http://www.mit.edu/~fadel/courses/MAS.s60/index.html

MAS.S60

How to Wirelessly Sense Almost Anything

Lecture 8:
Millimeter Waves

Lecturers

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TA

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This Week in Millimeter Waves

The New York Times

What Are Those Mysterious New Towers Looming Over New York's Sidewalks?

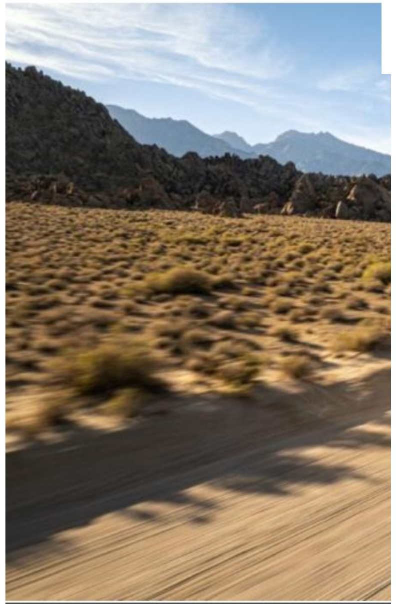
As the city upgrades to 5G wireless, the streetscape is changing. Not everyone is impressed.

Give this article

SN NEWS OPINION LAUNCH CIVIL COMMERCIAL MILITARY POL

New Starlink dish kit object'

by Jason Rainbow — October 26, 2022



Starlink can be used by any moving land
Musk. Credit: SpaceX

BREAKING DEFENSE

Special Features

AIR WARFARE, SPONSORED POST

Why countering small UAS and swarms demands highly capable radars

Threatened by drones that can work collaboratively and without GPS or a command link, it's important to have radars that can detect hundreds of incoming tracks so they can be defeated.

presented by RADA USA

RADA's RPS-82 (ieMHR) radar can detect a Group 1 drone at 10 kilometers, and if a target is bigger than Group 1 it can see even farther than that. Photo courtesy of RADA.

How to Wirelessly Sense Almost Anything

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals themselves

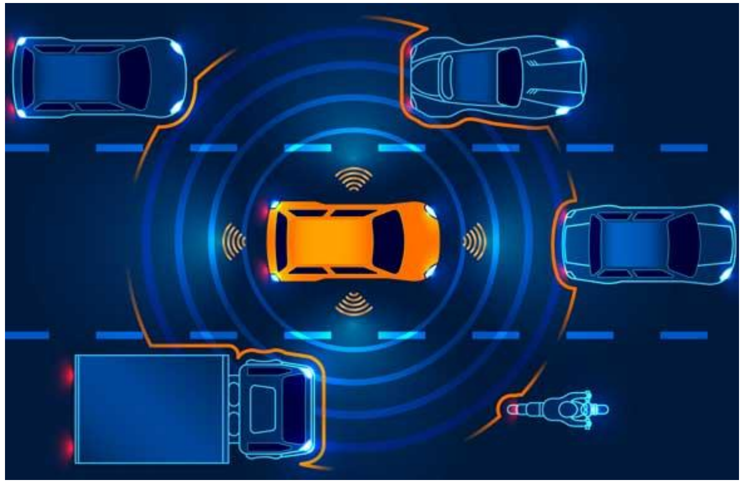
This lecture is a combination of both

Objectives of Today’s Lecture

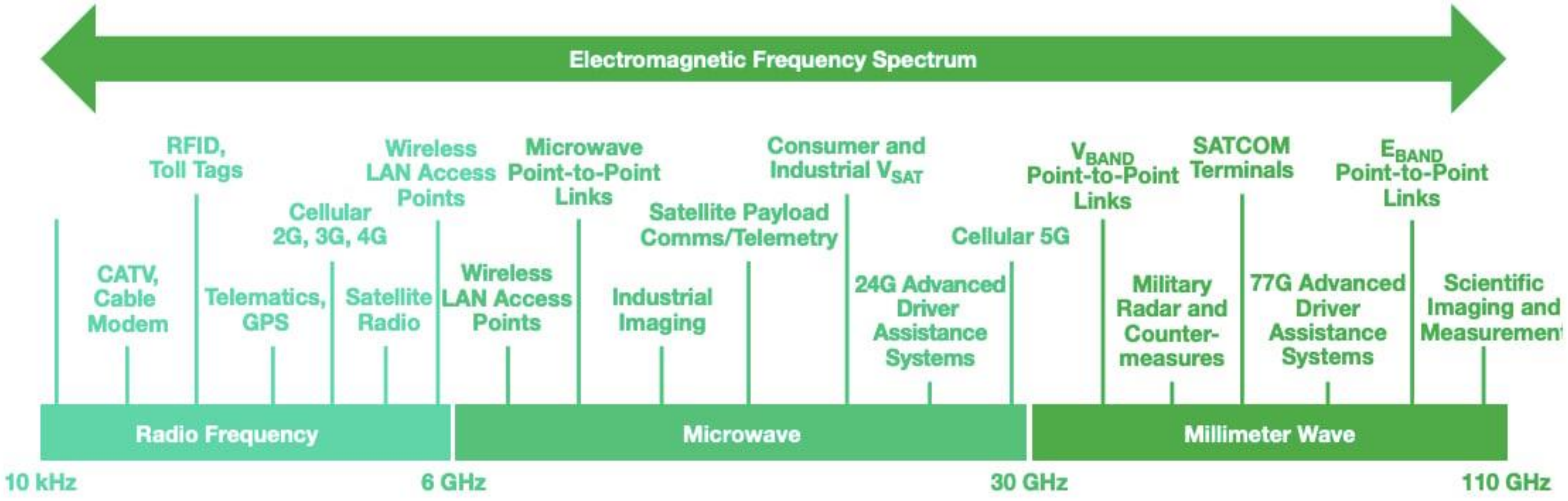
Learn the fundamentals of mm-wave technology and its major applications

1. Why is mm-wave technology attractive?
2. What are the major applications of mm-wave technology?
3. What are the enabling technological advances?
4. How does FMCW radar work?
5. Do mm-wave RFIDs exist and what role can they play?

Millimeter wave Technology

Millimeter waves in the EM Spectrum



Why millimeter waves?

Why Now?

Higher Data Rates

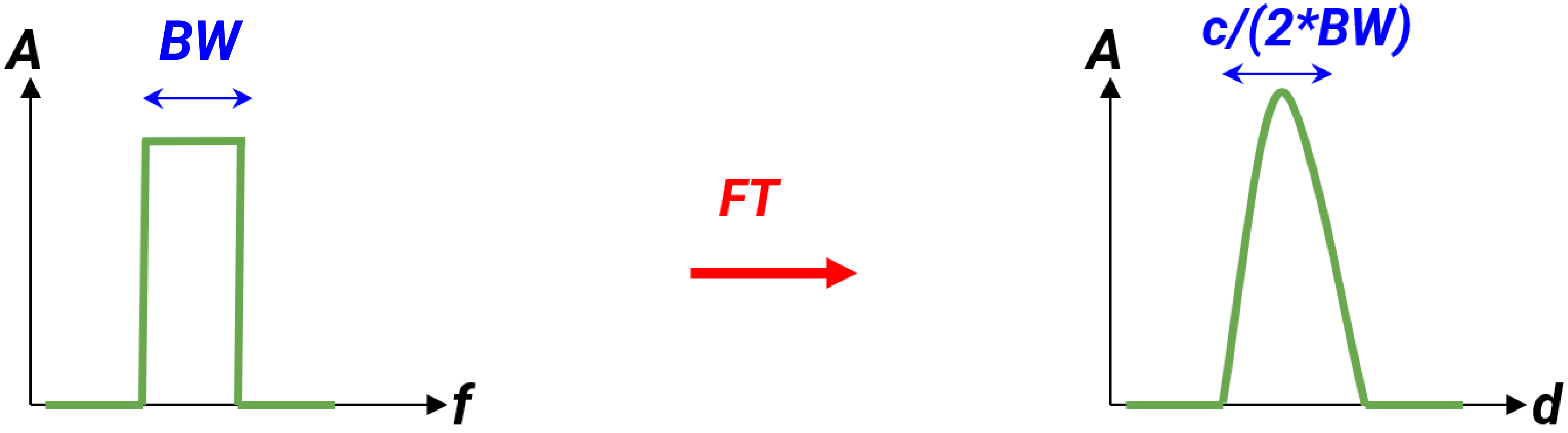
Large Bandwidth → High data rates

Shannon capacity:

$$C = B \log_2 (1 + S/N)$$

C is the channel capacity in bits per second (or maximum rate of data)
B is the bandwidth in Hz available for data transmission
S is the received signal power
N is the total channel noise power across bandwidth B

Higher Range Resolution

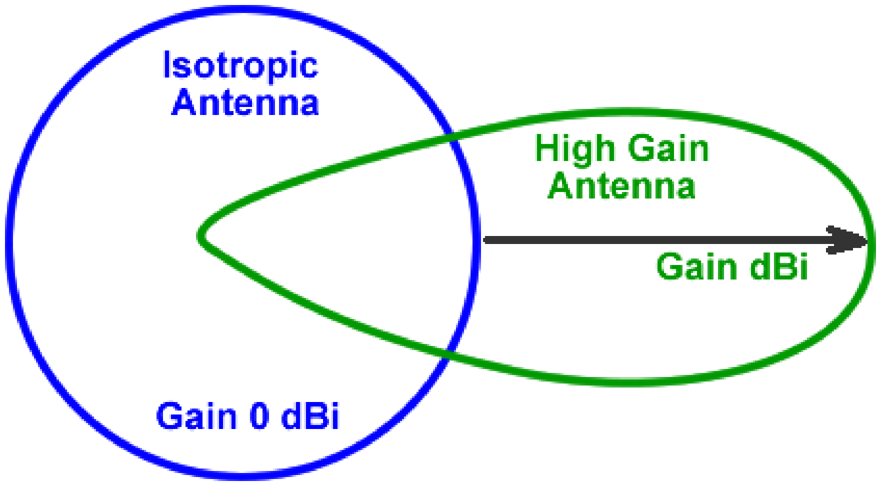


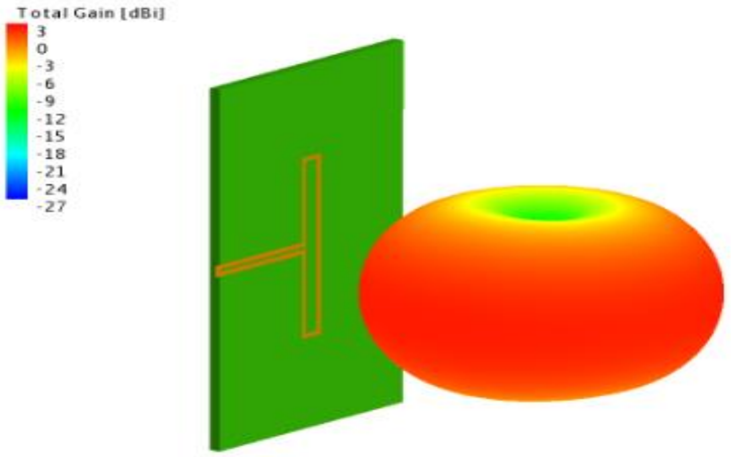
- **UHF (900MHz):** 25MHz of BW → 6m
- **24GHz Radars:** 250 MHz of BW → 60cm
- **Automotive Radars (77GHz):** 5GHz of BW → 3cm

Antenna Arrays

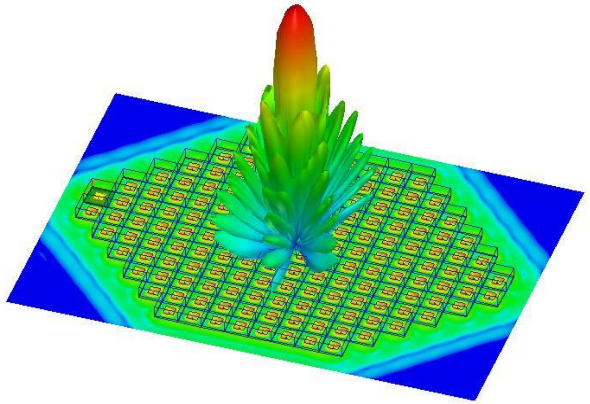
<u>Gain:</u> Measure of how well you can focalize your power

