EUROPEAN MICROWAVE WEEK
PORTE DE VERSAILLES
PARIS, FRANCE
22-27 SEPT. 2024
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Waves Connecting Europe

EuMA
European Microwave Association

SC-04
Radar Waveform Optimization Mastery

Part 1

Mohammad Alaee
Research Scientist
SPARC - SnT

Part 2

Robin Amar
Doctoral researcher
SPARC - SnT

Part 3

Linlong Wu
Research Scientist
SPARC - SnT

Part 4

Bhavani Shankar
Assistant Professor
Head of SPARC - SnT

https://www.uni.lu/snt-en/research-groups/sparc/
https://radarmimo.com/

Acknowledgement

uni.lu | SnT

Signal Processing Applications in Radar and Communications (SPARC)

Luxembourg National Research Fund

a sense for innovation IEE

Outline

Part 1: Classical Waveforms in SISO, Phased Array and MIMO Radars.

Part 2: MIMO Radar Waveform Multiplexing Techniques

Part 3: A Glimpse of Optimization on Radar Waveform Design

Part 4: Waveform Design beyond Classical Sensing

Part 1

Classical Waveforms in SISO, Phased Array and MIMO Radars

Radar Classification

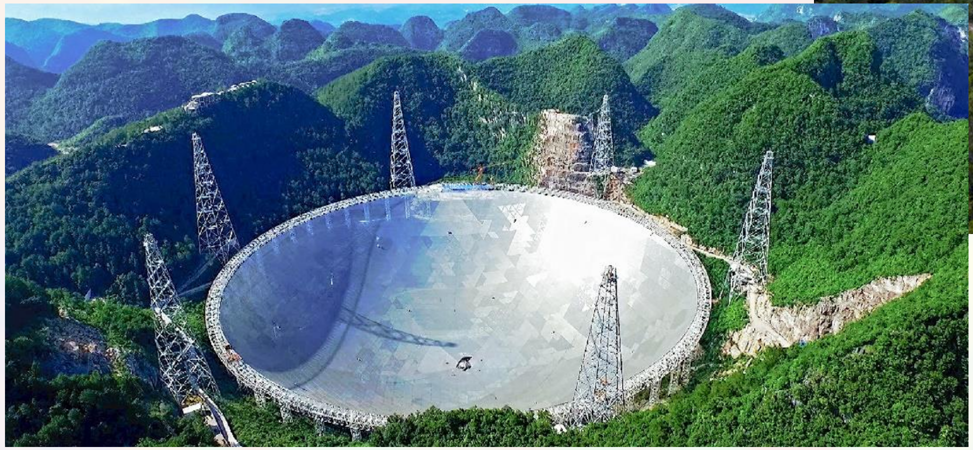
- **Frequency**
  - HF/ VHF Band
  - L Band
  - S Band
  - C Band
  - X Band
  - Ku, K, Ka Band
- **Waveform**
  - Un/modulated Pulse Radar
  - Un/modulated CW
  - OFDM/OTFS
  - Noise Radar
- **Applications**
  - Surveillance (Ground, Air, Sea) / Tracking
  - SAR/ Airborne
  - Weather
  - Automotive / Industry/ Health
  - Space
- **Type**
  - Primary
  - Secondary
- **Operation**
  - Active
  - Passive
- **Antenna Scan**
  - Mechanical
  - Phased Array / Digital Beamforming
  - MIMO
- **Geo Location**
  - Mono-static
  - Bi-static
  - Multi-static
- **Polarization**
  - Vertical
  - Horizontal
  - Circular
  - Dual Polarized

Space observation

The observatory's main instrument was the Arecibo Telescope, a 305 m (1,000 ft) spherical reflector dish built into a natural sinkhole, with a cable-mount steerable receiver and several radar transmitters for emitting signals mounted 150 m (492 ft) above the dish. Completed in 1963, it was the world's largest single-aperture telescope for 53 years, surpassed in July 2016 by the Five-hundred-meter Aperture Spherical Telescope (FAST) in China.

FAST has a 500 m (1,600 ft) diameter dish constructed in a natural depression in the landscape. It is the world's largest filled-aperture radio telescope[2] and the second-largest single-dish aperture, after the sparsely-filled RATAN-600 in Russia.[3][4]

https://en.wikipedia.org/wiki/Arecibo_Observatory



https://en.wikipedia.org/wiki/Five-hundred-meter_Aperture_Spherical_Telescope

Airport Surveillance Radar (ASR)

An **airport surveillance radar (ASR)** is a radar system used at airports to detect and display the presence and position of aircraft in the *terminal area*, the airspace around airports. It is the main air traffic control system for the airspace around airports. At large airports it typically controls traffic within a radius of 60 miles (96 km) of the airport below an elevation of 25,000 feet.

The primary radar typically consists of a large rotating parabolic antenna dish that sweeps a vertical fan-shaped beam of microwaves around the airspace surrounding the airport.

The secondary surveillance radar consists of a second rotating antenna, often mounted on the primary antenna, which interrogates the transponders of aircraft, which transmits a radio signal back containing the aircraft's identification, barometric altitude, and an emergency status code, which is displayed on the radar screen next to the return from the primary radar.

https://en.wikipedia.org/wiki/Airport_surveillance_radar

Marine radars

Marine radars are X band or S band radars on ships, used to detect other ships and land obstacles, to provide bearing and distance for collision avoidance and navigation at sea.

They are electronic navigation instruments that use a rotating antenna to sweep a narrow beam of microwaves around the water surface surrounding the ship to the horizon, detecting targets by microwaves reflected from them, generating a picture of the ship's surroundings on a display screen.

FAR-2318X-band, 12 kW, TR up
FAR-2328X-band, 25 kW, TR up
FAR-2328WX-band, 25 kW, TR down
FAR-2328-NXTX-band, 600W, TR up, Solid State

https://www.radioholland.com/product/furuno-far-23x8-marine-radar/

Animation of typical rotating X band marine radar antenna on ship. It radiates a narrow vertical fan-shaped beam of microwaves perpendicular to the long axis of the antenna, horizontally out to the horizon. With each rotation the beam scans the surrounding surface. Any ships or obstructions reflect microwaves back to the antenna, displaying on the radar screen.

https://en.wikipedia.org/wiki/Marine_radar

Airborne Warning And Control System

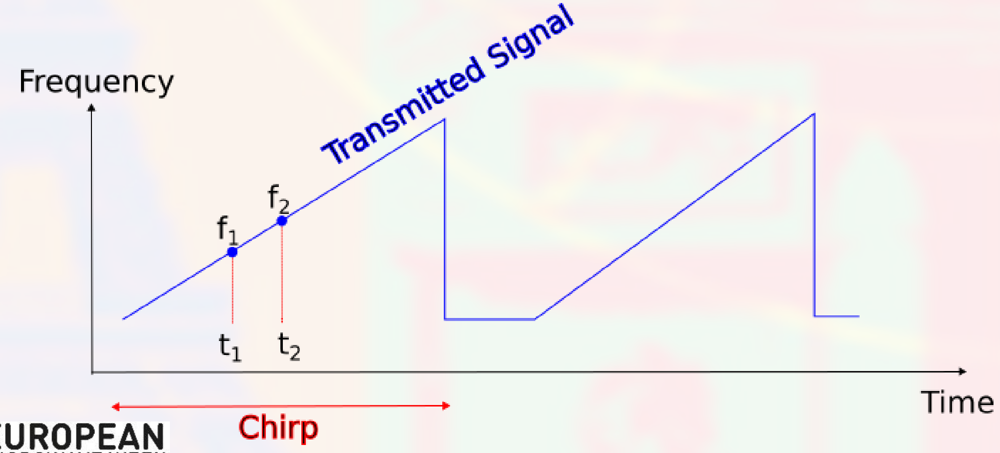
AWACS, abbreviation **of Airborne Warning And Control System**, a mobile, long-range radar surveillance and control center for air defense. The system, as developed by the U.S. Air Force, is mounted in a specially modified Boeing 707 aircraft.

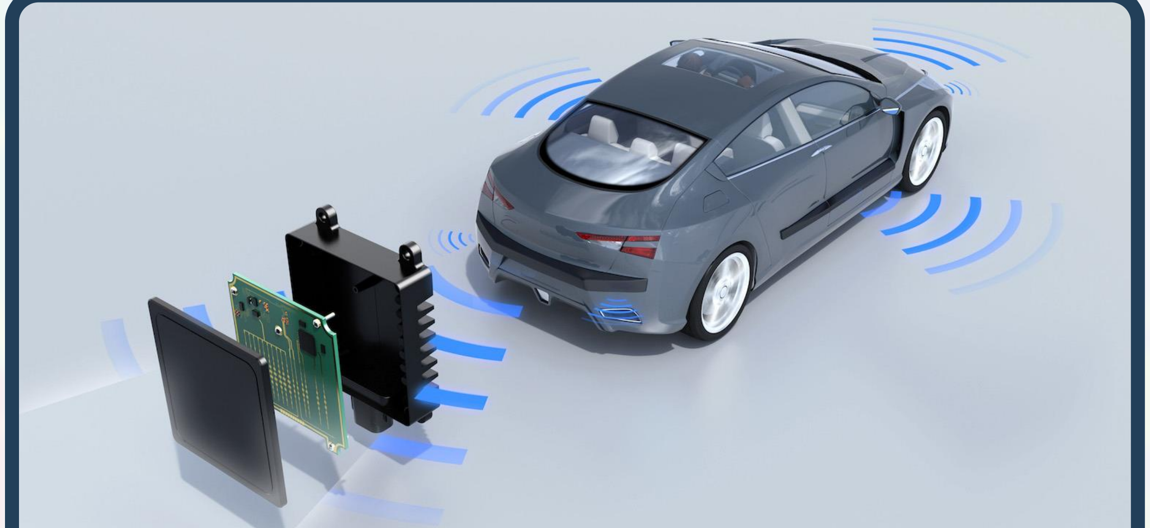
Its main radar antenna is mounted on a turntable housed in a circular rotodome 9 m (30 feet) in diameter, elliptical in cross-section, and 1.8 m deep at its centre. The radar system can detect, track, and identify low-flying aircraft at a distance of 370 km (200 nautical miles) and high-level targets at much greater distances. It also can track maritime traffic, and it operates in any weather over any terrain. An airborne computer can assess enemy action and keep track of the location and availability of any aircraft within range. The communications system, enabling the control of friendly aircraft in pursuit of enemy planes, operates over a single channel, secure from enemy interception, that is also relatively immune to jamming because of its high speed.

https://www.britannica.com/technology/AWACS

Automotive Radar

- ✓ Operating in mmWave (60GHz, and 79 GHz)
- ✓ More than 5GHz bandwidth
- ✓ Radar on chip (ROC)
- ✓ MIMO capabilities
- ✓ 4D Imaging Automotive MIMO Radars





https://h2tc.com.vn/en/product/radar-sensors/

Today's automotive radars enable the following ADAS capabilities:

- adaptive cruise control (ACC)
- lane change assistance
- collision avoidance
- emergency braking
- blind spot detection

What we cover in this short course

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Frequency
- HF/ VHF Band
- L Band
- S Band
- C Band
- X Band
- Ku, K, Ka Band

Waveform
- Unmodulated Pulse Radar
- Modulated Pulse Radar
- Unmodulated CW
- Modulated CW Radar
- OFDM/OTFS
- Noise Radar

Applications
- Surveillance (Ground, Air, Sea) / Tracking
- SAR/ Airborne
- Weather
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- Space

Type
- Primary
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Operation
- Active
- Passive

Antenna Scan
- Mechanical
- Phased Array / Digital Beamforming
- MIMO

Geo Location
- Mono-static
- Bi-static
- Multi-static

Polarization
- Vertical
- Horizontal
- Circular
- Dual Polarized

We address in this course

The assumption

We are not covering in this course

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Frequency

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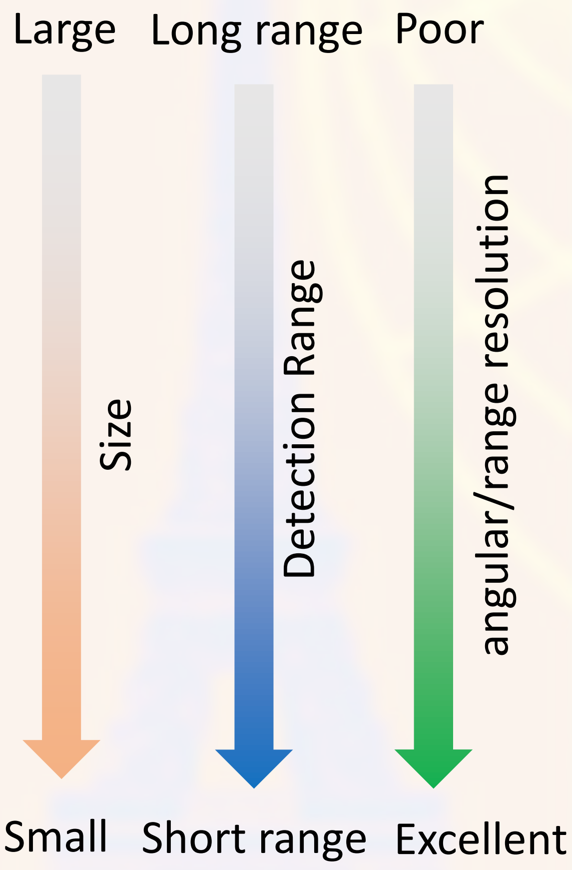

Radar Band	Operating Frequency
HF	3 – 30 MHz
VHF	30 – 300 MHz
UHF	300 – 1000 MHz
L	1 – 2 GHz
S	2 -4 GHz
C	4 – 8 GHz
X	8 – 12 GHz
Ku	12 – 18 GHz
Ka	27 – 40 GHz
mm (V & W)	40 – 300 GHz

Early warning
Long Range Air Surveillance

Ground/Air Surveillance
Weather Radar

SAR/GMTI
Air to Air

Automotive
Smart buildings / IoT Devices

Waveform

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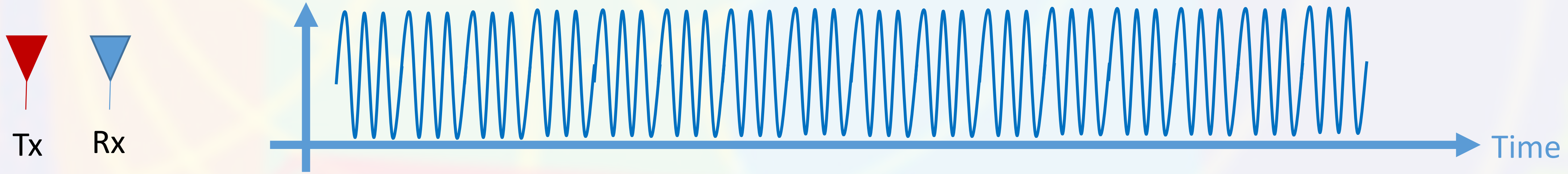
Unmodulated CW



