Phase Coherency

Translating Phase and Time Accuracy

to the Real World

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The Intro

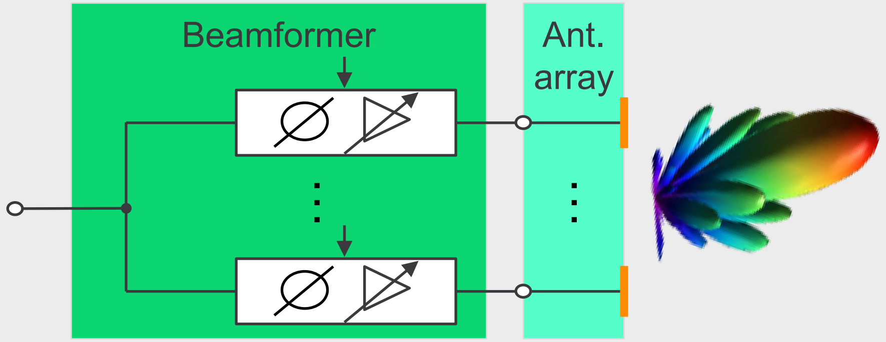
What this talk is about…

Multi-Antenna Systems
– Care about Synchronization

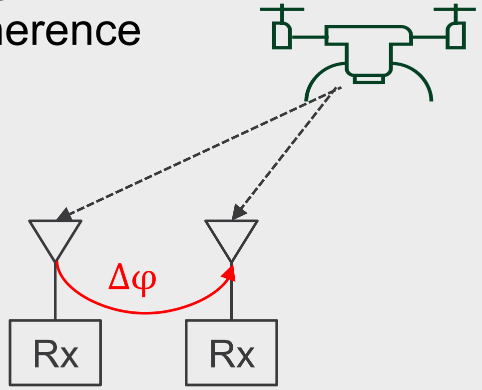
Applications involving multiple antennas require

Systematic phase relations between channels (“Phase Coherence”)

Beamforming –
Tx-Tx / Rx-Rx coherence



Direction Finding –
Tx-Tx / Rx-Rx coherence

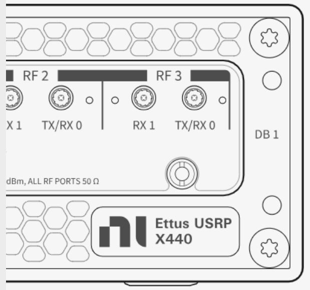


How accurate do we need to be?
1ps?? 1 degree at RF??

USRPs are designed with these applications in mind

Ettus USRP X440 –
Provides 8 coherent RF channels

Phase Accuracy –
Specifications



RX Phase Stability

Master Clock Rate [Hz]	Same Device		Device-to-Device	
	Peak-to-Peak [deg]	RMS [deg]	Peak-to-Peak [deg]	RMS [deg]
125e6	< 0.15	< 0.1	< 1.5	< 0.2
307.2e6	< 0.15	< 0.1	< 2.5	< 0.35
360e6	< 0.25	< 0.1	< 2.5	< 0.4
368.64e6	< 0.5	< 0.1	< 3.5	< 0.5
400e6	< 0.4	< 0.1	< 3.5	< 0.55
500e6	< 0.3	< 0.1	< 3.5	< 0.6
1000e6	< 0.35	< 0.1	< 4	< 0.6
2000e6	< 0.35	< 0.1	< 4	< 0.6

Does our USRP meet that need?

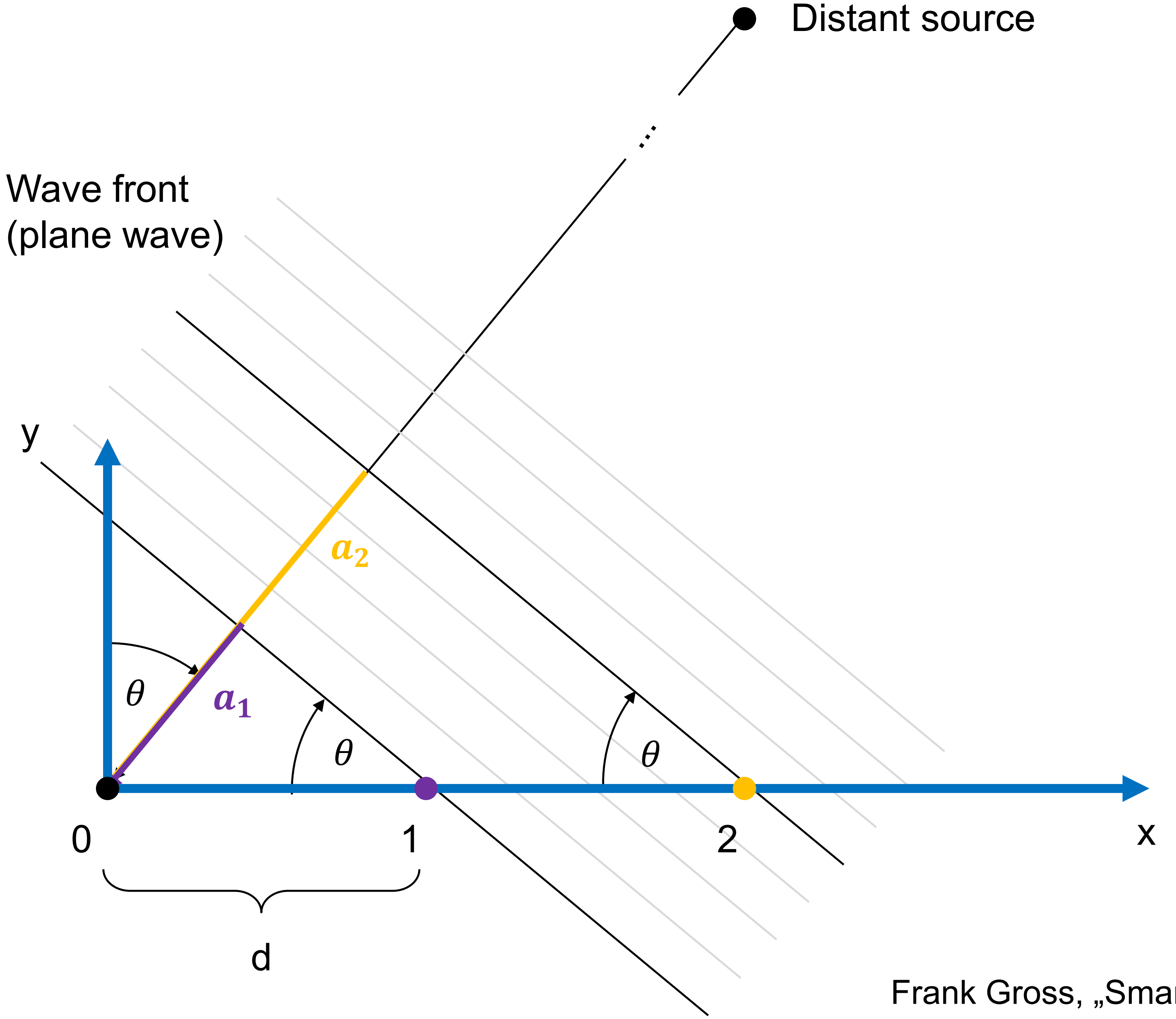
The Basics

Antenna Array and Direction

We’ll be quick!

Extra content in PDF

It’s All About the Phase



1. How much further has a plane wave to travel to reach antenna element i=0 compared antenna element i ?

$$a_i = i \cdot d \cdot \sin(\theta)$$

2. How much has the phase of a plane wave with wavelength λ changed over distance a_i?

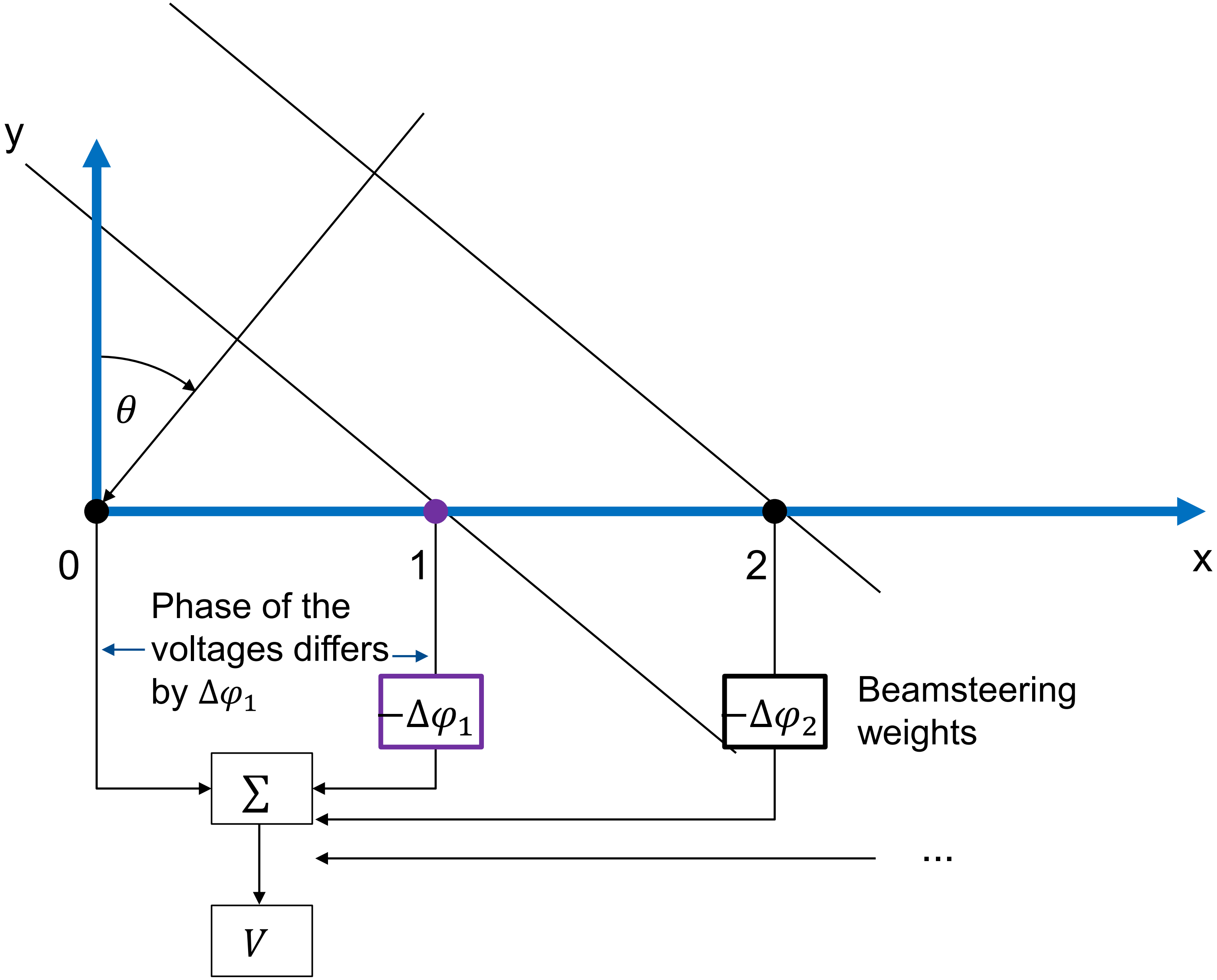
$$\Delta\varphi_i = i \cdot 2 \cdot \pi \cdot \boxed{\frac{d}{\lambda}} \cdot \sin(\theta)$$

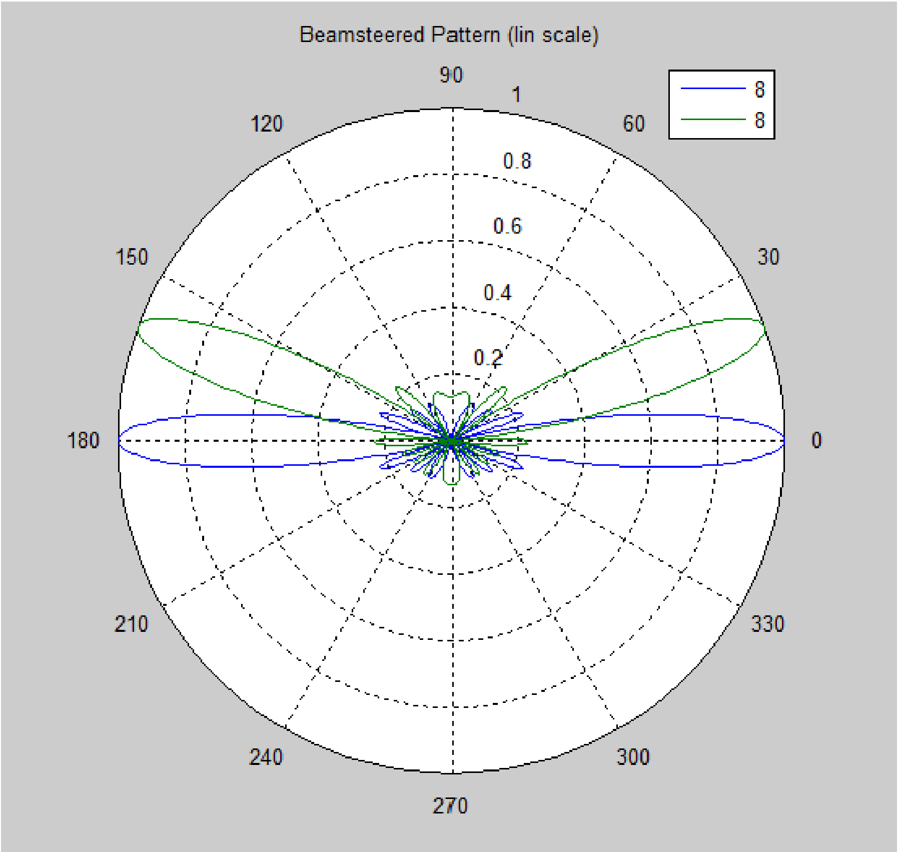
Relative antenna distance

3. Antenna element i is „ahead“ by $\Delta\varphi_i$

Frank Gross, „Smart Antennas for Wireless Communications“

To Steer or Not to Steer





- No beamsteering
- $\Delta\varphi_i$ chosen such that there is a coherent superposition for $\theta = 20°$
- How to pick $\Delta\varphi_i$

$$\Delta\varphi_i = i \cdot 2 \cdot \pi \cdot \frac{d}{\lambda} \cdot \sin(\theta)$$

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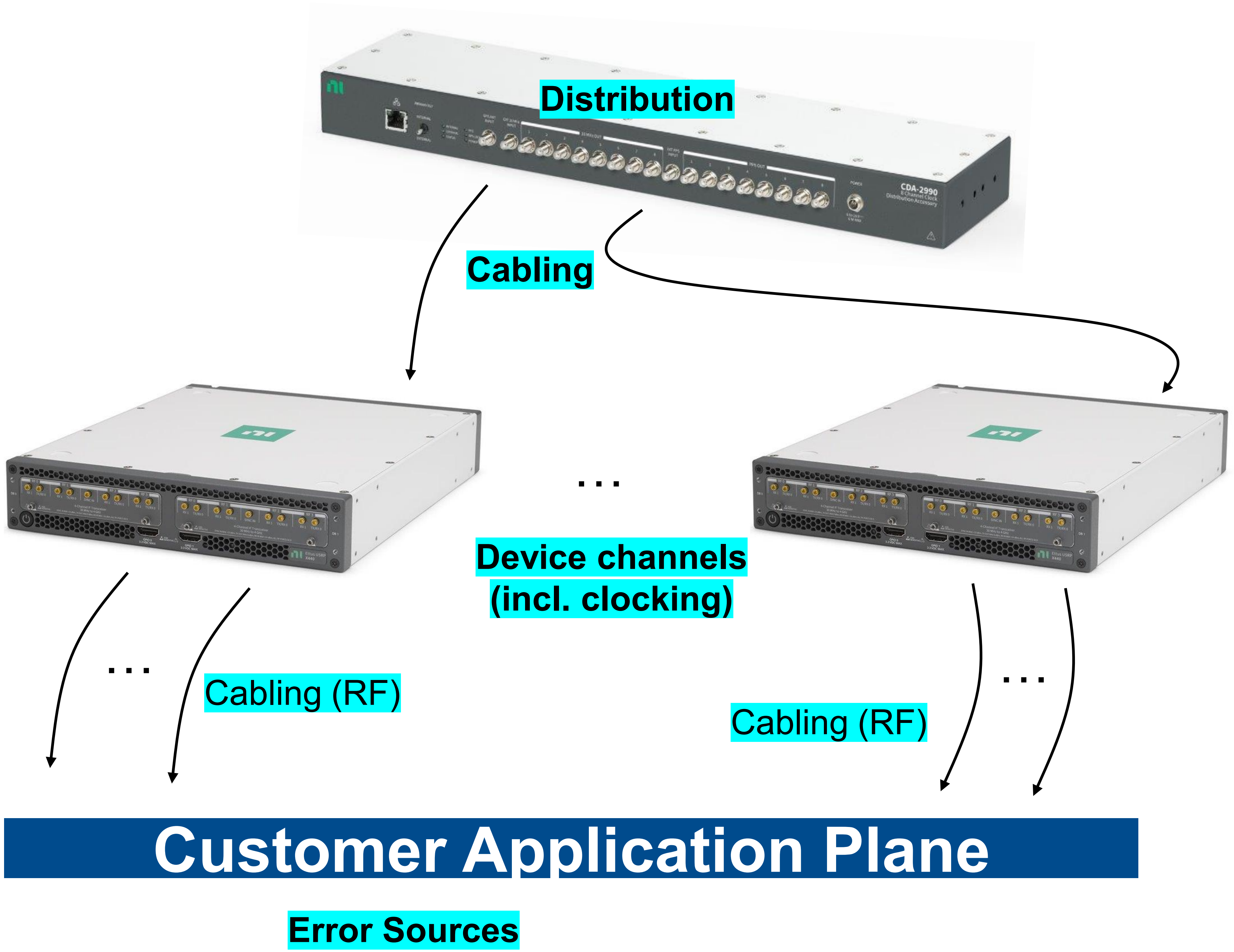
The Errors

What could possibly go wrong?

