Announcements

- Lab 1 posted
  - More after the demo!
- Complete NSF Access registration if you have not already
  - Submit your access username via canvas
- If you have recently registered for the course:
  - Fill out the background survey

L5: FMCW Radar

18-848 RadarML

Jiangyifei Zhu

jiangyifeizhu@cmu.edu

Frequency Modulated Continuous Waveform (FMCW) Radar

Phase modulation	Pulse-wave
Amplitude modulation	
Frequency modulation	**Continuous-wave**

FMCW Radar

- **Live Demo** — What Can Radar See?
- **FMCW Fundamentals** — How Does FMCW Radar Work?
- **Radar Configuration** — How Do We Configure Chirps and Antennas?
- **Radar Signal Processing** — How Do We Turn Raw Data into Useful Information?

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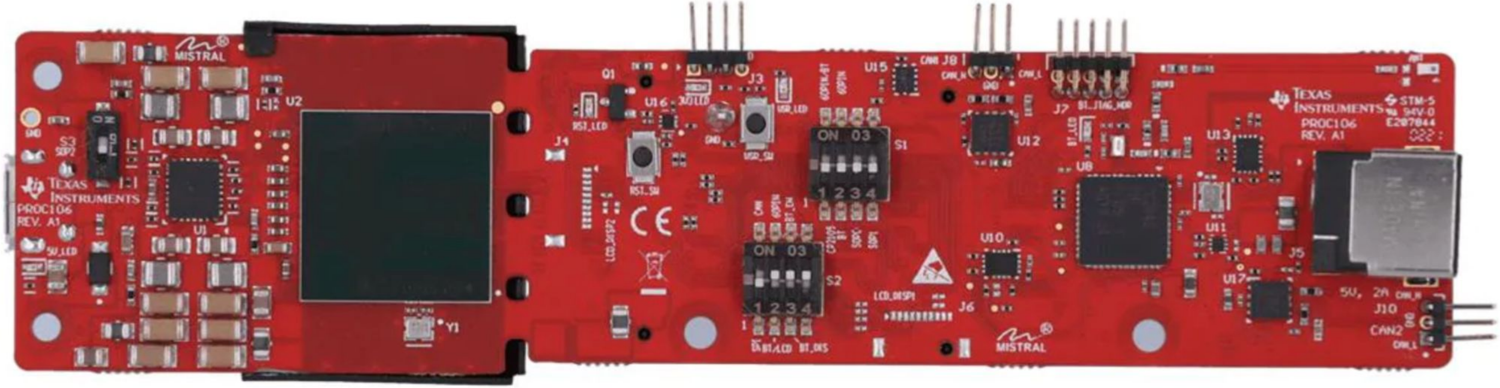
Our radar kit: TI AWR1843AOP