Unmodulated Pulse Radar

$$\text{Bandwidth} \approx \frac{1}{T_p} \quad \Rightarrow \quad \text{Time} \times \text{Bandwidth} \approx 1$$

Waveform Modulation or Pulse Compression

- Higher average power is proportional to pulse width
- Better resolution is inversely proportional to pulse width

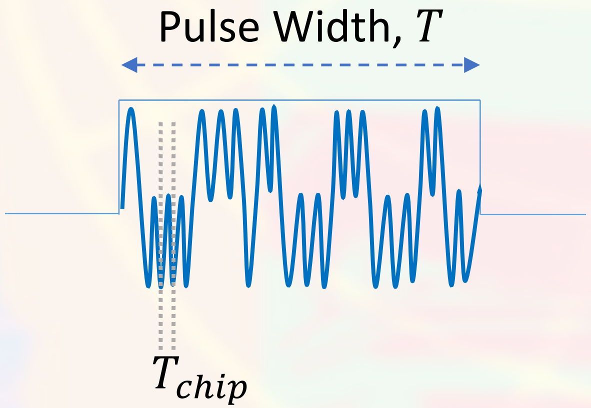
A long pulse can have the same bandwidth (resolution) as a short pulse if the long pulse be modulated with a "waveform"

energy of a long pulse + resolution of a short pulse

Time × Bandwidth ≫ 1

Pulse Compression (intra-pulse modulation)

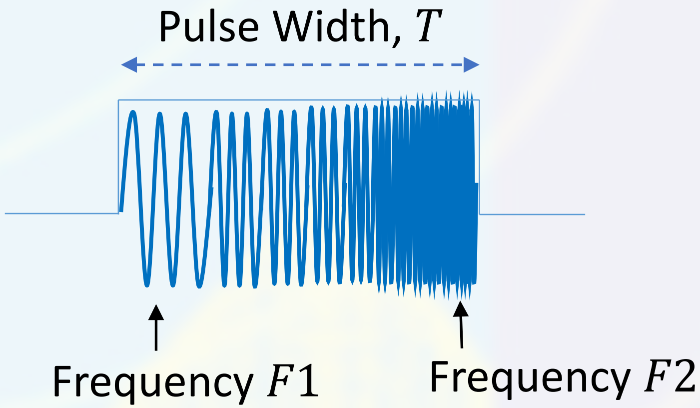
Phase Modulated Waveform



Bandwidth = $\frac{1}{T_{chip}}$

Time × Bandwidth = $\frac{\mathrm{T}}{T_{chip}}$

Frequency Modulated Waveform



Bandwidth = $\Delta F = F2 - F1$

Time × Bandwidth = $T \times \Delta F$

Why not using amplitude modulation?

Pulse Compression (intra-pulse modulation)

Time-Bandwidth Product

$$\boxed{SNR_{pc} = SNR_u \times \; (T \times B)}$$

SNR_{pc} is the signal-to-noise ratio for a modulated (pulse compression) pulse.
SNR_u is the signal-to-noise ratio for an unmodulated pulse.
T is the pulse length.
B is the pulse modulation bandwidth

$$SNR_u = \frac{P_t \, G_t G_r \lambda^2 n_p \sigma}{(4\pi)^3 k \; T_0 F_n B_n L_s R^4}$$

If $T \times B = N \Rightarrow$

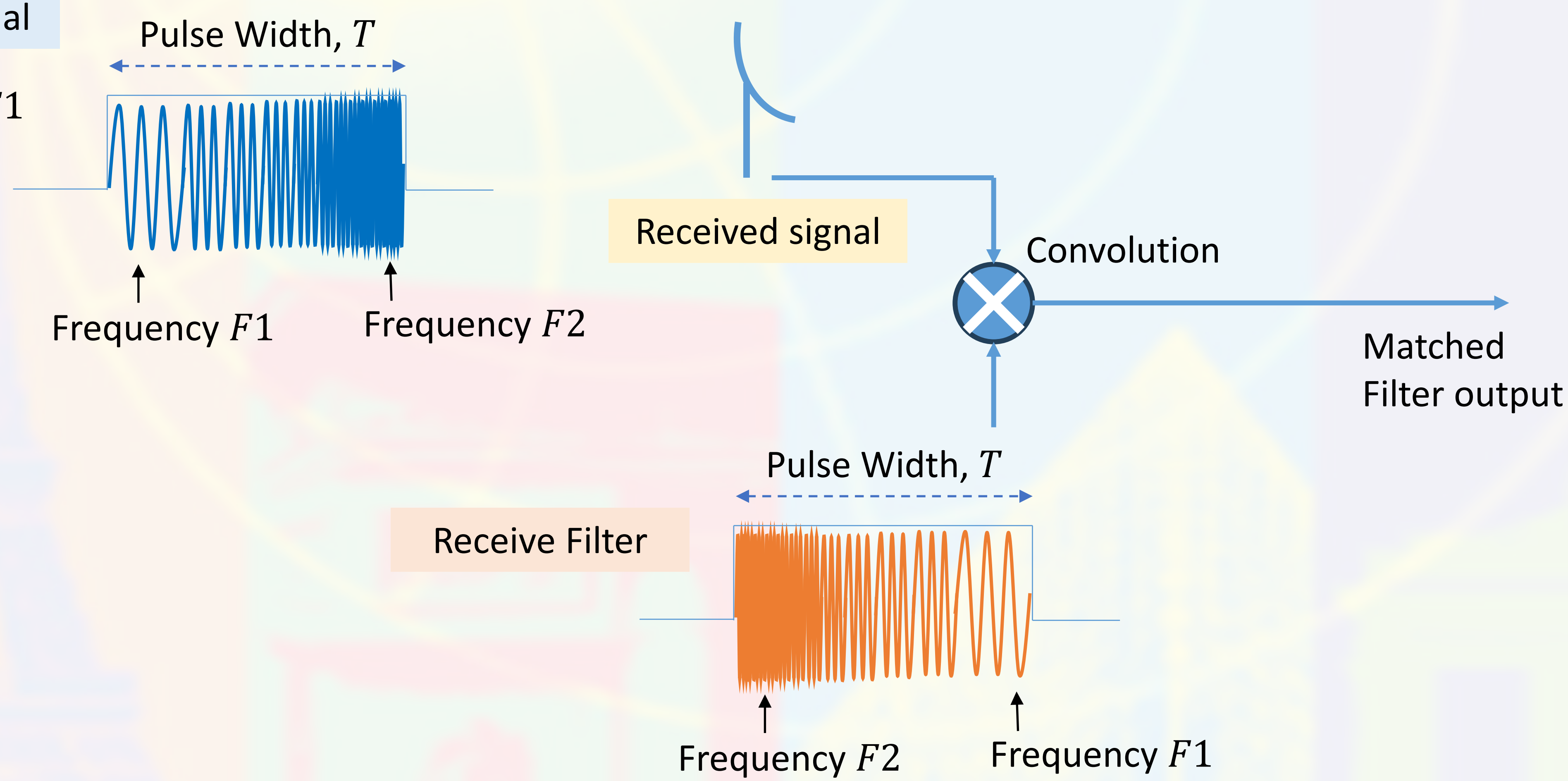
$$\boxed{SNR_{pc} = \frac{P_t \, G_t G_r \lambda^2 N n_p \sigma}{(4\pi)^3 k \; T_0 F_n B_n L_s R^4}}$$

How much is pulse compression loss?

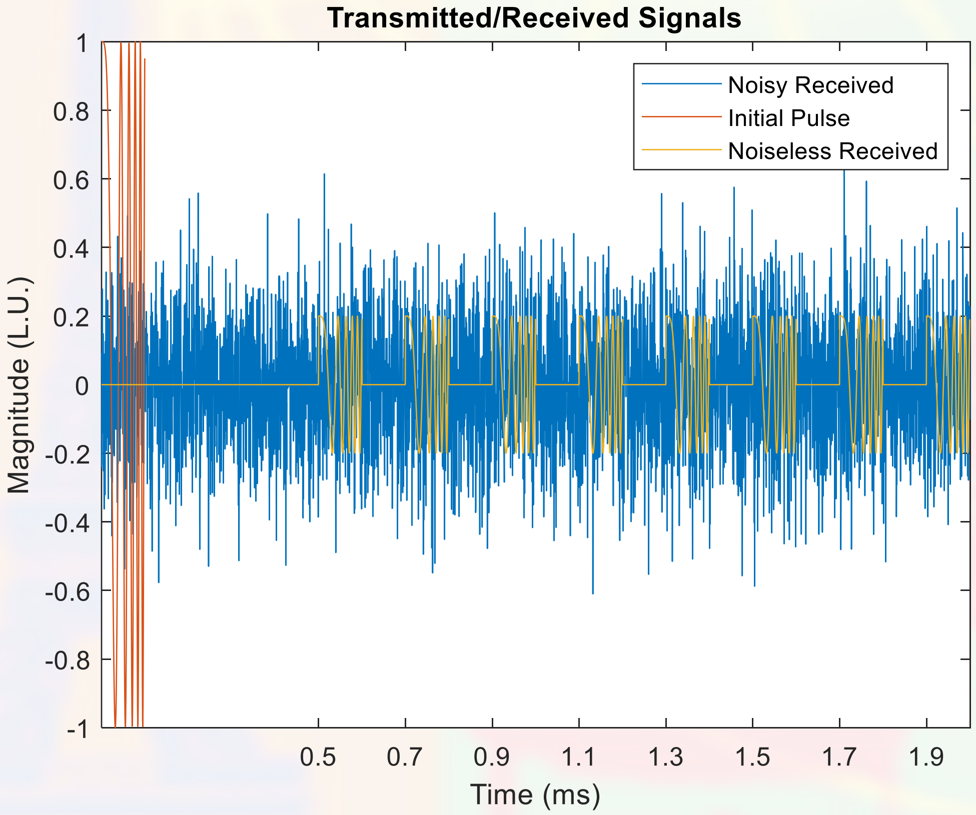
Pulse Compression

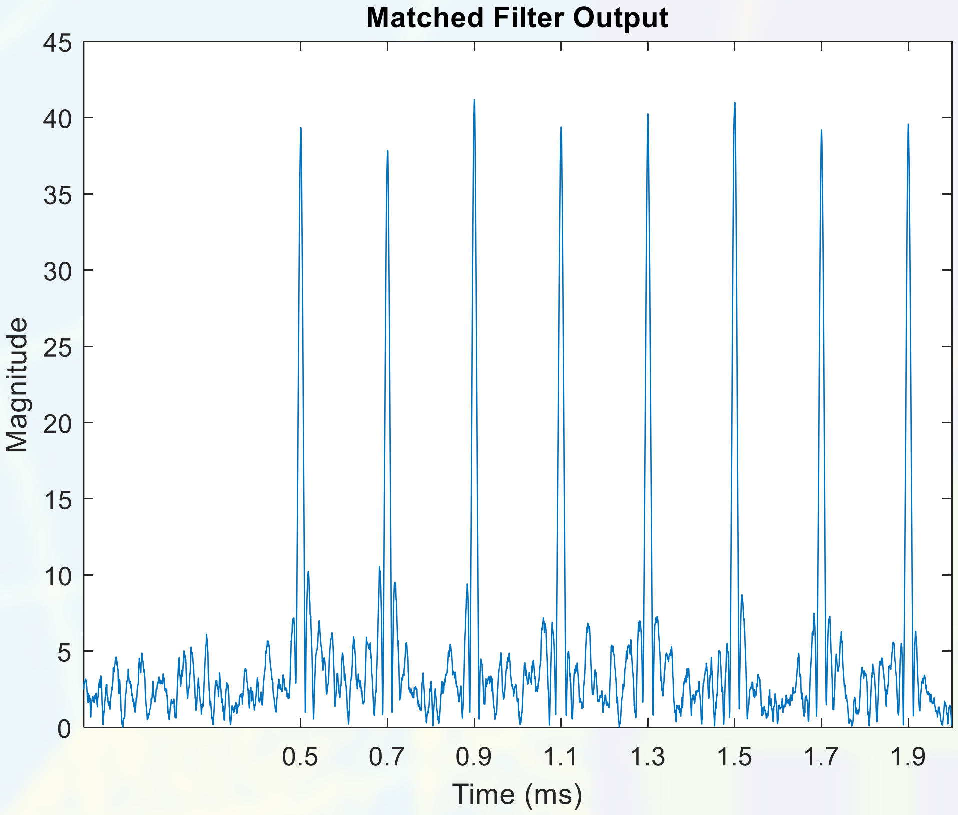
Transmit signal

$\mathrm{B} = F2 - F1$



Pulse Compression





Pulse Compression

- Instead of a short pulse, we transmit a modulated long pulse ($\Delta R = \frac{c}{2B}$)
- The energy of the transmitted pulse is now $P_t T$, so SNR will be increased by ***time-bandwidth product*** TB or $\frac{T}{\tau}$
- The maximum detection range for a given target is increased by a factor $\sqrt[4]{TB}$
- For $BT = 100$, the processing gain is $10 \log10(100) = 20\ dB$
- The maximum detection range for this target would be increased by a factor $\sqrt[4]{100} = 3.16$

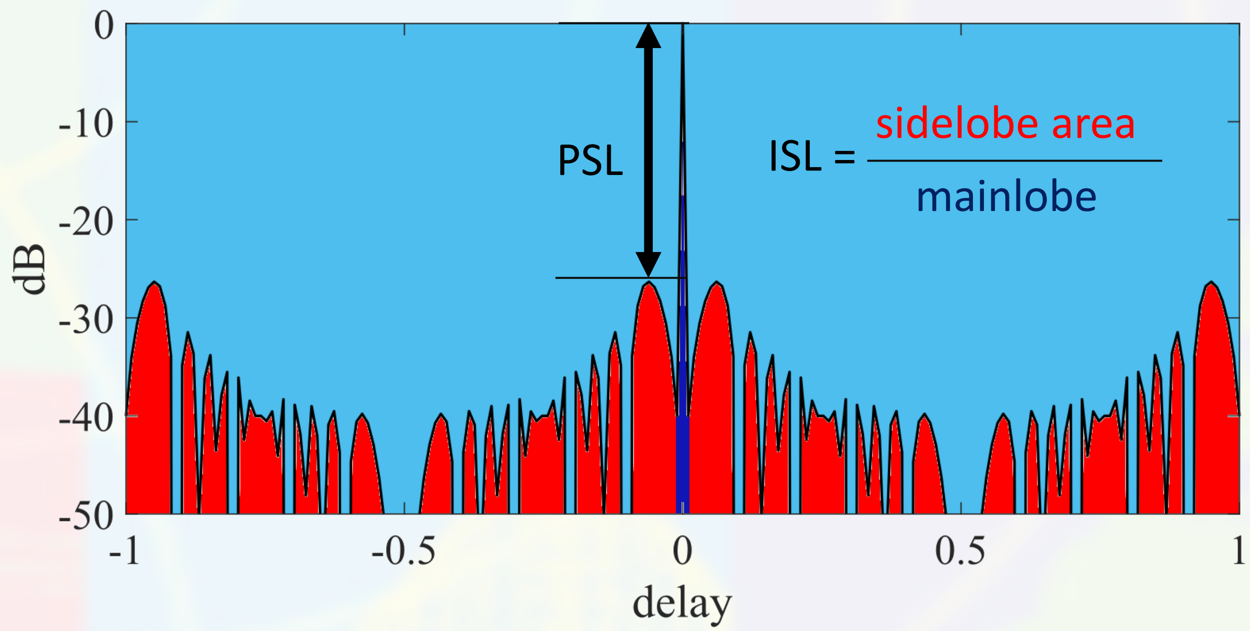
1. Blind Range [in pulse radar]
2. Sidelobes (PSL and ISL)
3. Doppler tolerance
4. Receiver linearity

