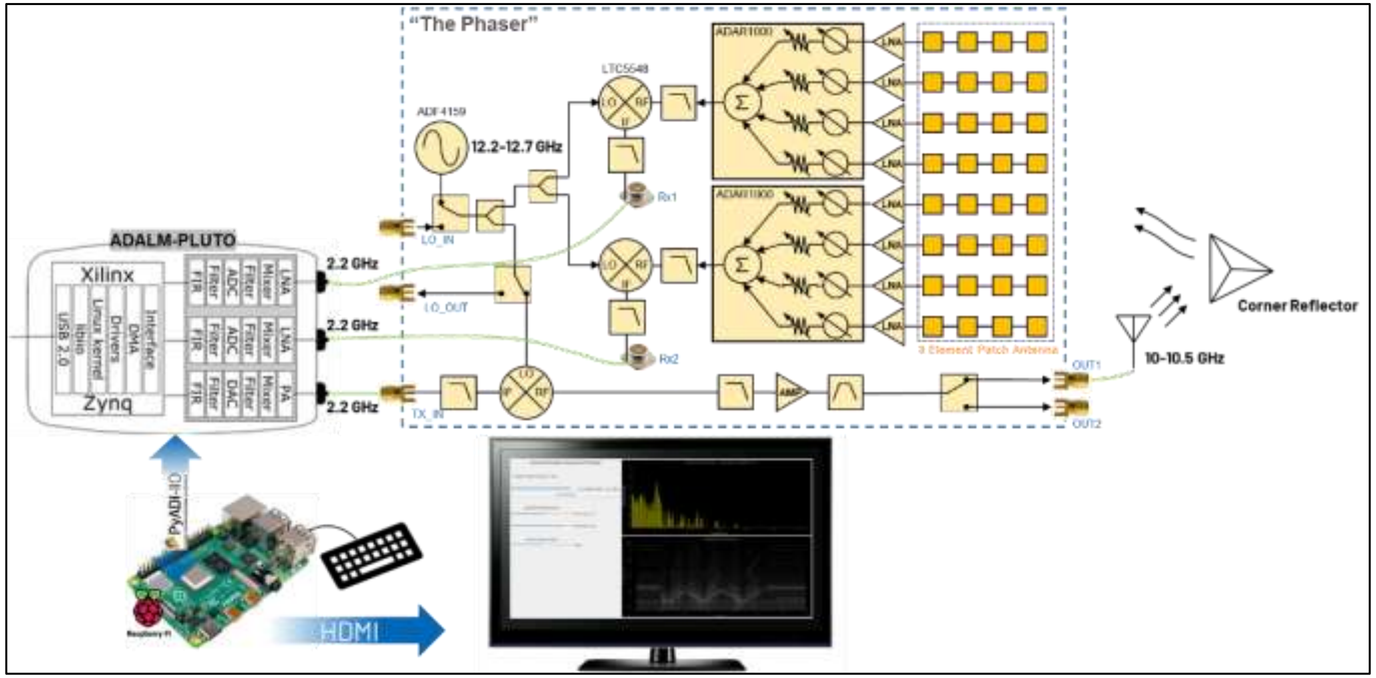
c = speed of light (3E8 m/s)
T_s = transmit frequency ramp rate
B = bandwidth of the frequency ramp
f_b = transmit to receive frequency difference