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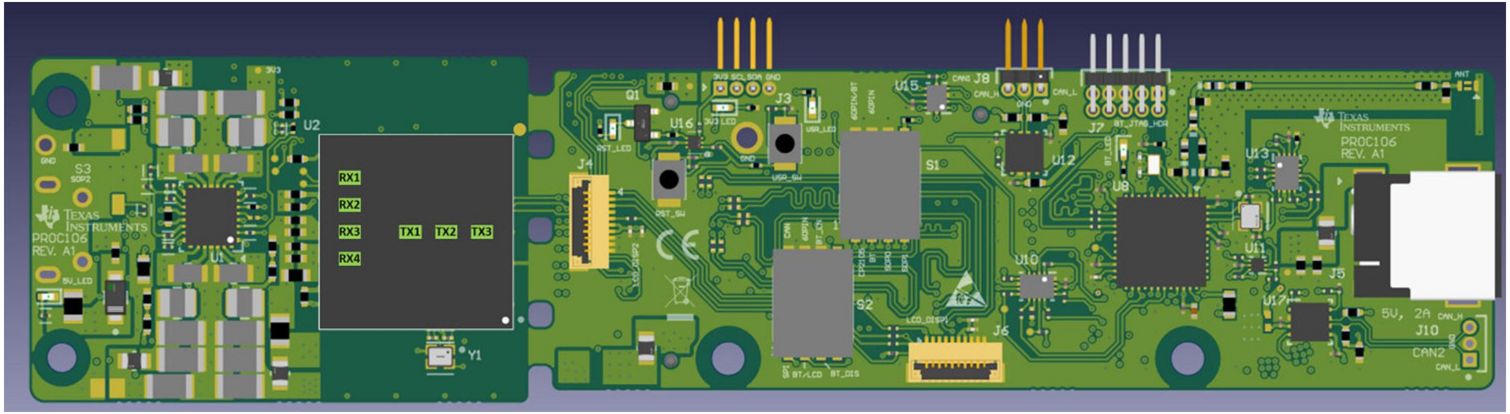
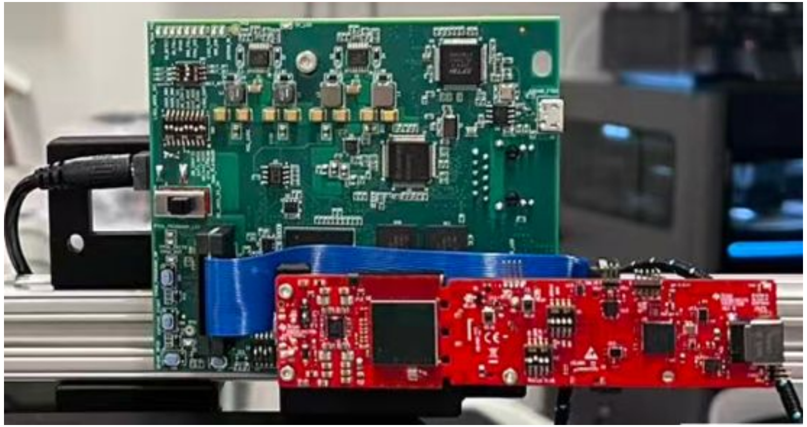


DCA1000 captures raw ADC data

Raw data streaming could be ~ 315Mb/s



Lab 1 Posted

- Submit via canvas; due 09/29
  - Lab kits available for checkout
  - One week revision period after comments are posted
- Complete NSF Access registration if you have not already
  - Submit your access username via canvas

FMCW Radar

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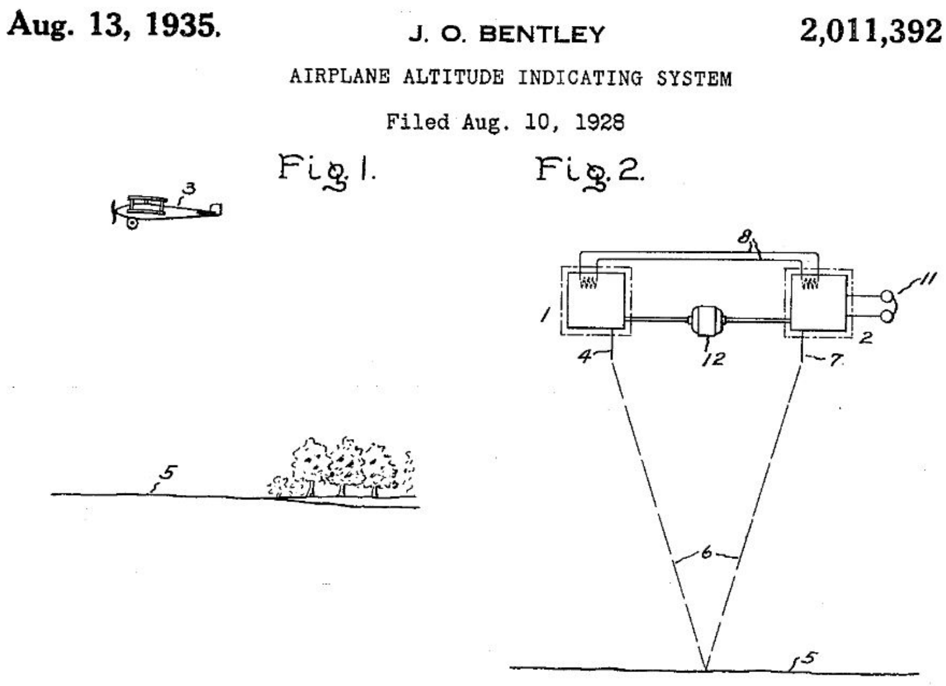
FMCW radar history: before World War II