Modelling errors based on X440

Example: Multi Channel System with X440



Simplified Model
(channel i relative to channel 0):

Common Reference

$\Delta t_{distribution,i}$

$\Delta t_{10M\_cable,i}$

$\Delta t_{channel,i}$

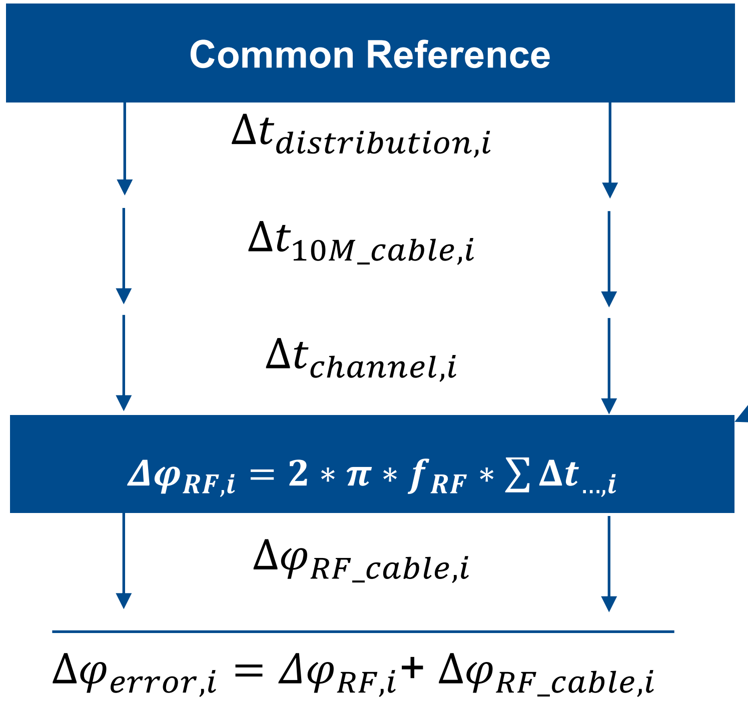
$$\Delta\varphi_{RF,i} = 2 * \pi * f_{RF} * \sum \Delta t_{\dots,i}$$

$\Delta\varphi_{RF\_cable,i}$

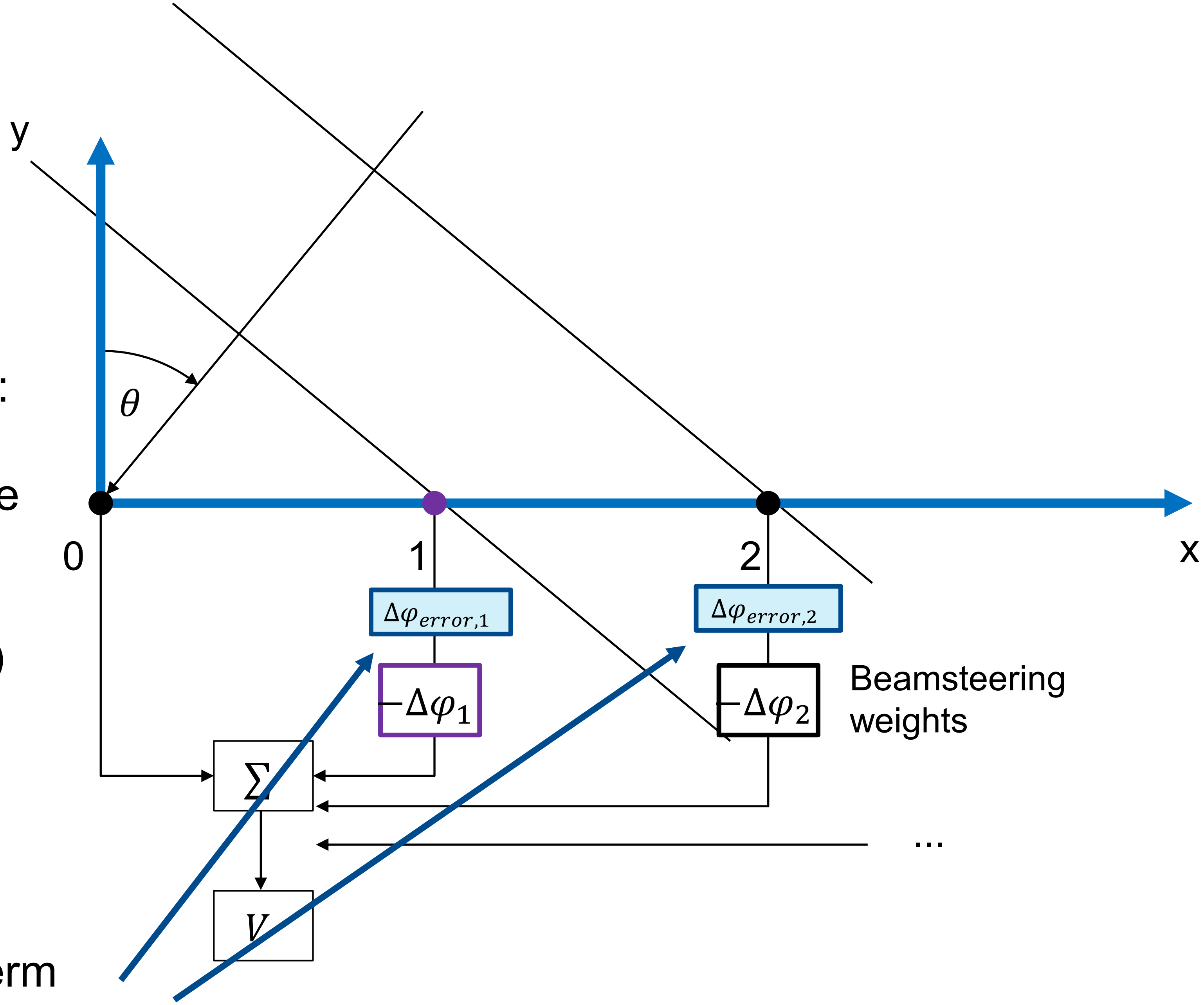
$$\Delta\varphi_{error,i} = \Delta\varphi_{RF,i} + \Delta\varphi_{RF\_cable,i}$$

Adding Error Terms to Model

Simplified Model
(channel i relative to channel 0):



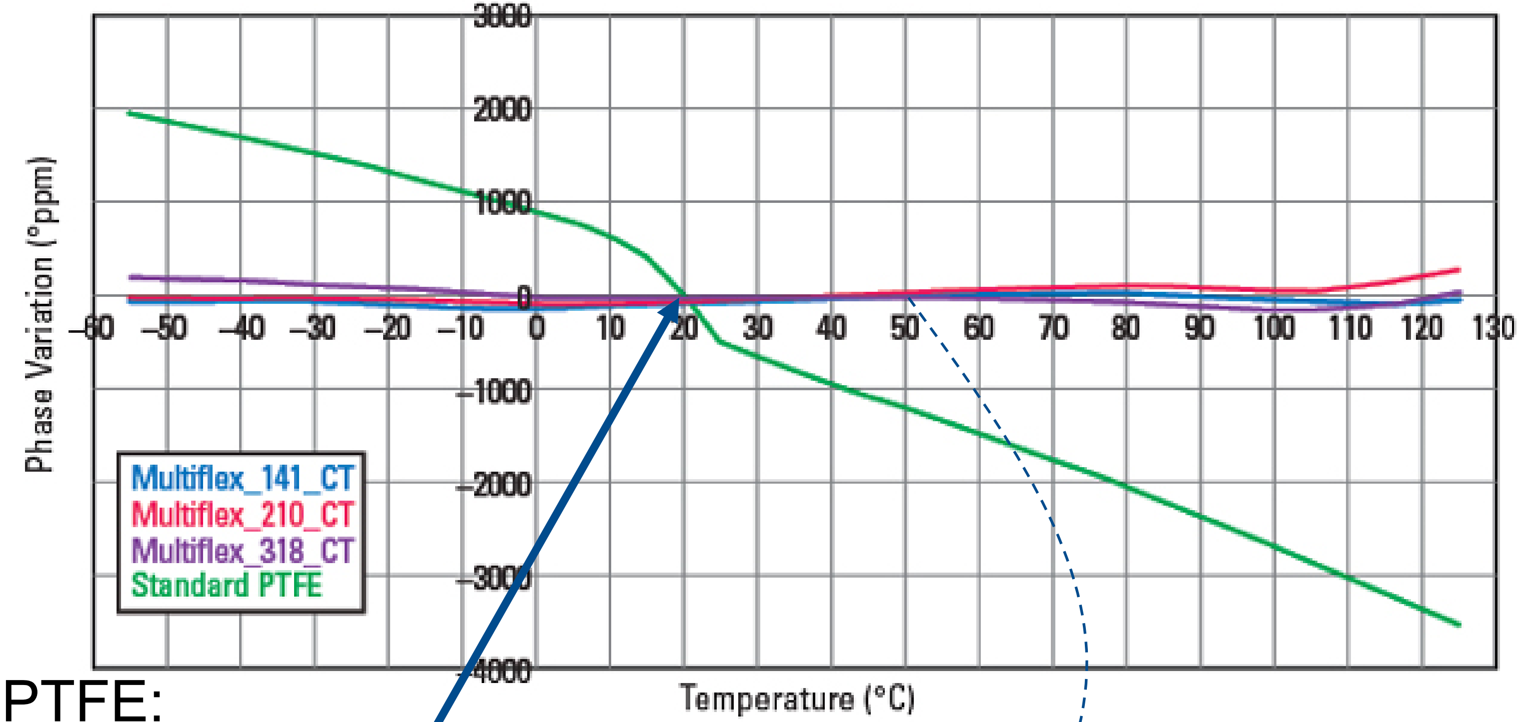
Time offsets / errors:
At RF frequencies these turn into phase offsets.
(Note: assumes narrowband signals)



Adding individual error term to each phase weight

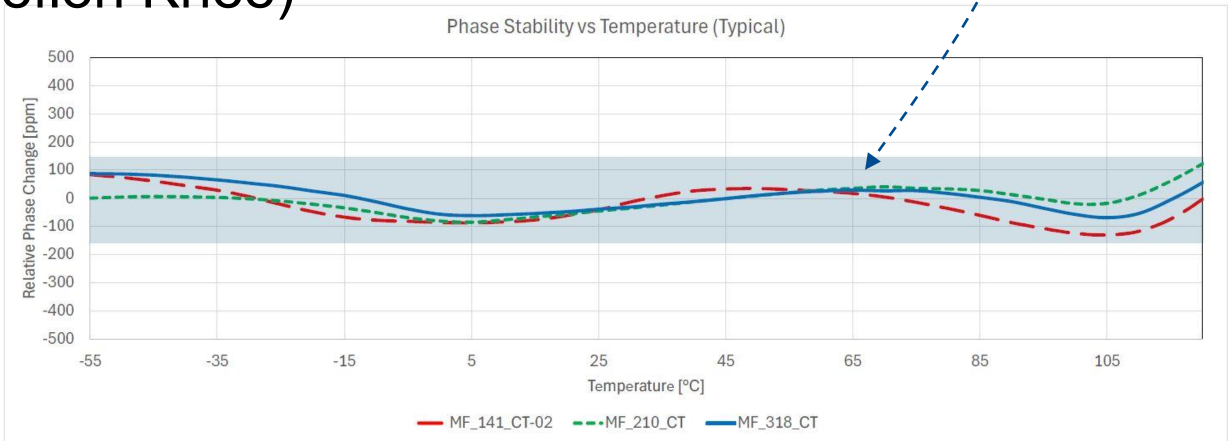
Errors of Cables and the Teflon Knee

Data published by Huber+Suhner in Microwave Journal



PTFE:
Highest Variation at room temp
(Teflon Knee)

Zoom in on high quality cables



From: Microwave Cable Family Provides Phase Stability over Temperature | 2020-03-05 | Microwave Journal;

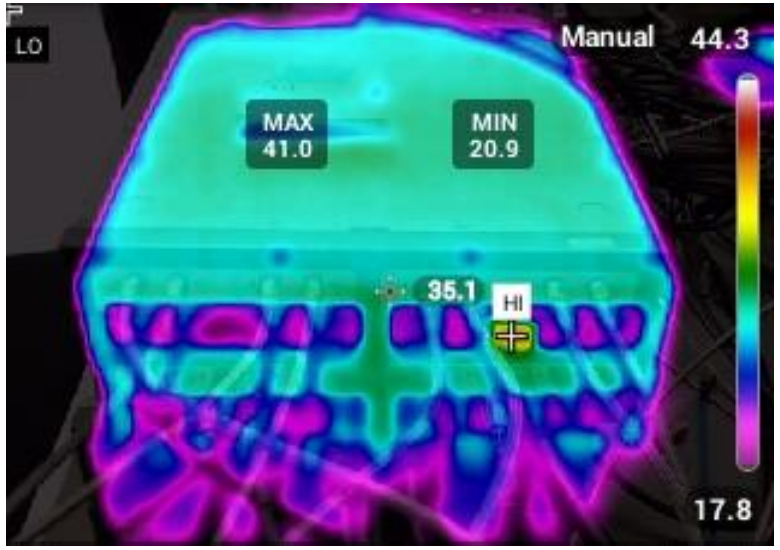
	1m PTFE-based	1m MF-141_CT
Electrical Length	4.8ns	4.0ns
Phase variation	2200ppm (0..55C) 5500ppm (-55..125C)	150ppm (0..55C) 300ppm (-55..125C)
Time Variation	11ps (0..55C) 26ps (-55..125C)	0.6ps (0..55C) 1.2ps (-55..125C)
Phase Variation at 1 GHz	3.8 deg (0..55C) 9.5 deg (-55..125C)	0.1 deg(0..55C) 0.2 deg(-55..125C)
Phase Variation at 18 GHz	37 deg (0..55C) 171 deg (-55..125C)	1.9 deg (0..55C) 3.9 deg (-55..125C)

Cables…
Time errors scale with length, temp.
Phase errors scale with length, temp., freq.
High quality cables are needed.
Shorter cables are beneficial.