Metrics for Goodness of the Waveforms

Low PSL
- avoid masking of weak targets

Low ISL
- mitigate deleterious effects of distributed clutter

Good Waveform



Conceptual definition of PSL and ISL measured on autocorrelation function response of a Golomb sequence

Some well-known good binary waveforms

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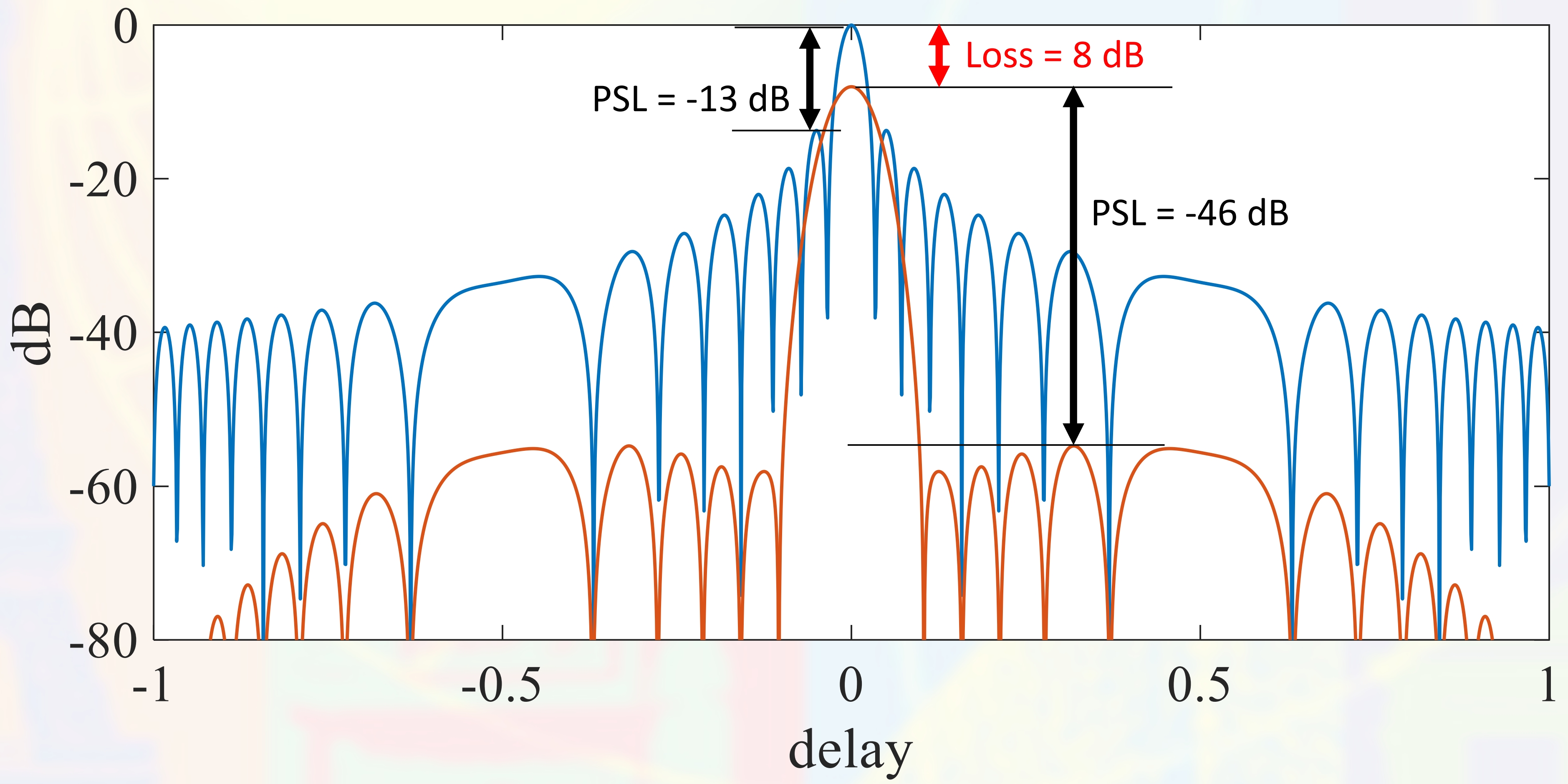
Some well-known binary sequences	
	Barker codes
	M-sequences (Maximum length sequences)
	Gold codes
	Kasami codes
	Minimum Peak Sidelobe (MPS) sequences

Limited in length

Hard to find

No constraint on aperiodic auto-correlation function

Good Waveforms; LFM

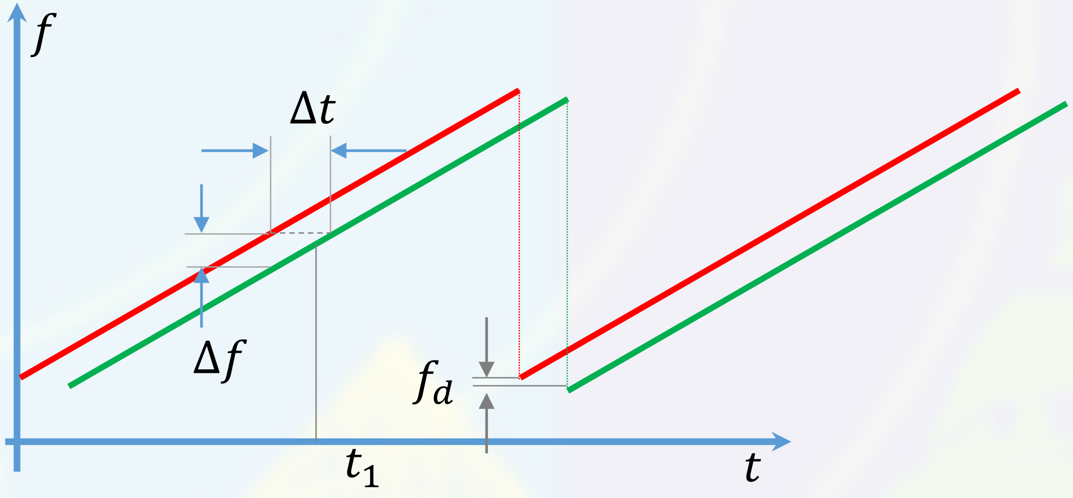


Pulse compression response for LFM (blue) and
Hamming weighted LFM (red)

FMCW radar

Tx Rx

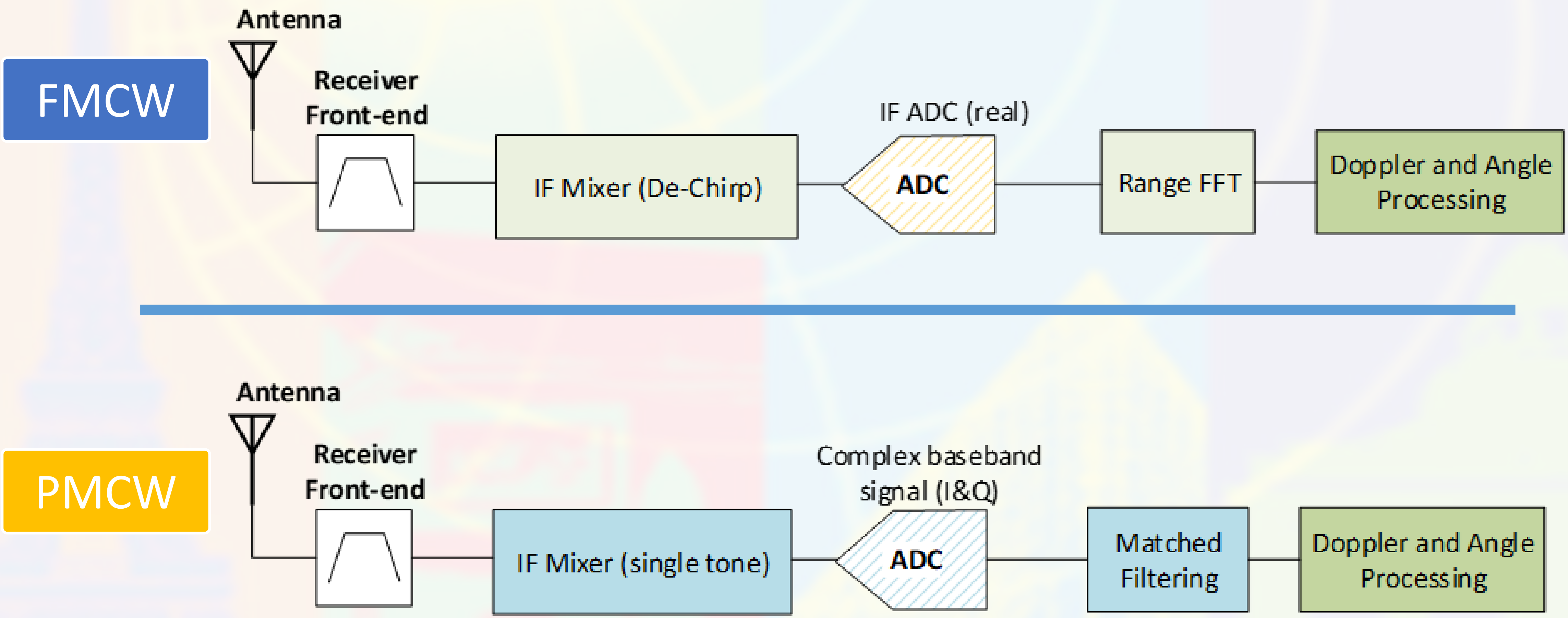
- ✓ Very small blind range
- ✓ Very high accuracy of range measurement
- ✓ Considerably simple implementation circuits based on stretch processing



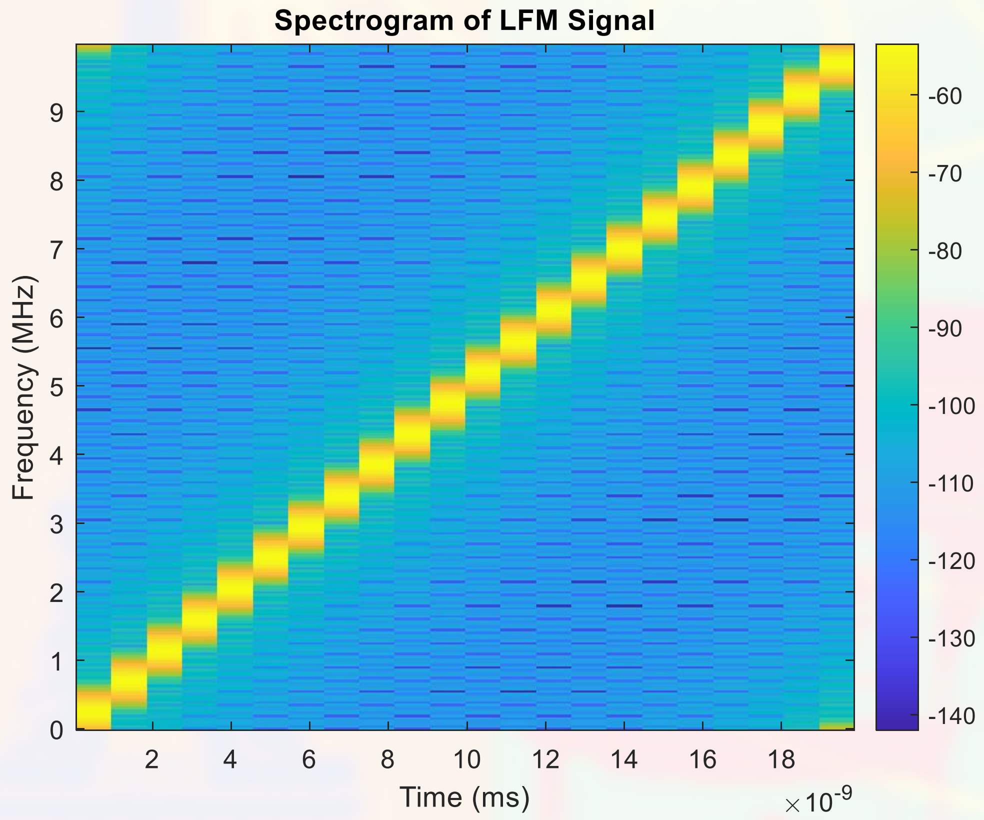
- ➢ Slow-Chirp and Fast-Chirp
- ➢ dechirp technique and Low sampling rate ADCs