$$G_r = \frac{A_r 4\pi}{\lambda^2}$$





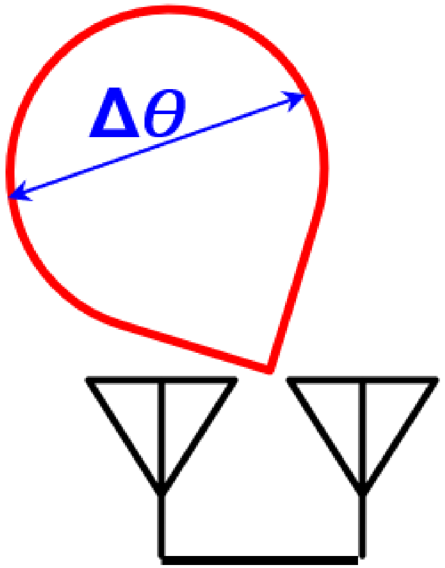
900 MHz

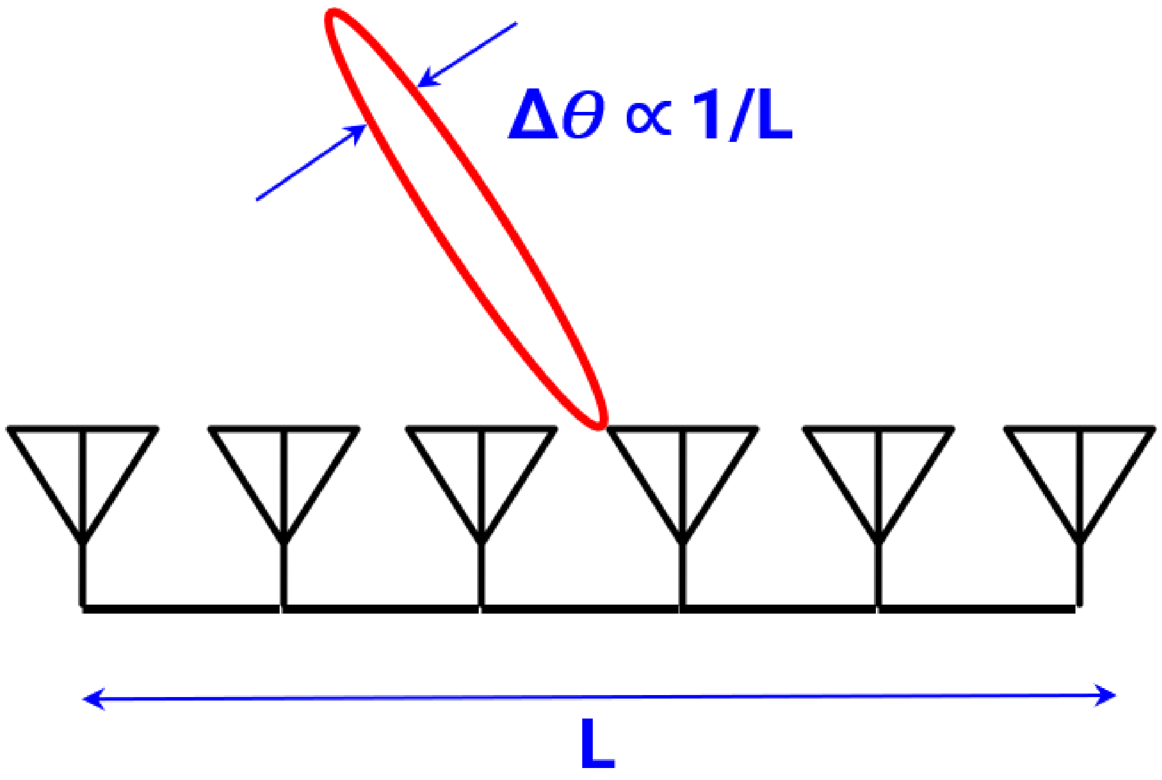


24 GHz

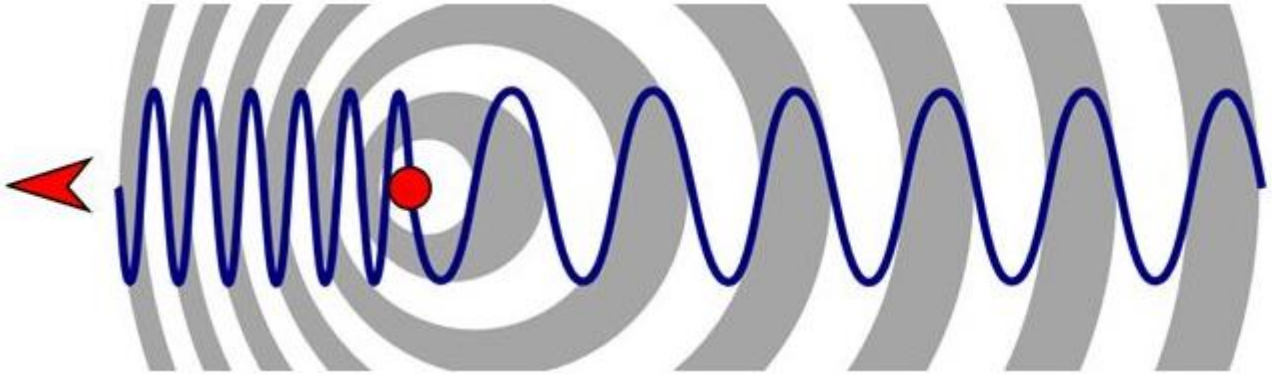
Higher Angular Resolution

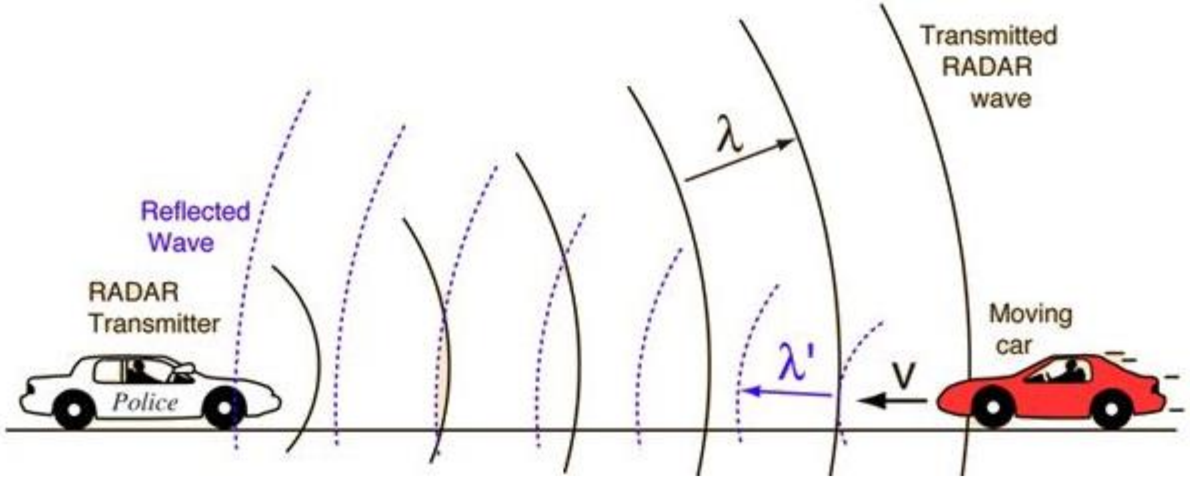
- Large Antenna Arrays





Doppler Effect

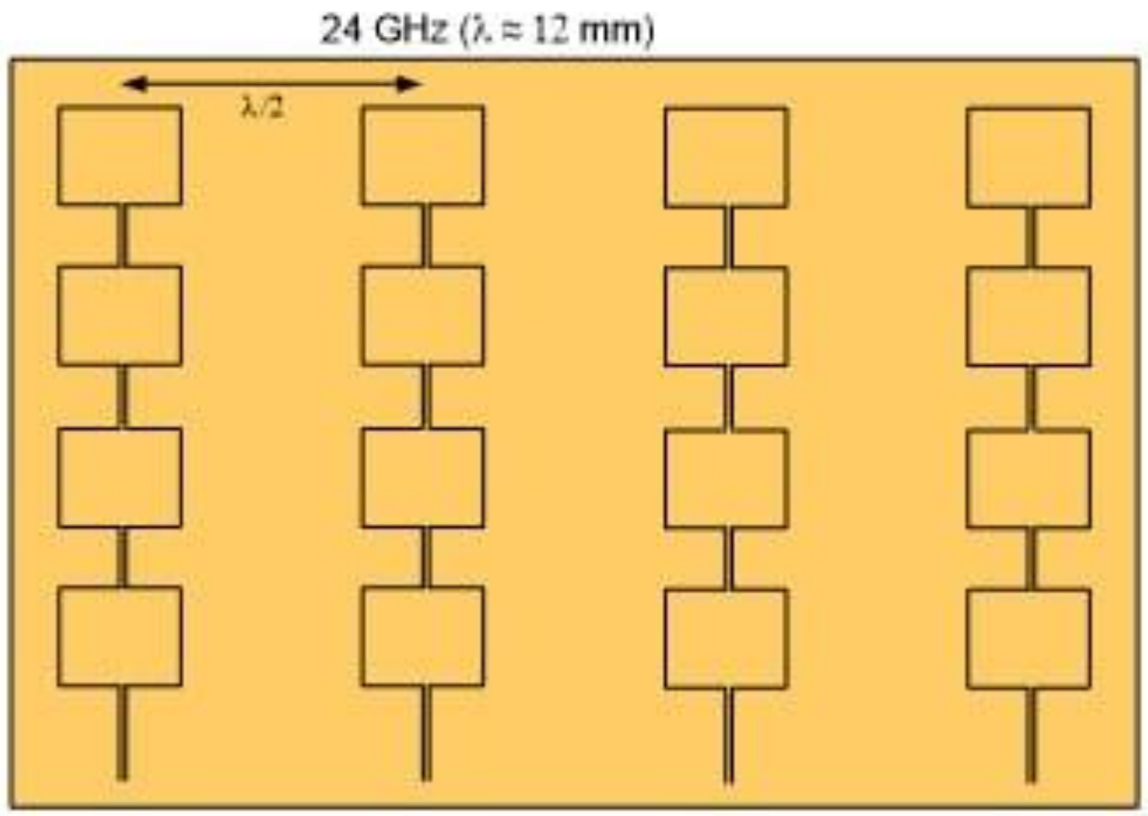


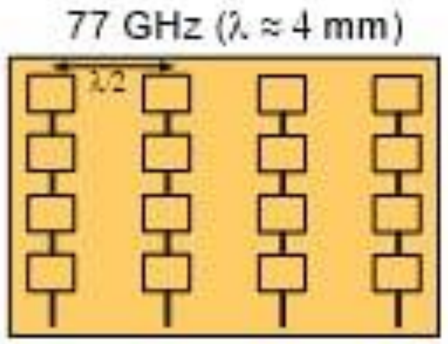


$$\Delta f = \frac{2\Delta v}{c} f_0$$

Miniaturization and Flexibility

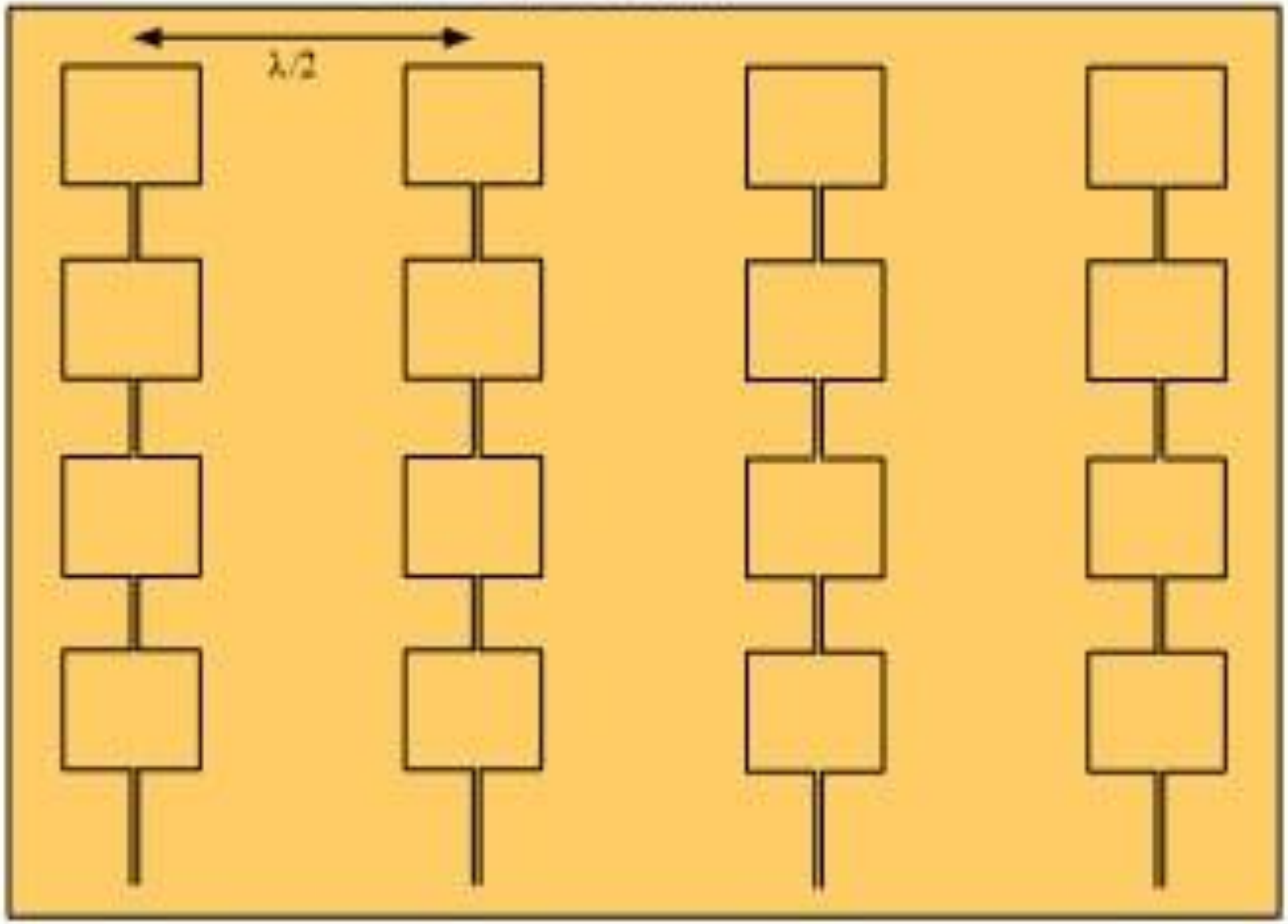
- Compact and easy to miniaturize
- Easier to design on flexible substrates



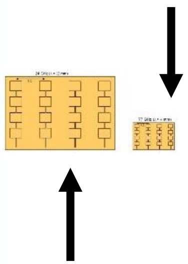


Miniaturization

2.4GHz (λ= 12cm)

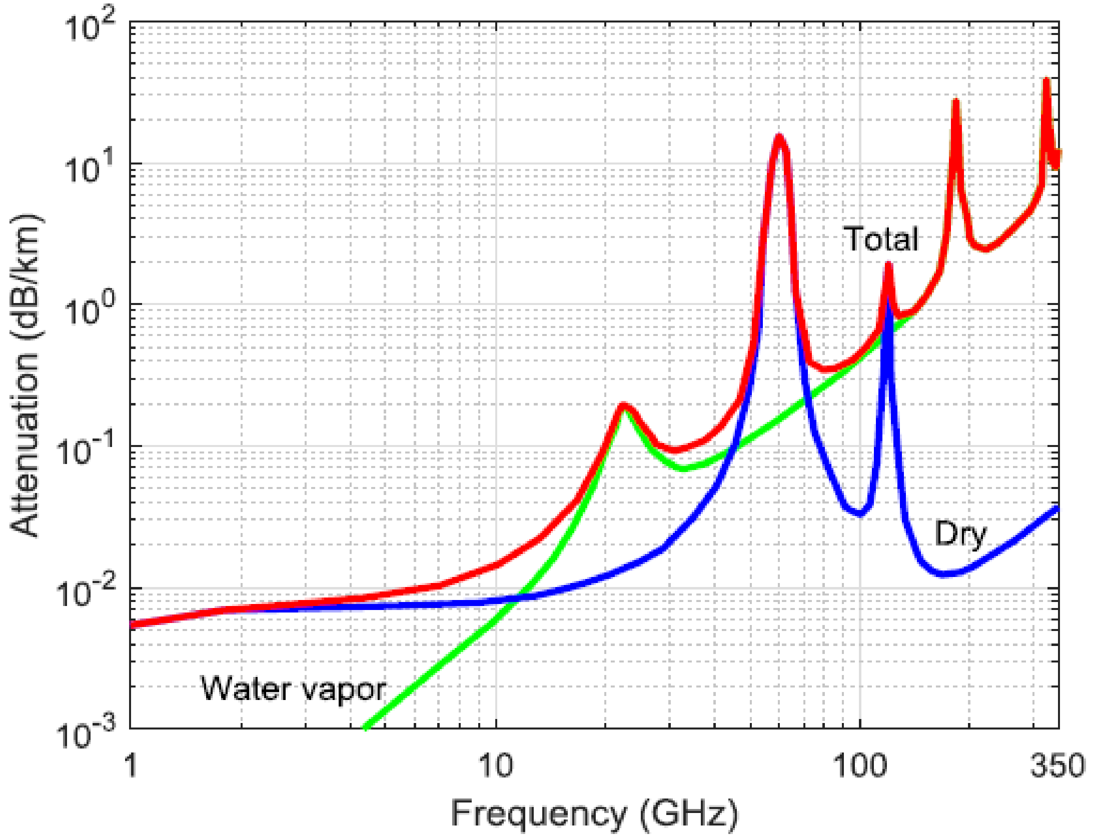


77 GHz (λ= 4 mm)



24 GHz (λ= 12 mm)

Challenge: Atmospheric Attenuation



Specific atmospheric attenuation versus frequency [2]. Pressure = 1 atm = 101.325 kPa, temperature = 15°C, water vapor density = 7.5 g/m3.

- mm-waves are susceptible to attenuation under moist conditions
- Below 50 GHz and between 70-110GHz: attenuation < 1dB/km
- With torrential rain (50mm/hour): scattering loss is 10dB/km at 30GHz

Harvey, James F., Michael B. Steer, and Theodore S. Rappaport. "Exploiting high millimeter wave bands for military communications, applications, and design." IEEE Access 7 (2019): 52350-52359.

Challenge: Path Loss

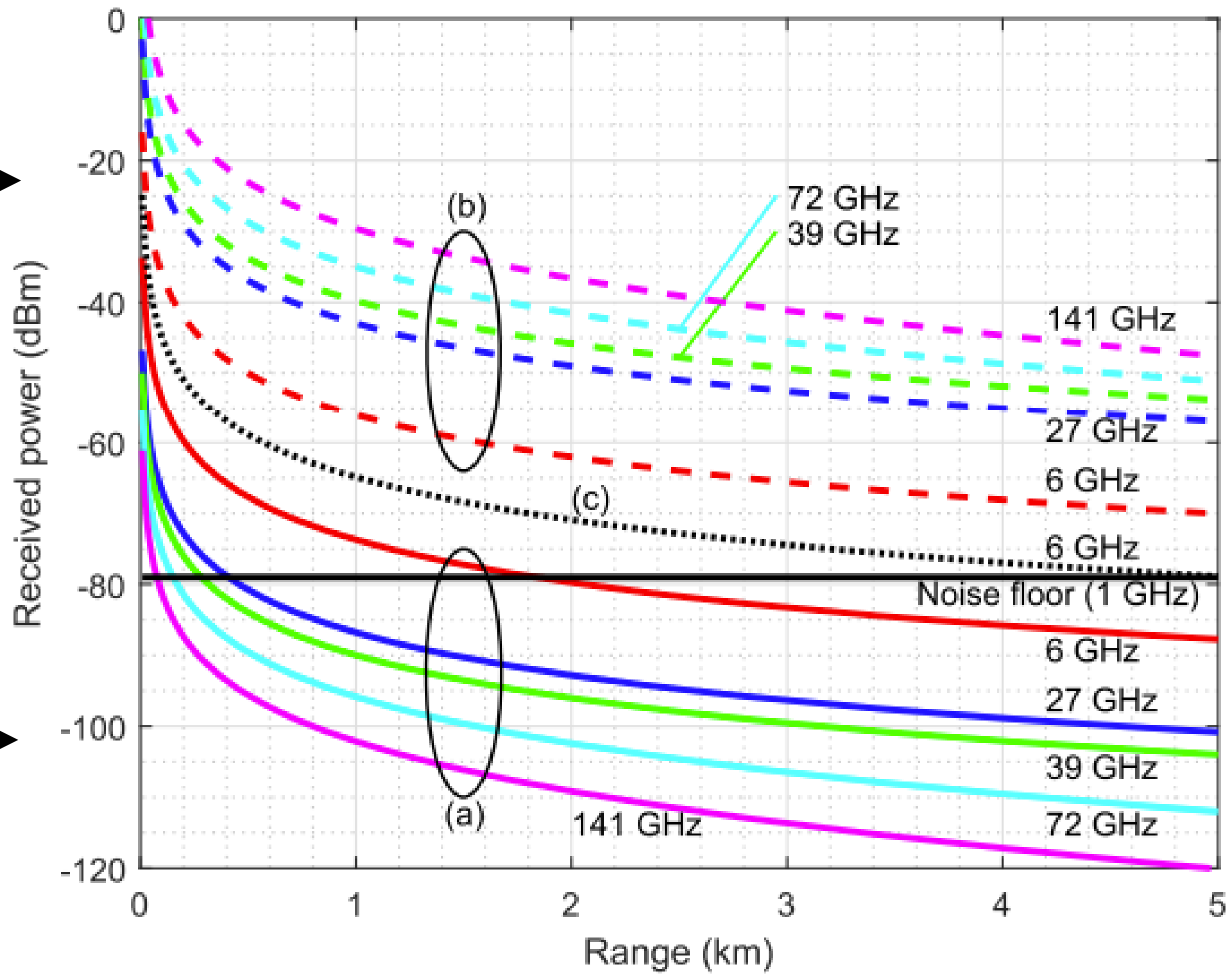
$$G_r = \frac{A_r 4\pi}{\lambda^2}$$

(b)

f (GHz)	λ (cm)	N	D_t	D_r	A_e (cm^2)	Beam-width
6	5	4	12.6	12.6	25	52.6°
27	1.11	81	254	254	25	11.3°
39	0.769	169	531	531	25	7.82°
72	0.417	576	1810	1810	25	4.23°
141	0.213	2209	6940	6940	25	2.16°

(a)

f (GHz)	λ (cm)	N	D_t	D_r	A_e (cm^2)	Beam-width
6	5.00	1	1.64	1.64	3.26	360°
27	1.11	1	1.64	1.64	0.161	360°
39	0.769	1	1.64	1.64	0.0772	360°
72	0.417	1	1.64	1.64	0.0227	360°
141	0.213	1	1.64	1.64	0.00592	360°



Harvey, James F., Michael B. Steer, and Theodore S. Rappaport. "Exploiting high millimeter wave bands for military communications, applications, and design." IEEE Access 7 (2019): 52350-52359.