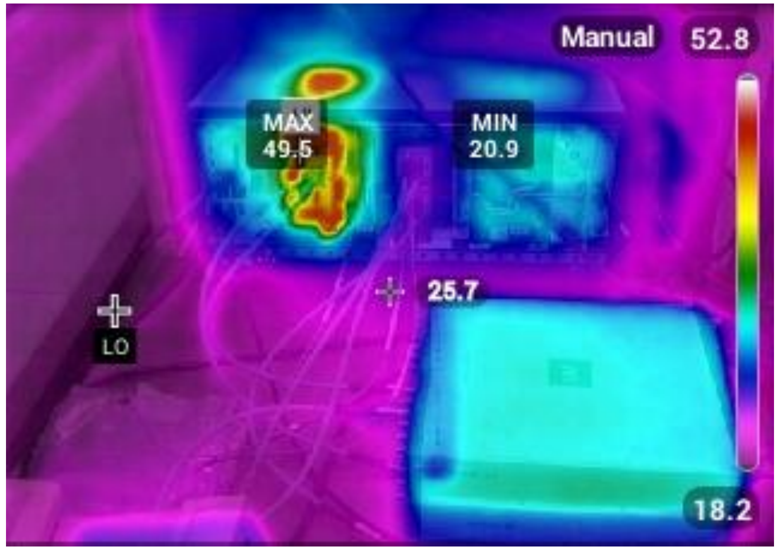
https://www.hubersuhner.com/en/newsroom/blog-and-literature/blog/introducing-multiflex-141-ct-02-cable-assemblies

No constant temperature – Even in the Lab!

Setup with 2 USRPs



Setup with PXI chassis



Pictures from lab with AC!

There is no such thing as constant temperature – airflow & surroundings will matter as well

More reason to have short, high-quality cabling

USRP Context – X440

We are specifying Phase Stability & Repeatability of X440:

https://www.ni.com/docs/en-US/bundle/ettus-usrp-x440-specs/page/specs.html

TX Phase Stability

Master Clock [Hz]	Same Device	Device-to-Device
125e6		
307.2e6		
360e6		
368.64e6		
400e6		
500e6		
1000e6		
2000e6		

RX Phase Stability

Master Clock Rate [Hz]	Same Device		Device-to-Device	
	Peak-to-Peak [deg]	RMS [deg]	Peak-to-Peak [deg]	RMS [deg]
125e6	< 0.15	< 0.1	< 1.5	< 0.2
307.2e6	< 0.15	< 0.1	< 2.5	< 0.35
360e6	< 0.25	< 0.1	< 2.5	< 0.4
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368.64e6		
400e6		
500e6		
1000e6		
2000e6		

RX Phase Stability

Master Clock Rate [Hz]	Same Device	Device-to-Device
125e6		
307.2e6		
360e6		
368.64e6		
400e6		
500e6		
1000e6		
2000e6		

Master Clock Rate [Hz]	Same Device [TX]	Same Device [RX]
	Peak-to-Peak [deg]	Peak-to-Peak [deg]
125e6	< 1.15	< 0.45
307.2e6	< 2	< 0.7
360e6	< 2.8	< 0.5
368.64e6	< 2.8	< 1
400e6	< 2.6	< 1.6
500e6	< 2.8	< 1
1000e6	< 2.5	< 0.5
2000e6	< 1.8	< 0.5

USRP Context – X440

We are specifying Phase Stability & Repeatability of X440:
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TX Phase Stability

Master Clock [Hz]	Same Device	Device-to-Device
125e6		
307.2e6		
360e6		

RX Phase Stability

Master Clock Rate [Hz]	Same Device	Device-to-Device
125e6		

Master Clock Rate [Hz]	Same Device [TX]	Same Device [RX]
	Peak-to-Peak [deg]	Peak-to-Peak [deg]

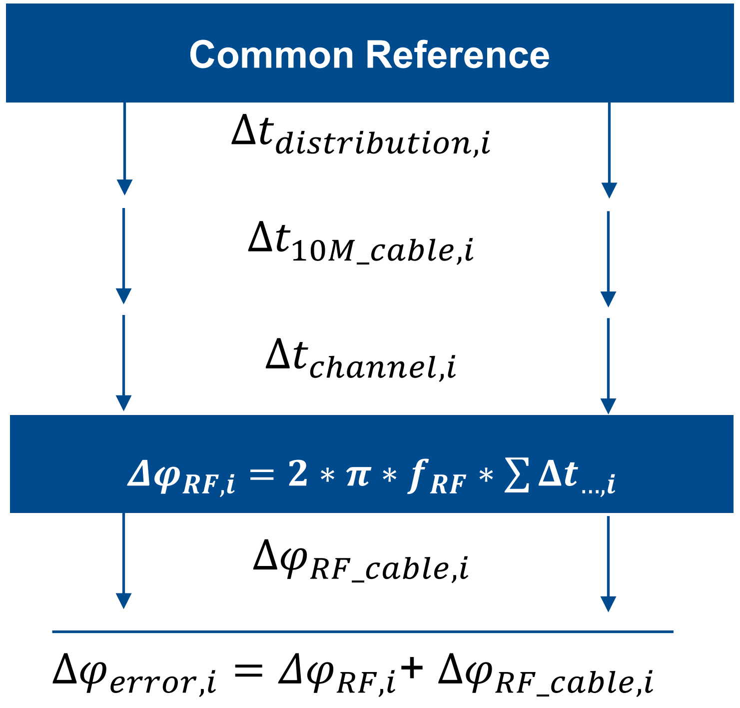
Note
Within the device, the phase relationship between channels is repeatable over sessions, retunes, and reboots. Across multiple devices, the phase relationship between channels is not preserved over retunes and reboots.

Phase stability/repeatability:

- Direct sampling device: sampling time offset turns to phase offsets
- Very stable phase relationships (in device, between devices)
- Repeatable within the device
- Repeatability between devices:
    - Small time offset at reboots possible (empirical ~+/-8..+/-15ps)
    - Phase offset at highest frequency could be up to ~+/-20 degree

Accuracy Budget – One single example

Simplified Model
(channel i relative to channel 0):

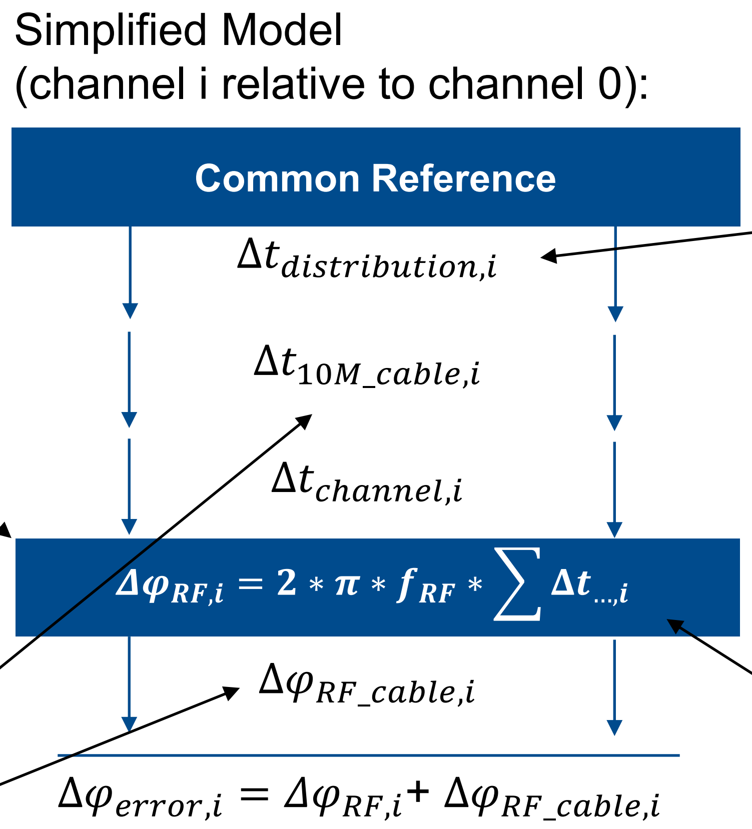


Contributor	2x co-located X440 RF at 2.4 GHz	Notes
$\Delta t_{distribution,i}$	N/A within device < 1 ps between devices	Single Octoclock, stable local temp., clocks sourced from single chip
$\Delta t_{10M\_cable,i}$	N/A within device 1ps between devices	1m Teflon-based, ~10 Kelvin when co-located; ~200ppm error based on plot in cable slide
$\Delta t_{channel,i}$	~1ps within device ~10ps between devices	~1 ps based on MCR 368.64 MSps RX repeatability pk-pk Ettus USRP X440 Specifications – NI ~10ps is based on non-exhaustive internal analysis; out-liers can be higher
$\Delta\varphi_{RF,i}$	$\sum \Delta t_{\ldots,i}$ = {1ps; 11ps} 0.9 degree within device 9.5 degree between devices	RF: 2.4 GHz Very useful for 8 channels in 1 X440 Some use between devices
$\Delta\varphi_{RF\_cable,i}$	~0.1 degree between any two channels	Using 1m MF-141_CT here, ~10 Kelvin when co-located; ~30ppm
$\boldsymbol{\Delta\varphi_{error,i}}$	**~1 degree within device** **~10 degree between devices**	Very good alignment in 1 device Major contributor: $\Delta t_{channel,i}$ between devices

More error sources plus things that help…

For wide bandwidths, expect phase deviations over IBW (time error → phase error)

Ethernet-based, GNSS-based distribution cause additional error mechanisms (order: nanoseconds)



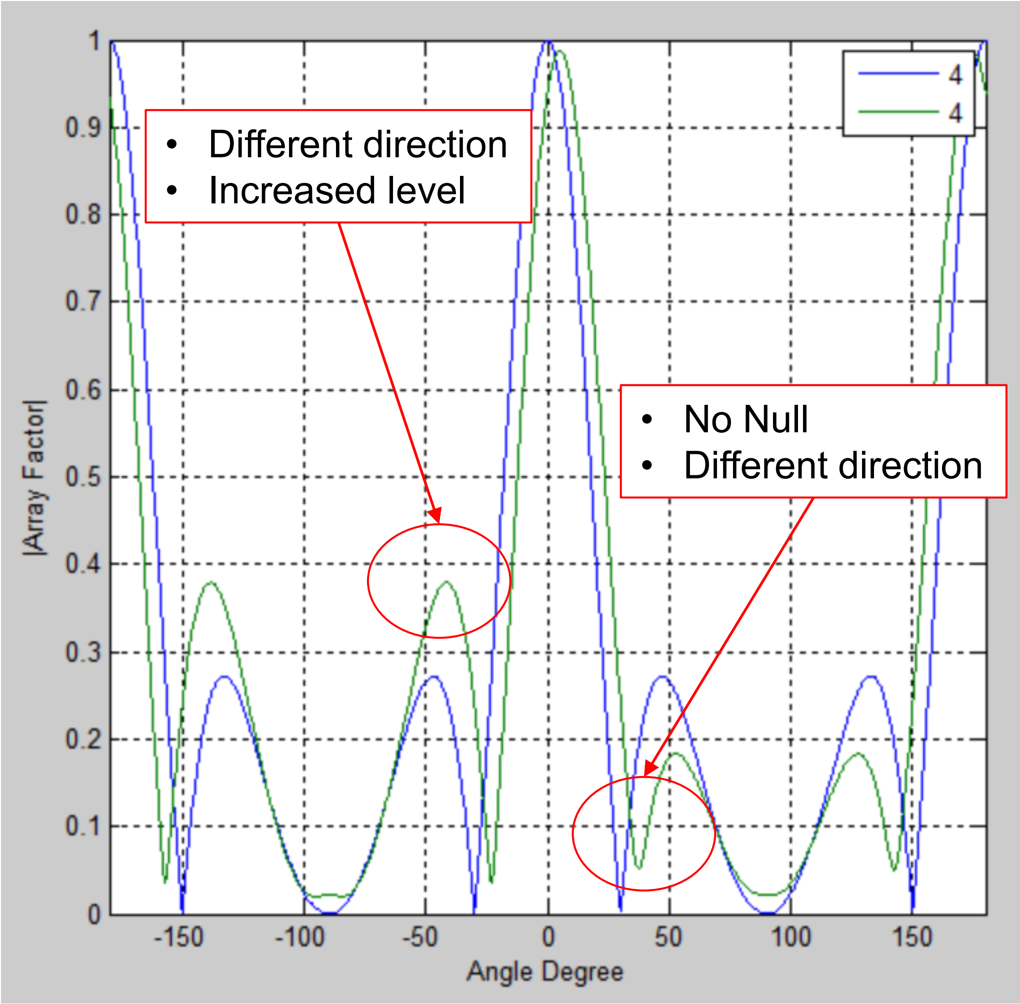
Impedance mismatches as well as bending/moving add to cable errors

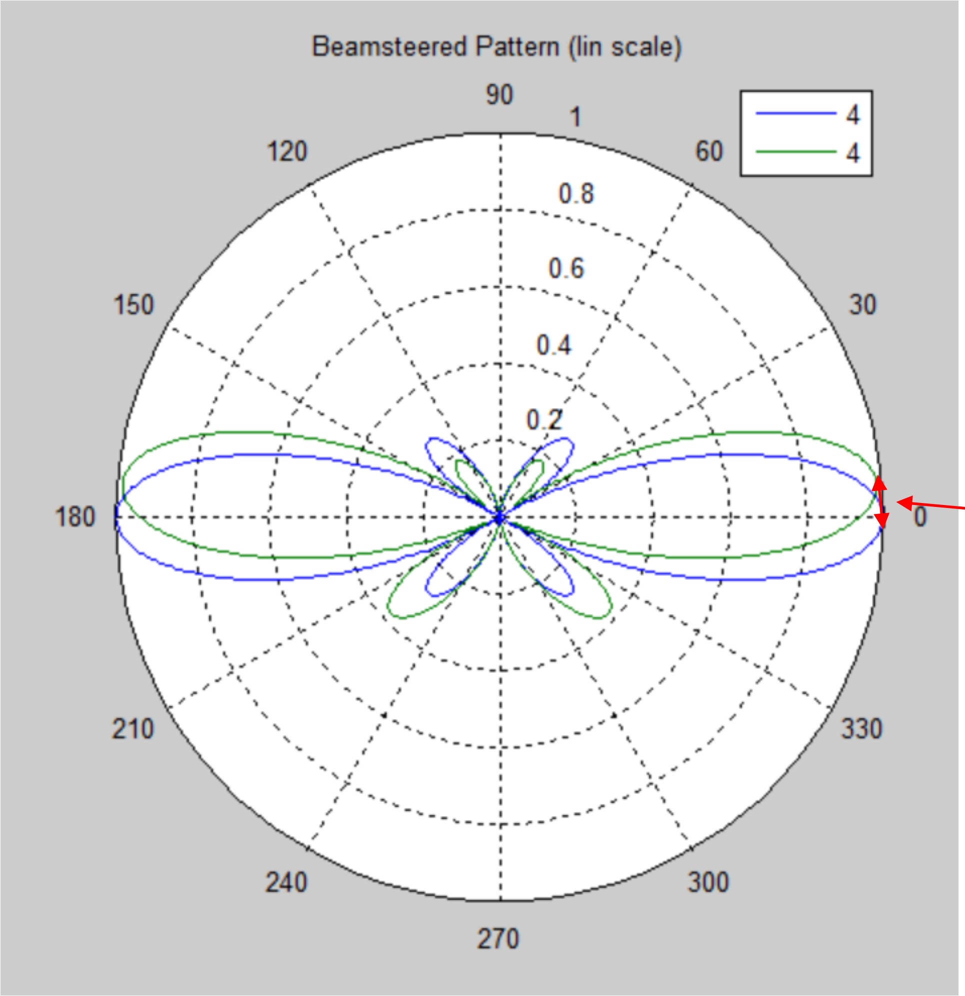
LO Sharing helps to reduce this error (and LO distribution adds to it again)

The Applications

… impacted by phase errors

How Does the Antenna Pattern Change under Phase Error?