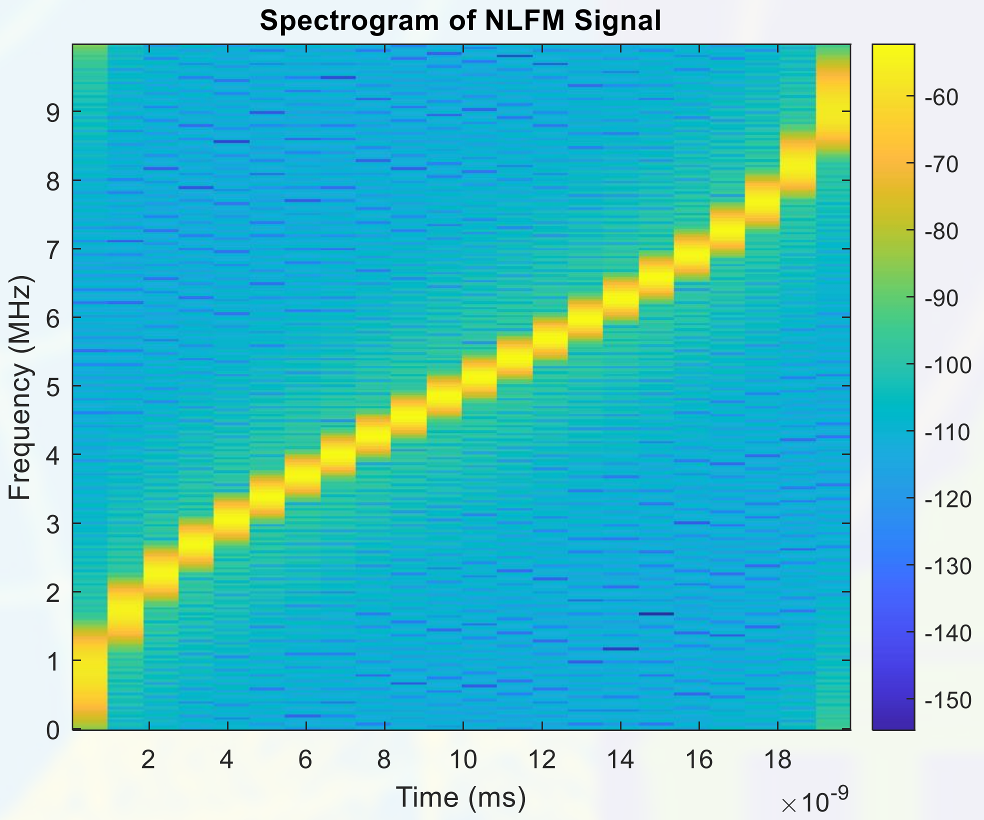
FMCW and PMCW

Tx Rx

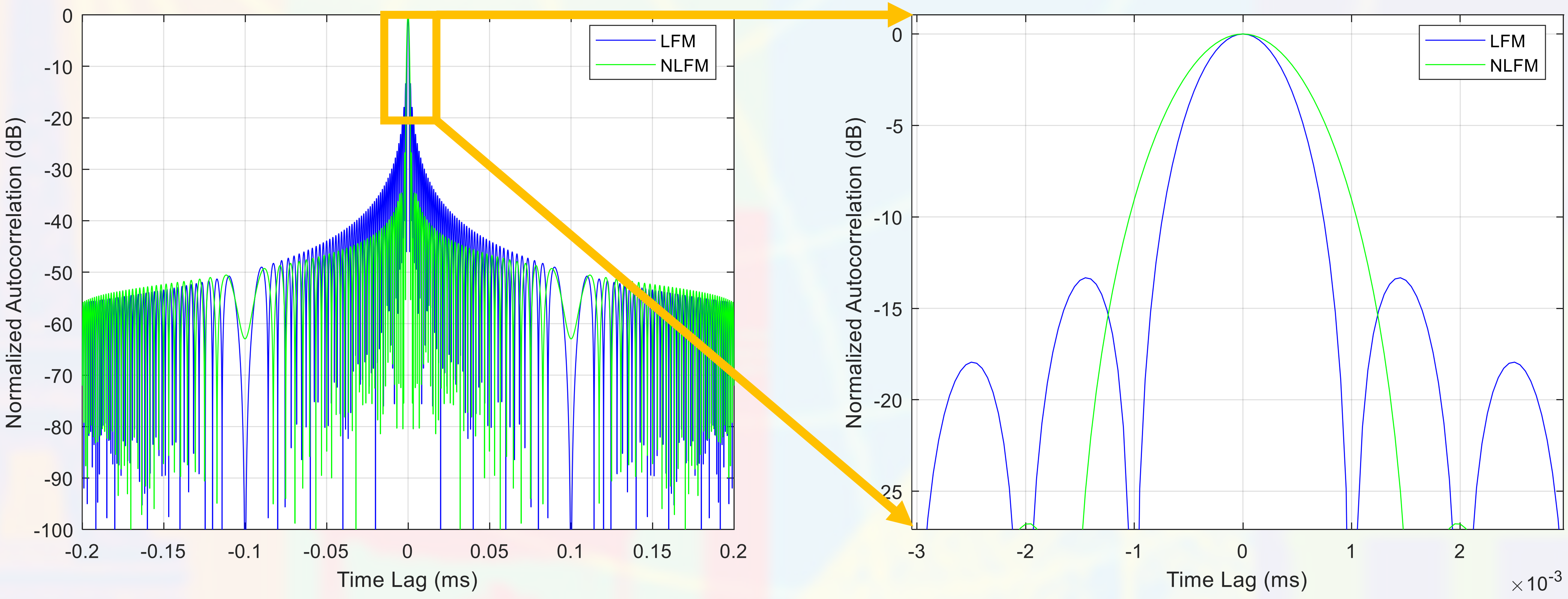


Nonlinear FM (NLFM)





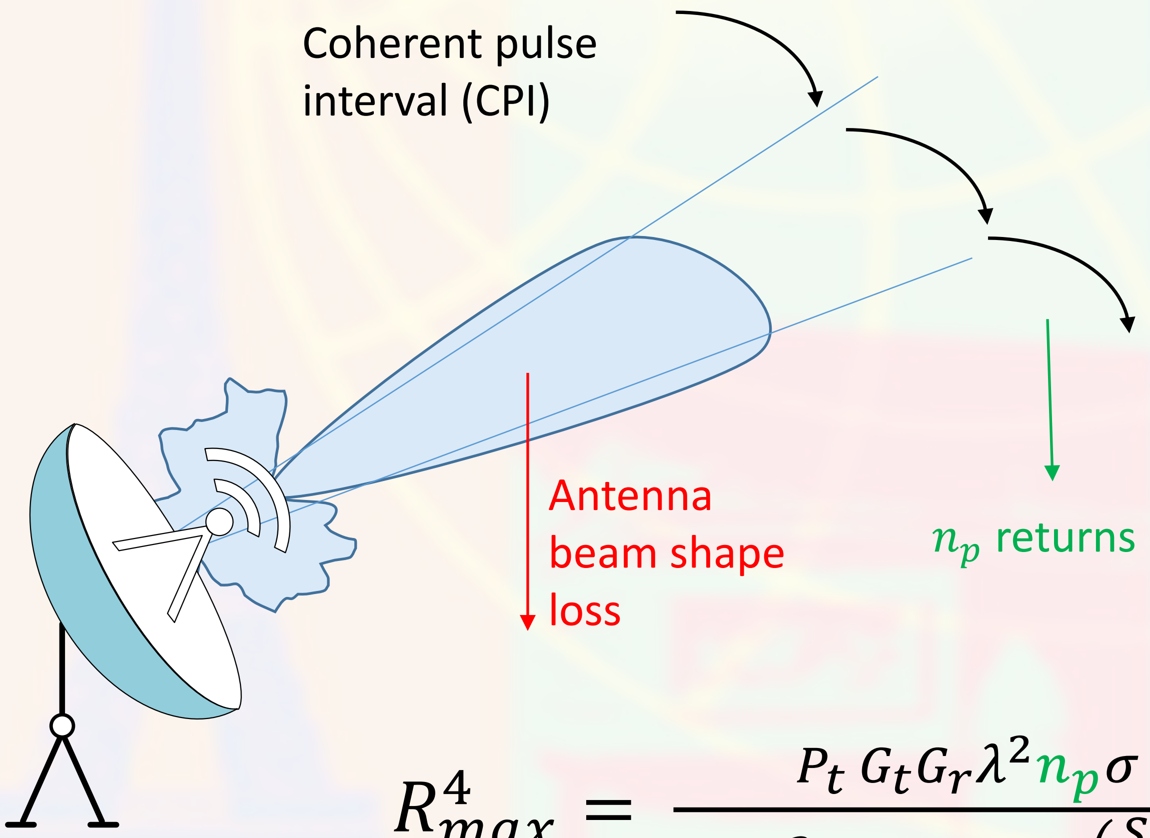
NLFM



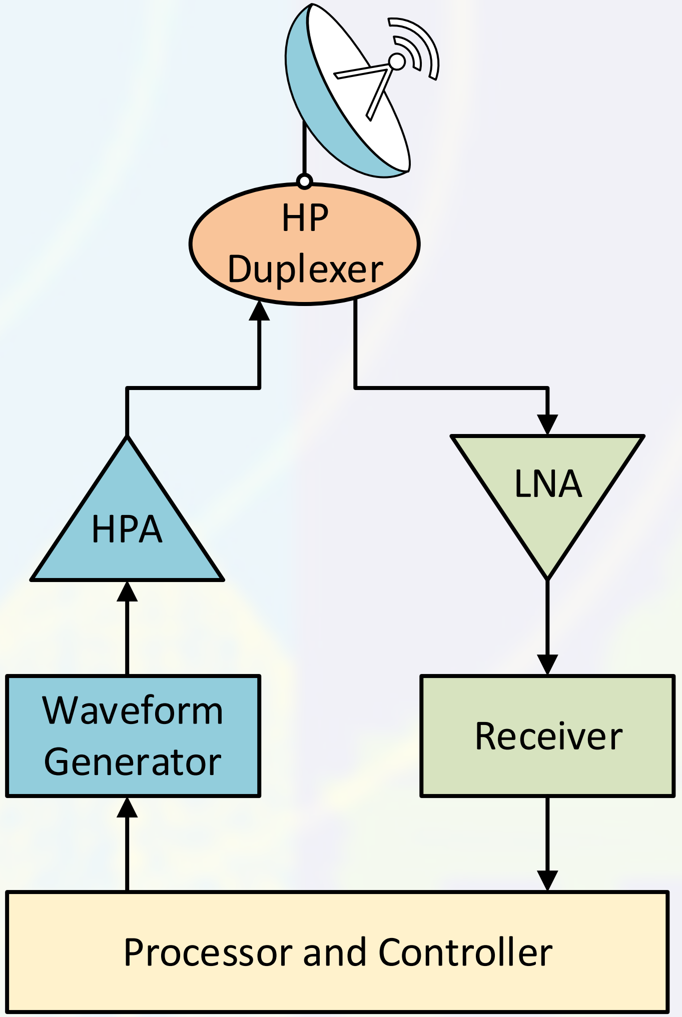
Normalized Autocorrelation (dB)
Time Lag (ms)
LFM
NLFM
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
-5
-15
-25
-3
-2
-1
1
2
×10^-3

Antenna – Mechanical Scan

Tx/Rx

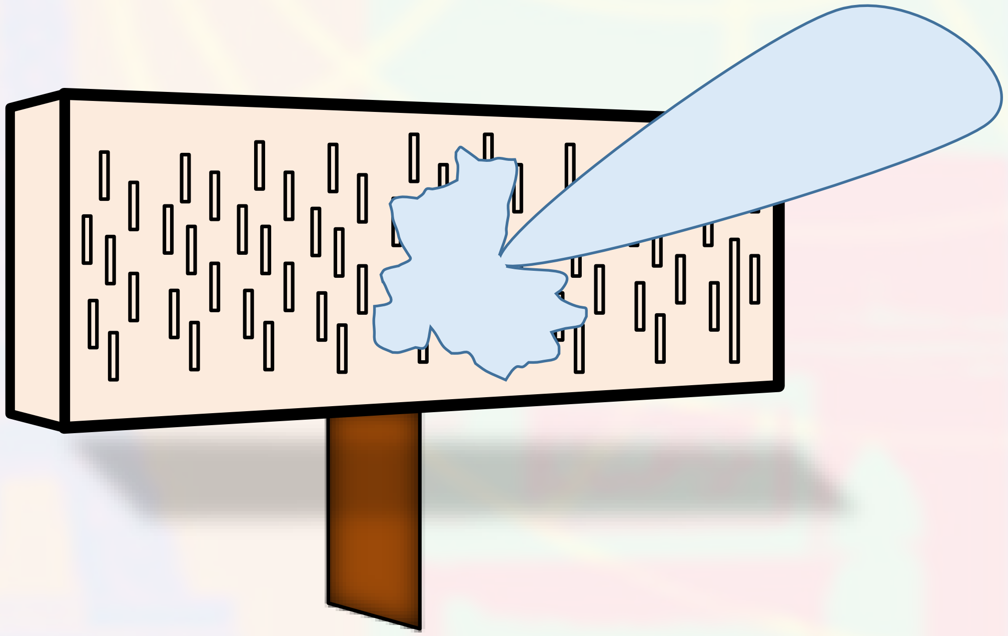


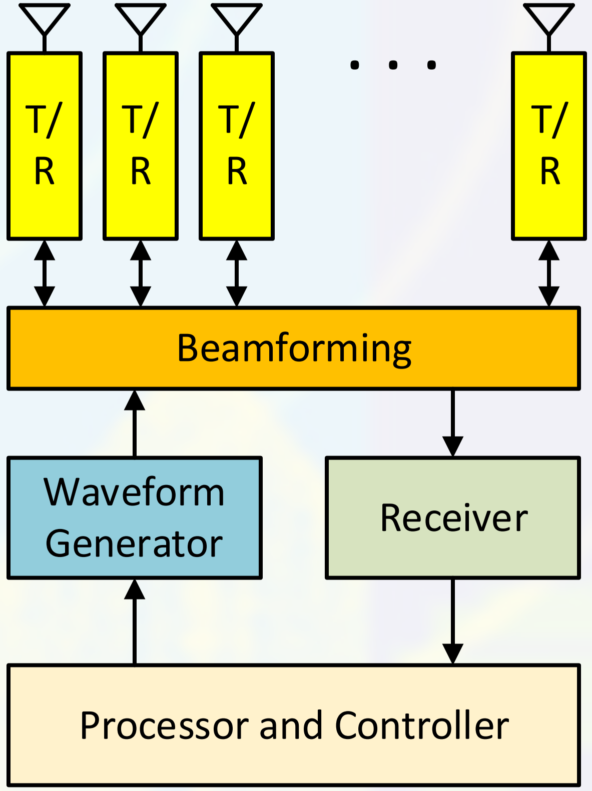
$$R_{max}^4 = \frac{P_t\, G_t G_r \lambda^2 n_p \sigma}{(4\pi)^3 k T_0 B_n F_n L_s \left(\frac{S}{N}\right)_{min}}$$



Antenna – Phased Array

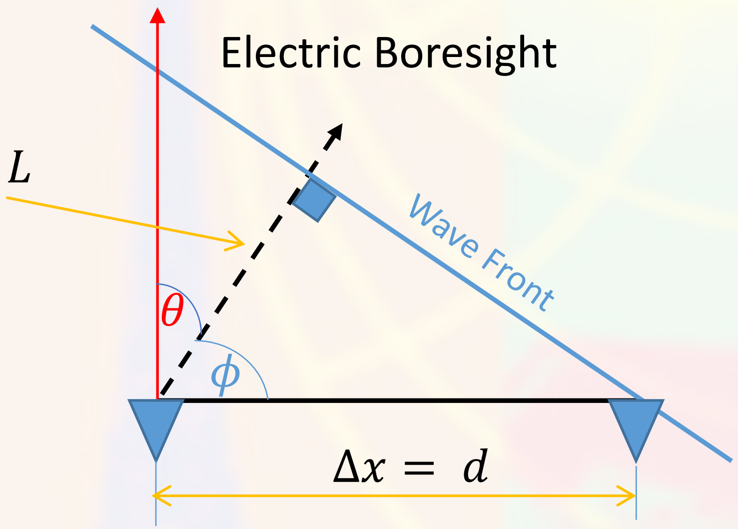
Tx/Rx





Active Phase Array

Antenna – Phased Array



$\cos\phi = \frac{L}{d}$, $\theta + \phi = 90$ $\cos\phi = \cos(90 - \theta) = \sin\theta$

$\sin\theta = \frac{L}{d} \Rightarrow$ $L = d\sin\theta$

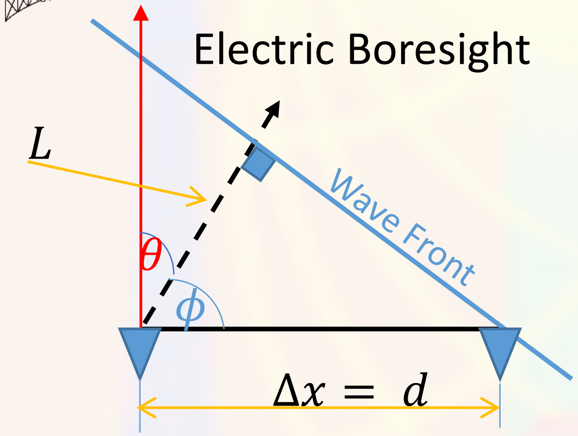
The phase variation across the array surface, or *aperture*, is the total path length variation times $\frac{2\pi}{\lambda}$

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

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

What happens if we increase d ?