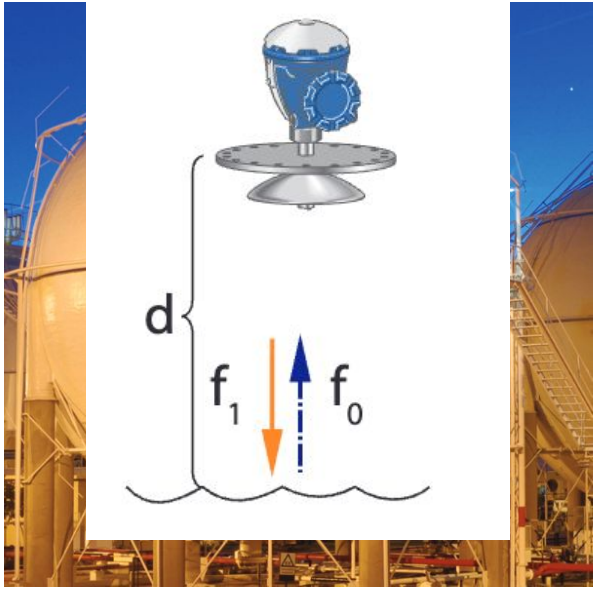


FMCW radar history

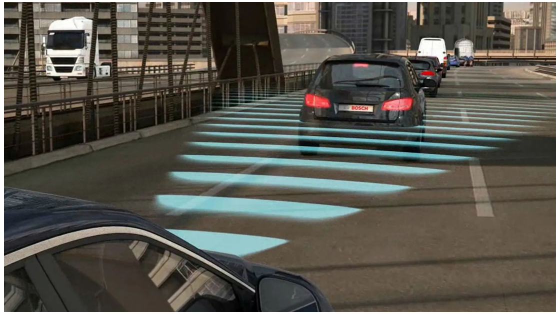
to the earth and back. Accordingly this difference in frequency will constitute an index of the altitude of the plane above the earth. I therefore, provide upon the plane means for producing a current having a frequency determined by the difference in frequency between the two received waves and utilize this current to operate suitable indicating apparatus whereby the operator may be continuously informed as to the altitude of his plane above the earth.