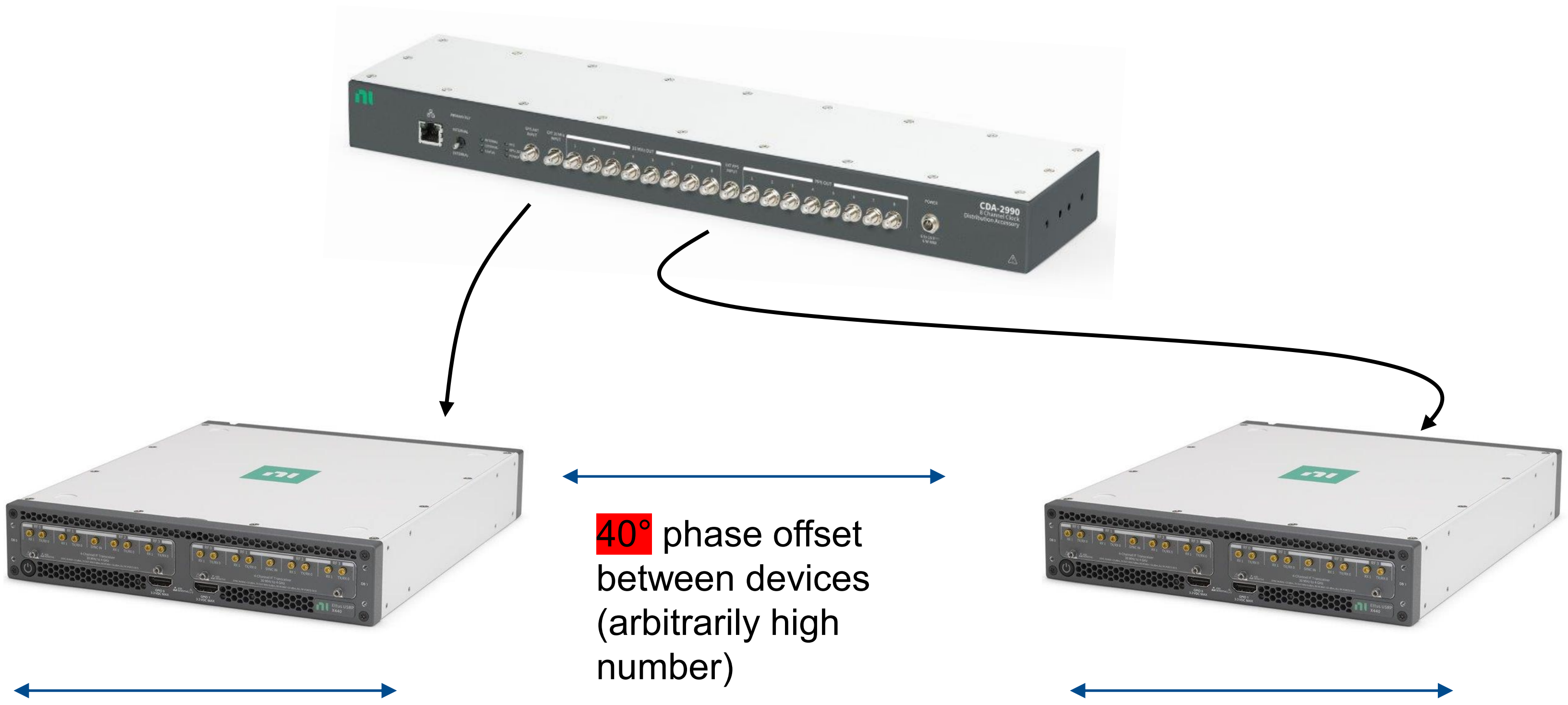
4 antenna ULA, d/λ=1/2

Blue: antenna pattern without phase error

Green: uniformly random distributed phase error within [+-30°]

- Reduced gain
- Beam points in different direction

Mapping Radio Channels to Antennas – Don‘t Care?



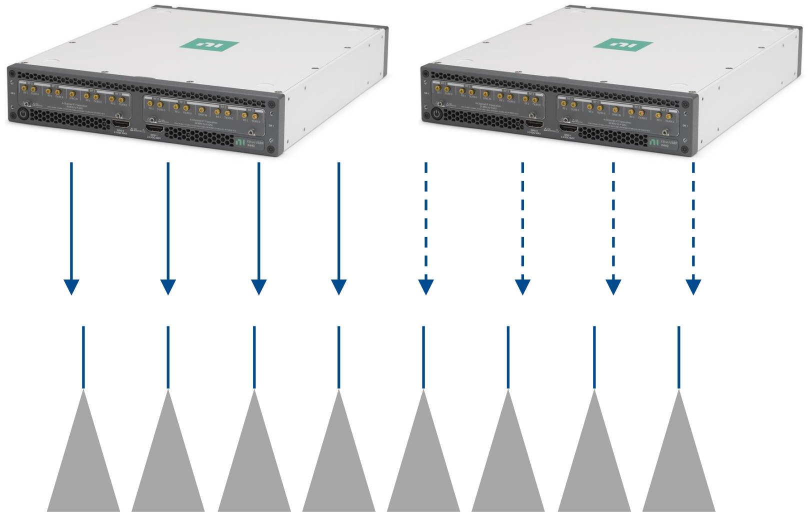
40° phase offset between devices (arbitrarily high number)

No phase offset between channels

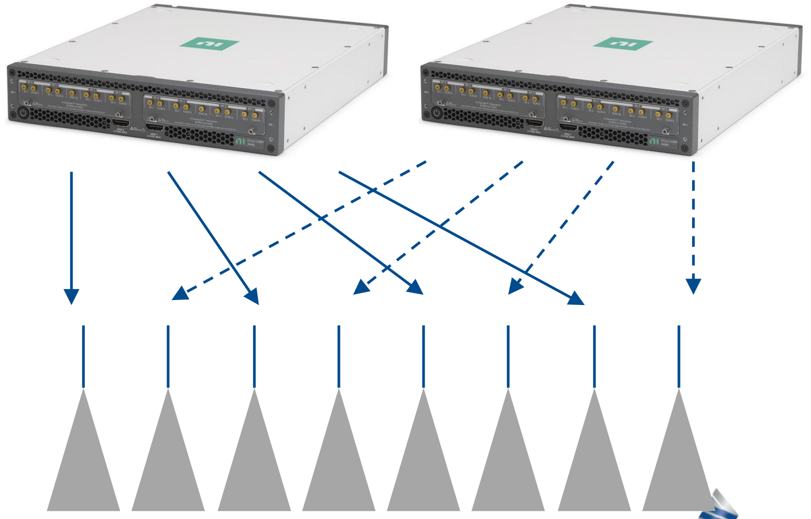
No phase offset between channels

Does it matter how I connect USRP RF ports to antennas in the array?

Block?



Interleaved?



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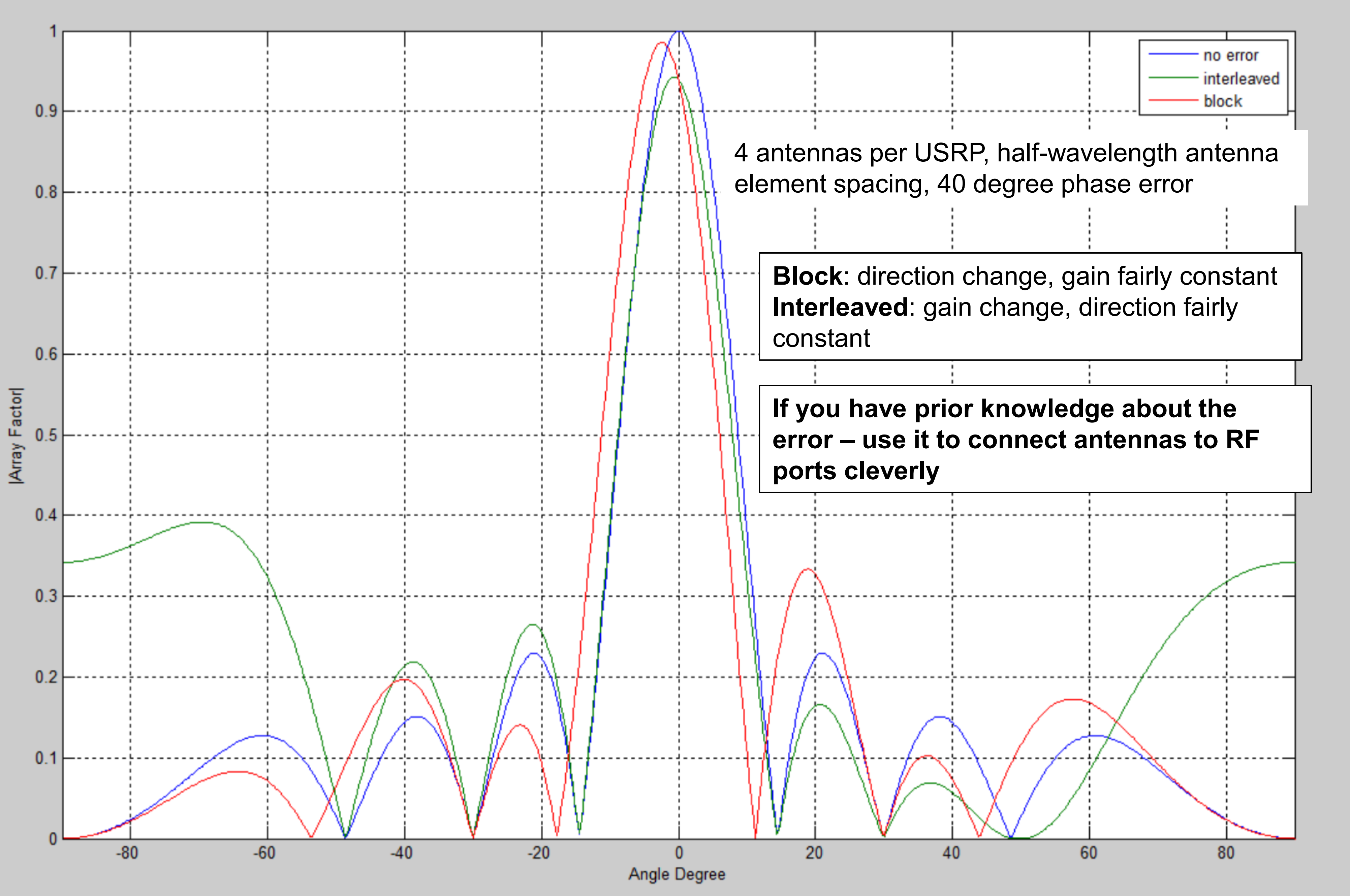
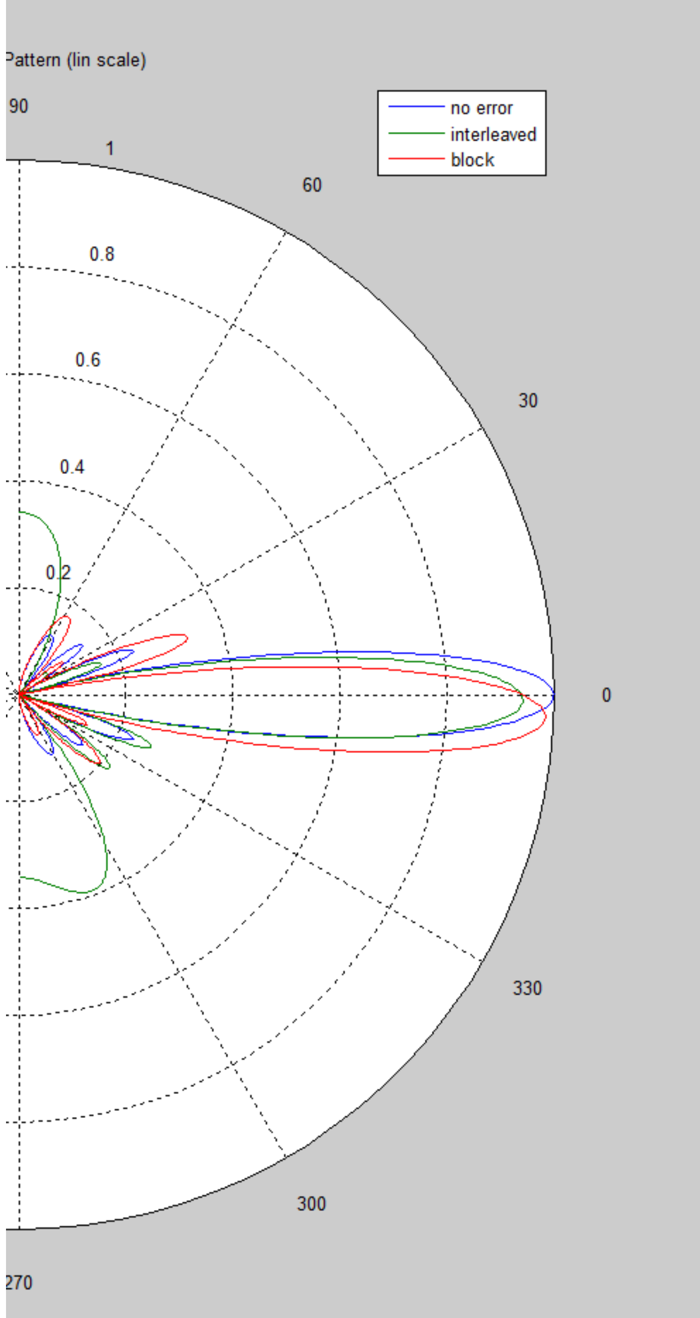
Mapping Radio Channels to Antennas – Don‘t Care?



4 antennas per USRP, half-wavelength antenna element spacing, 40 degree phase error

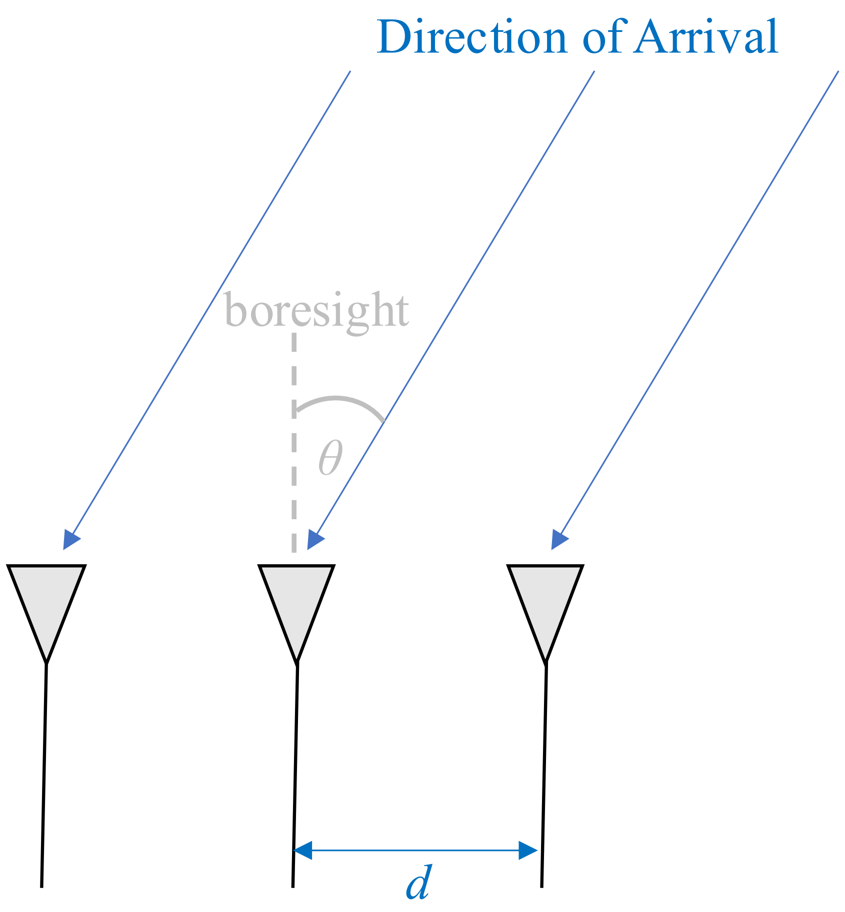
Block: direction change, gain fairly constant
Interleaved: gain change, direction fairly constant

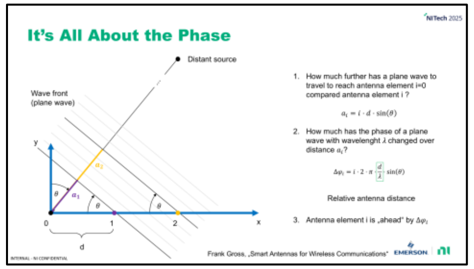
If you have prior knowledge about the error – use it to connect antennas to RF ports cleverly

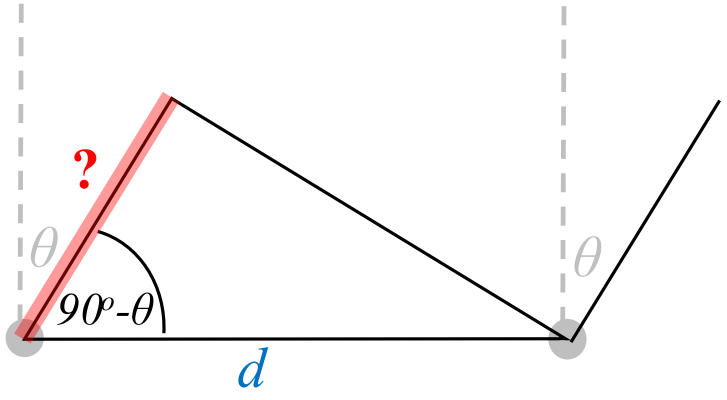


Direction Finding – AoA

AoA (Angle of Arrival): Refers to the direction from which the signal arrives at the receiving antenna array. It is widely used in applications where receivers need to locate transmitters, such as asset tracking or mobile localization.