Antenna – Phased Array



$$1$$

$$\exp -j\frac{2\pi(1)\Delta x \sin\theta}{\lambda}$$

$$\exp -j\frac{2\pi(2)\Delta x \sin\theta}{\lambda}$$

$$\vdots$$

$$\exp -j\frac{2\pi(\mathrm{N}-1)\Delta x \sin\theta}{\lambda}$$

$$+$$

$$(3\text{dB})\ \text{Beamwidth [rad]} \cong \frac{\alpha\lambda}{N\,\Delta x}$$

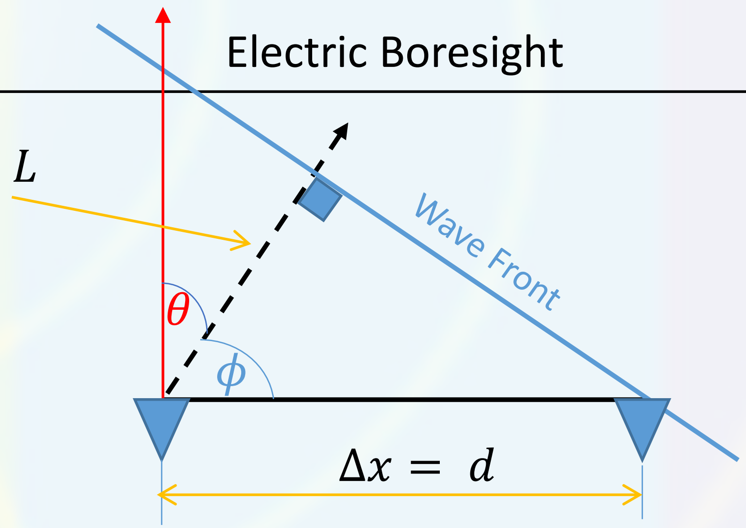
α is the beamwidth factor and is determined by the aperture taper function
N is number of antennas
Δx is the distance between two antenna elements

$$AF(\theta) = \frac{1}{N}\sum_{n=0}^{N-1} \exp\left(-j\frac{2\pi}{\lambda}\mathrm{n}\Delta x \sin\theta\right)$$

This expression is referred to as the array factor (AF)

If the element is assumed to be an isotropic radiator, which has no angular dependence, then the array factor and the phased array radiation pattern will be equal.

Antenna – Phased Array



$$1$$

$$\exp -j\frac{2\pi(1)\Delta x \sin\theta}{\lambda}$$

$$\exp -j\frac{2\pi(2)\Delta x \sin\theta}{\lambda}$$

$$\vdots$$

$$\exp -j\frac{2\pi(\mathrm{N}-1)\Delta x \sin\theta}{\lambda}$$

$$\boxed{\boldsymbol{a}(\theta) = \left[1, \exp\left(-j\frac{2\pi\Delta x \sin\theta}{\lambda}\right), \ldots, \exp\left(-j\frac{2\pi(\mathrm{N}-1)\Delta x \sin\theta}{\lambda}\right)\right]^T \in \mathbb{C}^N}$$

Steering vector

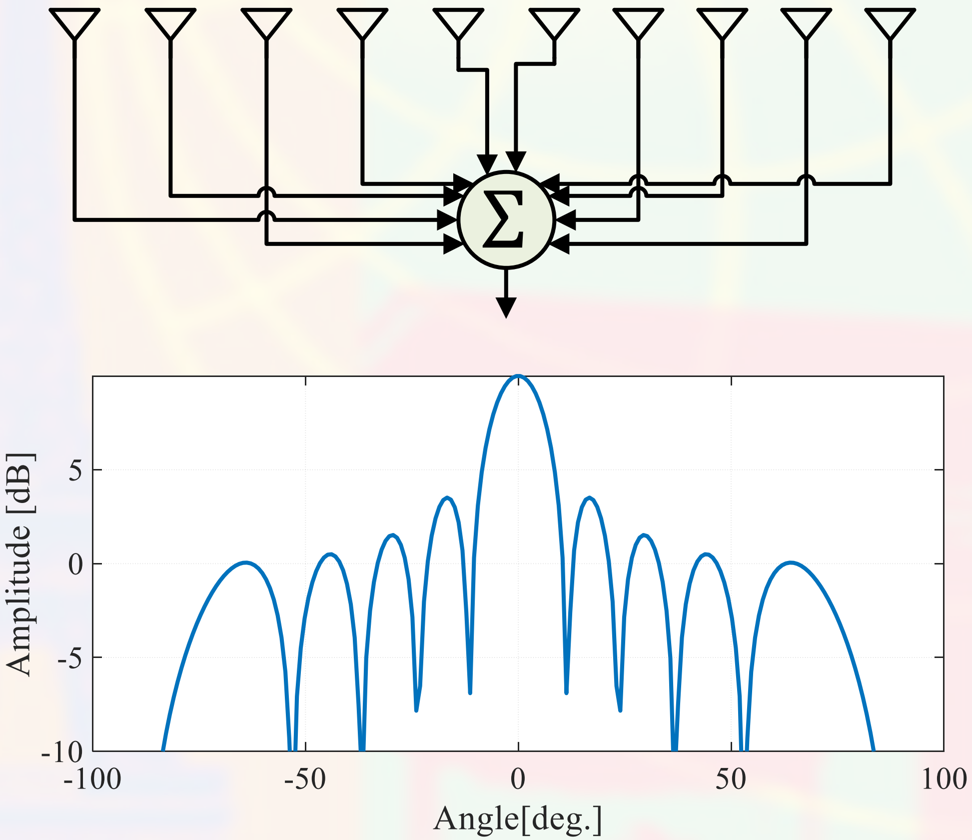
$$AF(\theta) = \boldsymbol{w}^H(\theta)\,\boldsymbol{a}(\theta)$$

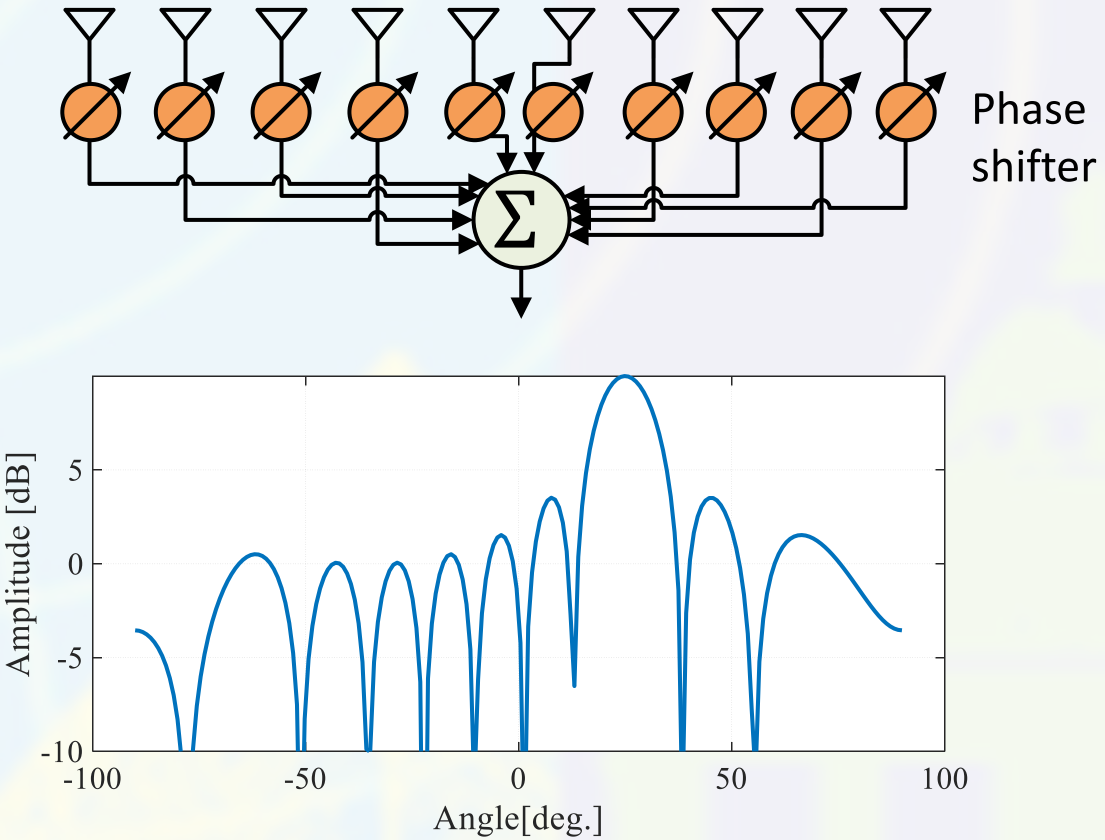
Weights

Can include
amplitude and phase

✓ steer beam to a desired angle
✓ control the sidelobe levels

Antenna – Phased Array

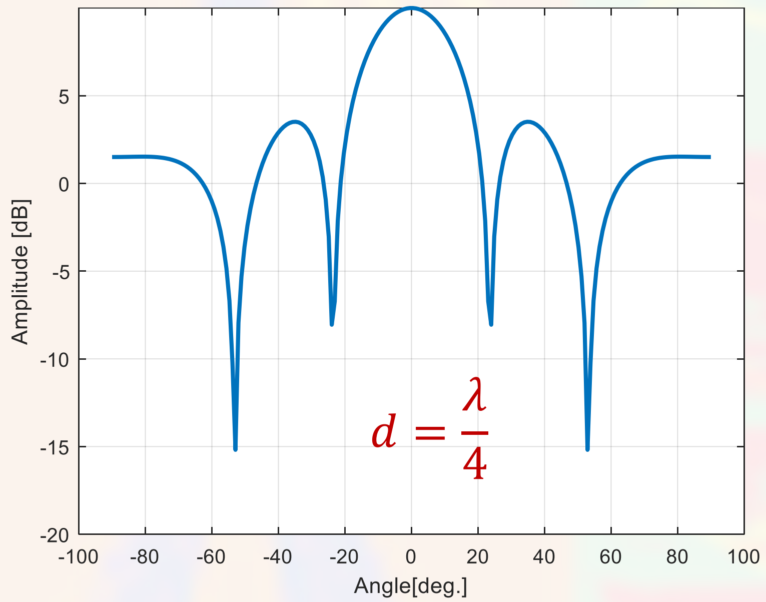


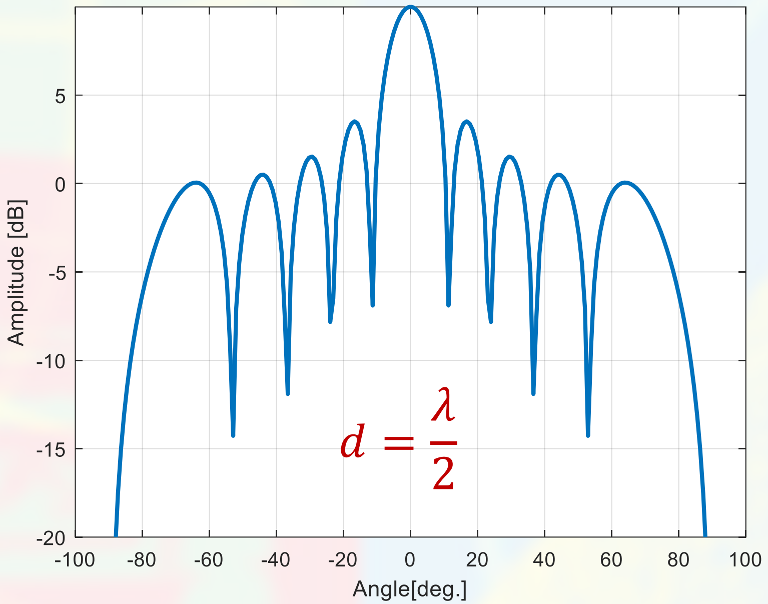


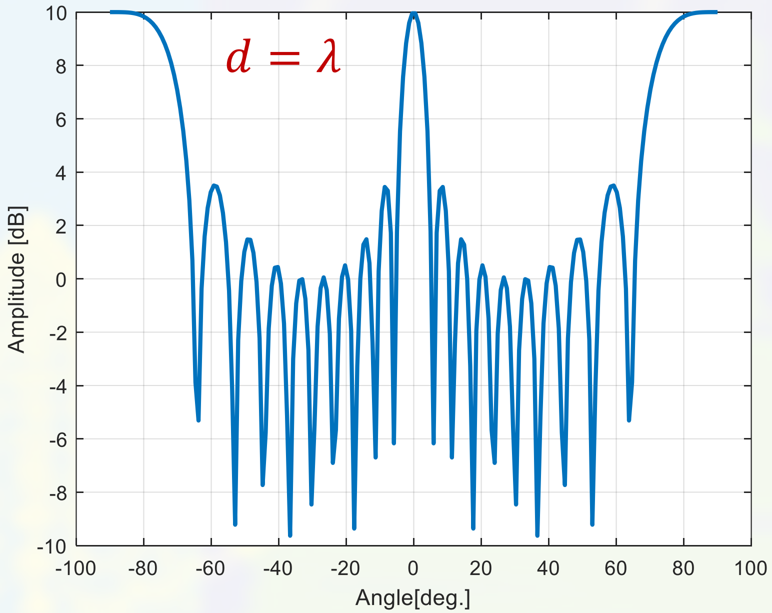
Antenna – Phased Array

Linear Array

$N = 10$ Isotropic Elements
No Phase Shifting







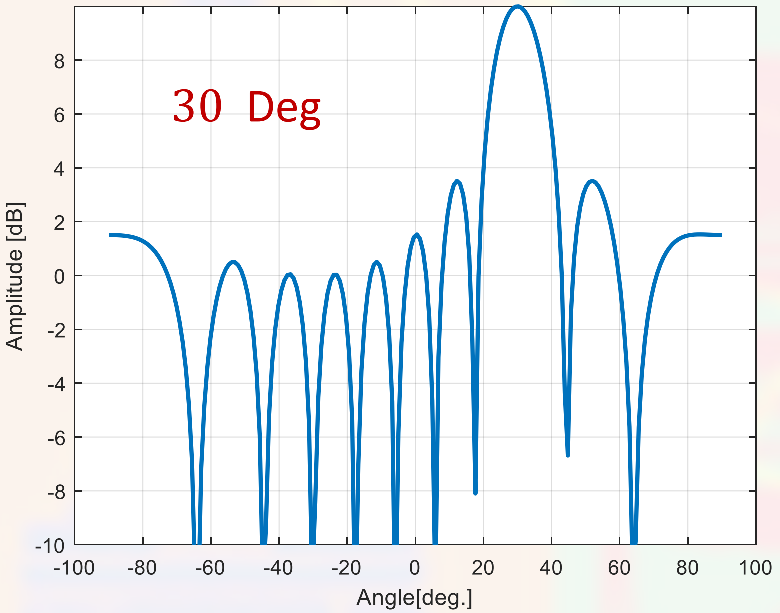
Limit element separation to $d < \lambda$ to prevent grating lobes for broadside array