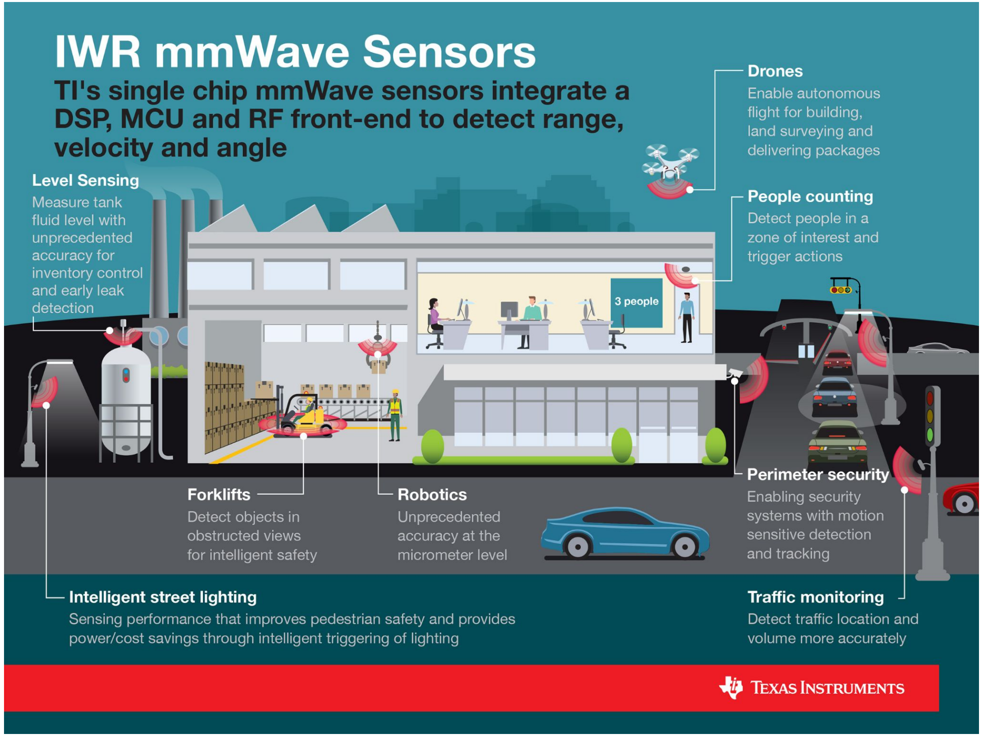
One of the earlier application

Figure 2.9: First high precision radar gauge installed in 1985 on a refinery tank.



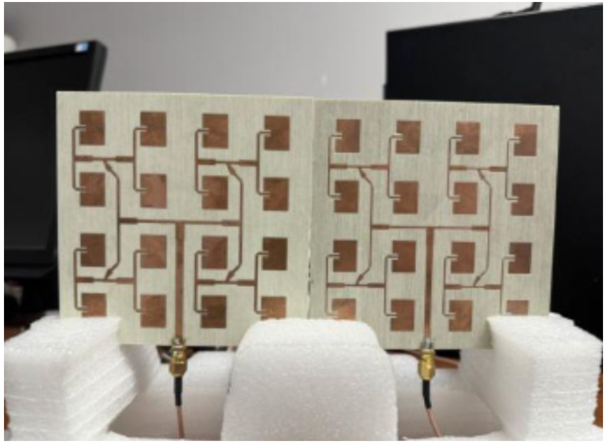
FMCW radar: mass adoption

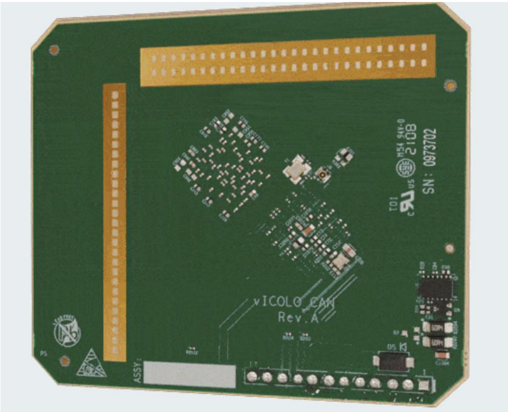


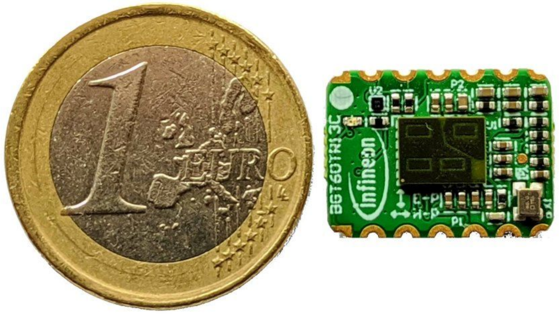


FMCW radar today

Physical size depends mainly on operating frequency and antenna aperture.