Diving into the Major Applications

Mm-waves for:

- Military/Defense
- Starlink/Space
- 5G
- Automotive Industry

Mm-wave for Defense Applications

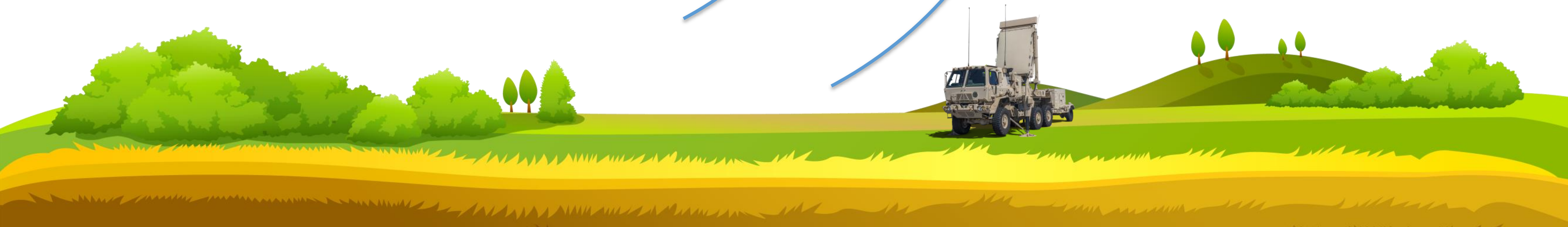
How are the properties of mm-waves important for radars?

- Count targets, localize them, identify them, track them, know their speed

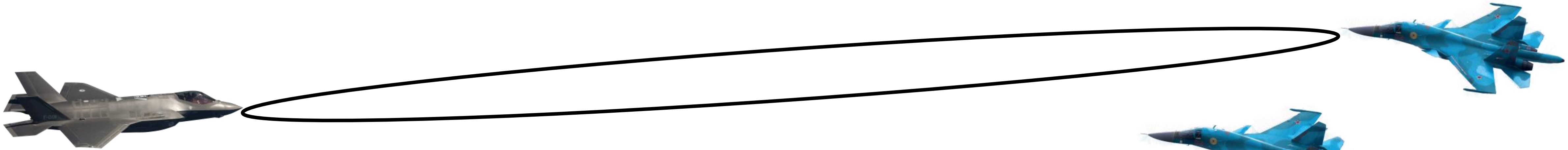
Radar: Detect target (VHF)

Problems:

- Everything looks like a target (including the ground)
- No ability to count targets (resolution)
- Easily detectable by ground radars

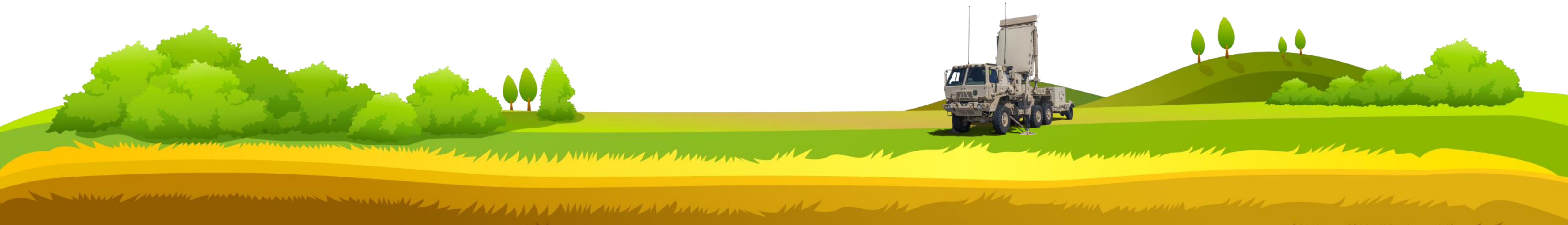


Radar: Directive array (X-band)



Problems:

- Needs to be steered
- Misses everything that is not in the beam

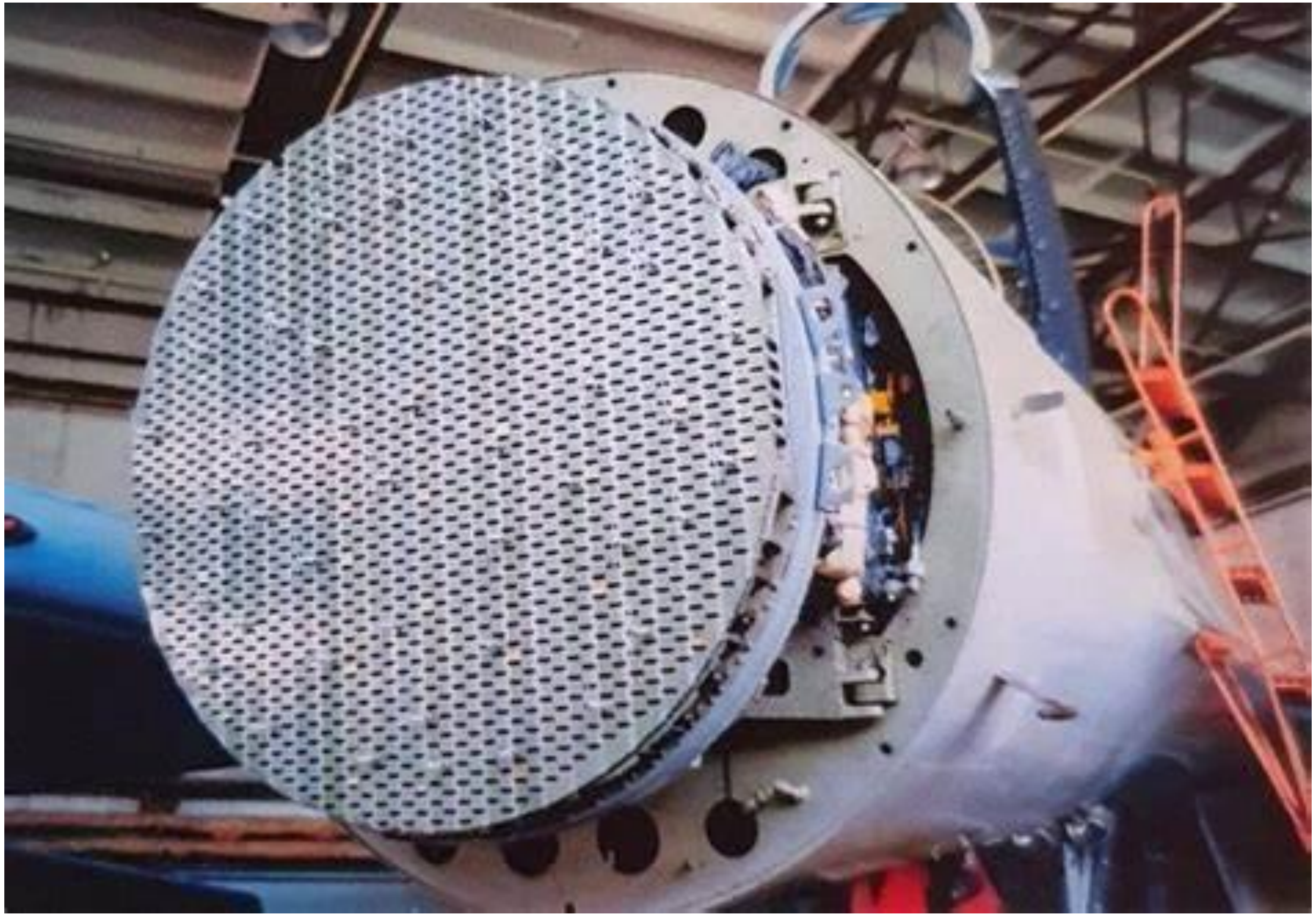


Mechanical Steering

Problems:

- Can only transmit and receive in one direction at a time
- Slow steering
- Unreliable mechanical elements

Passive Electronically Scanned Array (PESA)



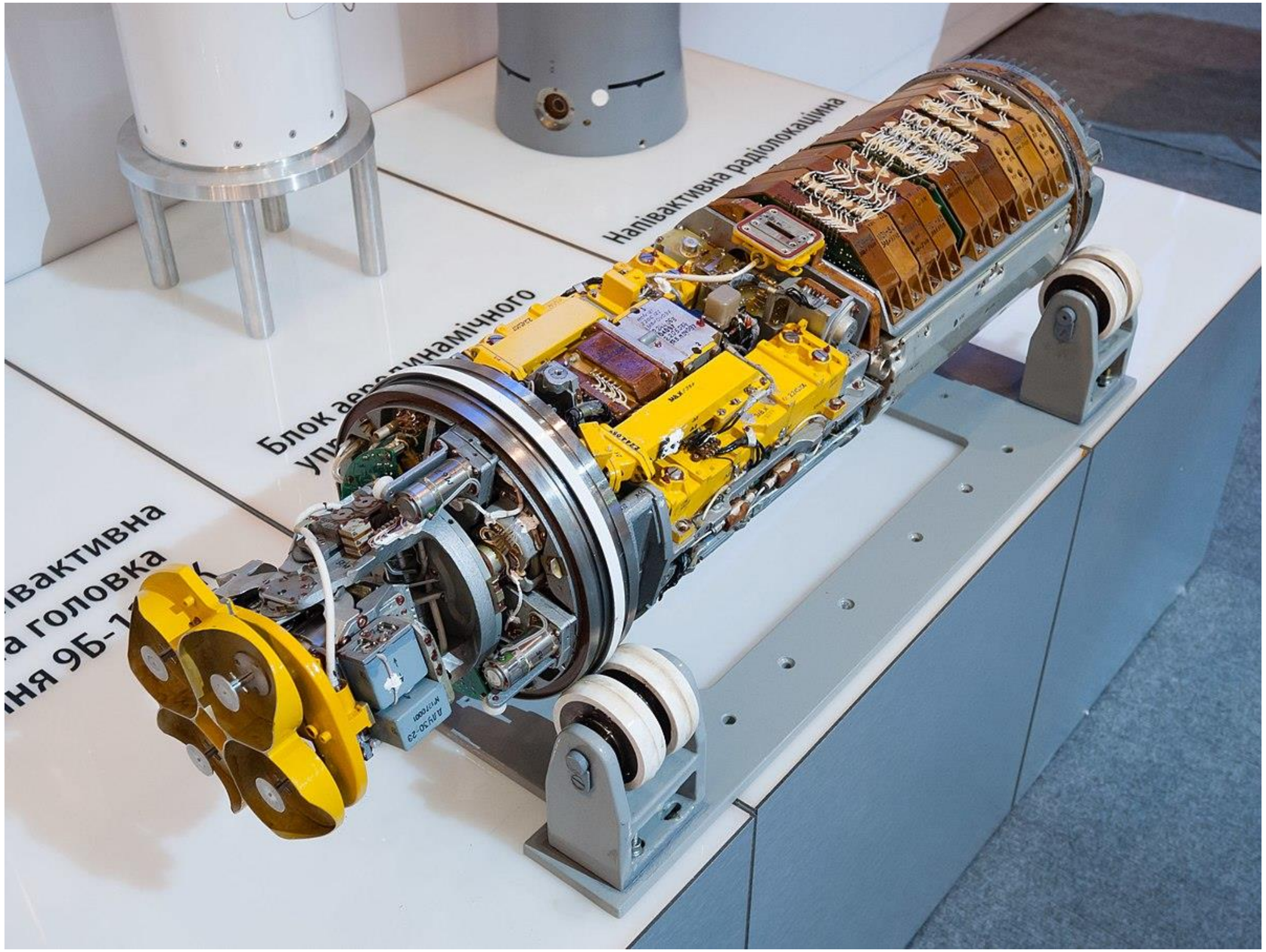
Benefits:

- Fast steering
- Can generate arbitrary radiation patterns

Problems:

- All antennas transmit the same signal

Passive radar-guided Missile



- Follows the reflection of the plane's radar signal projected onto the target

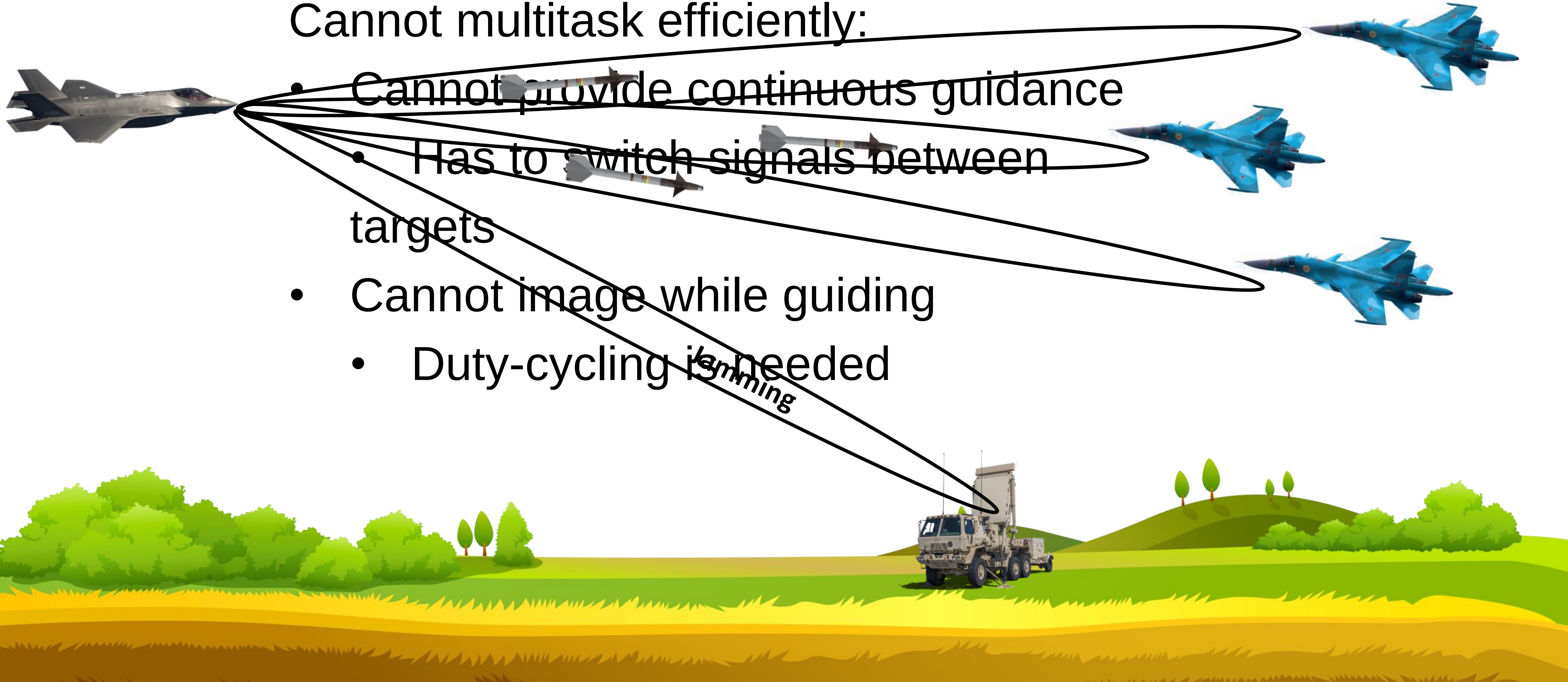
Advantages:

- Much longer range than IR-guided missiles
- More difficult to fool

Radar: Target illumination

Cannot multitask efficiently:

- Cannot provide continuous guidance
  - Has to switch signals between targets
- Cannot image while guiding
  - Duty-cycling is needed



Active Electronically Scanned Array (AESA)

Benefits:

- Can do everything at the same time
- Always receives signals from all directions
- Emminently reconfigurable (iPhone in the sky)

Problems:

- Very expensive
- Requires tons of computational power

The idea of Starlink

Established Satellite Internet:

- Ku (12-18GHz) and Ka band (26–40 GHz)
- GEO orbit (stationary in the sky, 22,236 mi away)
- High latency (600 ms)

Starlink:

- Multiple bands (10–51 GHz)
- LEO orbit (340 mi)
  - Path loss decreases by 4000x -> 36 dB better SNR (everything else equal)
  - Latency decreases by 60x

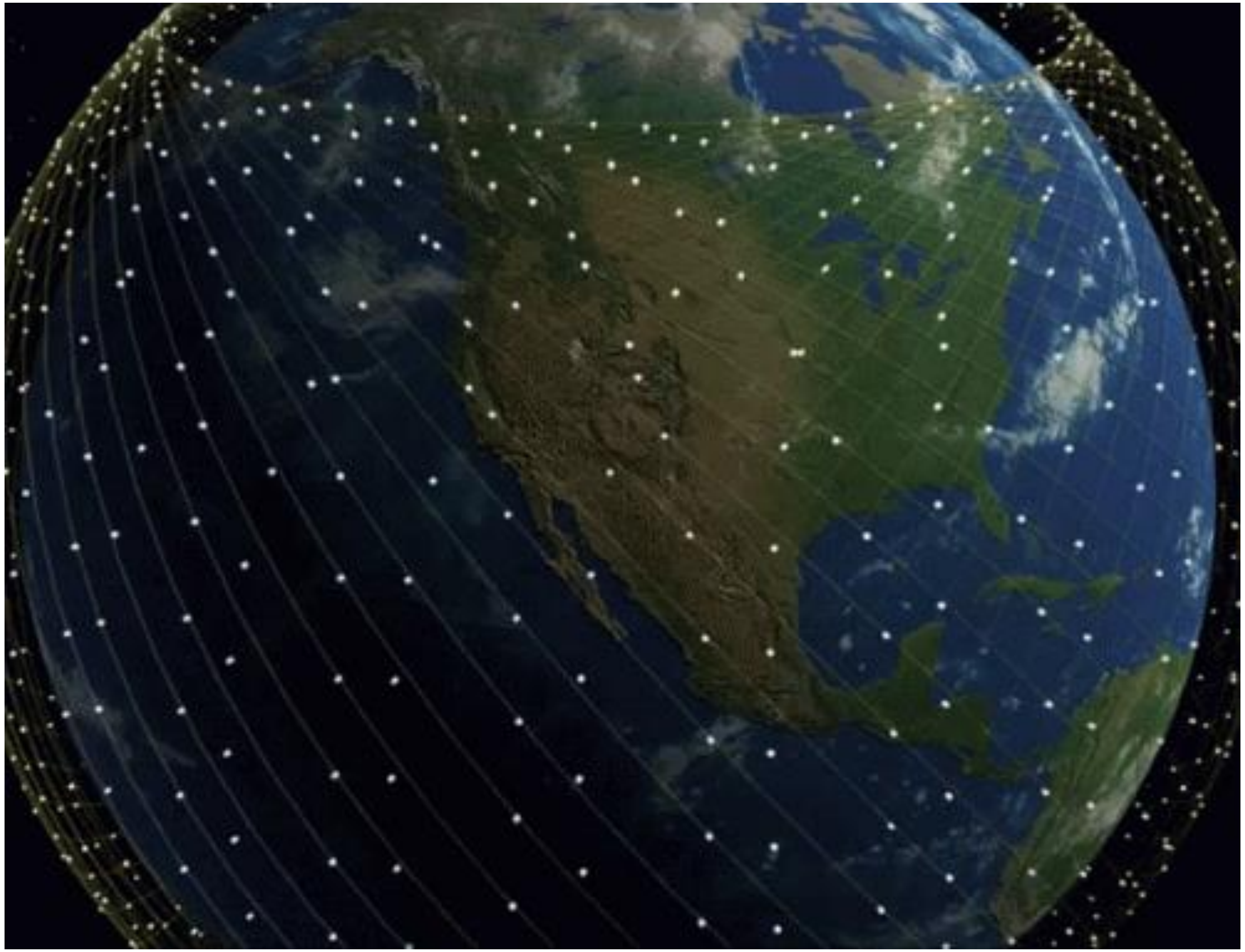
The idea of Starlink

Problems:

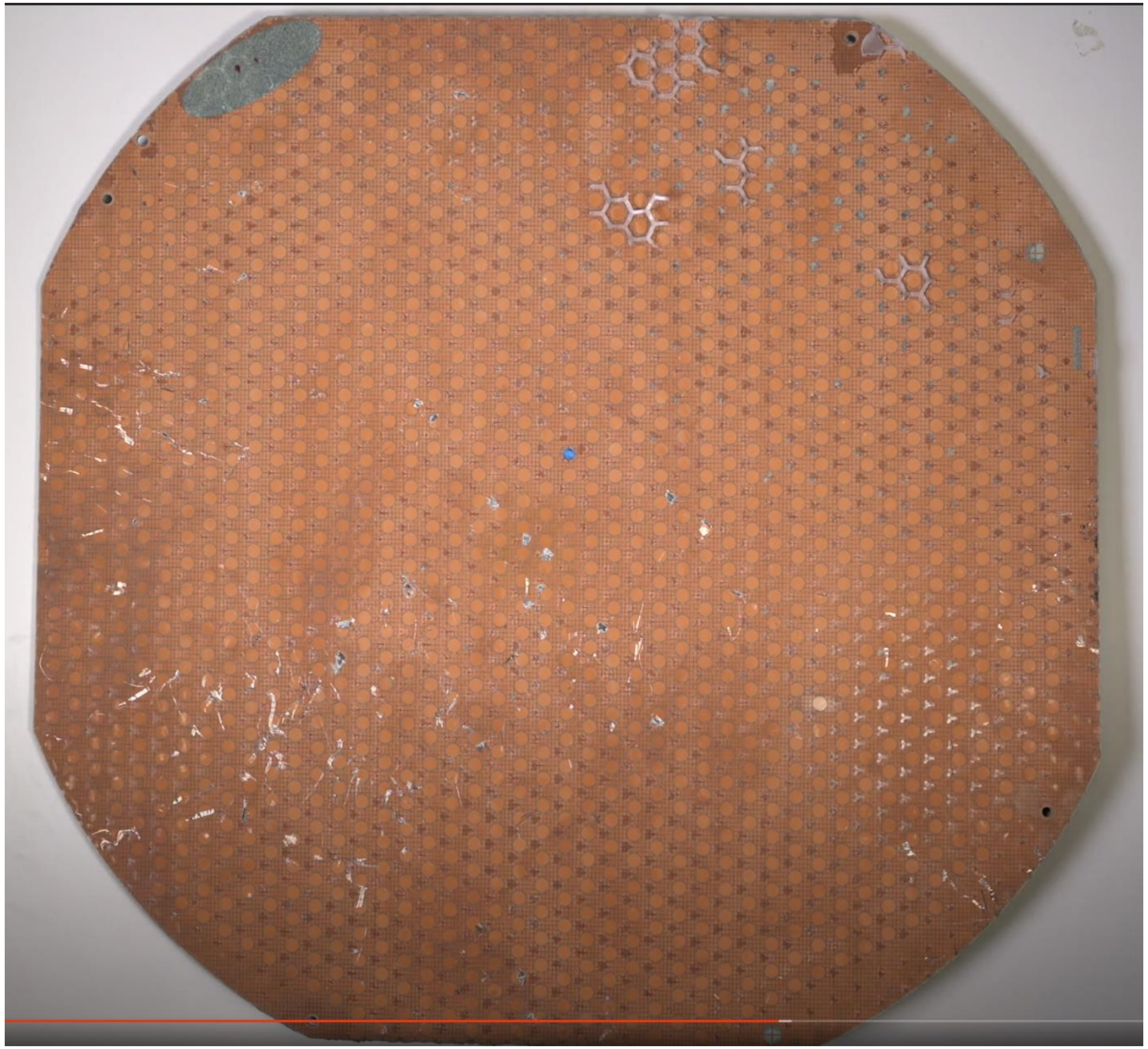
- Satellites zoom by quickly

Solution:

- Lots of satellites (about 60,000)
- Lots of ground base-stations
- Steerable arrays on both ends



Starlink terminal



YouTube Channel: The Signal Path

Hybrid Mechanical/PESA/AESA:

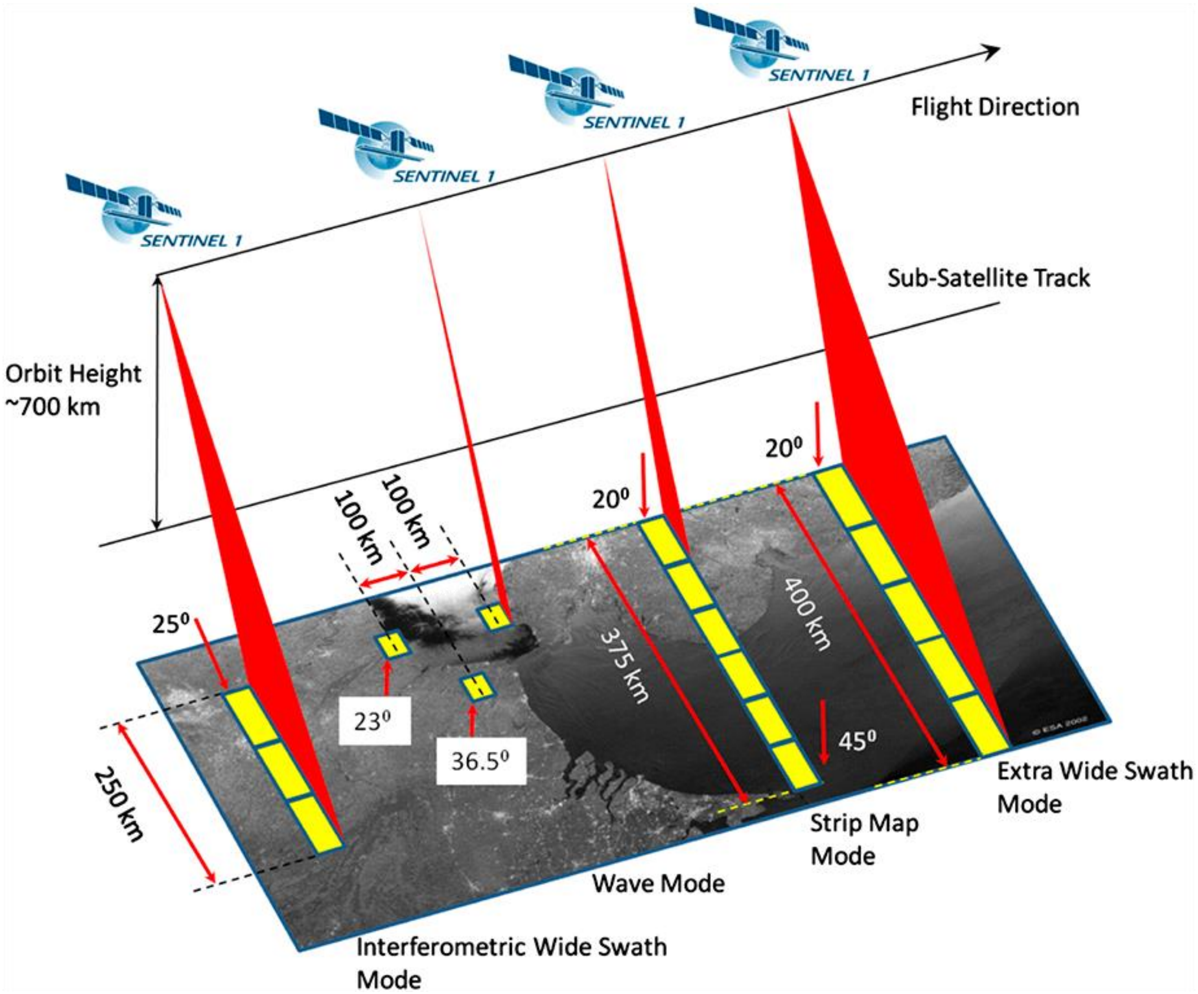
- Is mechanically tiltable
- Sub-arrays are PESA
- These are put together in AESA fashion

Benefits:

- Lowers the cost and size
- Not as sensitive to low manufacturing tolerances

Satellite Imaging with SAR

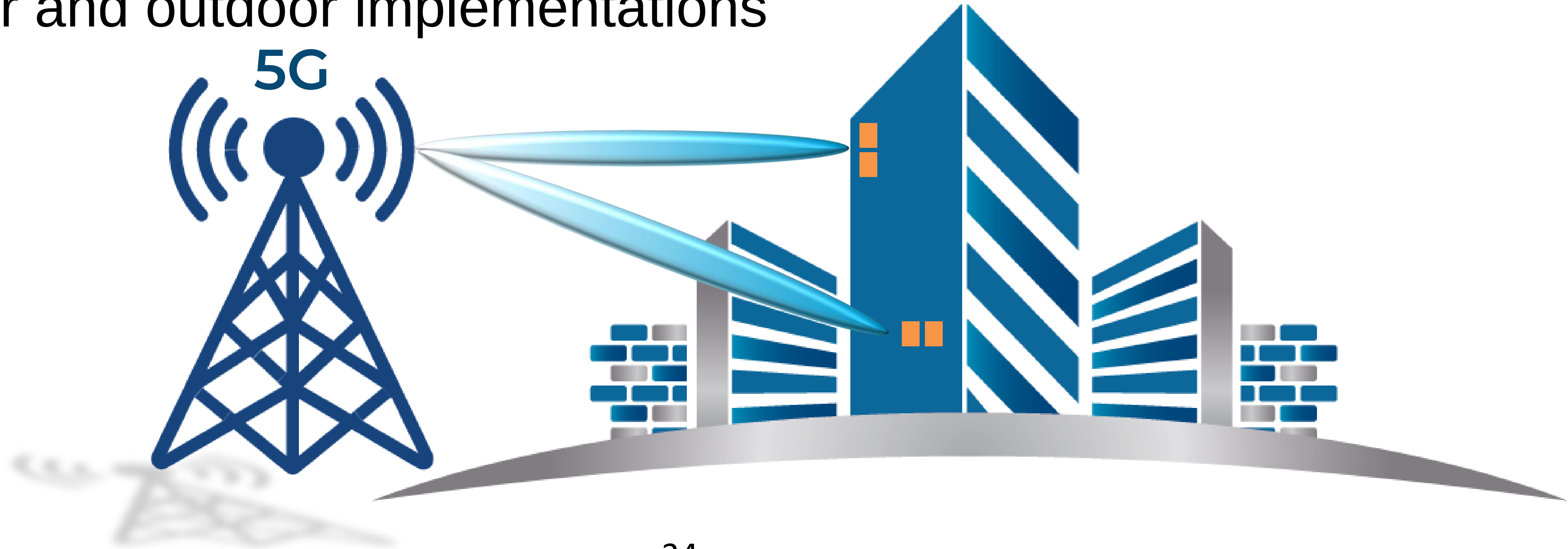
Satellite Imaging



Airport Scanners

5G/mm-waves

- Attractive to Telecom Companies due to high data rates
- <u>New Market: Powering</u>
  - High gain, High EIRP (75dBm)
  - Small Cell size (180m)
  - Indoor and outdoor implementations



Millimeter Waves in Automotive Industry

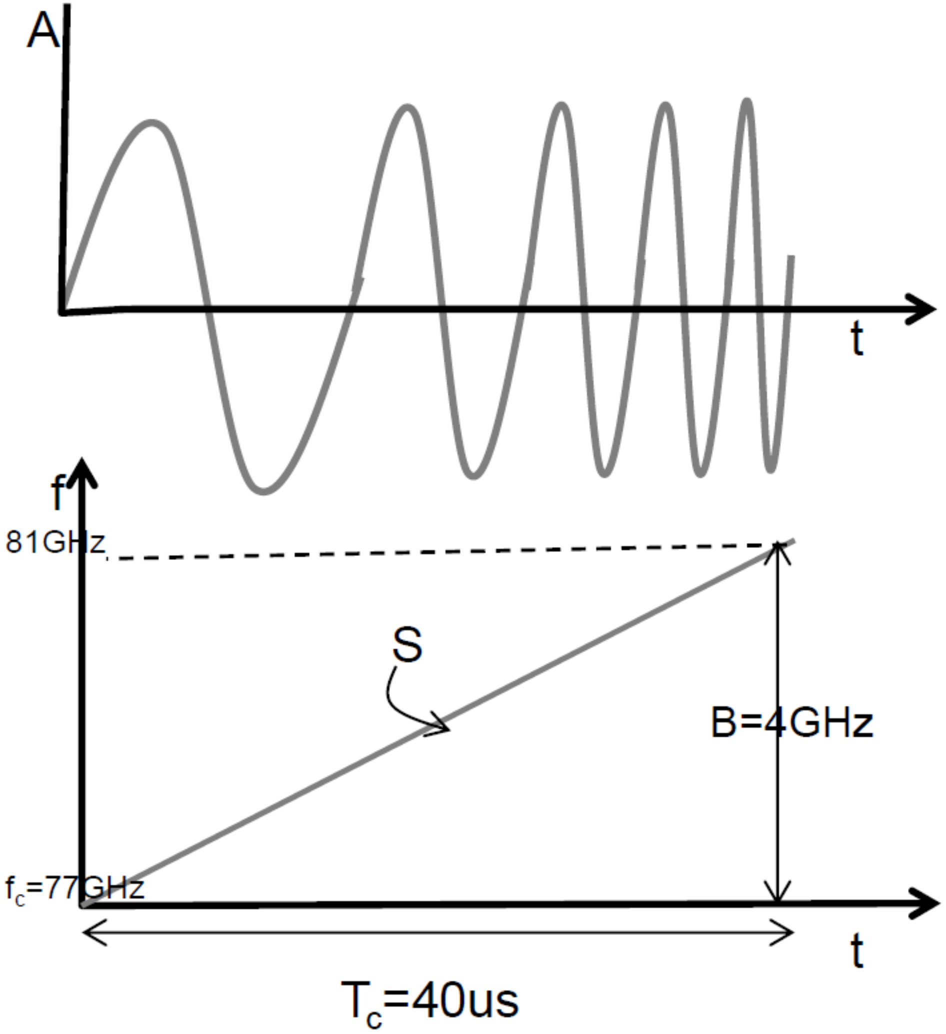
Why FMCW?