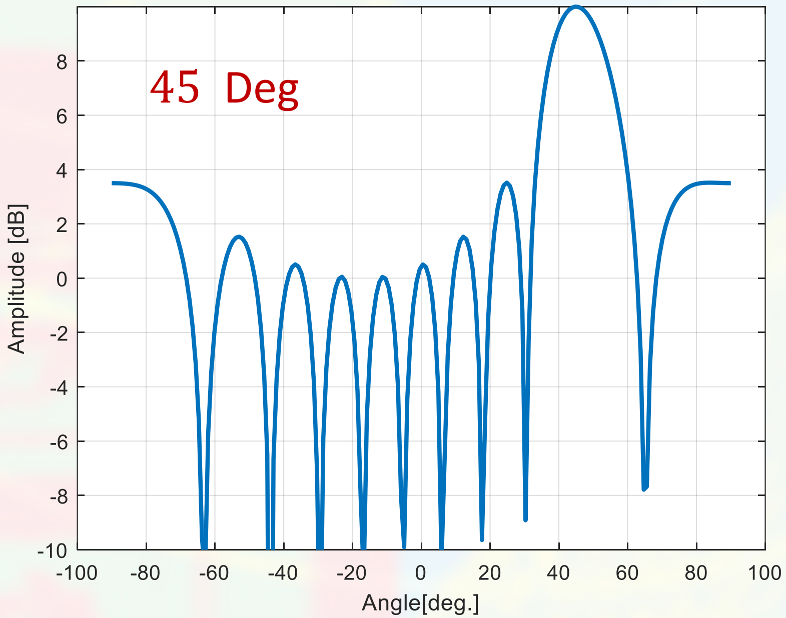
Antenna – Phased Array

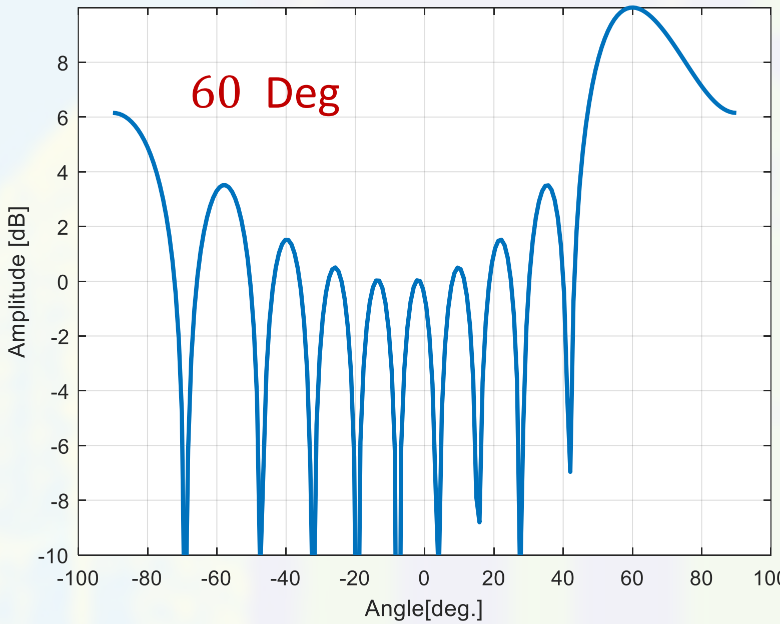
Linear Array

$N = 10$ Isotropic Elements

$d = \frac{\lambda}{2}$, Beam pointing direction = 30, 45 , 60







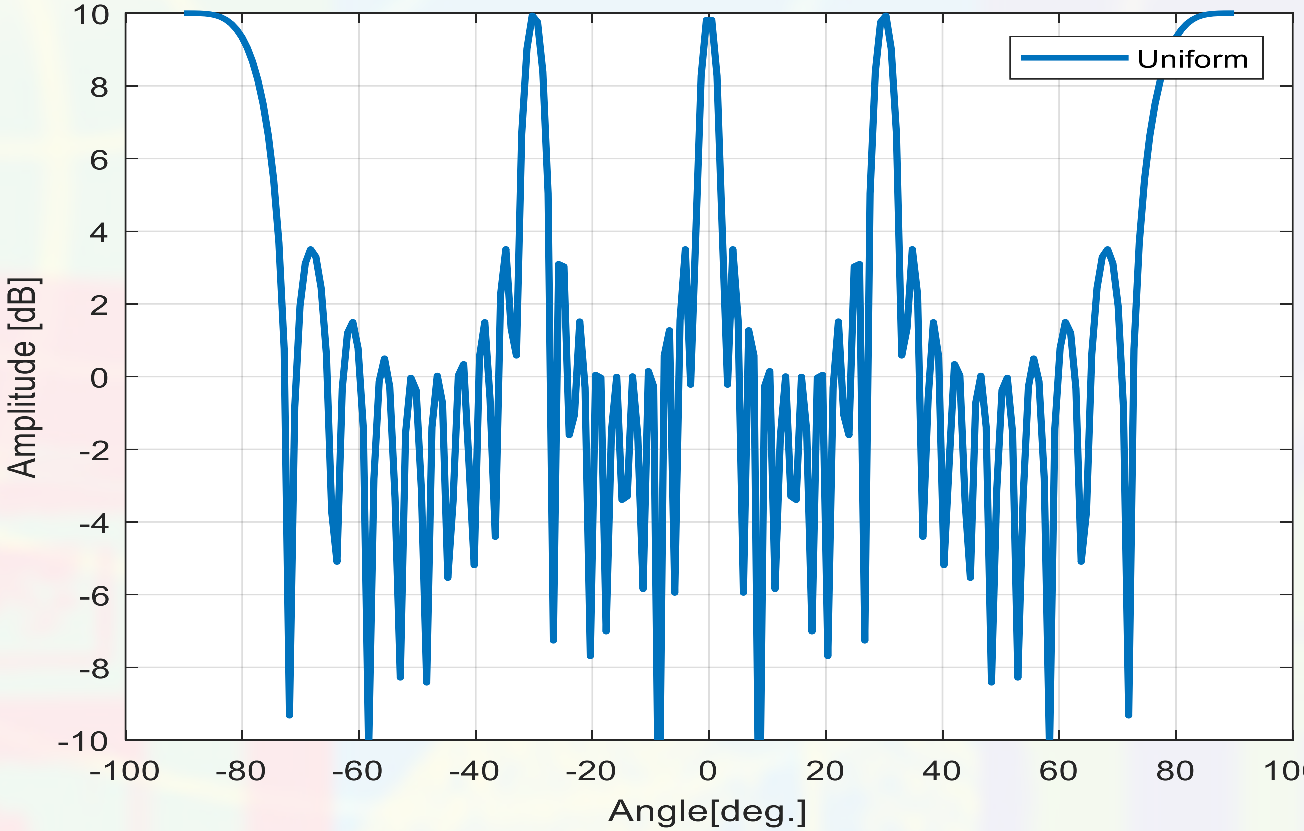
Antenna – Phased Array

Linear Array

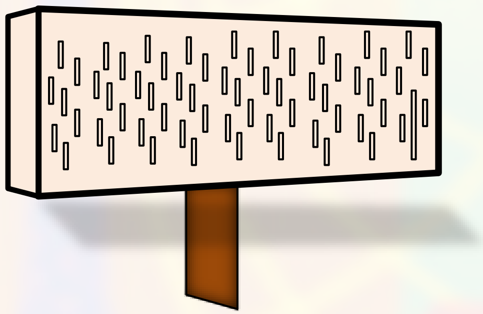
$N = 10$ Isotropic Elements
No Phase Shifting

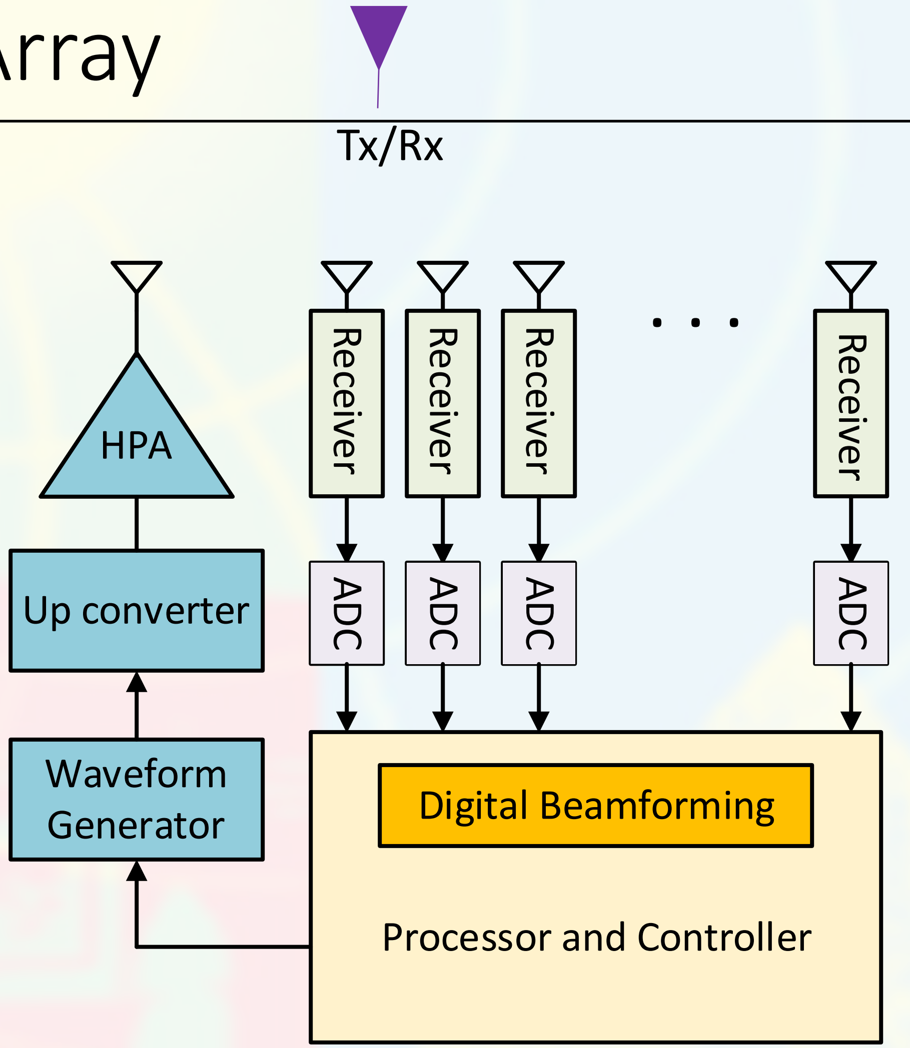
$d = 2\lambda$

What are side effects of grating lobes ?



Antenna – Phased Array

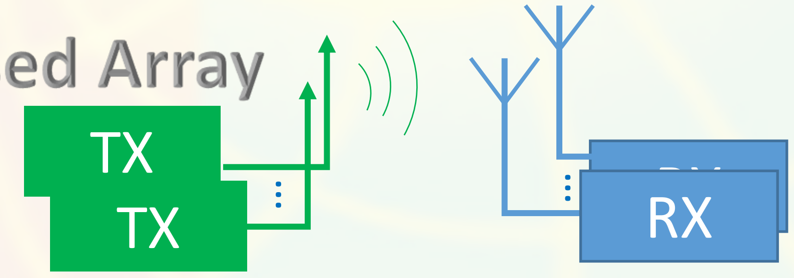




Phase Array Radars
with Digital Beamforming

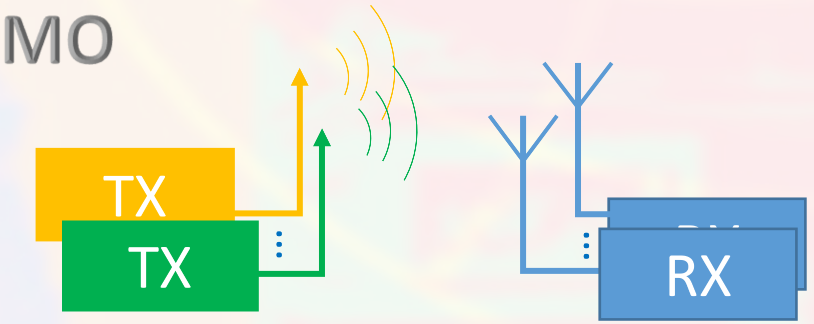
Antenna – MIMO Radars

Phased Array



Single Input Multi Output

MIMO



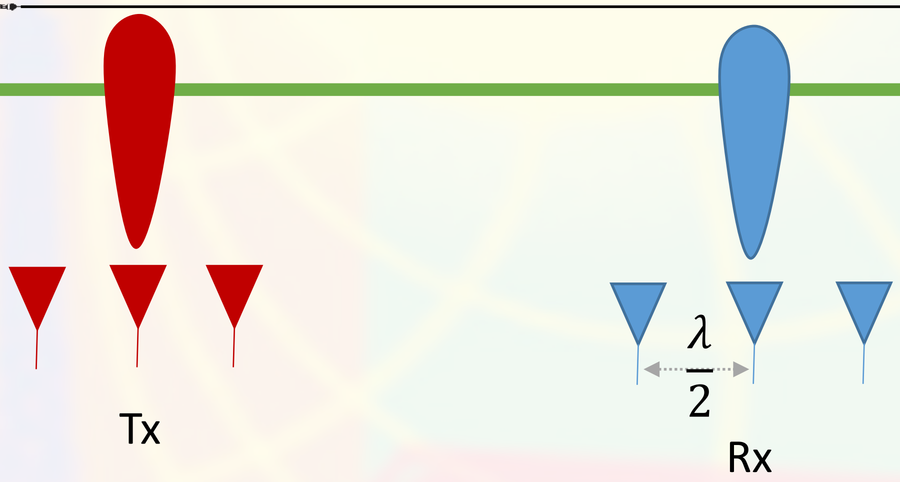
Multi Input Multi Output

Waveform

Phased Array and MIMO Radars

SNR For Single Pulse

A

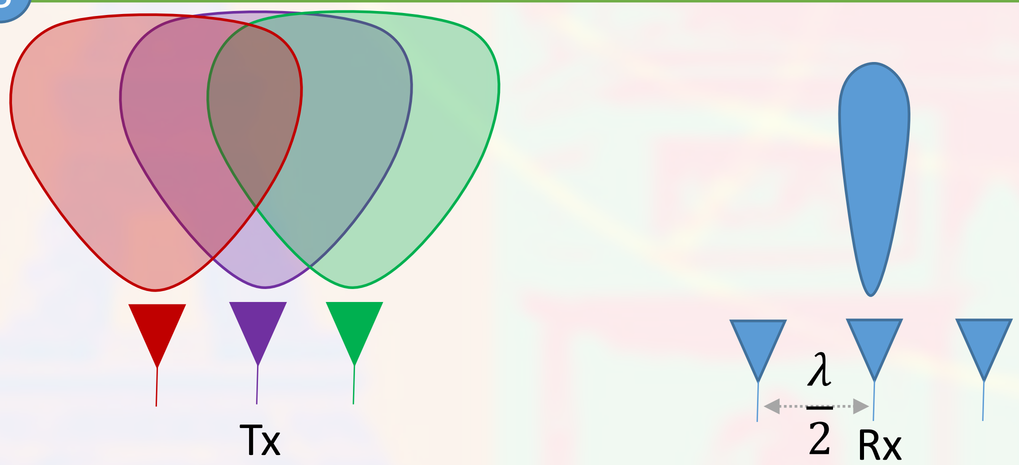


Phased Array

The Tx antennas transmit a single waveform.

$$\mathrm{SNR} \propto G_t G_r \underbrace{N\tau}_{}^{T_{pulse}}$$

B



MIMO

Every antenna element will emit a different waveform. Why?