Reference: Tobias Otto, Principle of FMCW

Lab 7-1: Radar

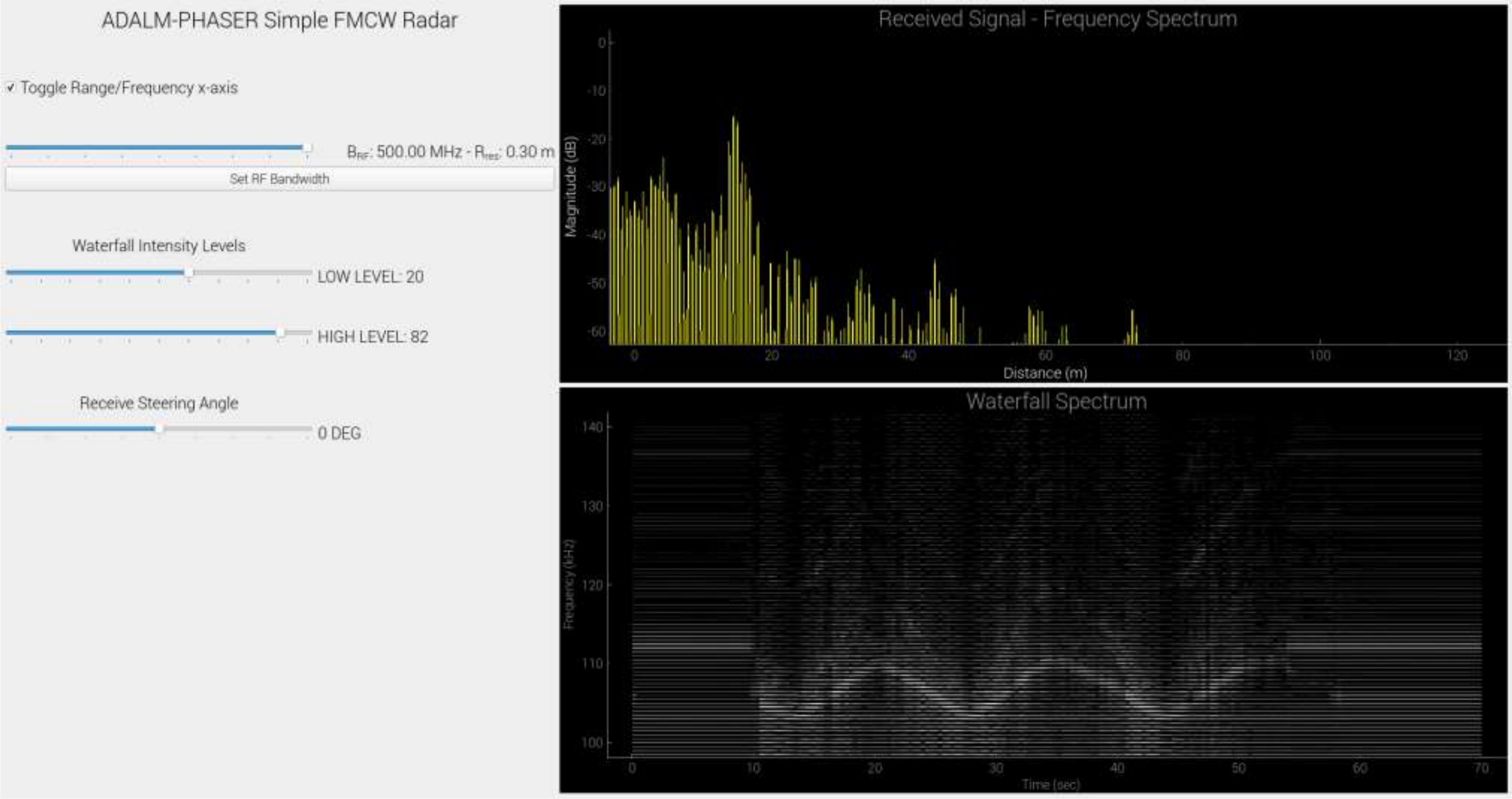
Workshop Lab Guide

Lab 9: FMCW Radar



1. Turn off the HB100!
2. Place the corner reflector about 1 meter from the array
3. Place the Vivaldi transmit antenna next to the phased array and point it at the corner reflector.