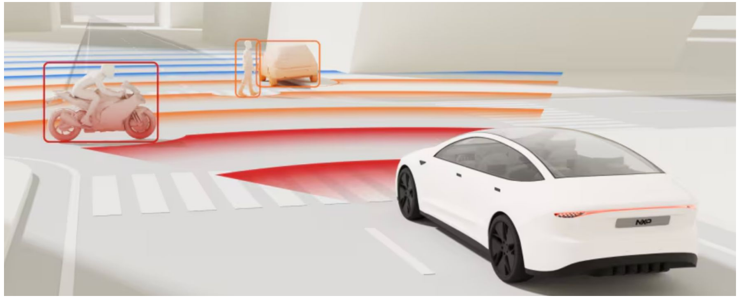


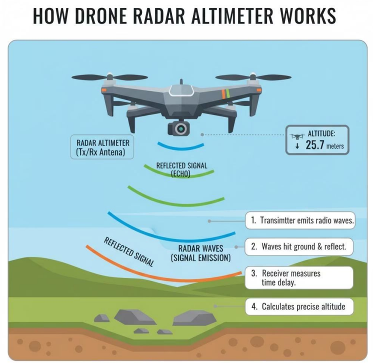




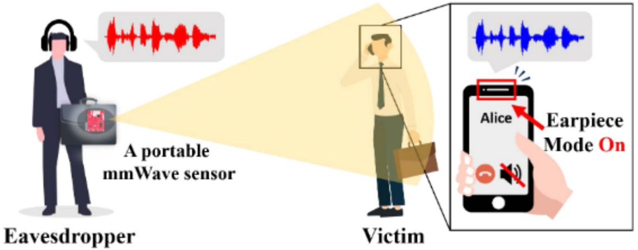
Eac patch antenna is in the dimension half of wavelength

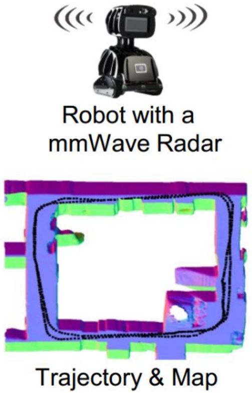
FMCW radar applications

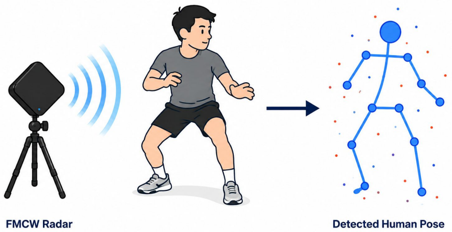


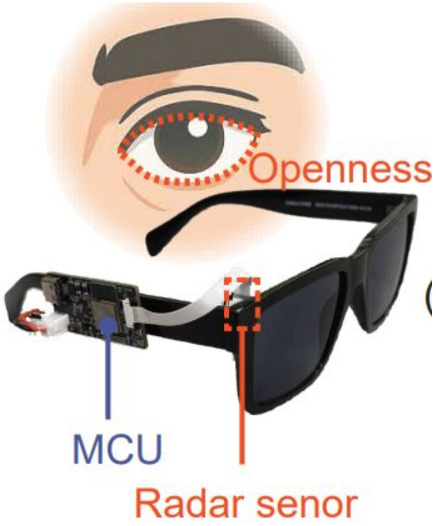


FMCW radar research









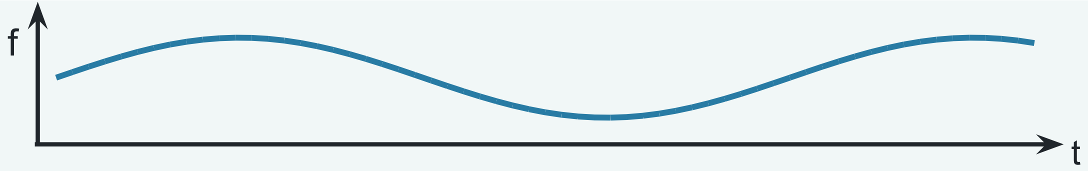
Frequency Modulation — Revisit

$$s(t) = A\cos 2\pi[f_c + f(t)]t + \phi$$

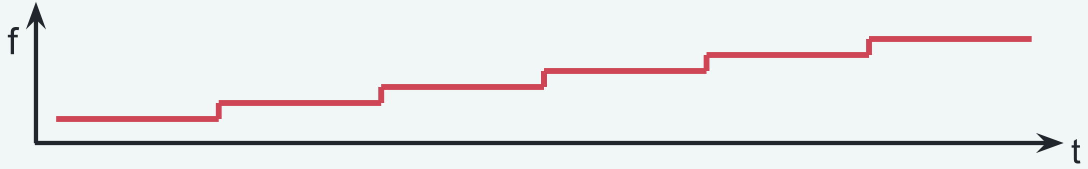
Frequency modulation can take different forms