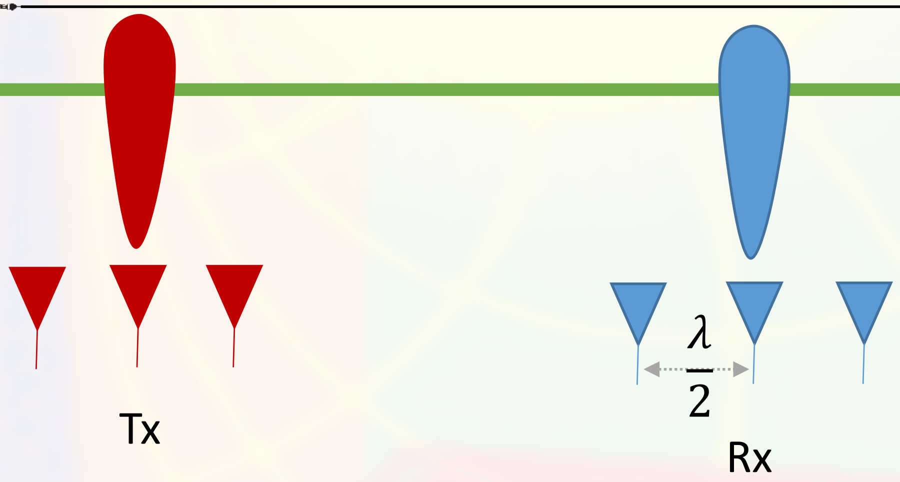
$$\mathrm{SNR} \propto \frac{G_t}{N_t} G_r \overbrace{N\tau}^{T_{pulse}}$$

MIMO single pulse SNR that is N_t times lower

Phased Array and MIMO Radars

SNR For CPI

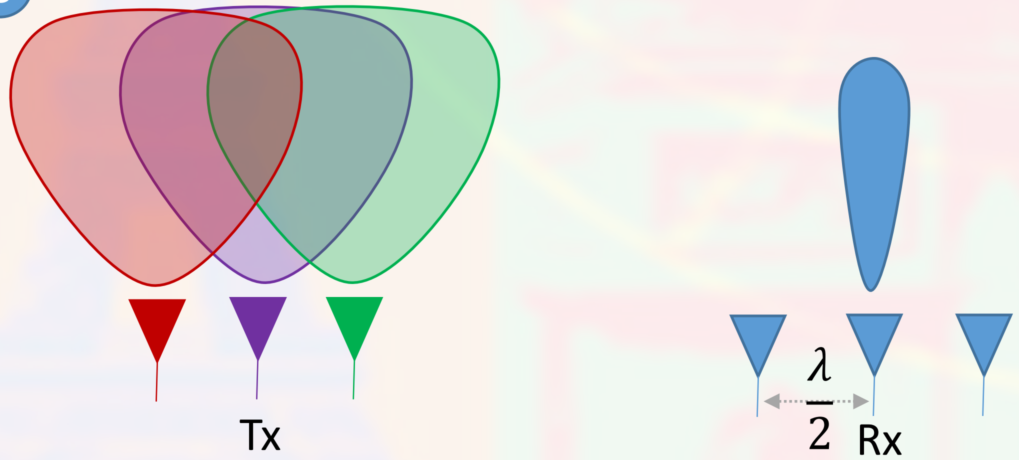
A



Phased Array

$$\text{SNR} \propto G_t G_r T_{PA}$$

B



MIMO

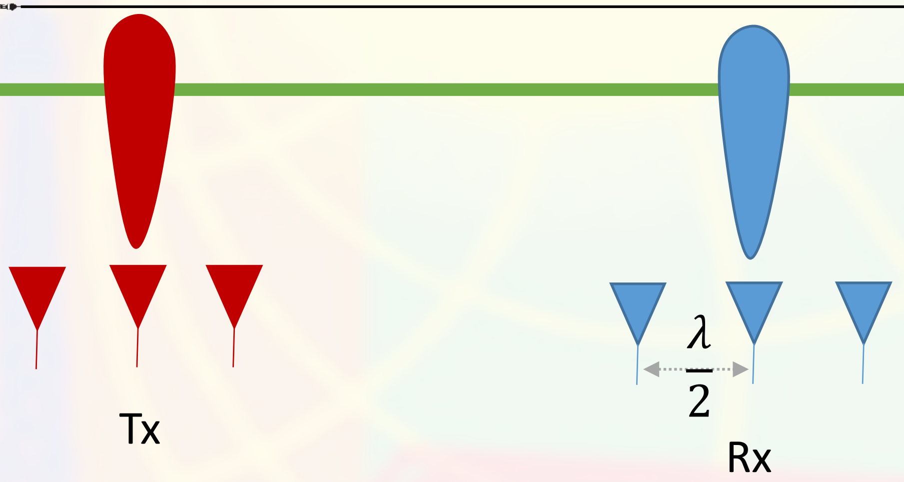
$$\text{SNR} \propto \frac{G_t}{N_t} G_r T_{MIMO}$$

If $T_{MIMO} = N_t\, T_{PA}$, MIMO obtains same SNR over CPI as PA

Phased Array and MIMO Radars

Area Rate

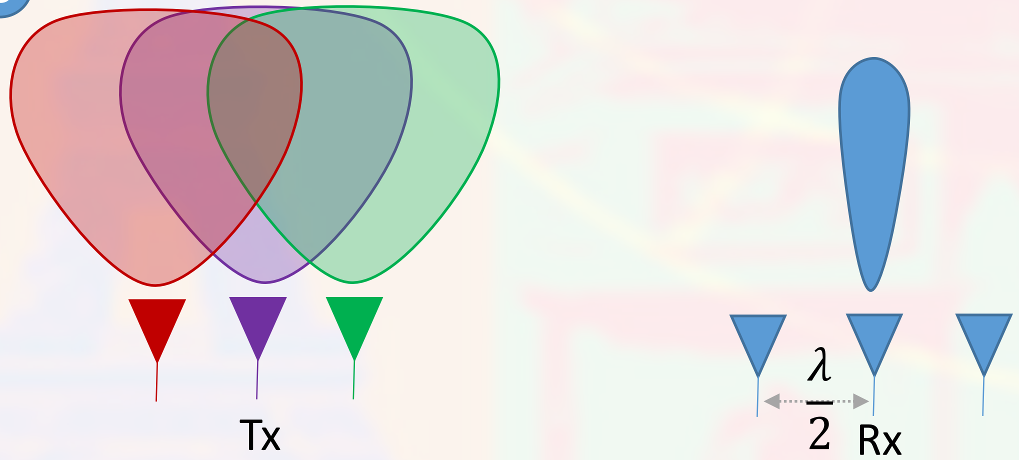
A



Phased Array

$$\text{Area rate} = \frac{4\pi R^2}{G_t T_{PA}}$$

B



MIMO

$$\text{Area rate} = \frac{4\pi R^2}{\frac{G_t}{N_t} T_{MIMO}}$$

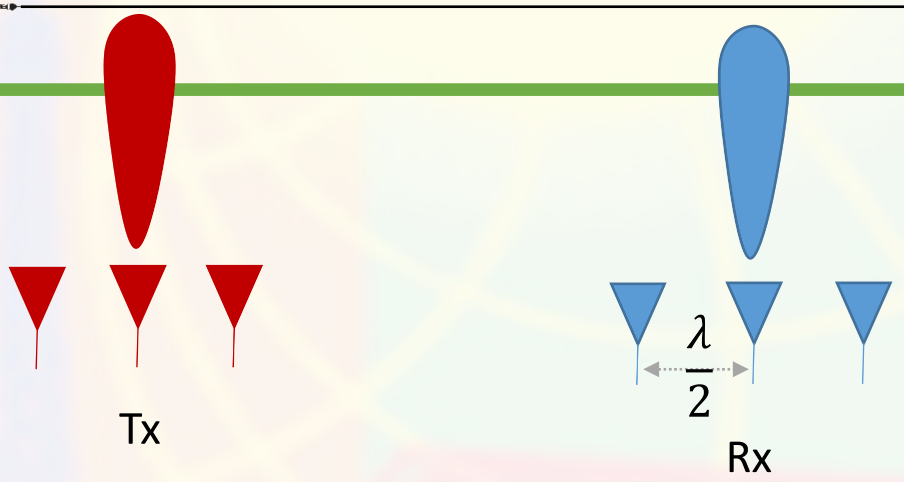
If T_{MIMO} = T_{PA} , MIMO searches N_t times faster than PA

If T_{MIMO} = N_t T_{PA} , MIMO searches at the same speed as PA and provides same SNR with better Doppler resolution than PA