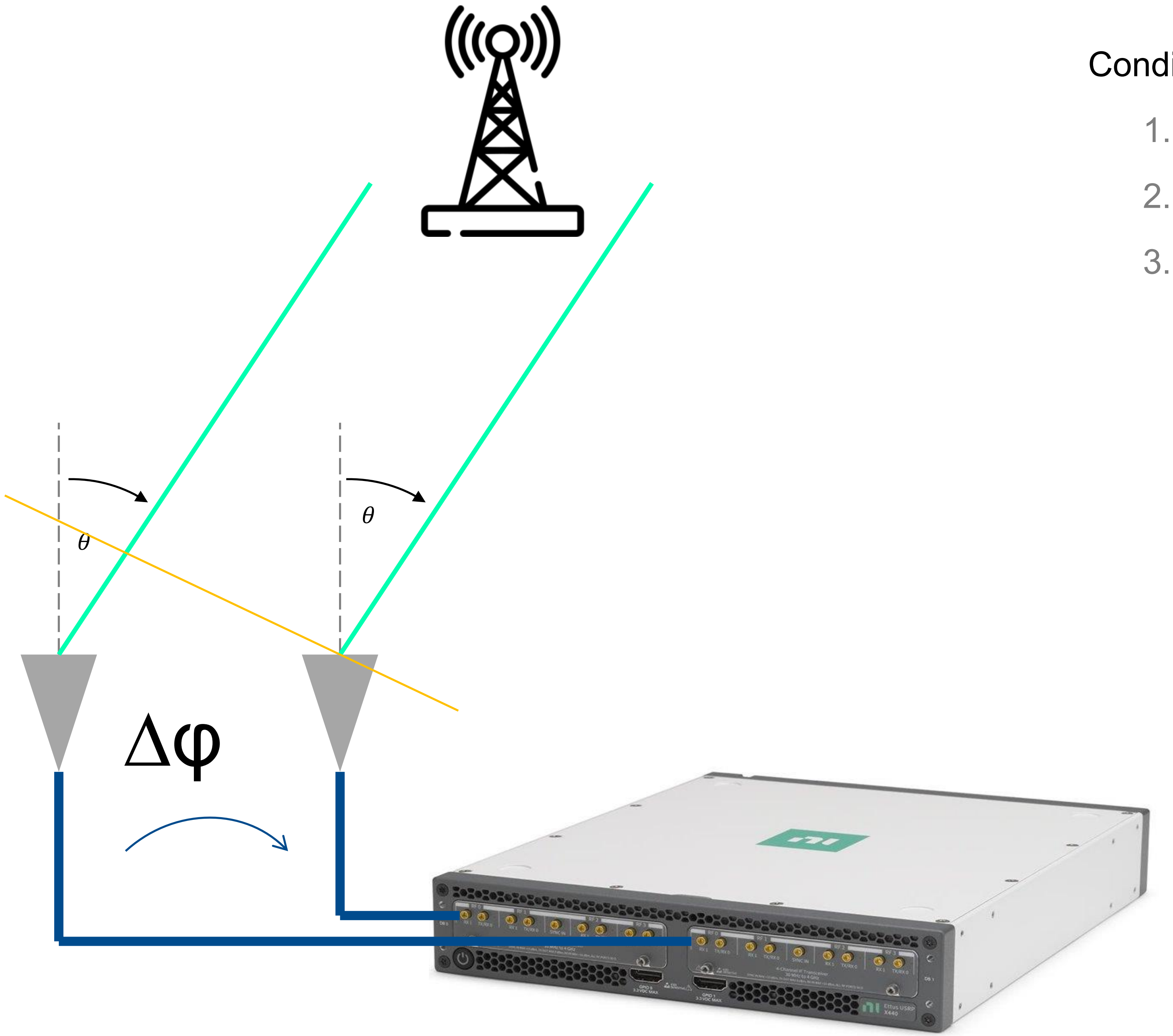


$$d = {}^{d_m}/_{\lambda} : distance\ relative\ to\ \lambda$$

$$d_m : distance\ between\ antennas$$

$$\lambda : wavelength$$

AoA with X440



Conditions:

1. Static Object transmitting CW at fixed frequency and angle
2. X440('s) and 2 Antennas with a relative spacing of d=0.5
3. Focusing on Error introduced by USRP (ignoring all other effects)

Simplified Model
(channel i relative to channel 0):

Common Reference

$\Delta t_{distribution,i}$

$\Delta t_{10M\_cable,i}$

$\Delta t_{channel,i}$

$$\Delta\varphi_{RF,i} = 2 * \pi * f_{RF} * \sum \Delta t_{\ldots,i}$$

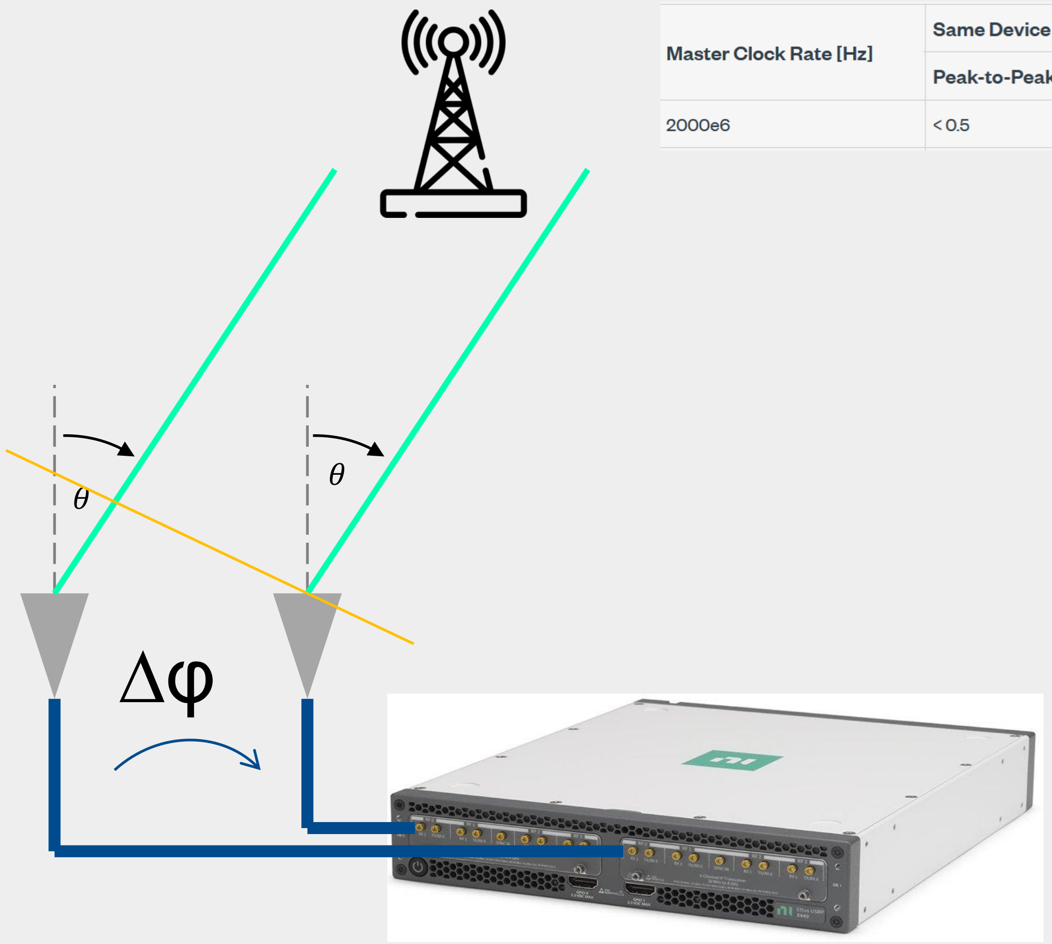
$\Delta\varphi_{RF\_cable,i}$

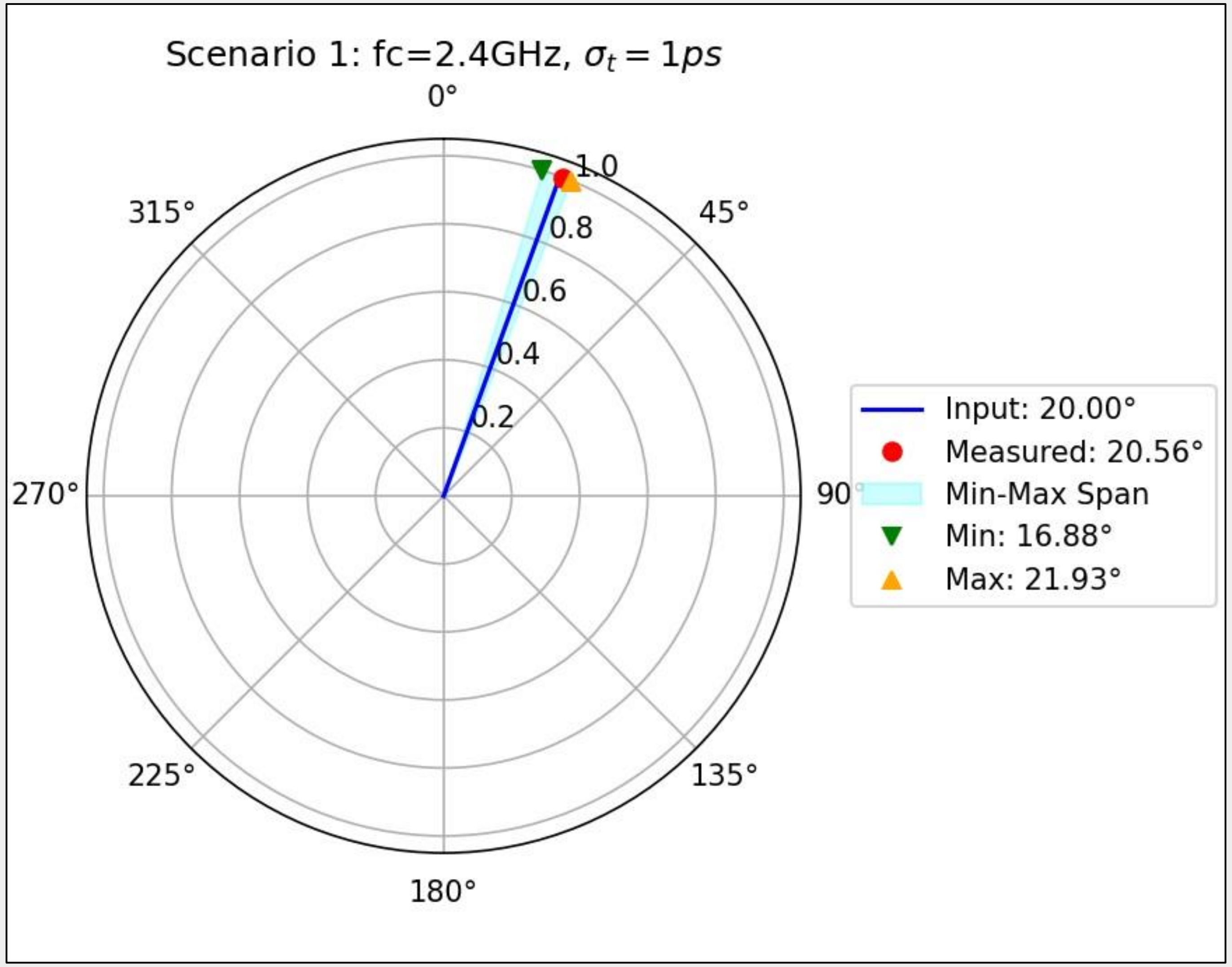
$$\Delta\varphi_{error,i} = \Delta\varphi_{RF,i} + \Delta\varphi_{RF\_cable,i}$$

AoA – How does the USRP impact the Angle?

Single Device

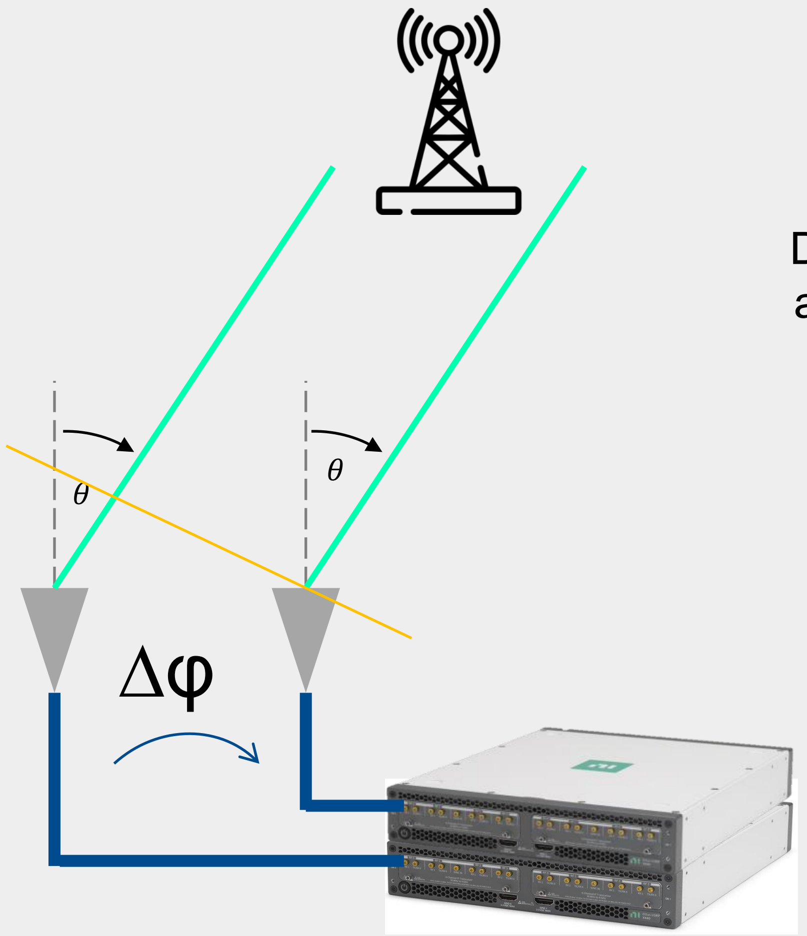
Master Clock Rate [Hz]	Same Device [RX] Peak-to-Peak [deg]
2000e6	< 0.5