- Easy to integrate into silicon ICs (compared to pulse radars)
- Low IF bandwidth
- Run without interfering with each other (because of chirping)

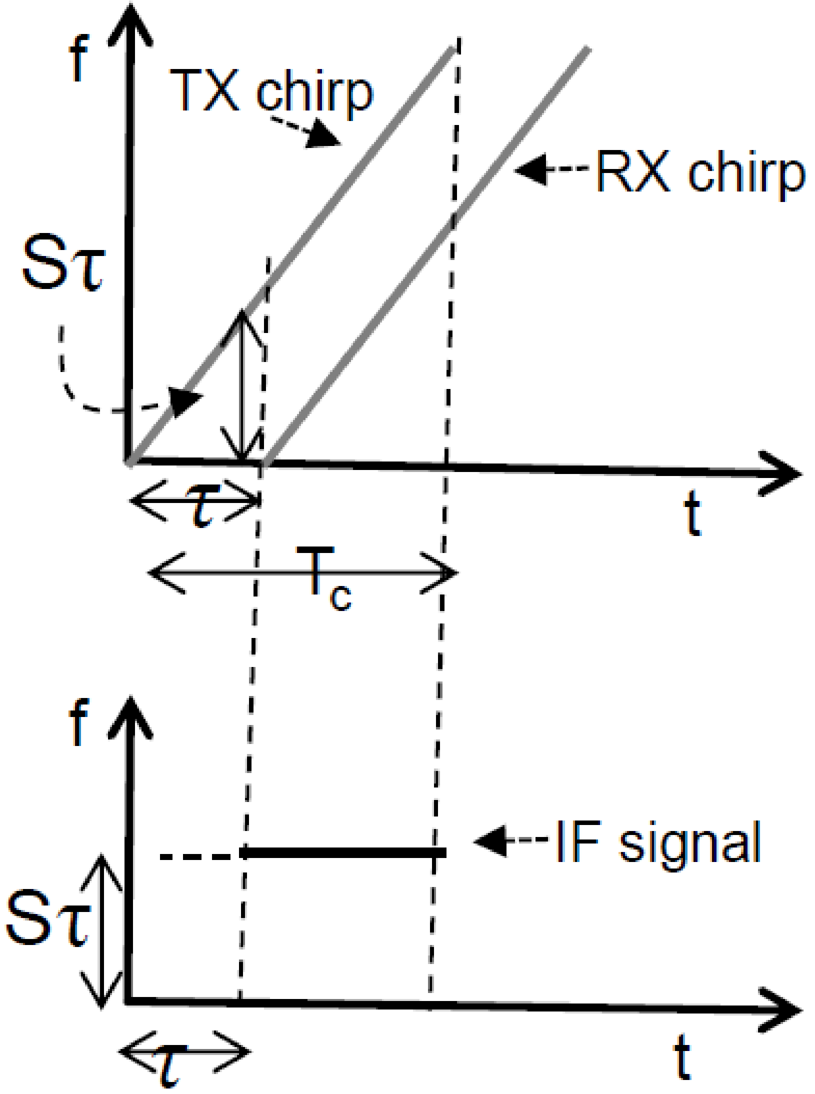
How does it work?

How do you localize, identify between targets?

What is a chirp?



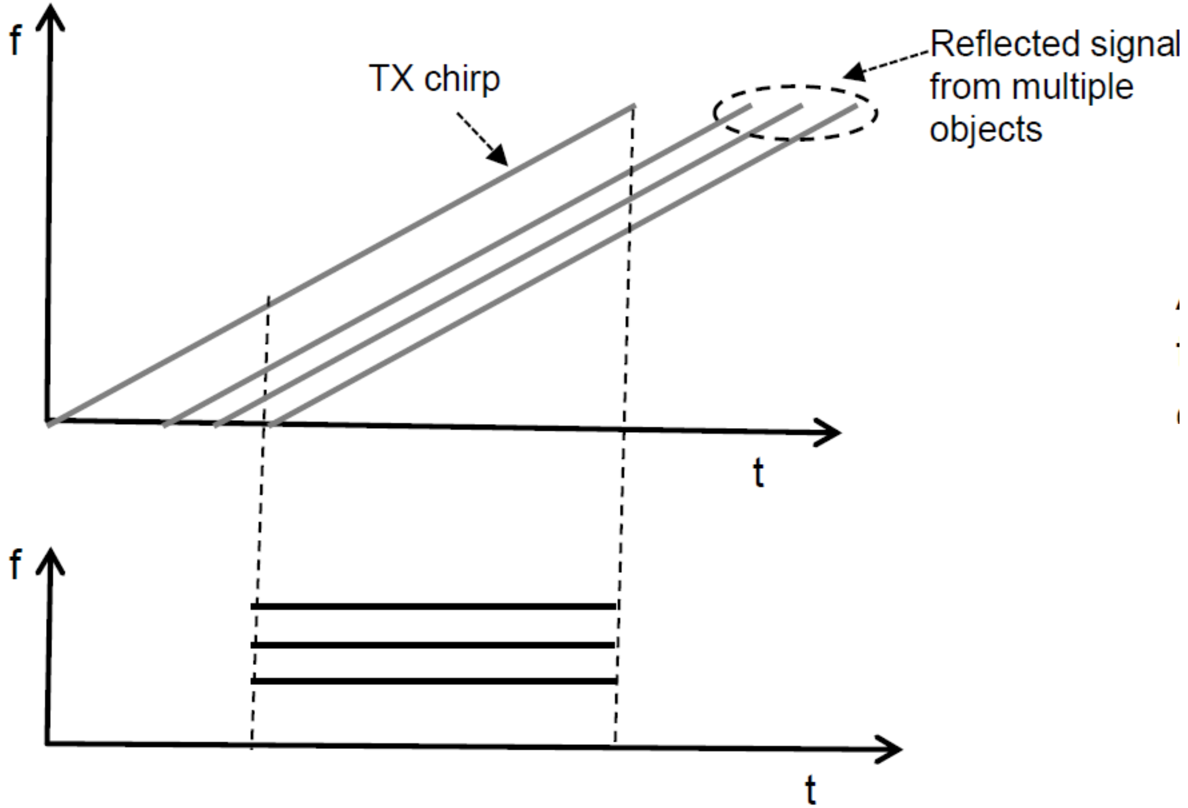
The IF signal



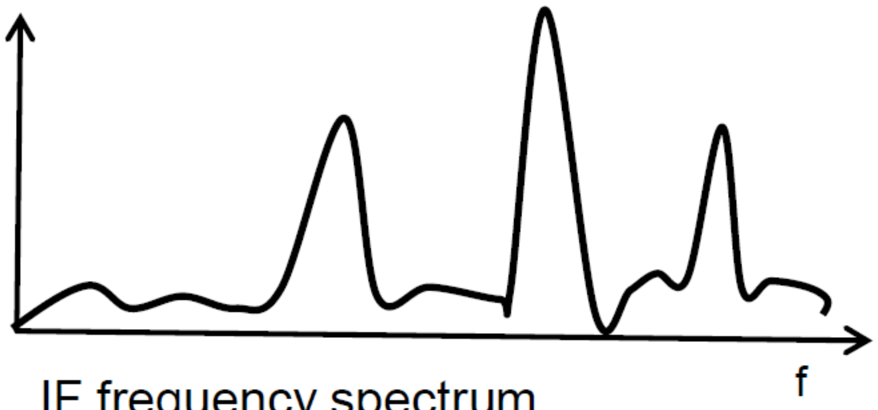
A single object in front of the radar produces an IF signal with a constant frequency of f_{beat} = S2d/c

Multiple objects in front of the radar

Multiple reflected chirps at the RX antenna

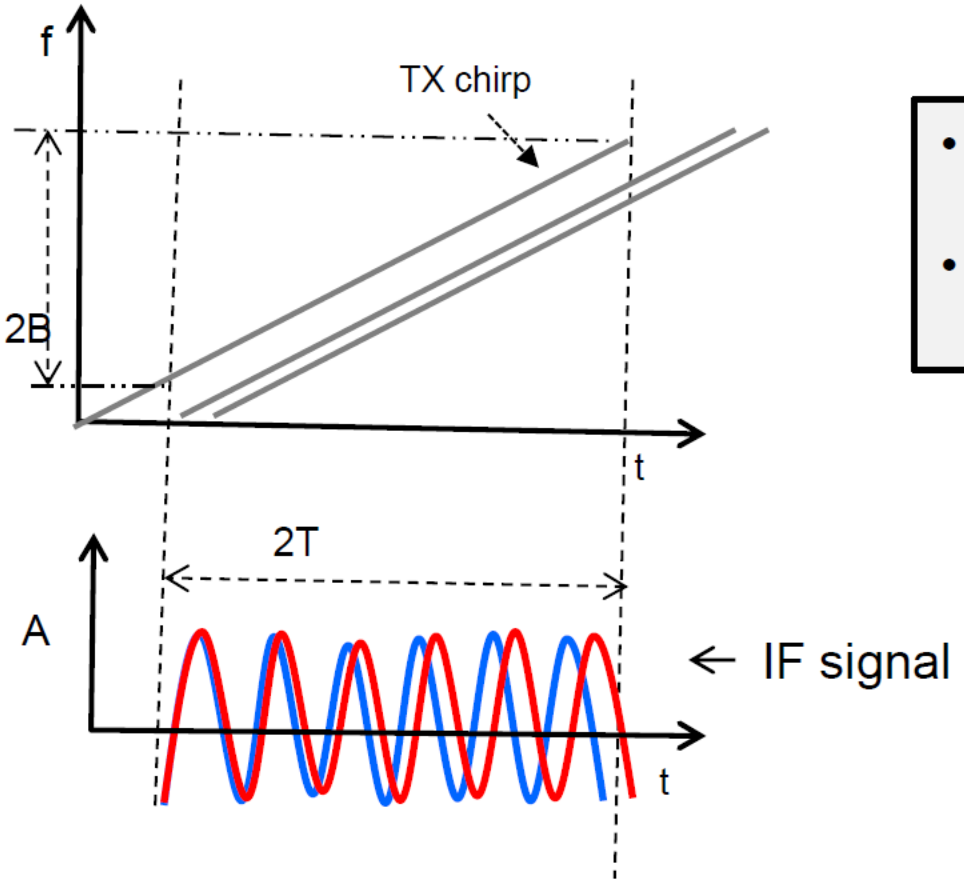


Multiple tones in the IF signal

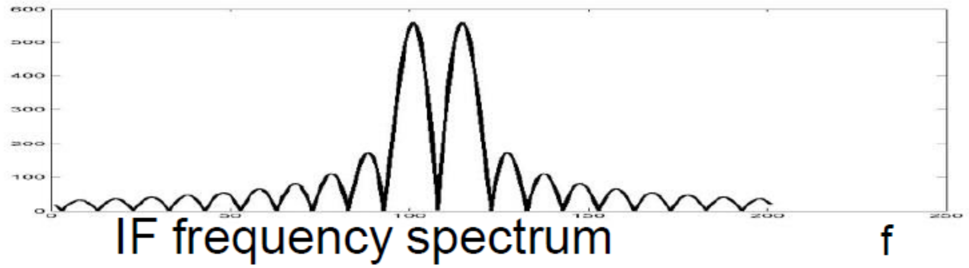


IF frequency spectrum

Range Resolution in a radar



- The two objects can be resolved by increasing the length of the IF signal.
- Note that this also proportionally increases the bandwidth. Thus intuitively: Greater the Bandwidth => better the resolution

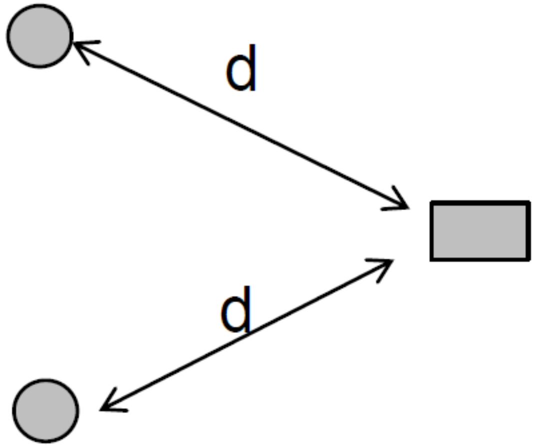


The Range Resolution (d_{res}) depends only on the Bandwidth swept by the chirp $d_{res} = c/2B$

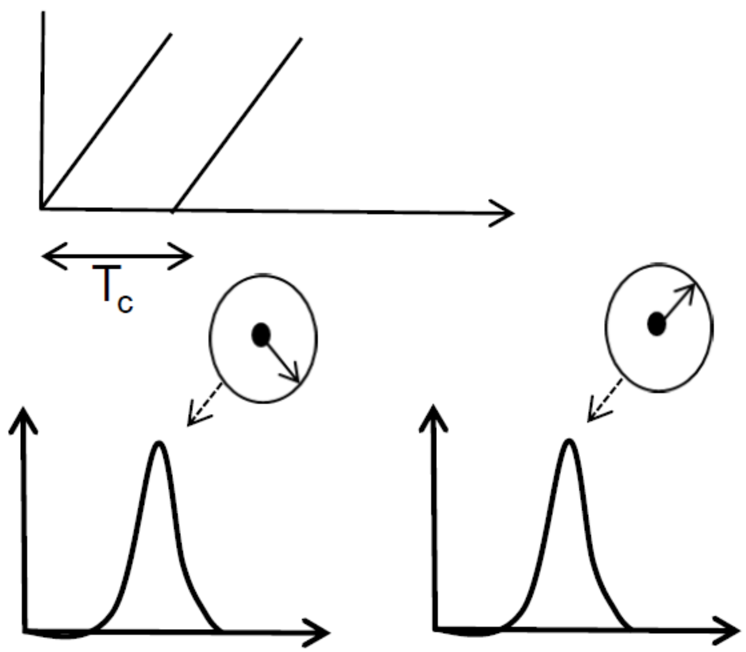
Texas Instruments

Question

- Two objects equidistant from the radar. How will the range–FFT look like?