Phased Array and MIMO Radars

Area Rate and SNR For CPI

A

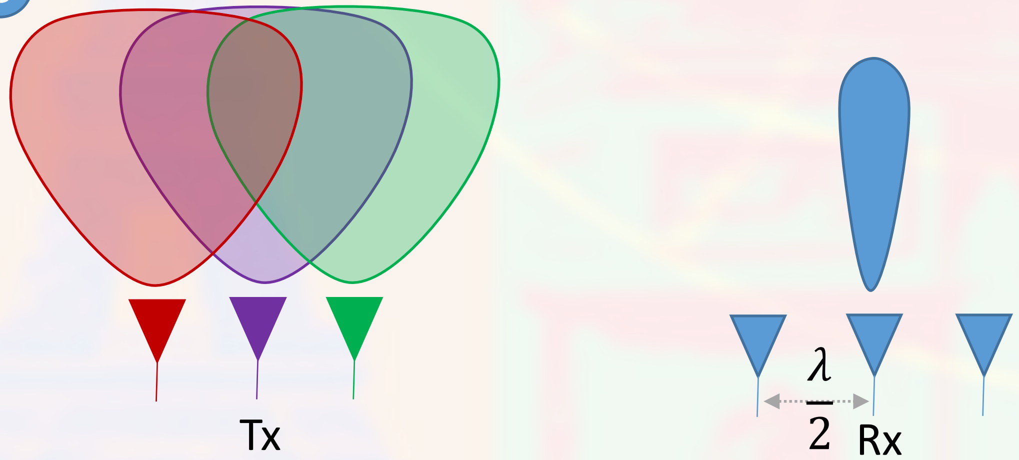


Phased Array

$$\text{SNR} \propto G_t G_r T_{PA}$$

$$\text{Area rate } = \frac{4\pi R^2}{G_t T_{PA}}$$

B



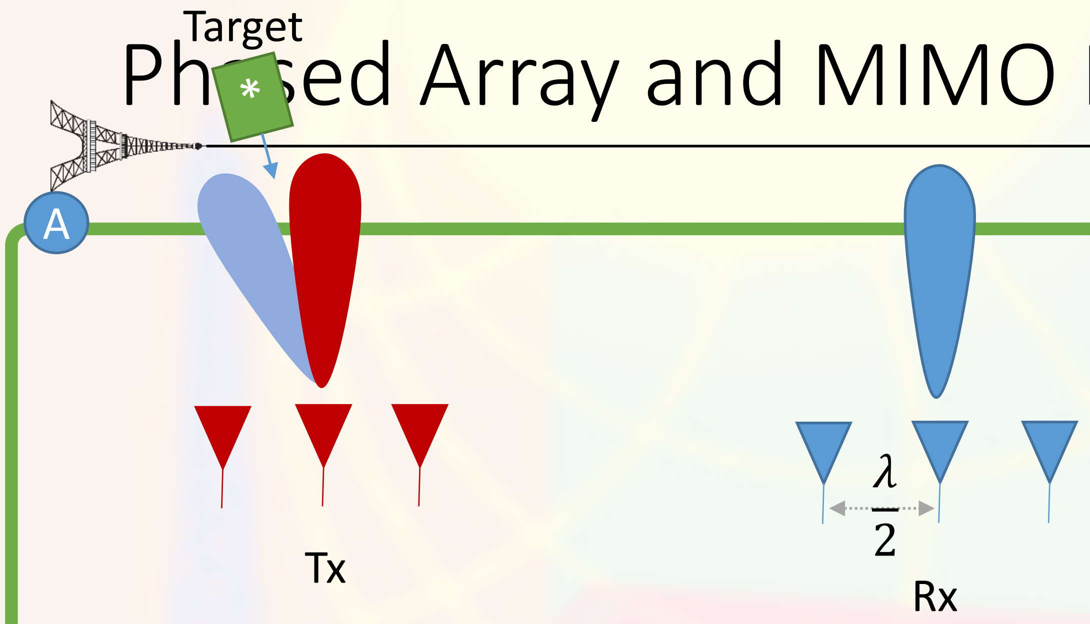
MIMO

$$\text{SNR} \propto \frac{G_t}{N_t} G_r T_{MIMO}$$

$$\text{Area rate } = \frac{4\pi R^2}{\frac{G_t}{N_t} T_{MIMO}}$$

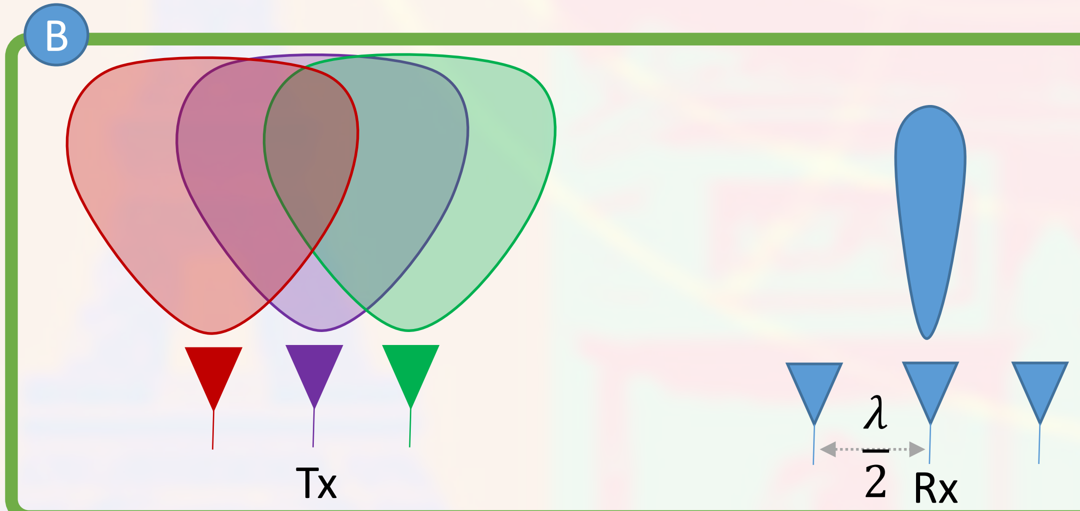
Phased Array and MIMO Radars

Beam Shape Loss



Phased Array

Analog phased array beam shape results in loss up to 6 dB



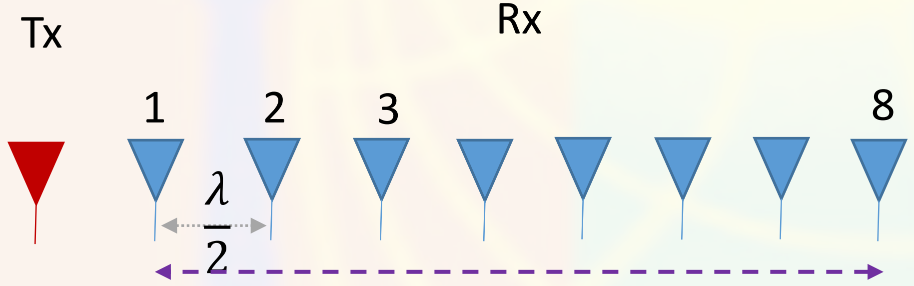
MIMO

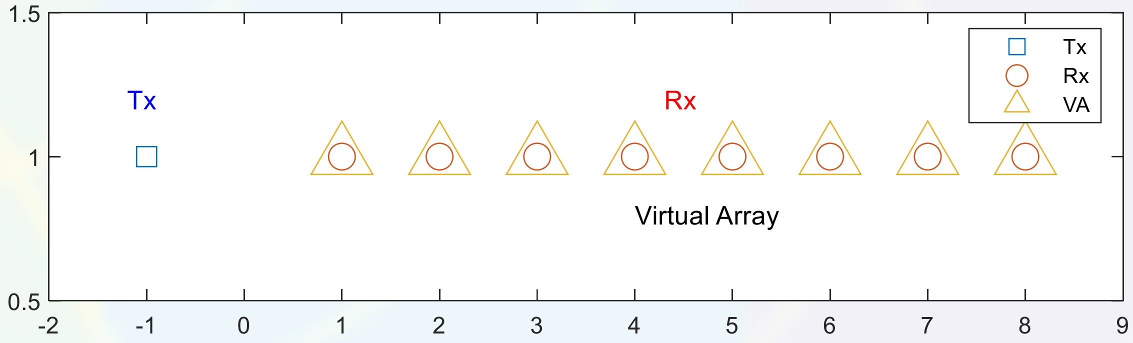
MIMO radar can eliminate Tx beam shape loss and reduce Rx beam shape loss

Phased Array and MIMO Radars

A

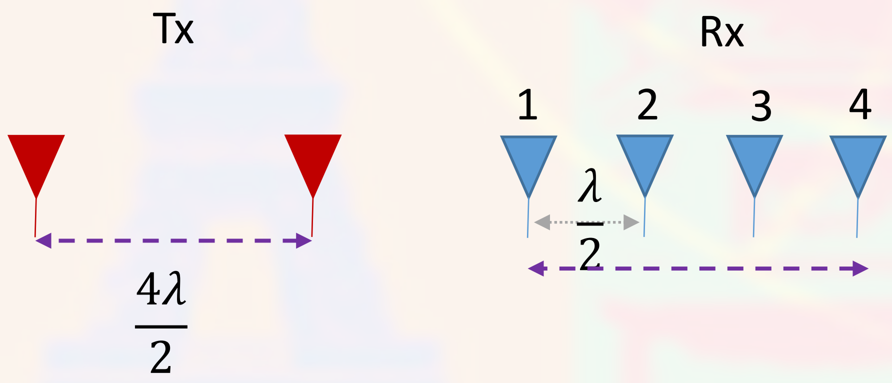
Phased Array

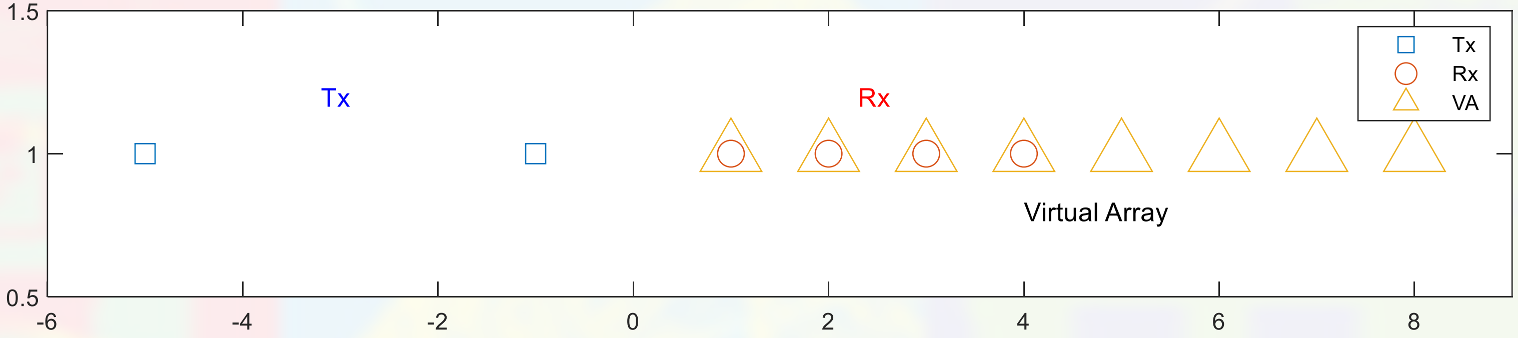




B

MIMO



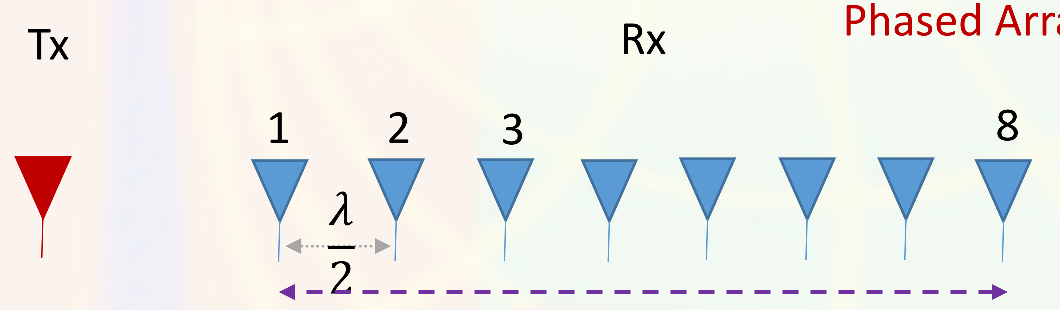


Compare (A) and (B) in terms of: Two-way antenna beampattern (angular resolution)

Phased Array and MIMO Radars

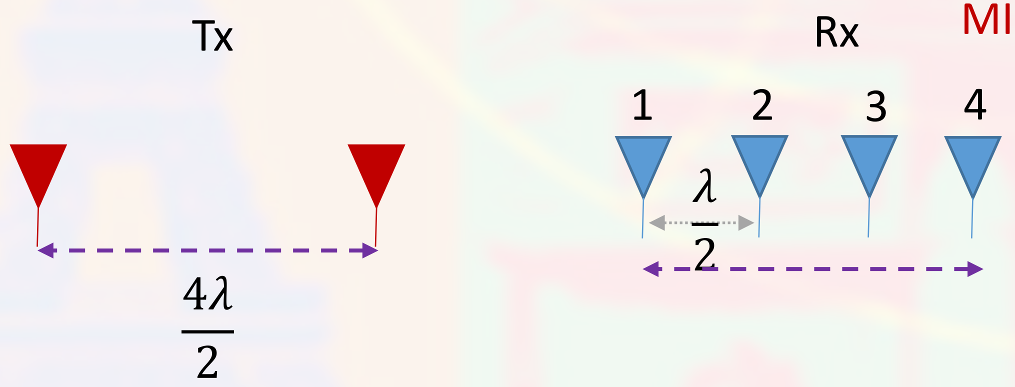
A

Phased Array

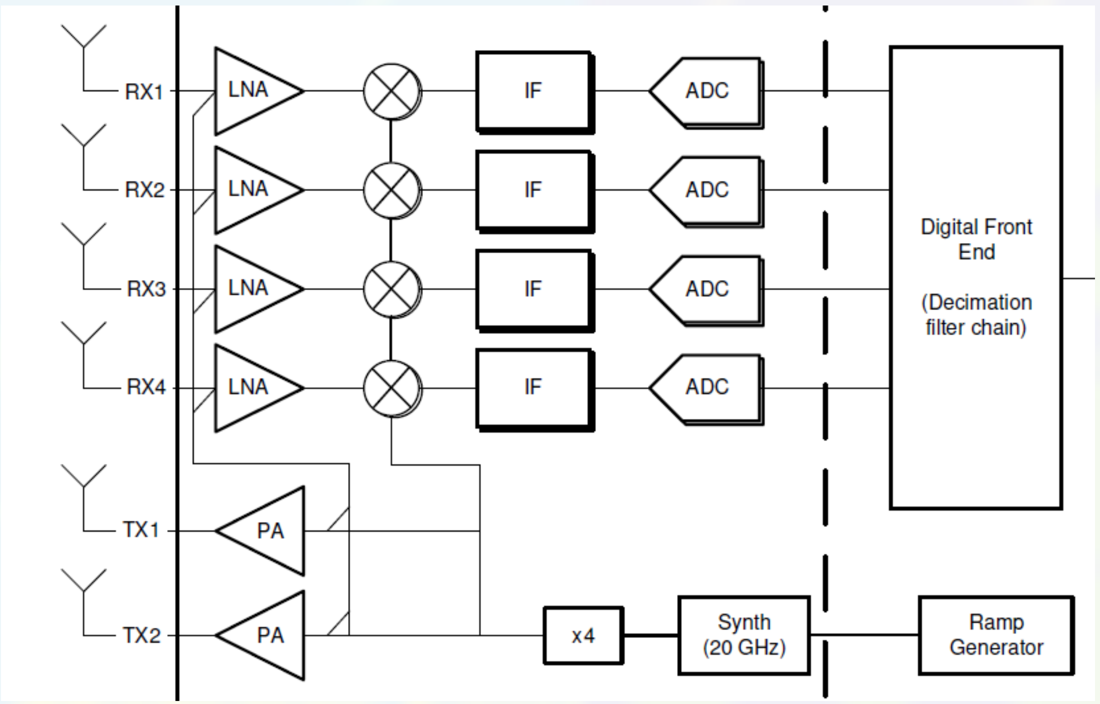


B

MIMO



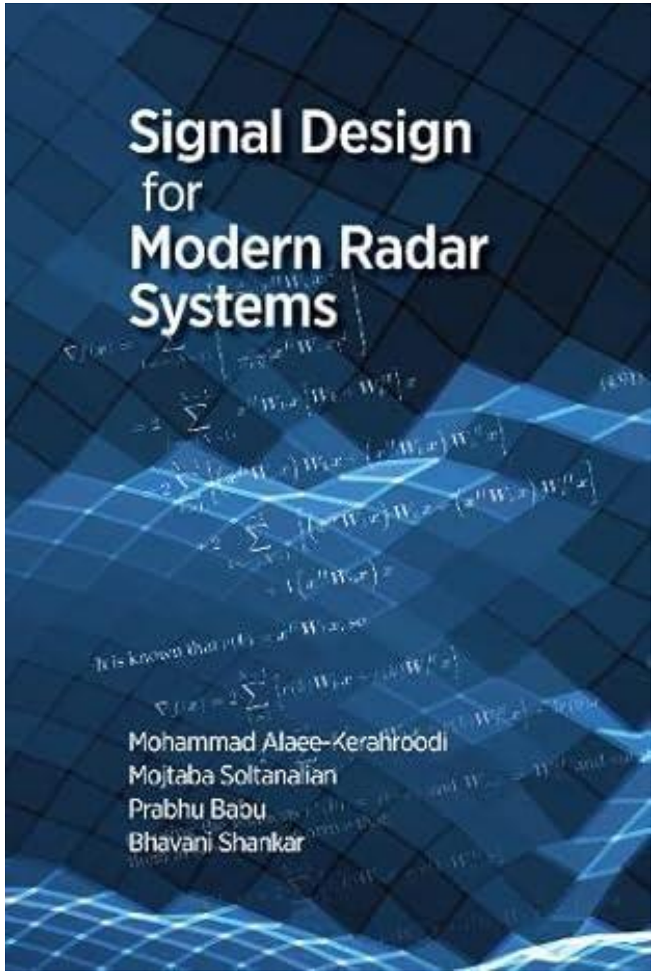
AWR1642 Single-Chip 77- and 79-GHz FMCW Radar sensor



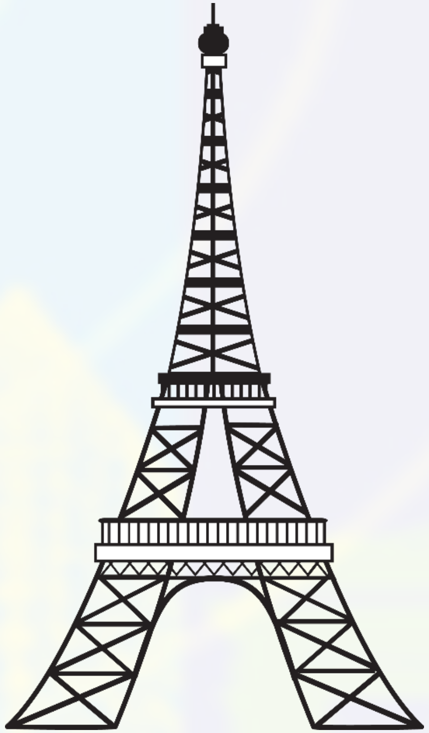
https://www.ti.com/product/AWR1642

What could be waveform for MIMO Radars?

Learn More!



Alaee-Kerahroodi, Mohammad, et al. *Signal design for modern radar systems*. Artech House, 2022.



Thanks!