Linear chirp

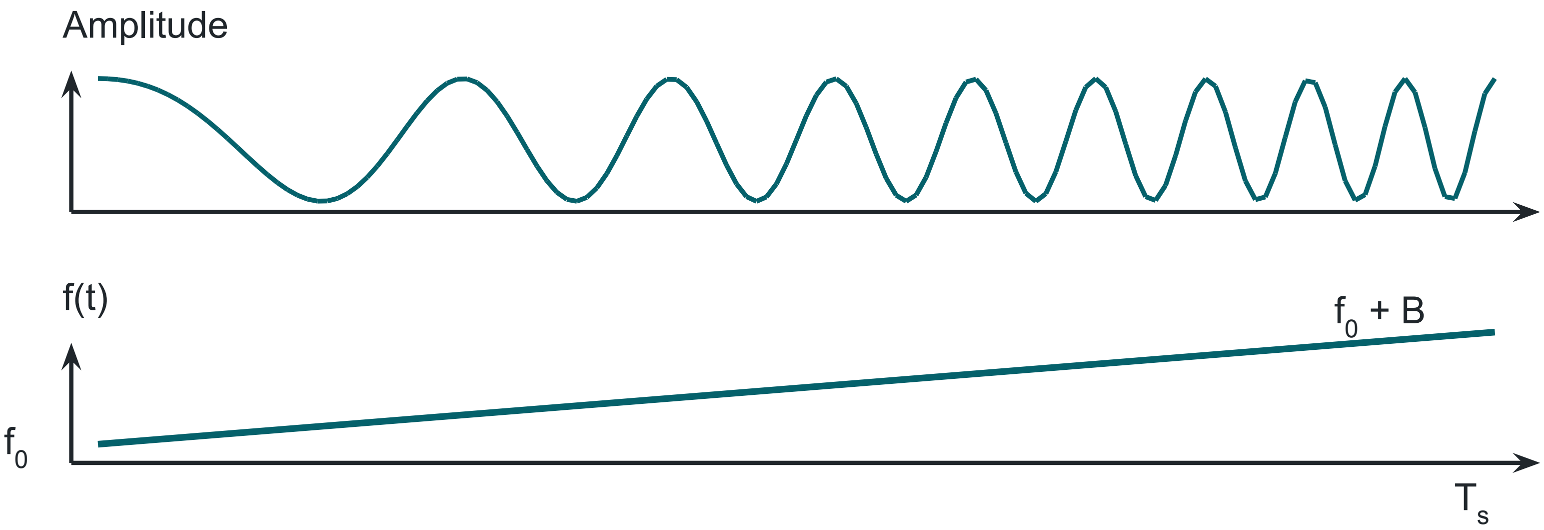
Sinusoidal FM



Stepped frequency



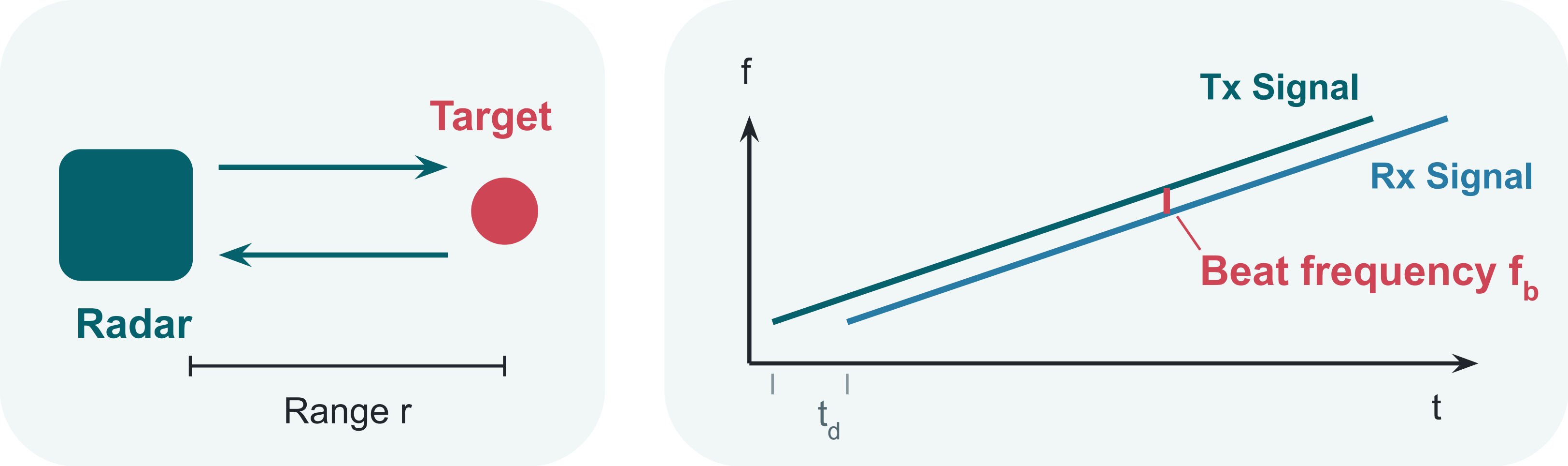
A linear chirp speeds up at a constant rate



$$f(t) = f_0 + St \qquad S = B / T_s$$

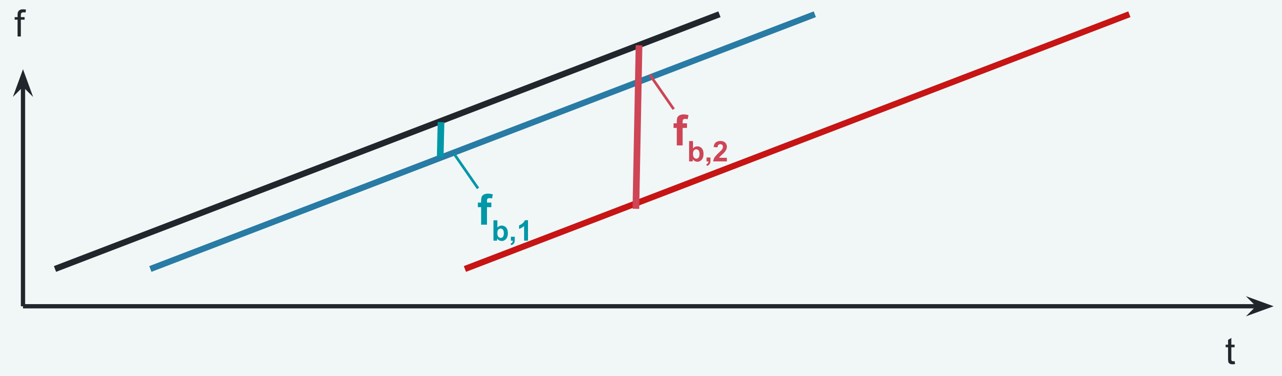