How to measure the velocity (v) of an object using 2 chirps



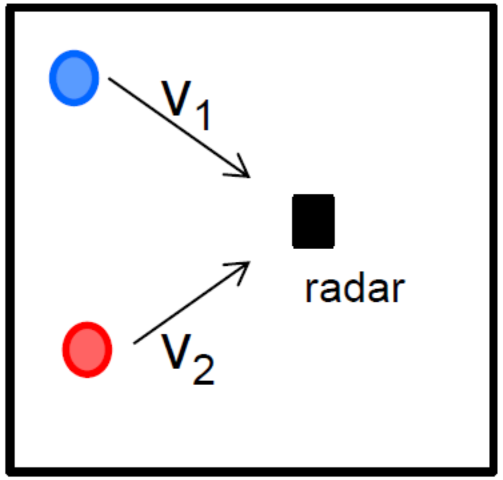
- Transmit two chirps separated by T_c
- The range-FFTs corresponding to each chirp will have peaks in the same location but with differing phase.
- The measured phase difference (ω) corresponds to a motion in the object of vT_c

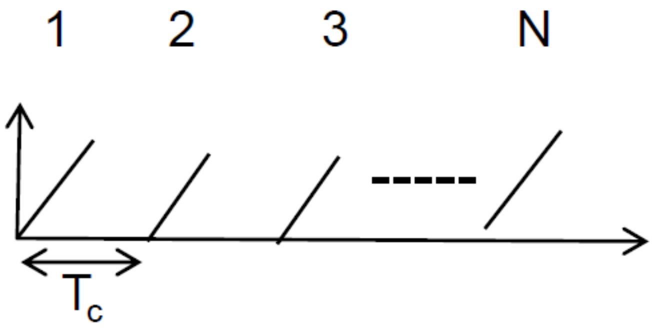
$$\omega = \frac{4\pi v T_c}{\lambda} \Rightarrow v = \frac{\lambda \omega}{4\pi T_c}$$

The phase difference measured across two consecutive chirps can be used to estimate the velocity of the object

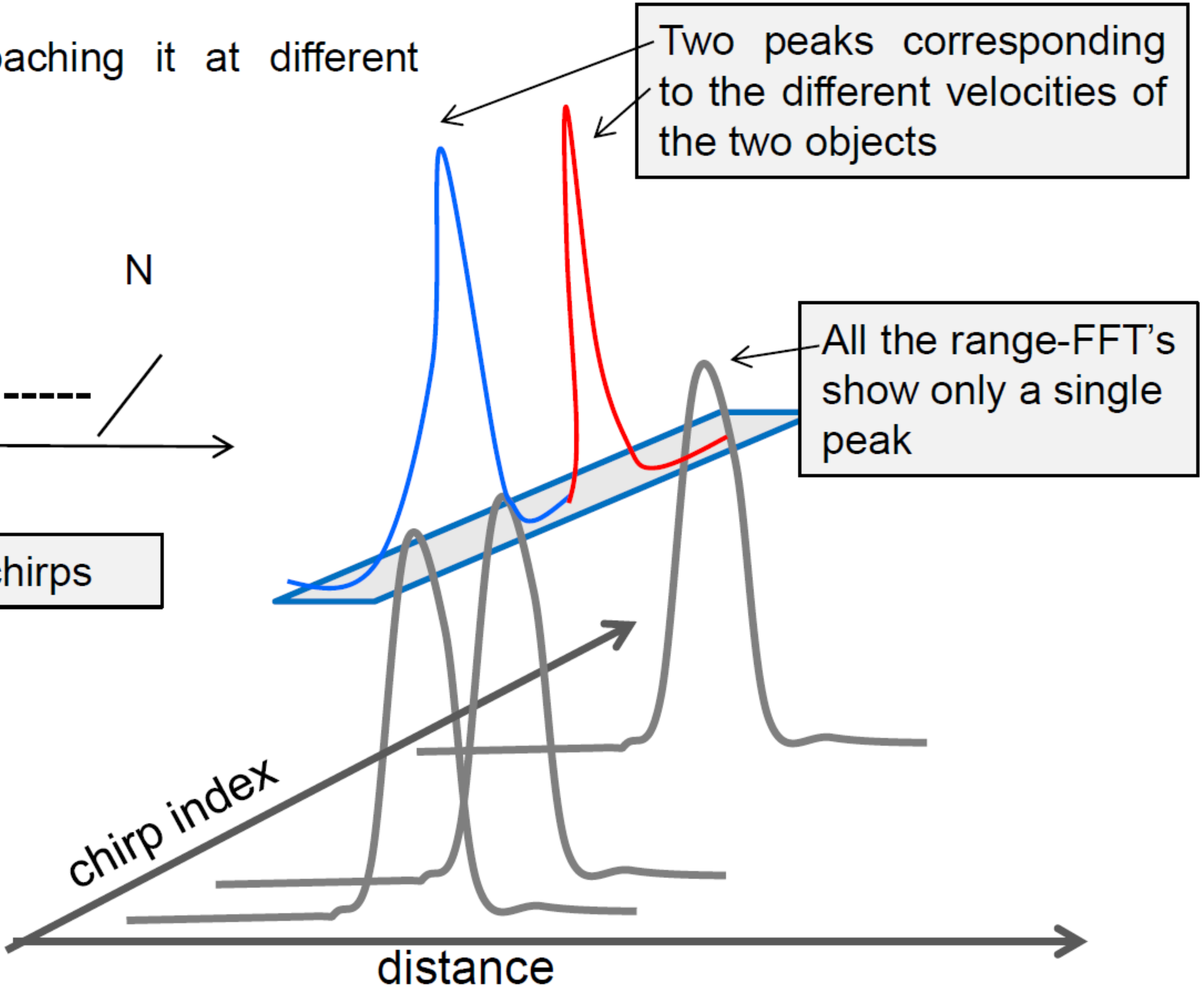
Visualizing the 2D-FFT

Two object equidistant from the radar approaching it at different velocities





Radar transmits N chirps

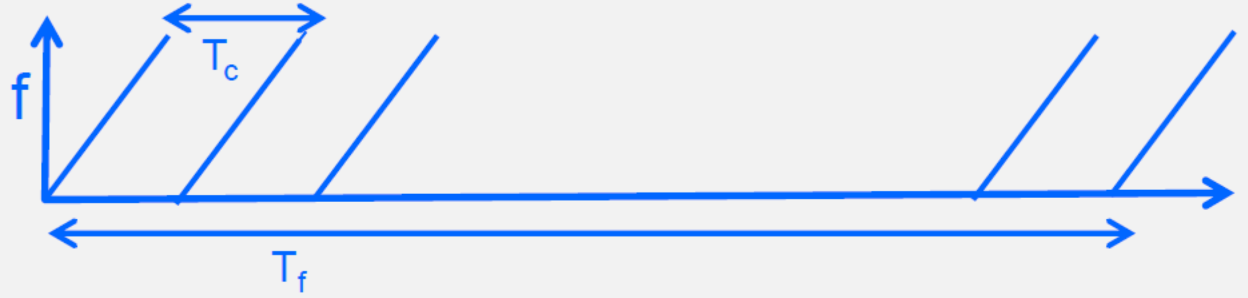


Max Velocity and Velocity Resolution

The maximum relative speed (v_{max}) that can be measured by two chirps spaced T_c apart is

$$v_{max} = \frac{\lambda}{4T_c}$$

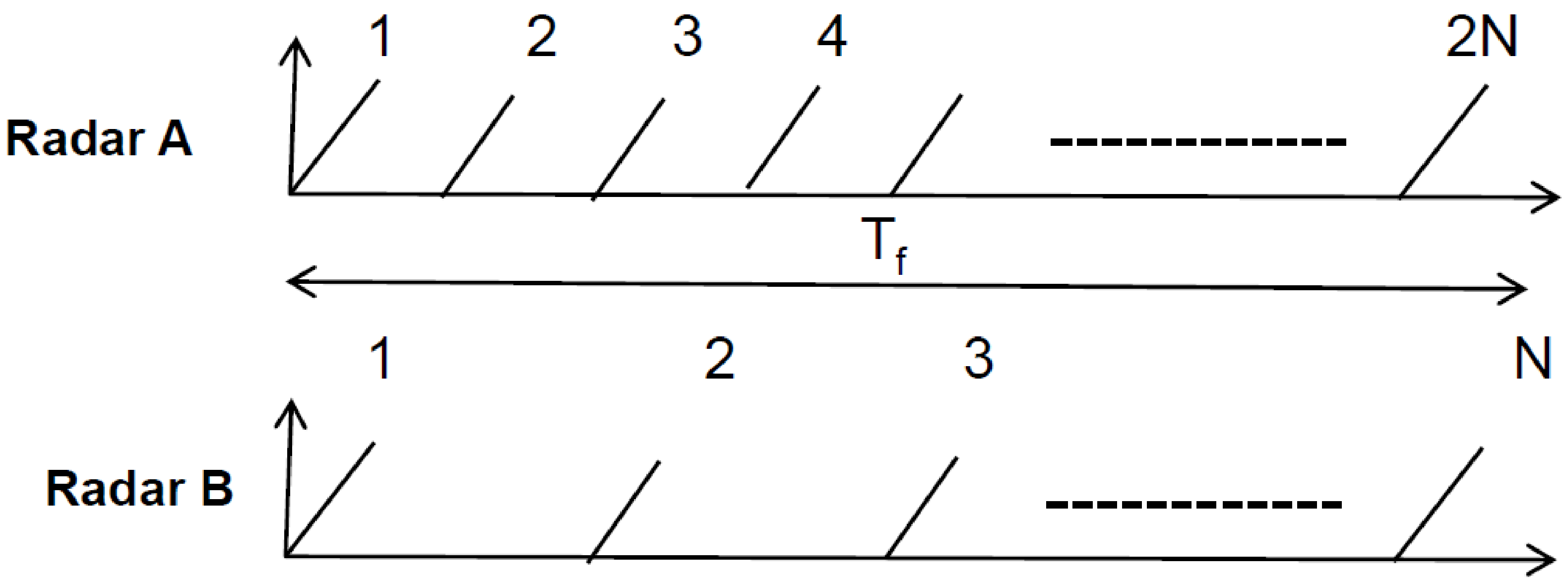
Thus higher v_{max} requires closely spaced chirps



The velocity resolution of the radar is inversely proportional to the frame time (T_f)and is given by

$$v_{res} = \frac{\lambda}{2T_f}$$

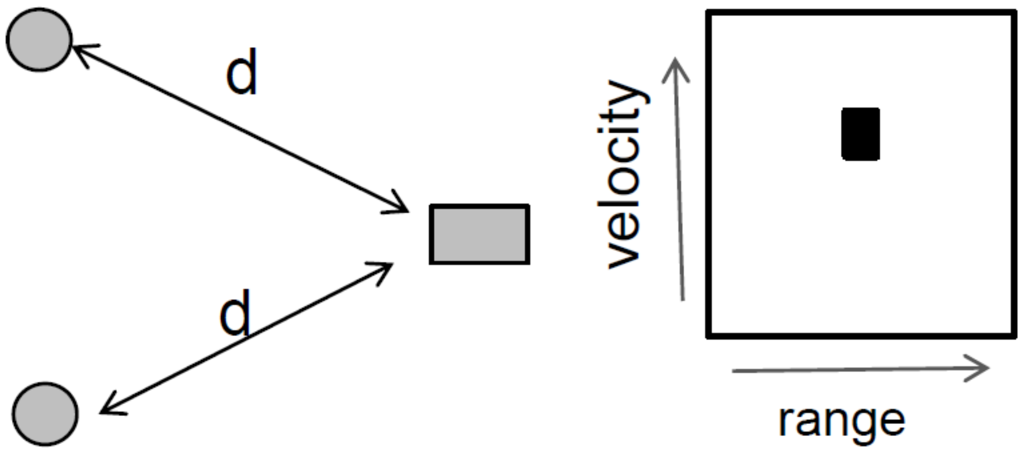
Question



What can you say about the maximum measurable velocity (v_{max}) and velocity resolution (v_{res}) of the 2 radars?

Question

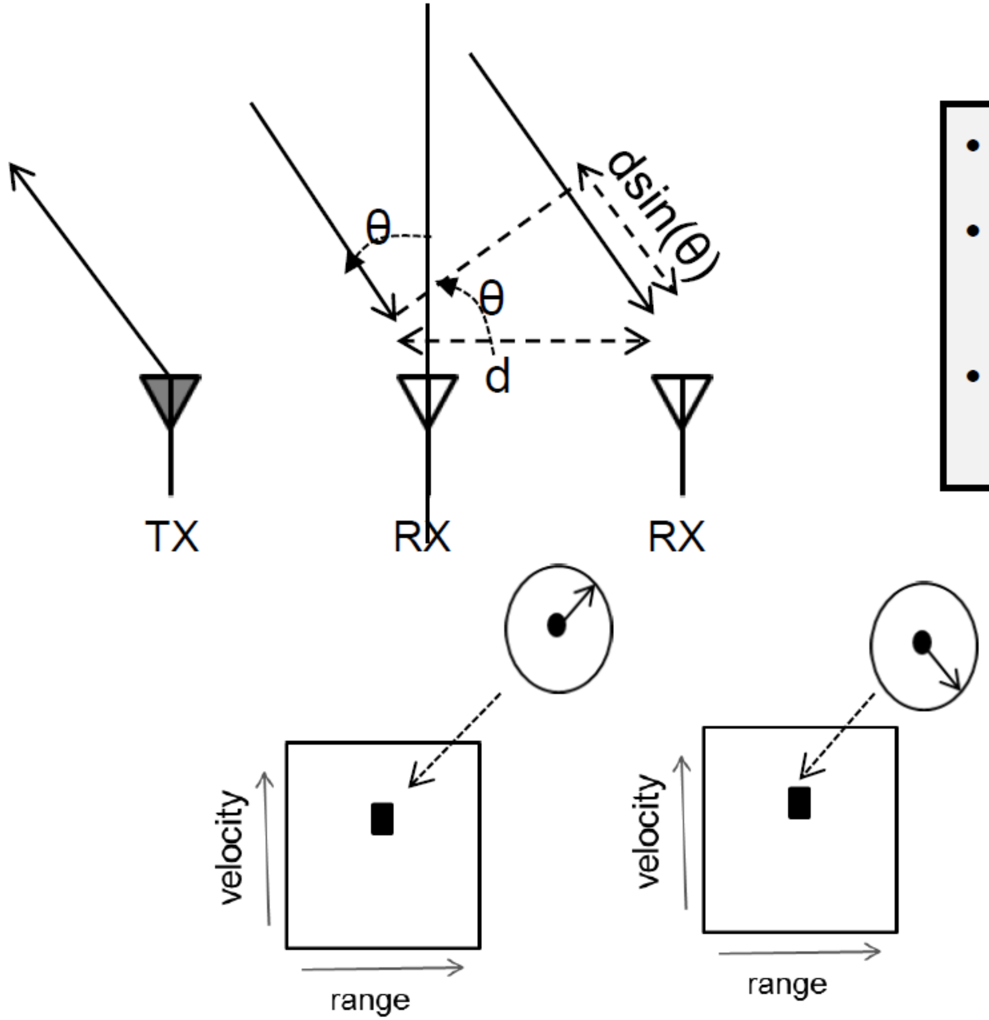
Two objects equidistant from the radar and with the same velocity relative to the radar. How will the range-velocity plot look like?



How do we separate these two objects?