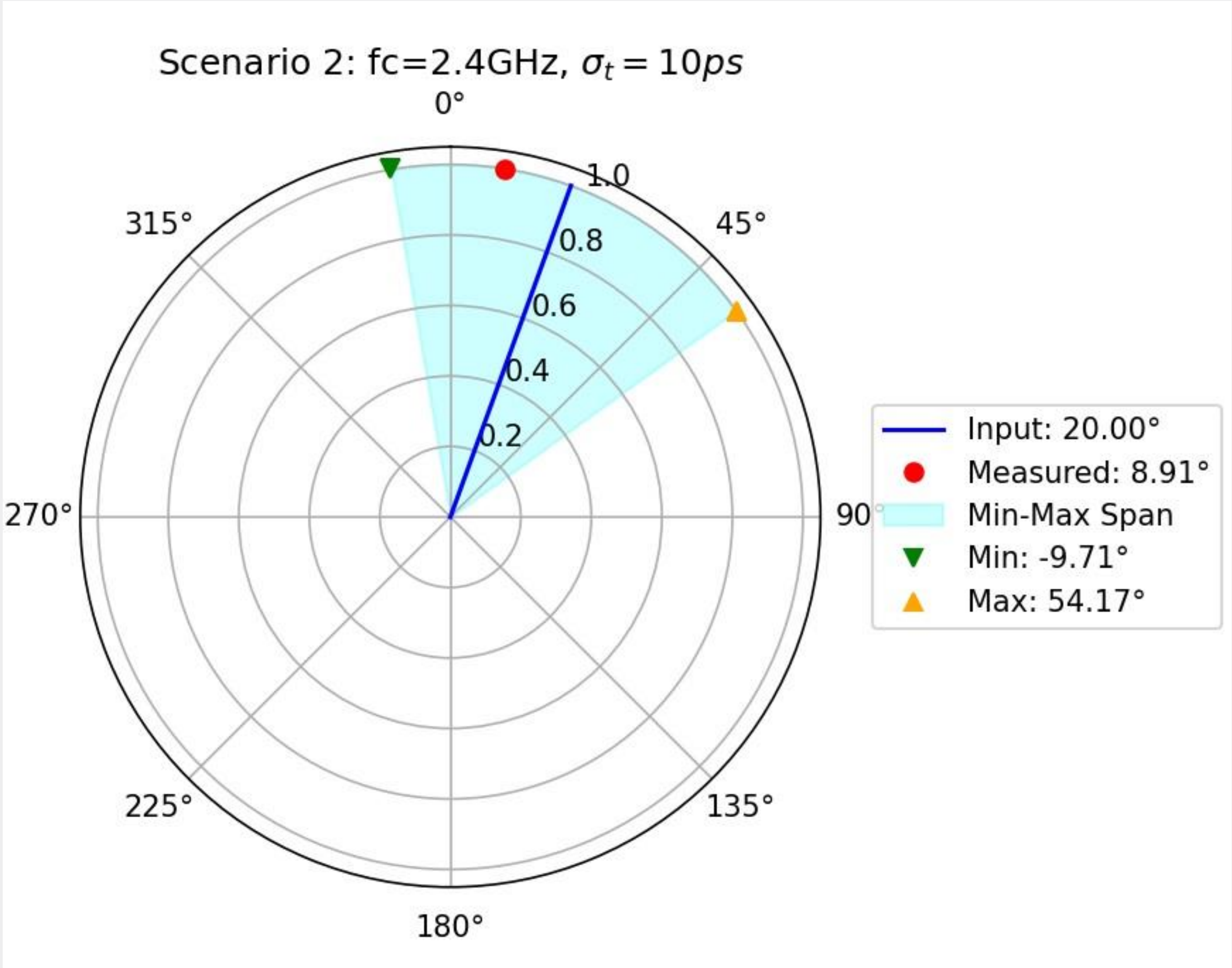
AoA – How does the USRP impact the Angle?

Dual Device



$$\varphi = 2\pi \Delta t f_c$$

Due to HW limitation additional error over devices



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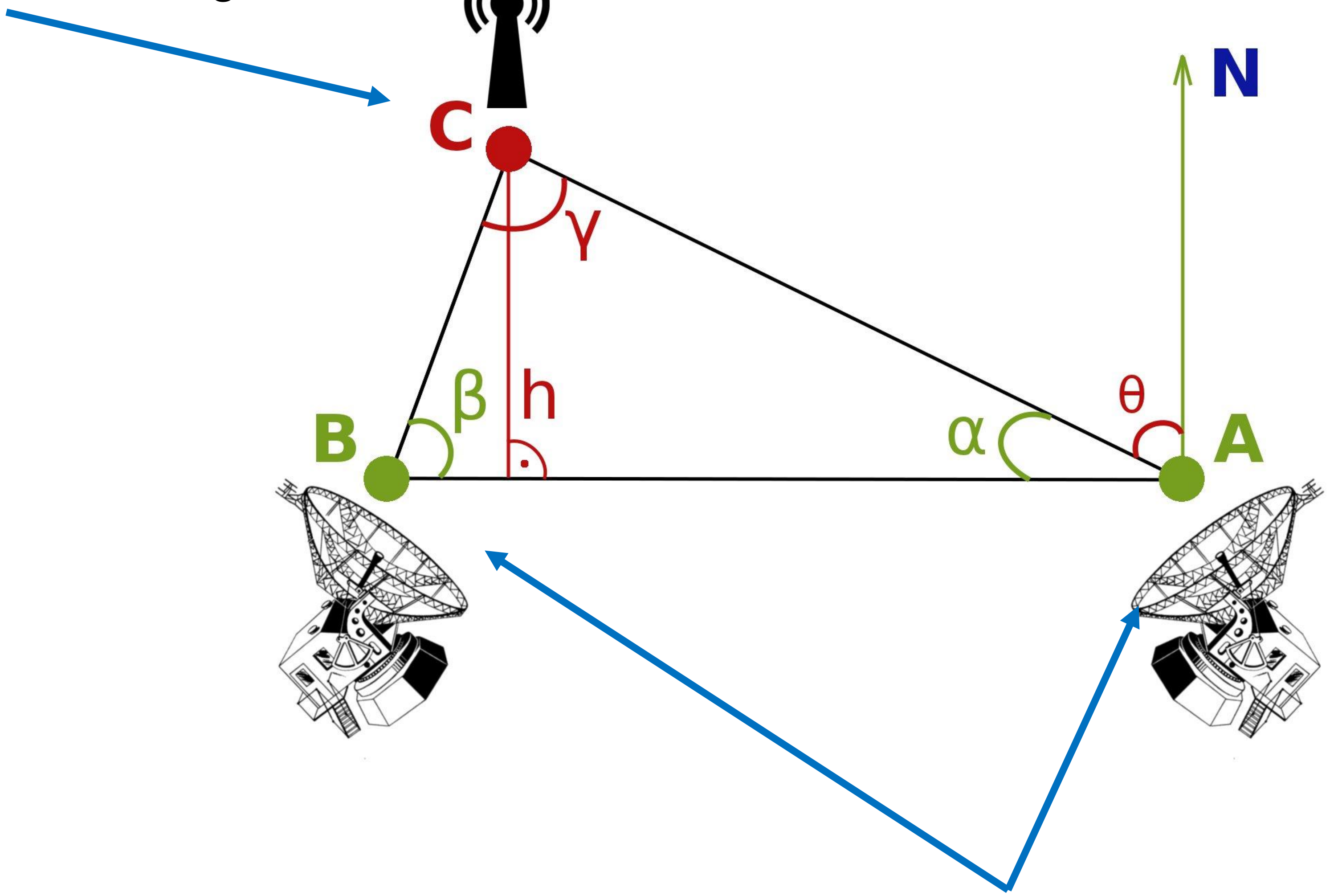
Direction Finding – Triangulation

By **triangulation**, the location of a radio source can be determined by measuring its direction from two or more locations

Intersection of both angles

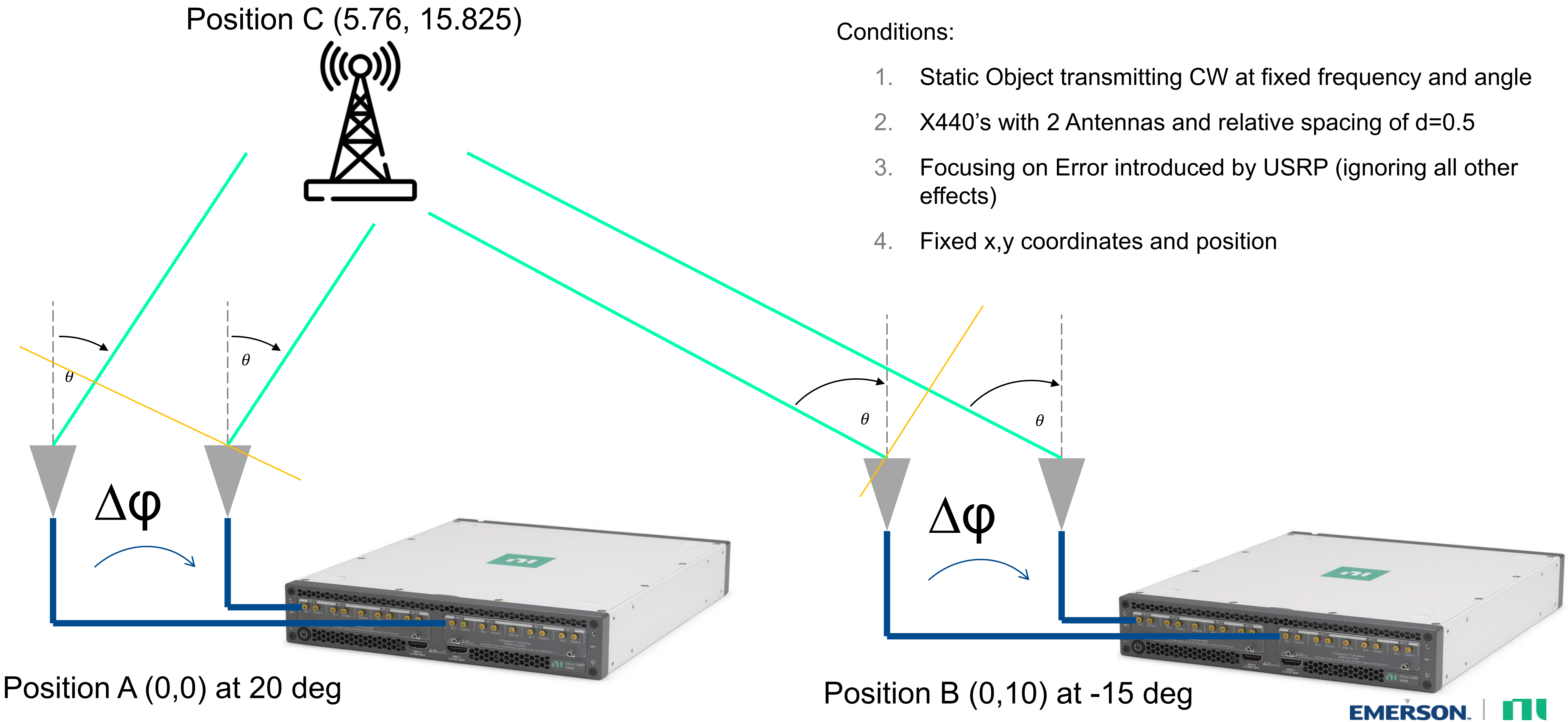


Position A and B coordinates fixed

Triangulation with X440

Conditions:

1. Static Object transmitting CW at fixed frequency and angle
2. X440's with 2 Antennas and relative spacing of d=0.5
3. Focusing on Error introduced by USRP (ignoring all other effects)
4. Fixed x,y coordinates and position



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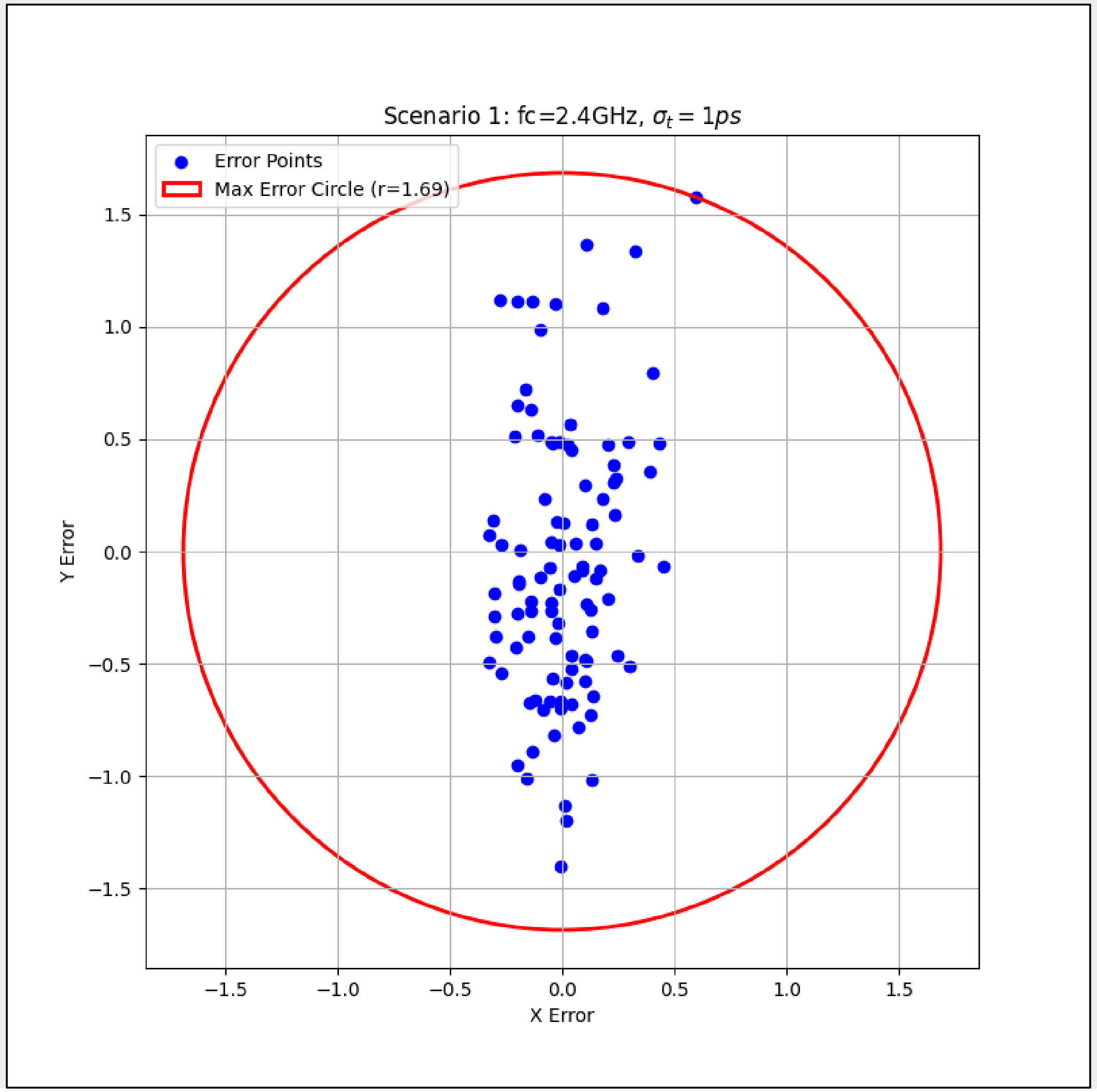
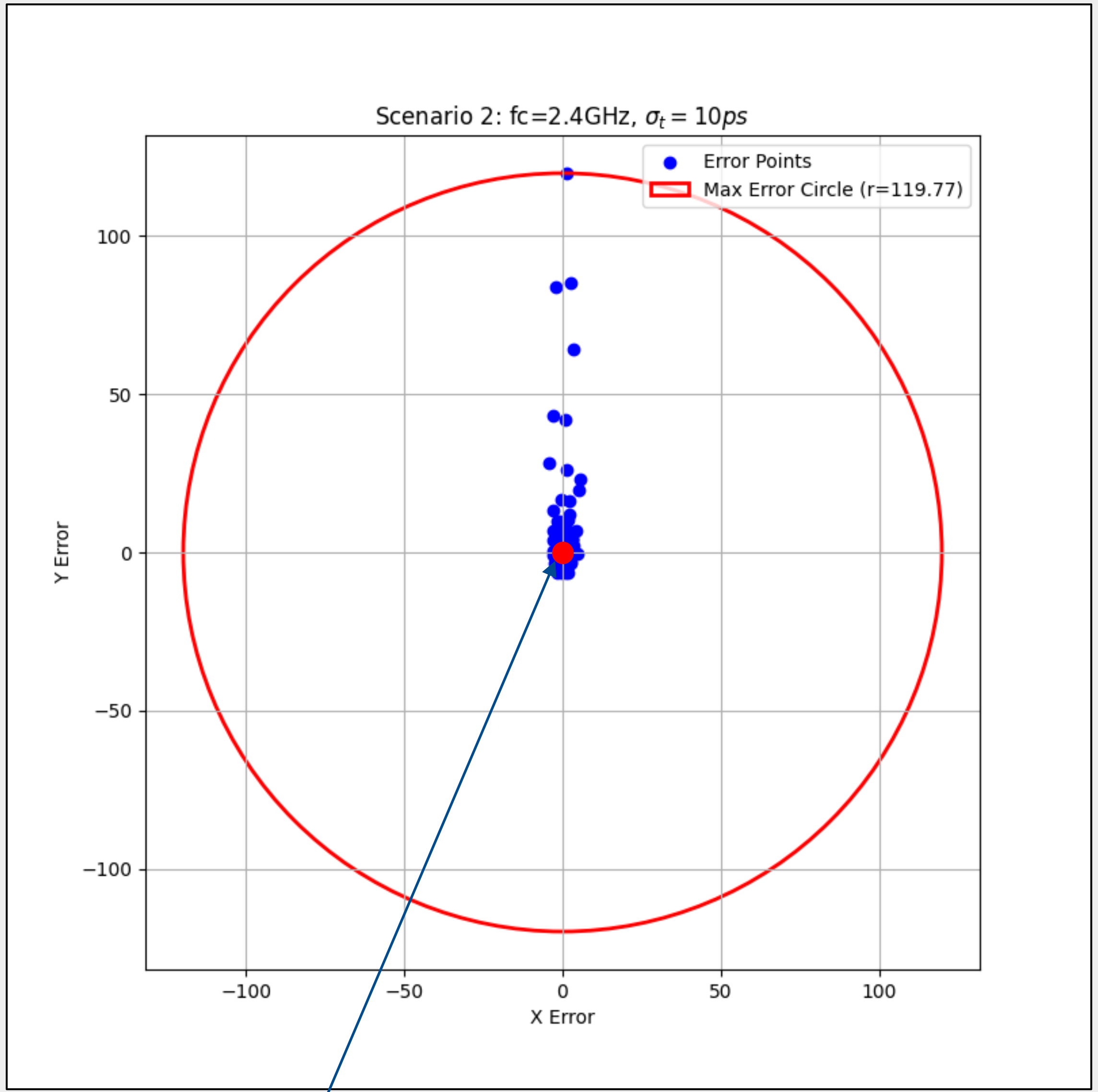
Triangulation – Single Device