B: bandwidth T_s = chirp time f_0: start frequency S: frequency slope

A target reflects back the signal with a round-trip delay



$t_d = 2r/c \qquad f_b = St_d$

Multiple echoes create multiple beat frequencies

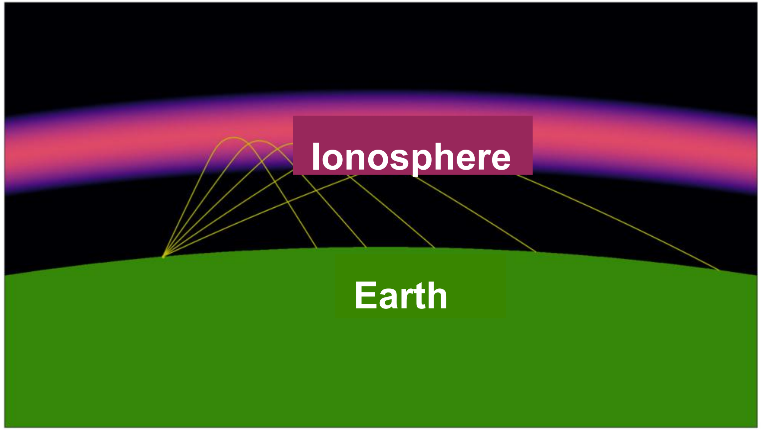


More delay → larger f_b → greater range

Why FMCW?