–Need multiple antennas to estimate the angle of arrival

How to measure the AoA of an object using 2 RX antennas



- TX antenna transmits a frame of chirps
- The 2D-FFT corresponding to each RX antenna will have peaks in the same location but with differing phase.
- The measured phase difference (ω) can be used to estimate the angle of arrival of the object

$$\omega = \frac{2\pi d \sin(\theta)}{\lambda} \Rightarrow \theta = \sin^{-1}\left(\frac{\lambda\omega}{2\pi d}\right)$$

Max AoA and AoA Resolution

The maximum field of view that can be serviced by two antennas spaced d apart is

$$\theta_{max} = \sin^{-1}\left(\frac{\lambda}{2d}\right)$$

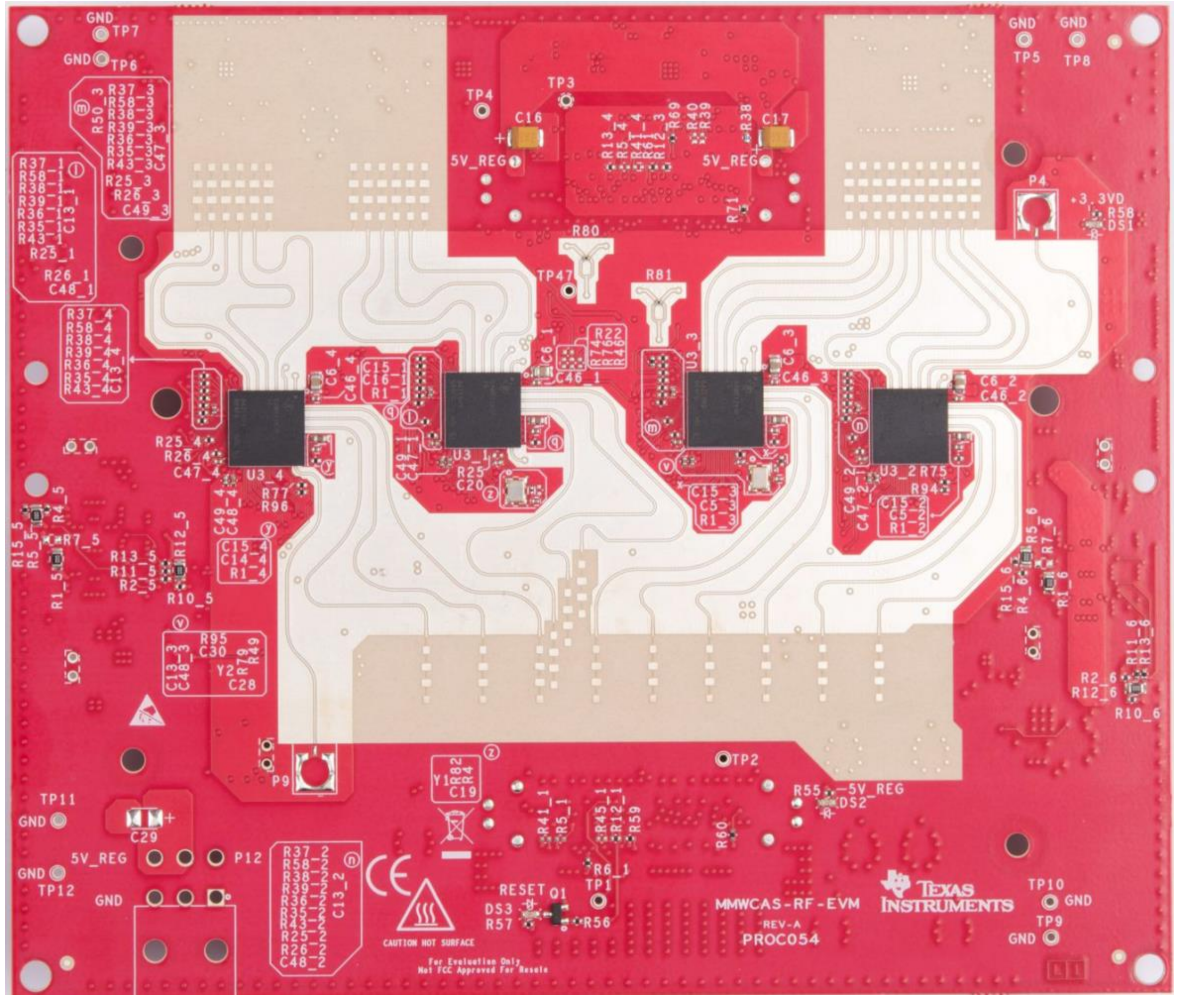
A spacing d of λ/2 results in the largest field of view (+/- 90°)

Angle resolution given by : $\theta_{res} = \frac{\lambda}{Nd\cos(\theta)}$

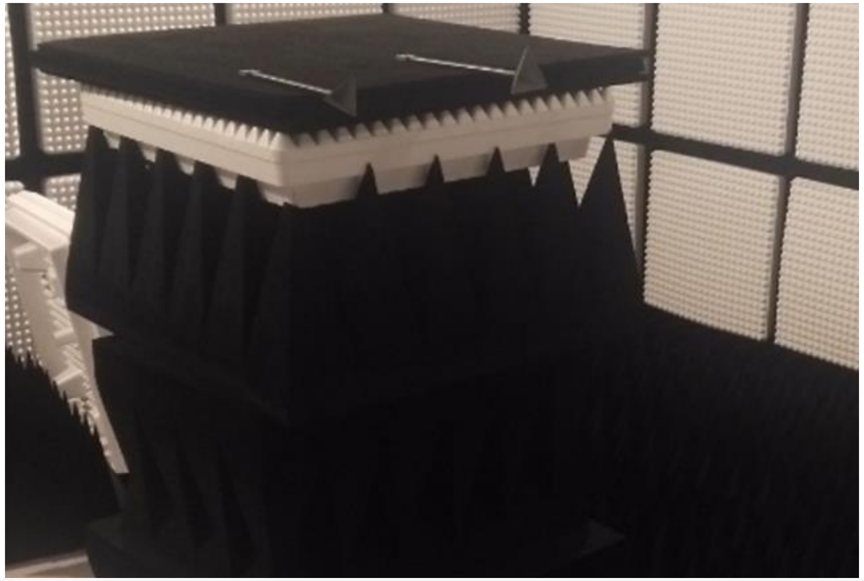
Resolution is often quoted assuming d=λ/2 and θ=0 => $\theta_{res} = \frac{2}{N}$

TI Cascade Radar Design

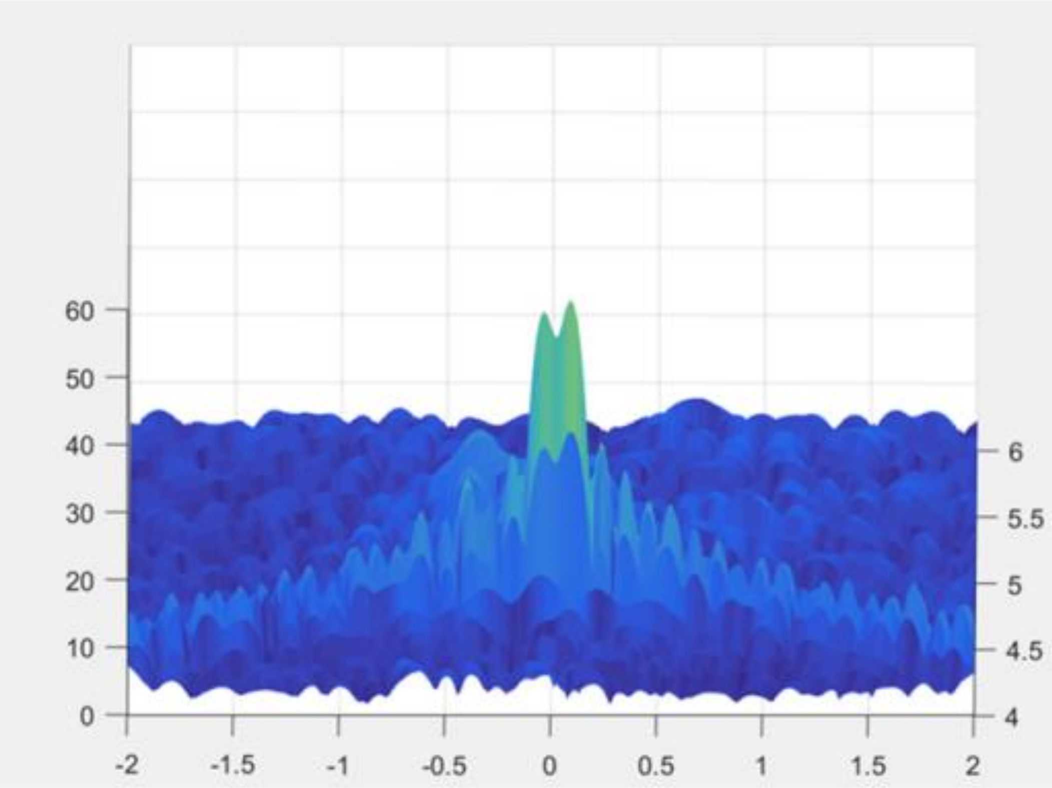
- 76-81GHz of BW
- 12 Tx channels, 16 Rx channels
- Angular resolution of 1.4deg
- Detect objects at a distance beyond 350m with range resolution of 35cm
- Human RCS objects detectable at a distance of 150m

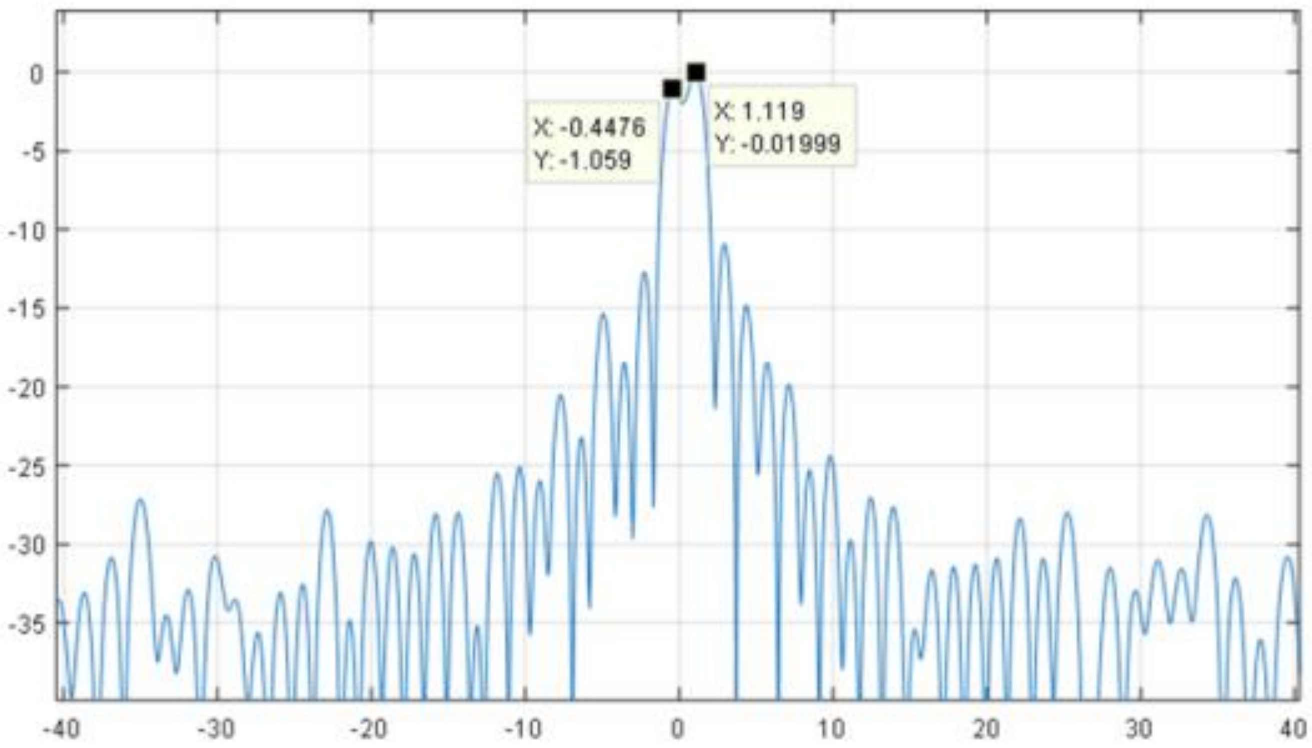


Angular Resolution

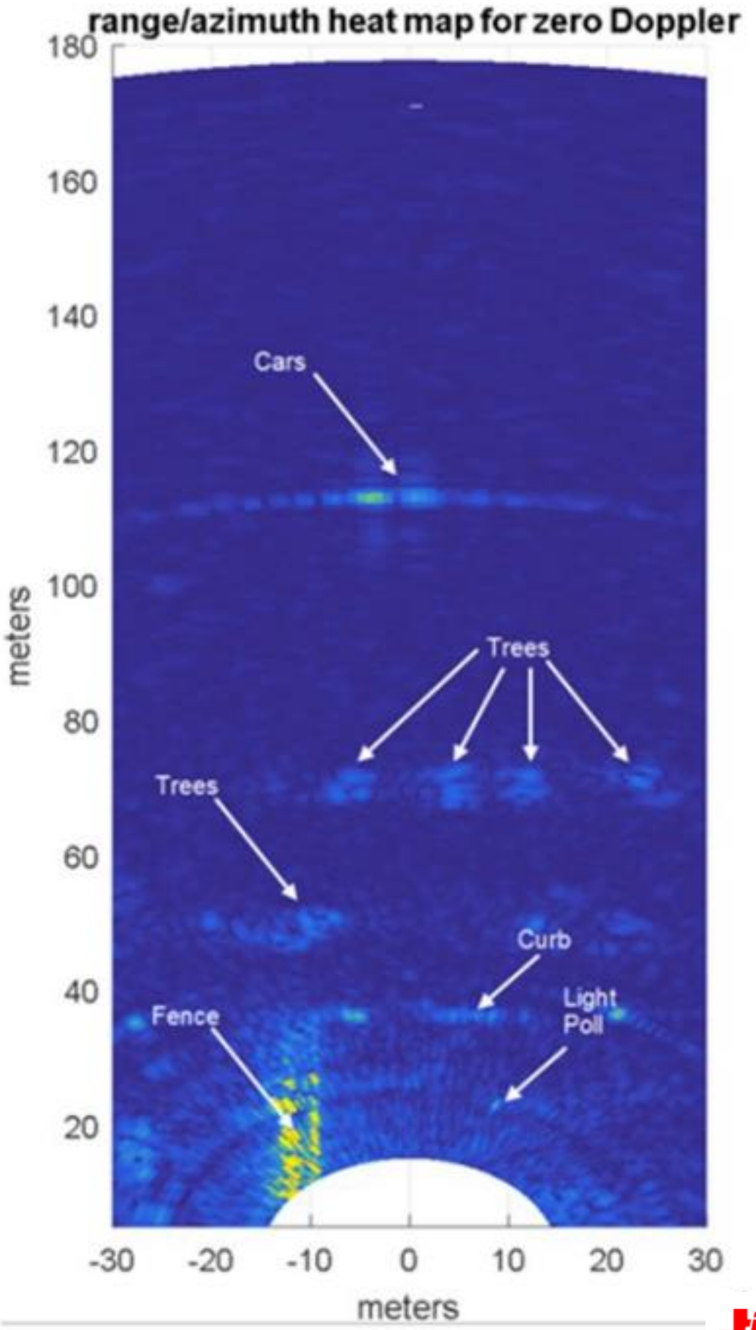


- Two Corner Reflectors Separated by 1.5 Degrees in Azimuth
- Range-Azimuth FFT Plots Showing Detected, Separated Peaks From Both Reflectors