Lab 9: FMCW Radar



ADALM-PHASER Simple FMCW Radar

☑ Toggle Range/Frequency x-axis

B_{RF}: 500.00 MHz - R_{res}: 0.30 m

Waterfall Intensity Levels

LOW LEVEL: 20

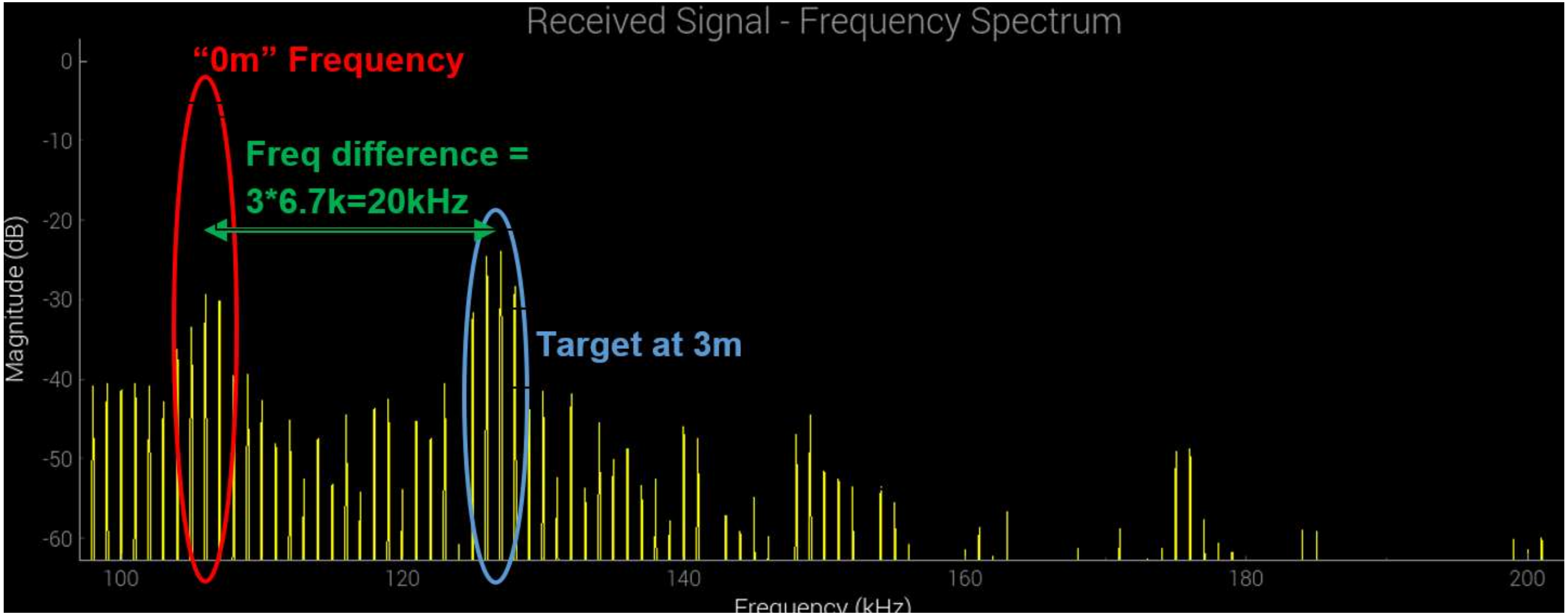
HIGH LEVEL: 82

Receive Steering Angle

0 DEG

1. From Thonny, select “RADAR_FFT_Waterfall.py” and click the green “Run” button

Lab 9: FMCW Radar



Move the target to approximately 1m and observe the FFT plot.

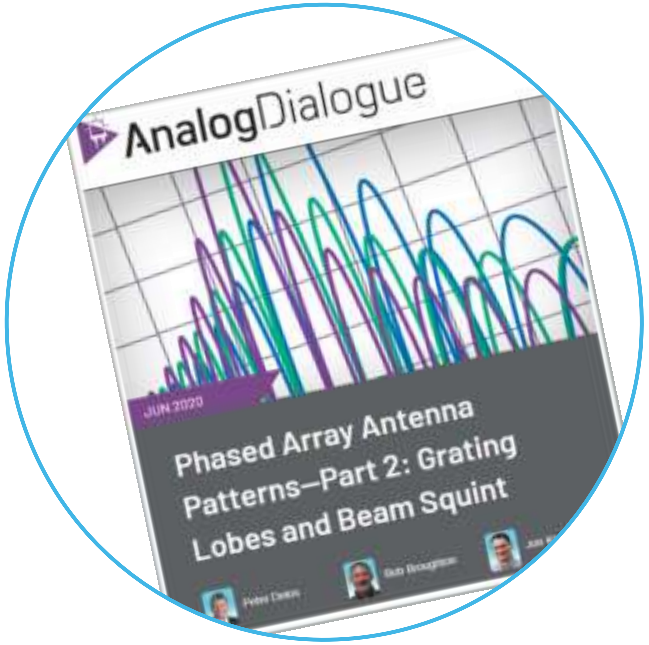
Did the frequency move by about 6.7kHz? Try moving to 2m, or 3m.