Position C (5.76, 15.825)

	Error
Min Error X	-0.3
Max Error X	0.6
Min Error Y	-1.4
Max Error Y	1.6
Max Absolute Error	1.7

Triangulation – Dual Device

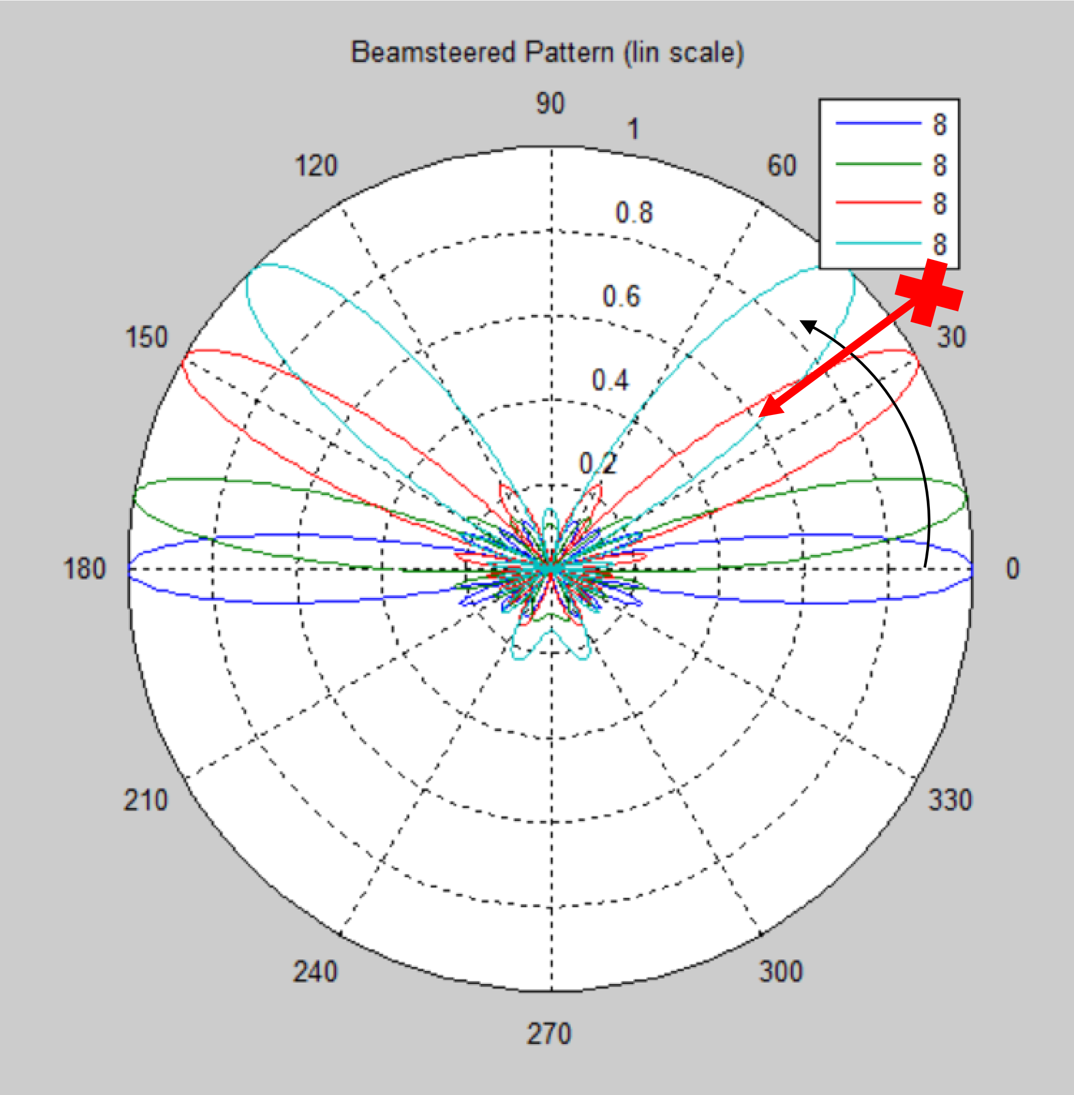


Position C (5.76, 15.825)

	Error
Min Error X	-4.3
Max Error X	5.8
Min Error Y	-6.5
Max Error Y	119.8
Max Absolute Error	119.8

Single Device (Max Error = 1.7)

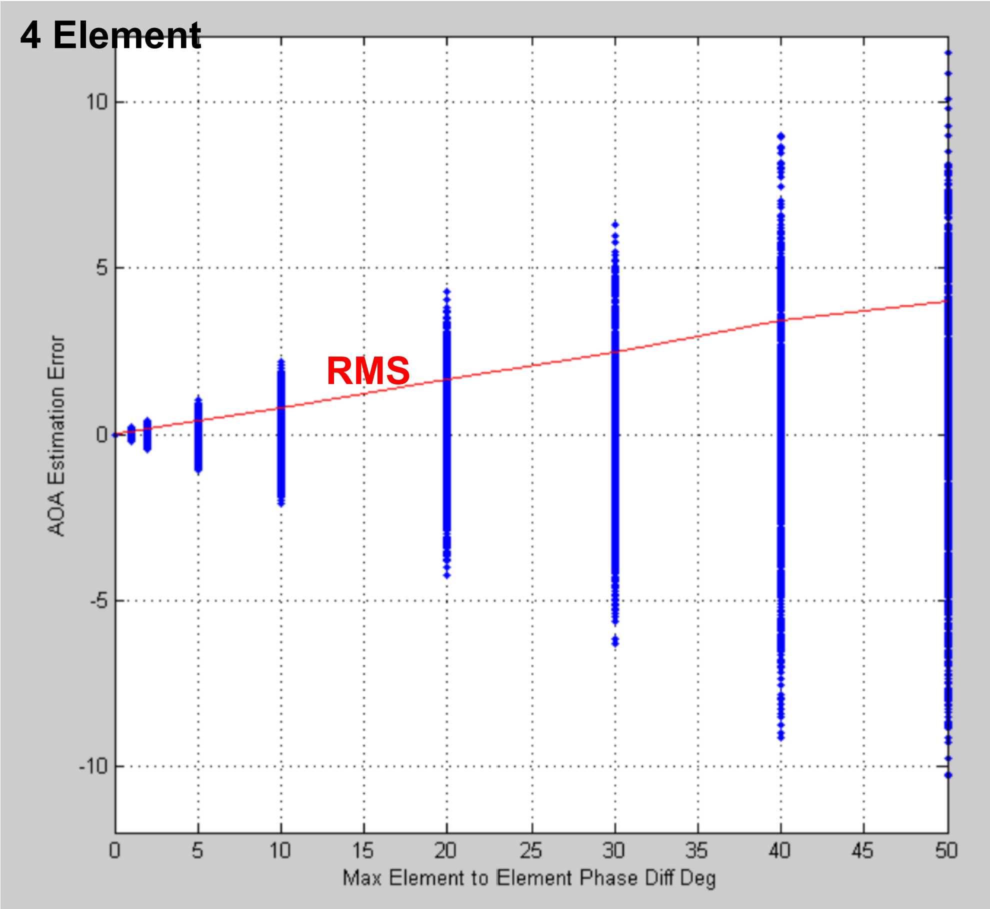
Application: Direction Finding

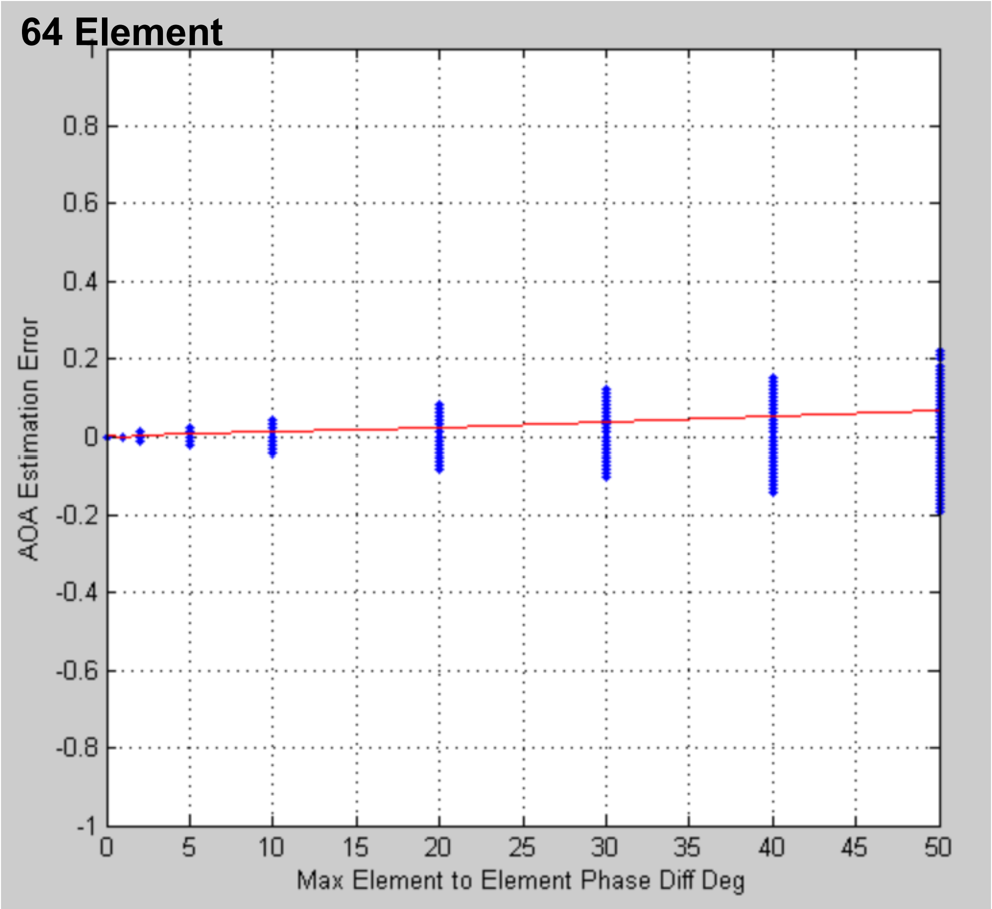


Simplest Algorithm:

- steer the array in all directions
- Declare the steering direction that maximizes the received power to be the estimated AOA
- Phase errors, changing the direction of the main lobe, result in an AOA estimation error

Application: Direction Finding





Phase errors are uniformly random distributed within the range shown on the x-Axis

Incident wave arrives from AOA = 0°

Large arrays can average random phase variations → higher accuracy under error

Application: Cellular Communications

Scenario: an area is covered from a cell tower through a set of predefined, orthogonal beams

- Orthogonal: all other beams have placed nulls in the direction where a certain beam has its maximum

Each beam serves a certain area and a distinct set of users.

Frequency reuse can be possible if beams are orthogonal

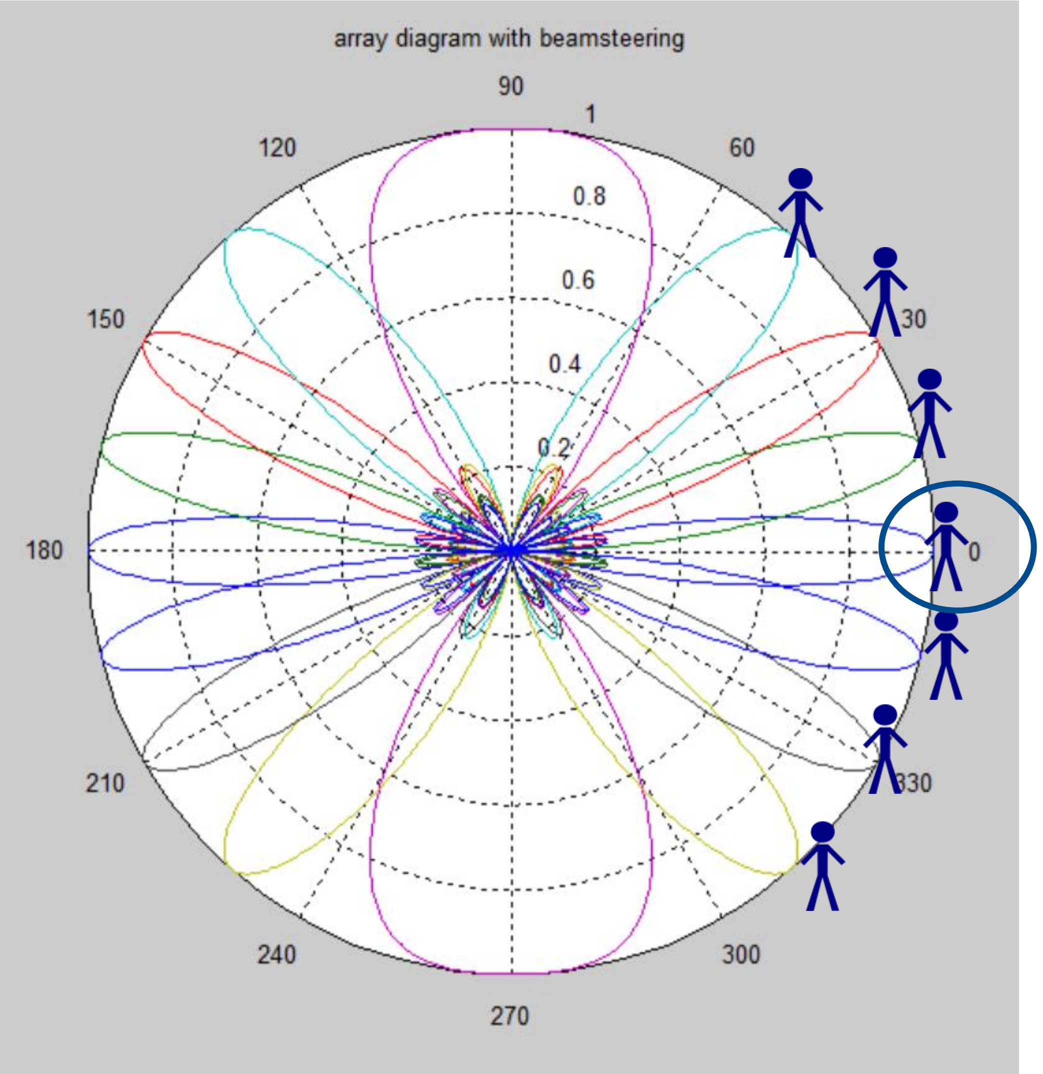
- Frequency reuse: two or more beams using the same frequency