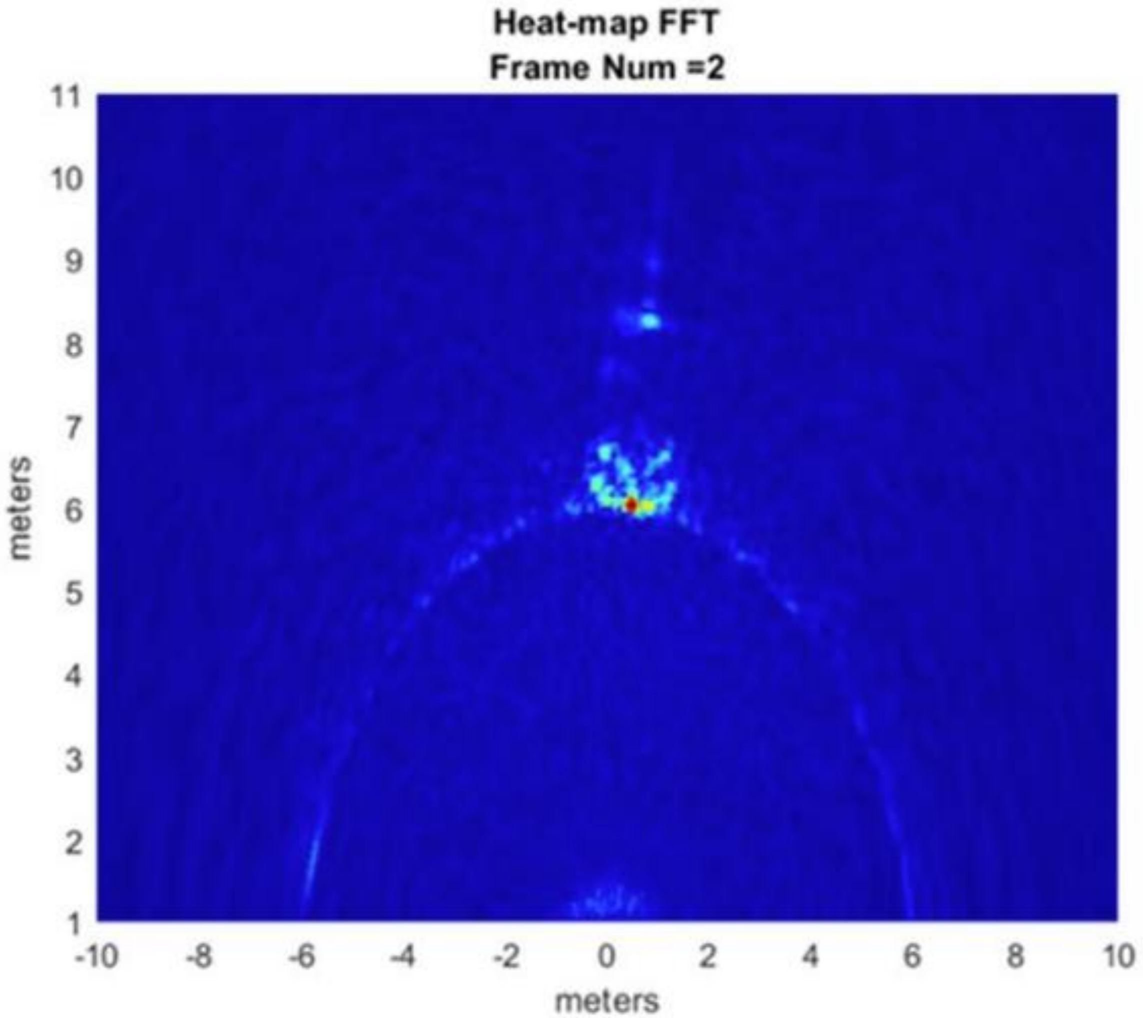




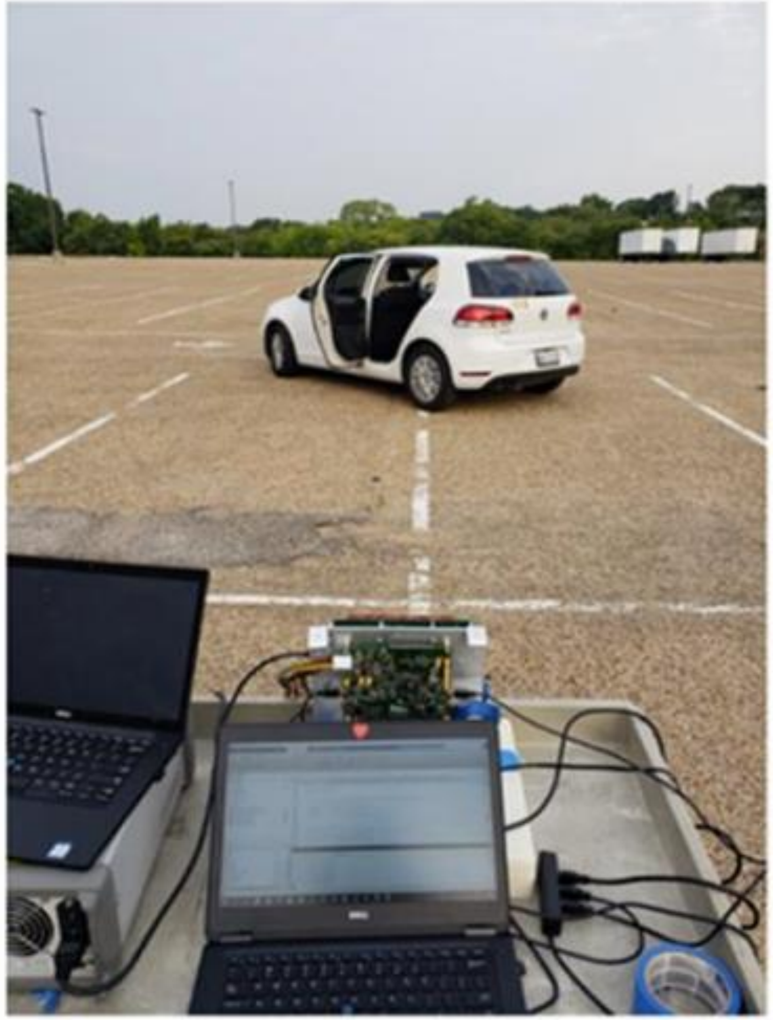
Radar Imaging

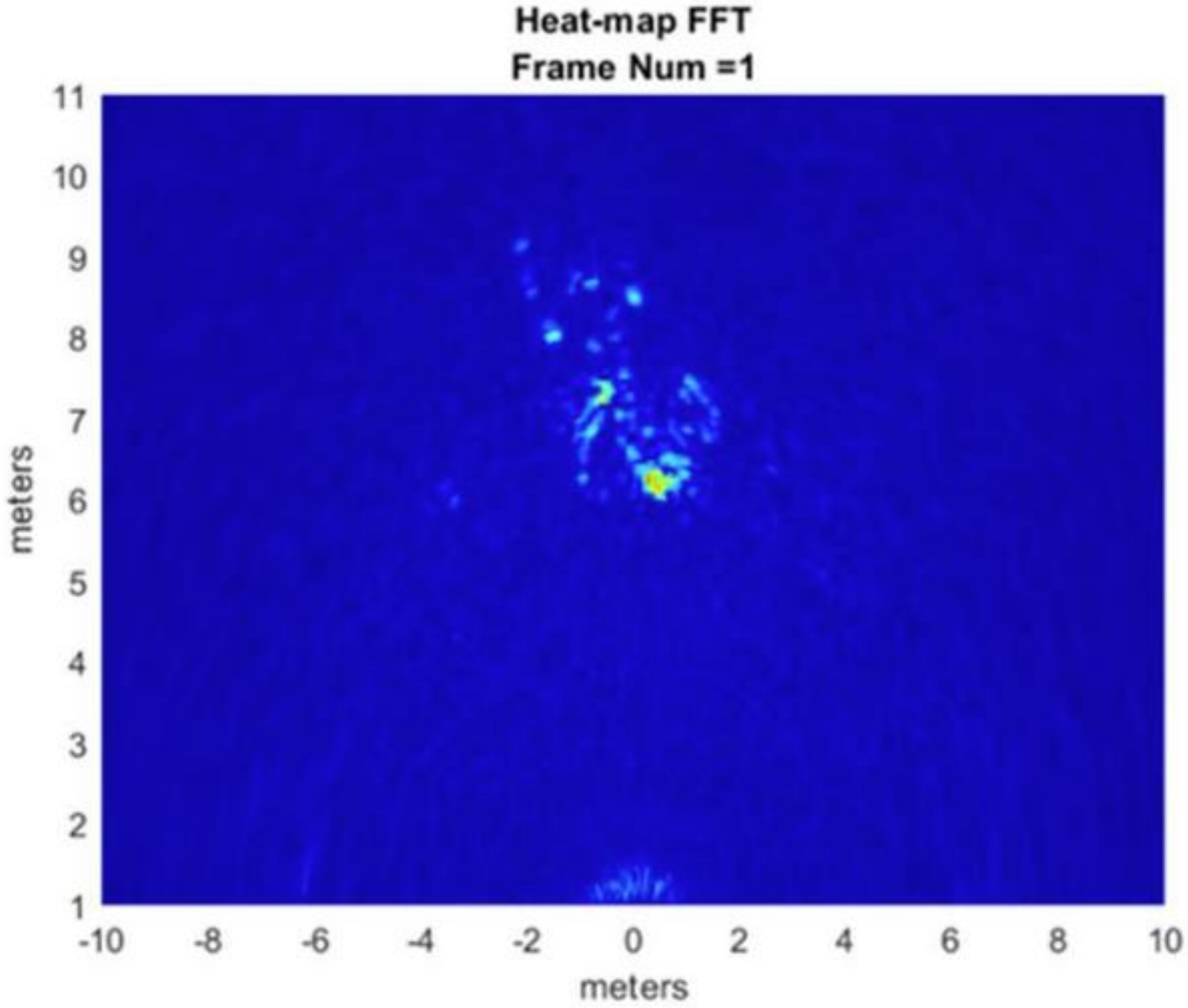


Radar Imaging



Radar Imaging



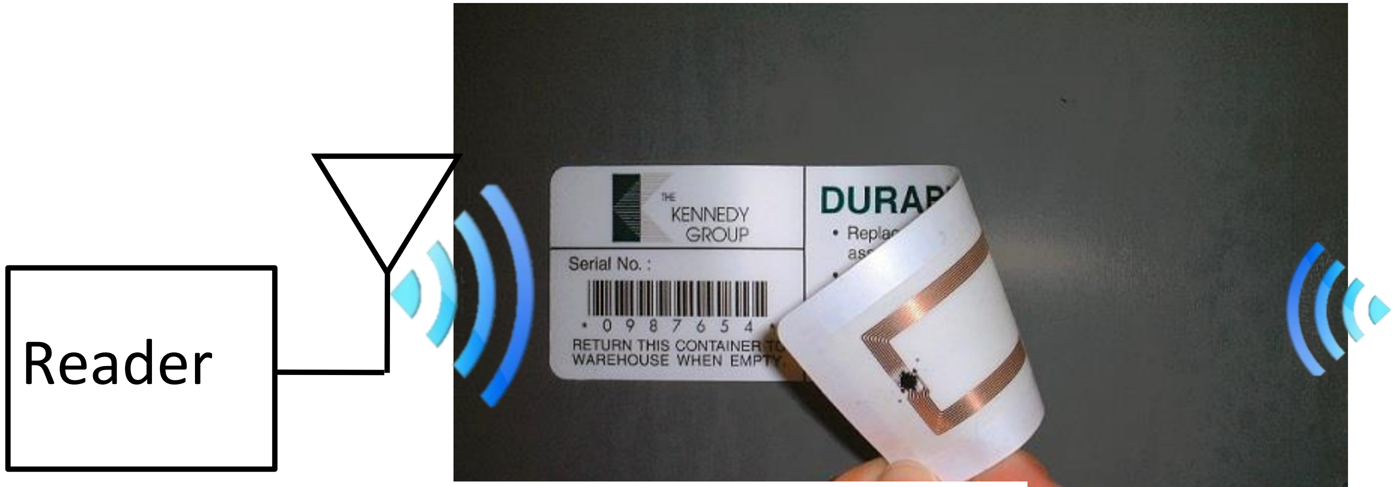


What if we had smart markers in the environment?

- Fully passive
- Operate at relatively long-ranges
- Can be accurately localized
- Low-cost

Basic Principle of Operation

RFID: cheap battery-free stickers



Reply to wireless reader
with a unique identifier

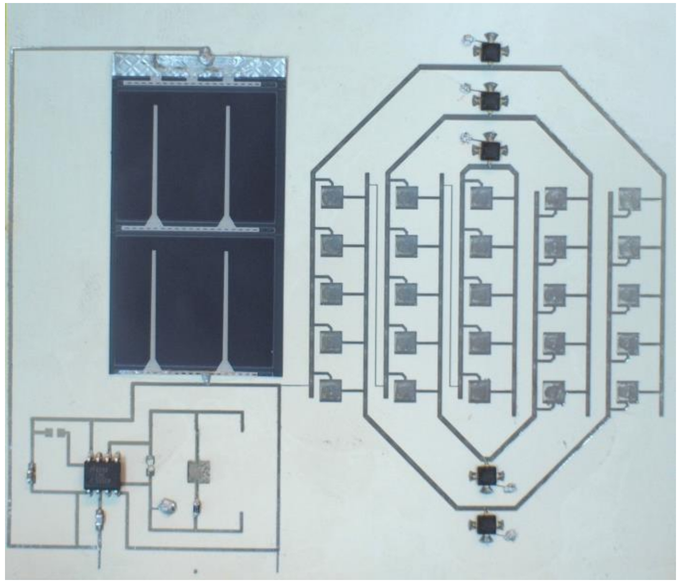
Retrodirectivity Concept

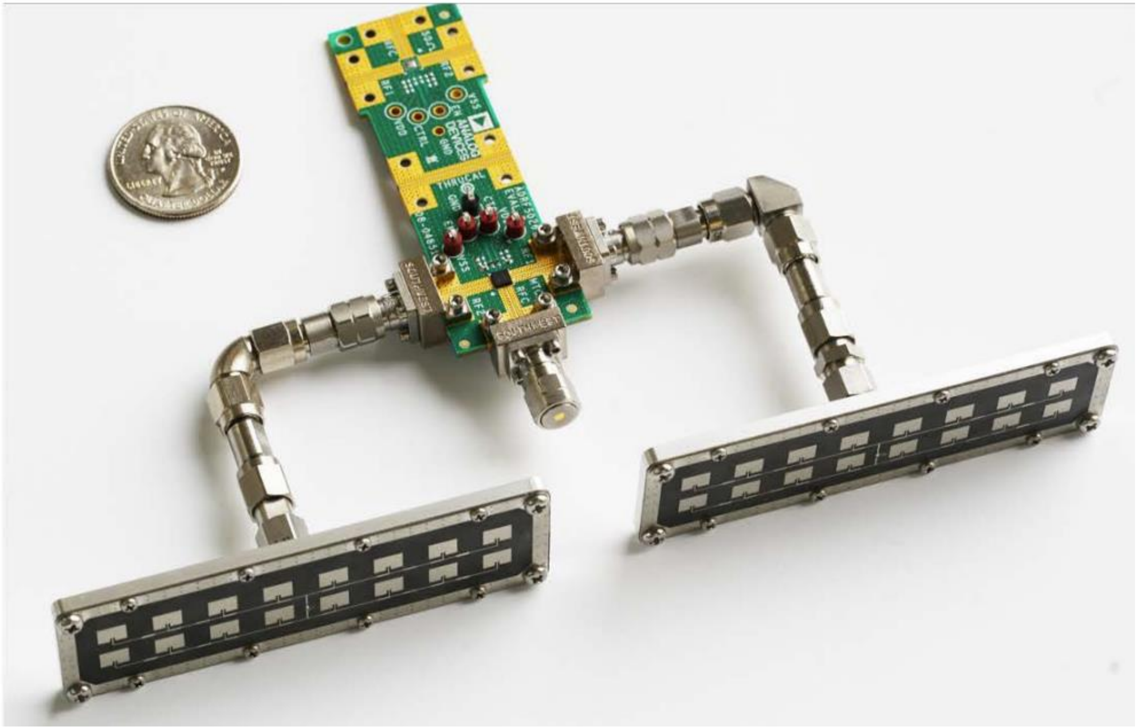
Current
RFID Reader

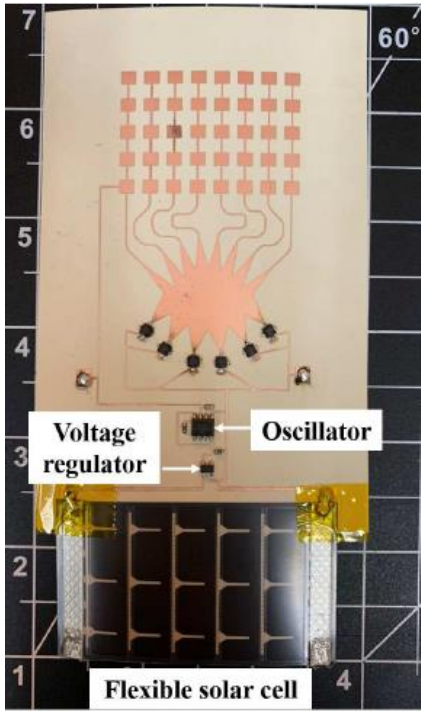
mmID Reader

Credits: Atheraxon

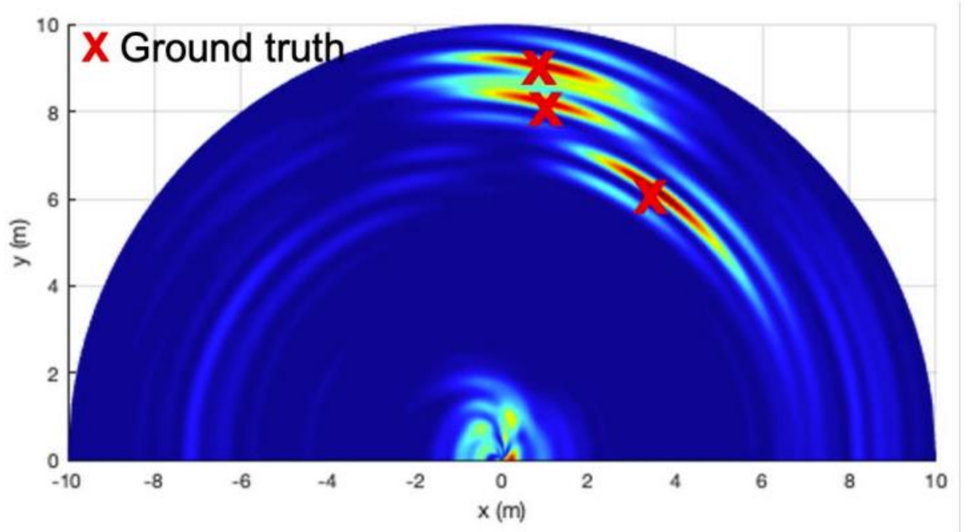
State-of-the-Art Retrodirective mmIDs







mmIDs as Smart Targets



Where is Millimeter Wave technology today?

1. **Research-wise:**
   - Mm-wave powering
   - mmIDs
   - Applications: Automotive, Robotics, AR, Health, Digital twinning
2. **Real-world Uses:**
   - Leading companies: Nokia, Ericsson, Texas Instruments
   - Multiple startups in the space: Sivers Semiconductors, Kymeta, Echodine, Evolv, Atheraxon
   - Used in automotive industry, space, defense, 5G
3. **Standards:**
   - 5G FR2

Objectives of Today's Lecture

Learn the fundamentals of mm-wave technology and its major applications

1. Why is mm-wave technology attractive?
2. What are the major applications of mm-wave technology?
3. What are the enabling technological advances?
4. How does FMCW radar work?
5. Do mm-wave RFIDs exist and what role can they play?

Next Class: Low-Power Wide-Area Networks

1) Required

- Choir
- NetScatter

2) Reminders

- Progress Report 1: Fri, November 10