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Conclusion

Workshop Goals:

1. Gain an **intuitive** understanding of beamforming concepts
2. **Hands on** experimenting with these concepts
3. Path to quickly **prototype** your own phased array system



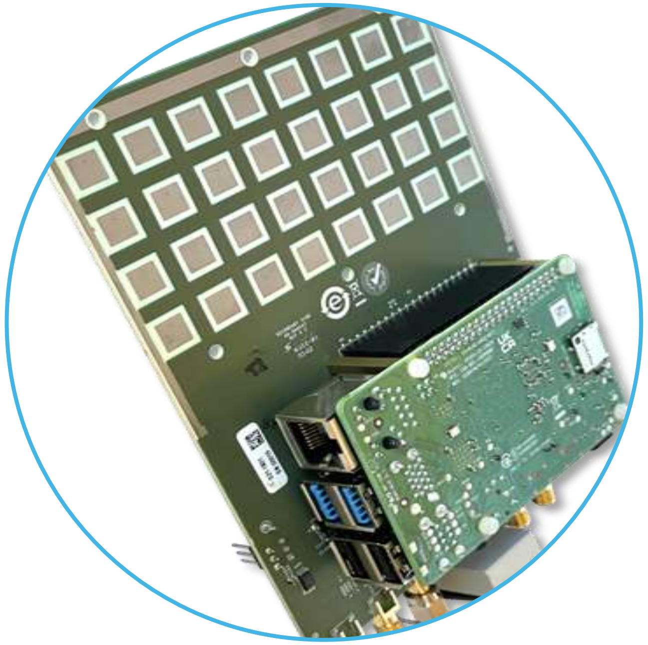
AnalogDialogue

JUN 2020

Phased Array Antenna Patterns—Part 2: Grating Lobes and Beam Squint

Math and Theory

+



Accessible Hardware

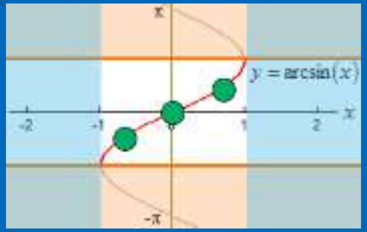
=

Understanding

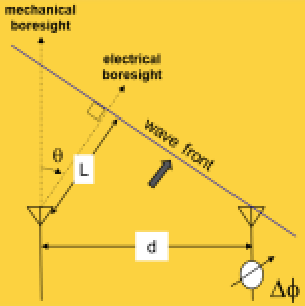
Summary of the Phased Array Workshop

Digitizer

Antenna Impairments

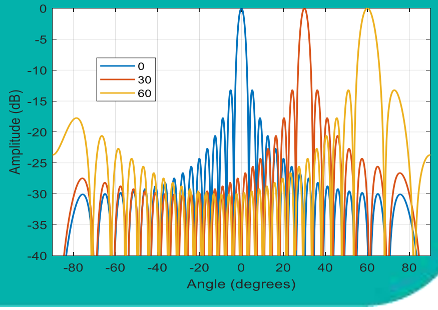


Steering Angle

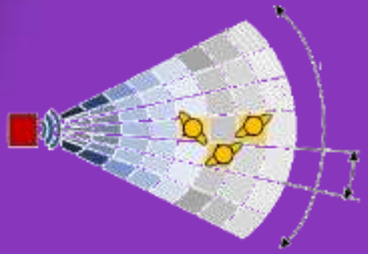


Monopulse Tracking