Proxy for numerical evaluation: →

- 8-antenna ULA
- DFT matrix beamformer

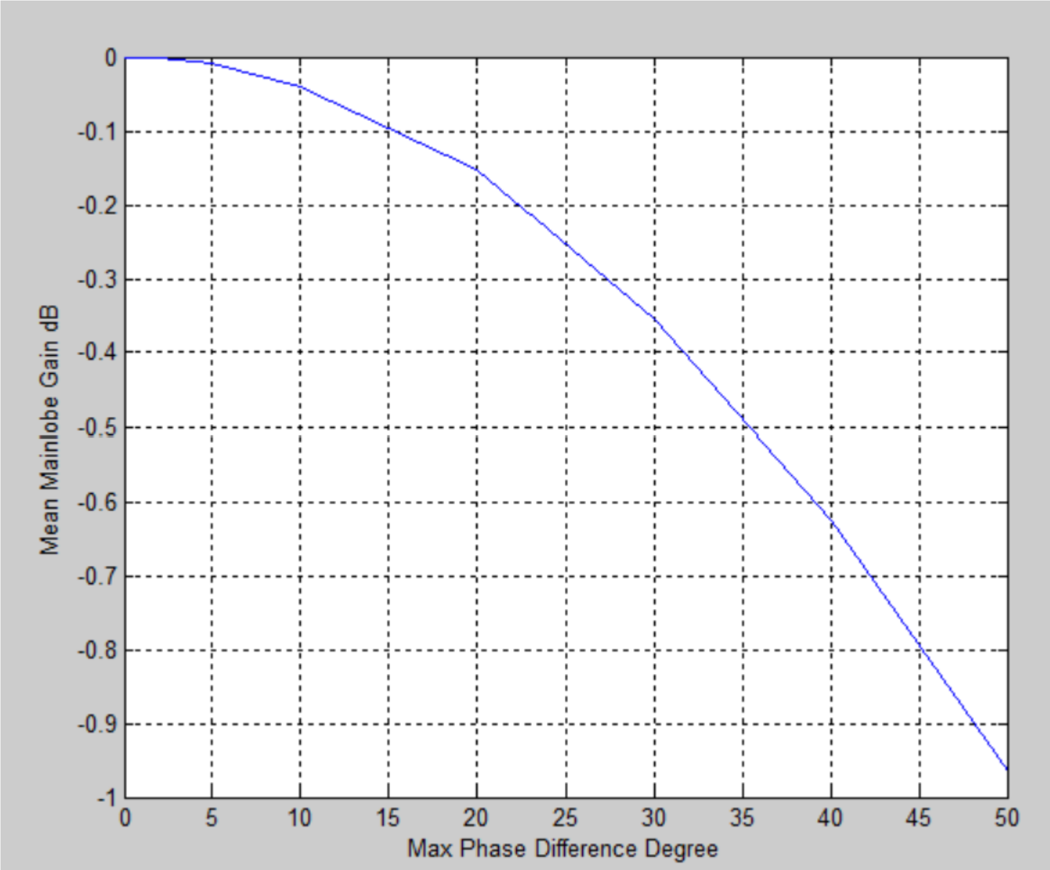
Random phase errors will change {Main lobe, side lobe, Null} direction and power levels. → Next slide

- Uniformly distributed random phase errors

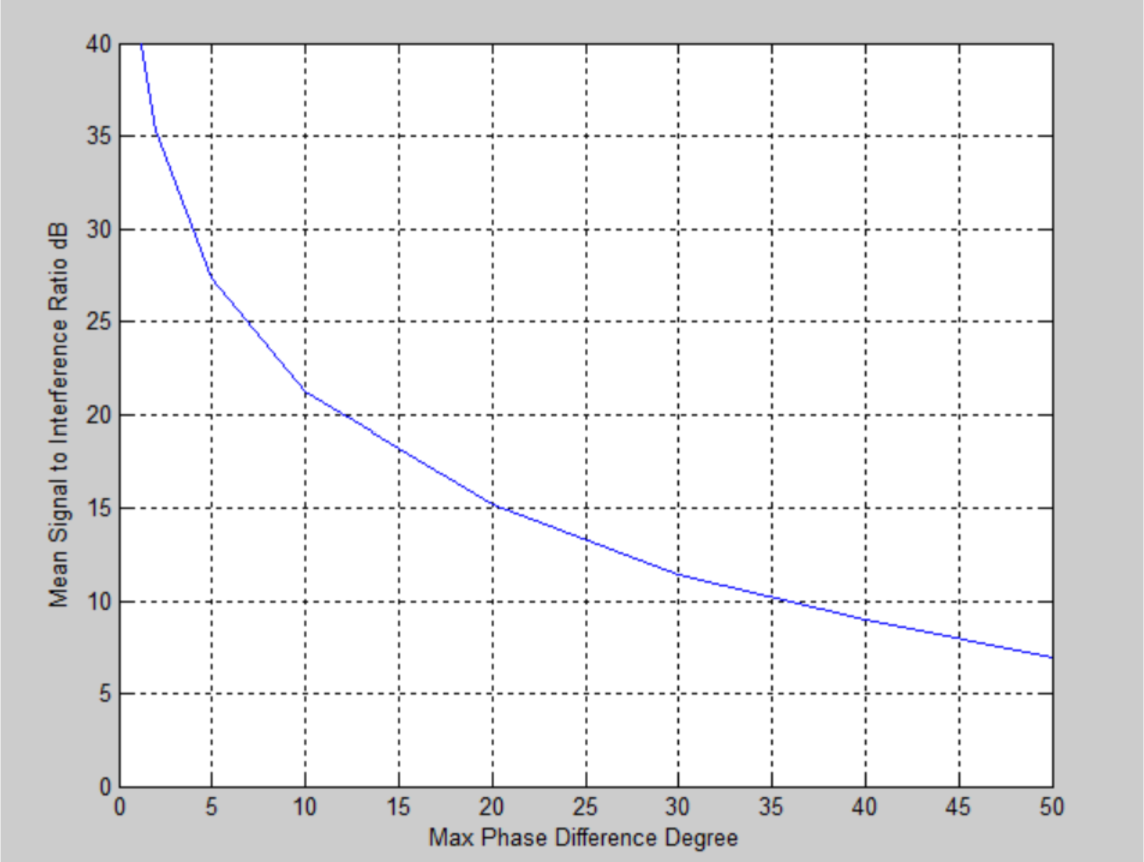


- Each beam serves a different user
- Each beam transmits on the same frequency
- Any user is not interfered by a signal for other users as beams are orthogonal

Application: Cellular Communications



The gain loss of the main lobe is marginal unless phase errors are substantial



The interference* can be substantial, even at small phase errors, limiting frequency reuse

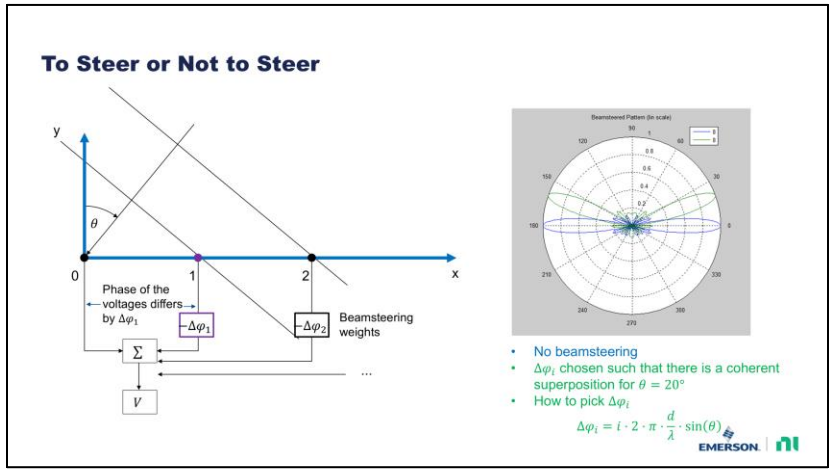
*Interference: contribution of other beams in the main lobe direction of a specific beam. Would be 0 in case there are no phase errors.
Signal: contribution of a specific beam in it's main lobe direction.

The Outro

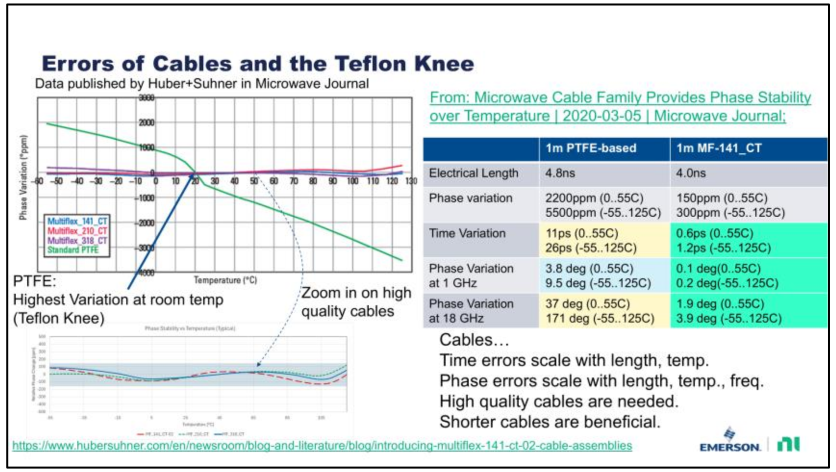
Some news – and take-aways…

From Realistic Models to the Real World

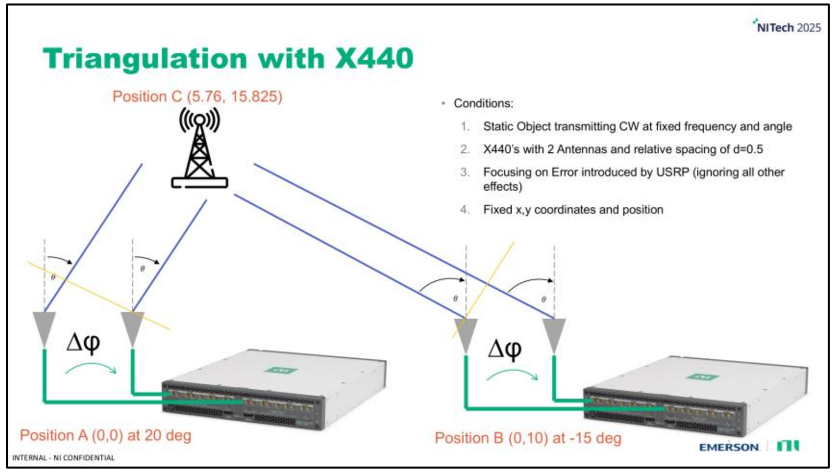
Start with Basics → **Add Errors** → **Go to Prototyping**



Every application has a different set of performance care-abouts



With realistic error terms / models, simulation gets more insightful



Real world complexities (antenna patterns, SNR, movement, …)

Helping with Prototyping – Work-In-Progress – GR-DOA with X440 and Timed Complex Multiplier

Applications and Examples

Update of Direction-Finding Whitepaper using GR-DOA OOT module and Ettus USRP X440

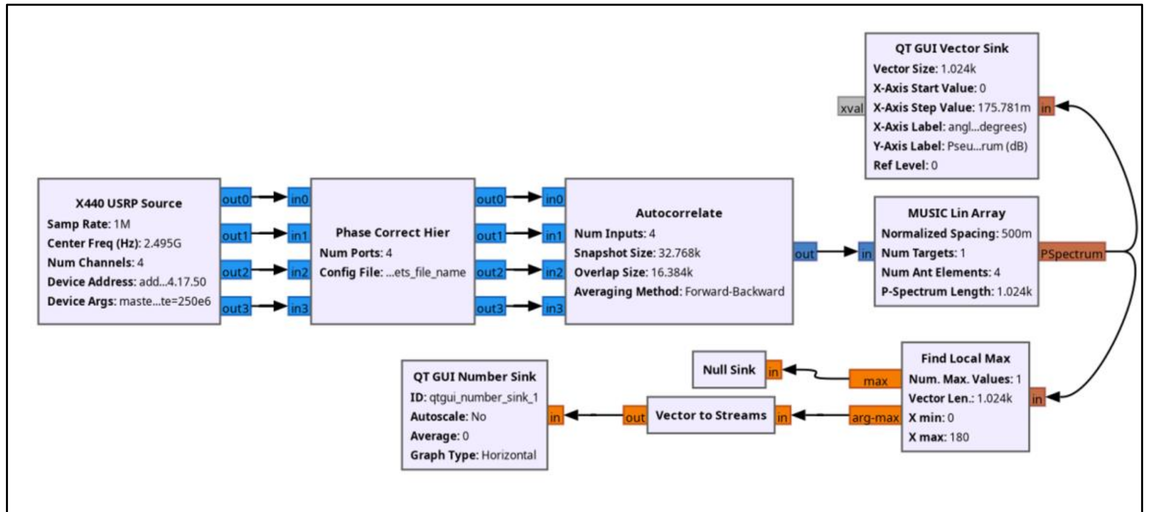
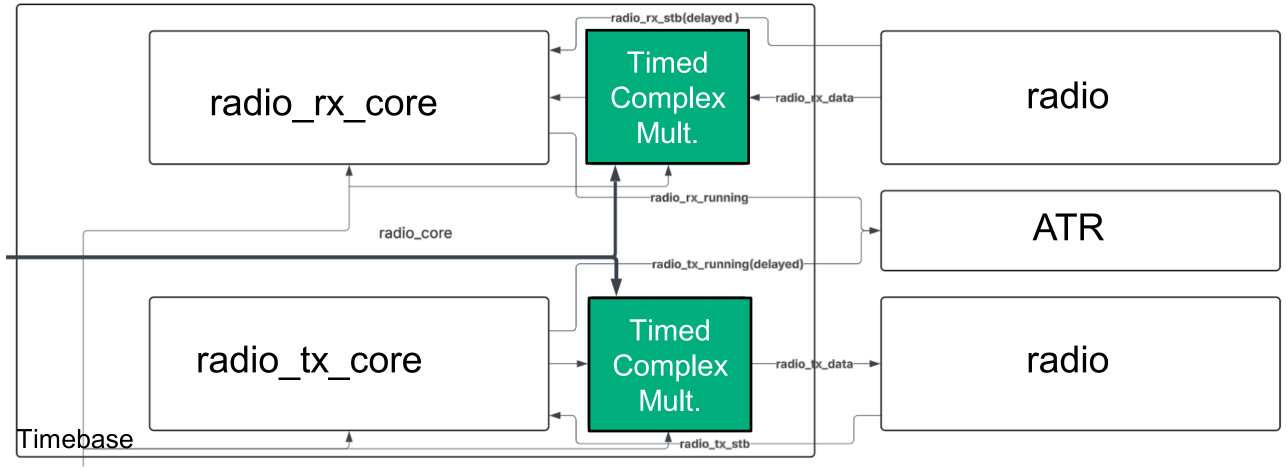


Figure 6: MUSIC DoA Estimation Flowgraph for Linear Antenna Arrays.

Easier getting started by using GNU Radio

USRP Product Feature

Adding a Timed Complex Multiplier to USRP radio block in UHD



Allows:

- Enabler for phase alignment
- Timed adjustment of beam weights

Is 1ps too accurate?
Is it not enough?
It depends.

The end…

…Questions?