Antenna Patterns



Radar



Summary and Conclusion

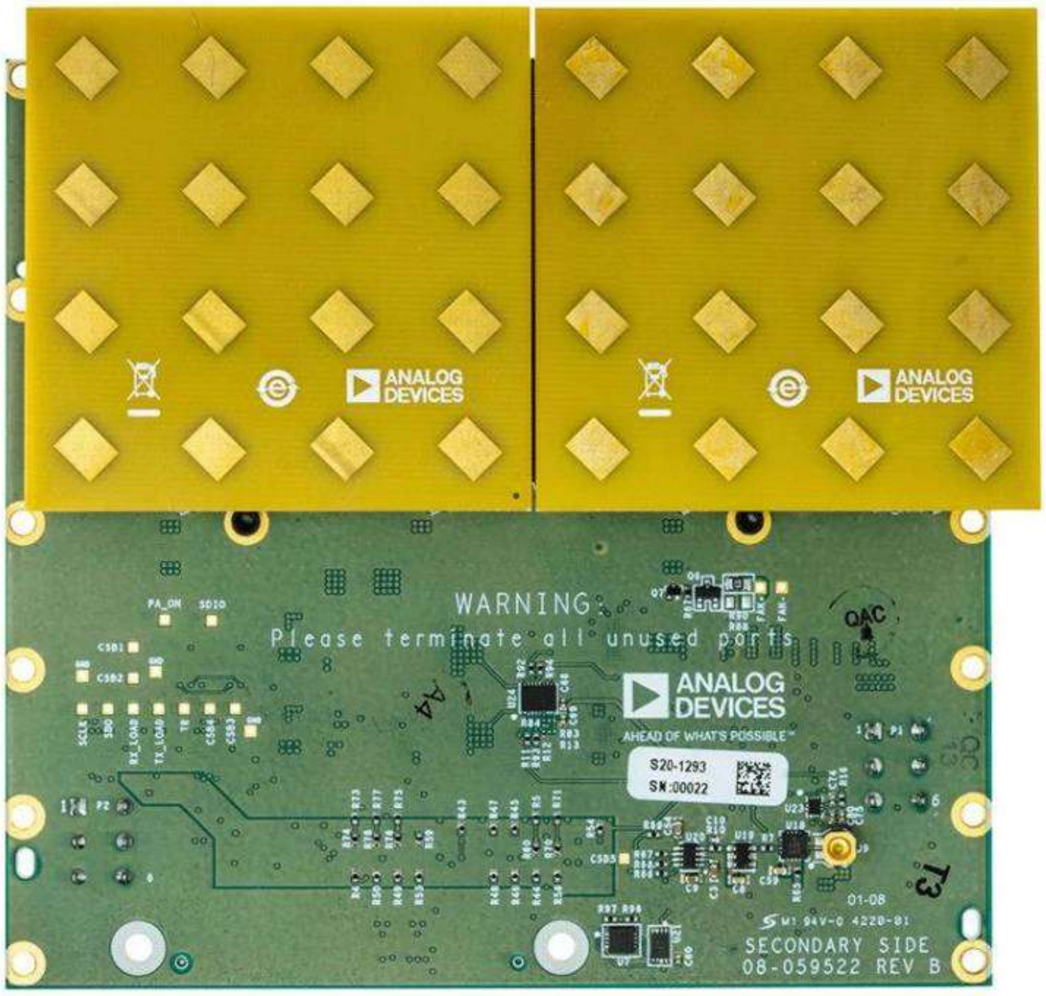
- For more information, including additional labs and lectures, please visit:

  wiki.analog.com/phaser (under development! Check back in a few weeks).

- Many of these labs and lectures were sourced from a 3 part white paper found here:
  - https://www.analog.com/en/analog-dialogue/articles/phased-array-antenna-patterns-part1.html

- A more complete, “professional”, phased array radar system is available here:
  - https://wiki.analog.com/resources/eval/developer-kits/x-band-dev-kit

  But all of the concepts from ADALM-PHASER, and nearly all of the software will be applicable to this system as well



X-Band Phased Array Platform