Ionosphere sounding (1925)

Pulsed radio echoes

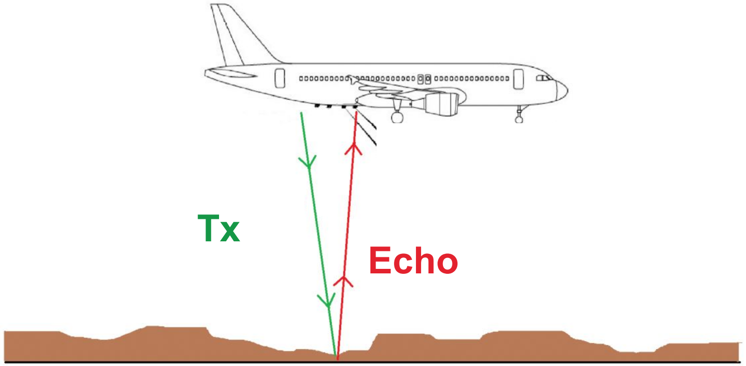


Example height: 150 km

Round-trip delay: 1 ms

Aircraft radar altimeter

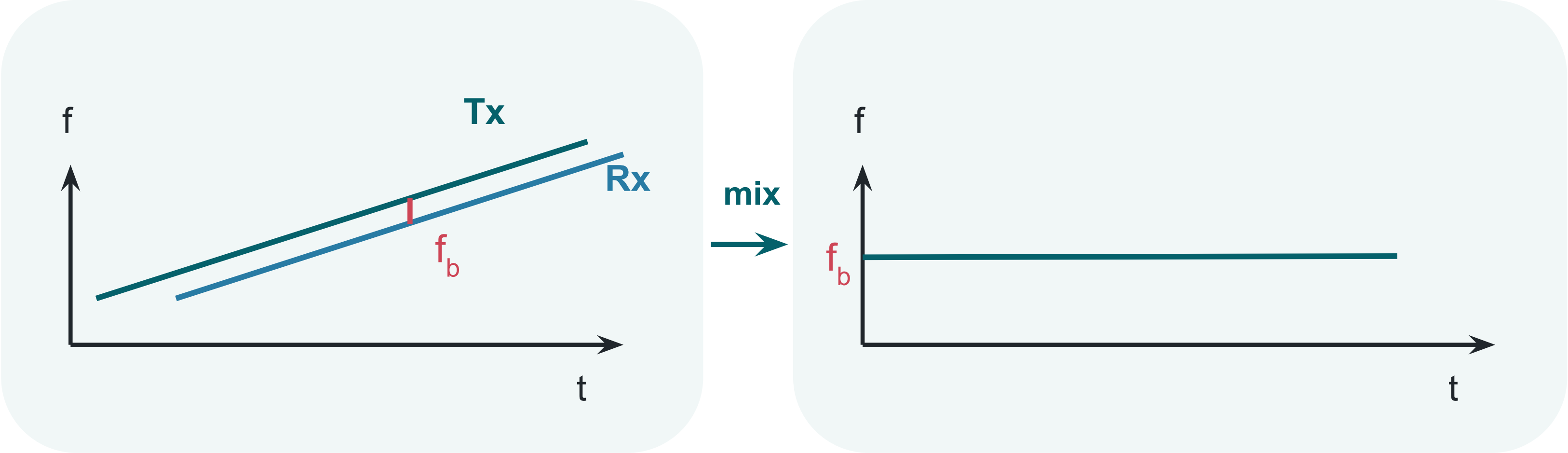
FMCW measures height above ground



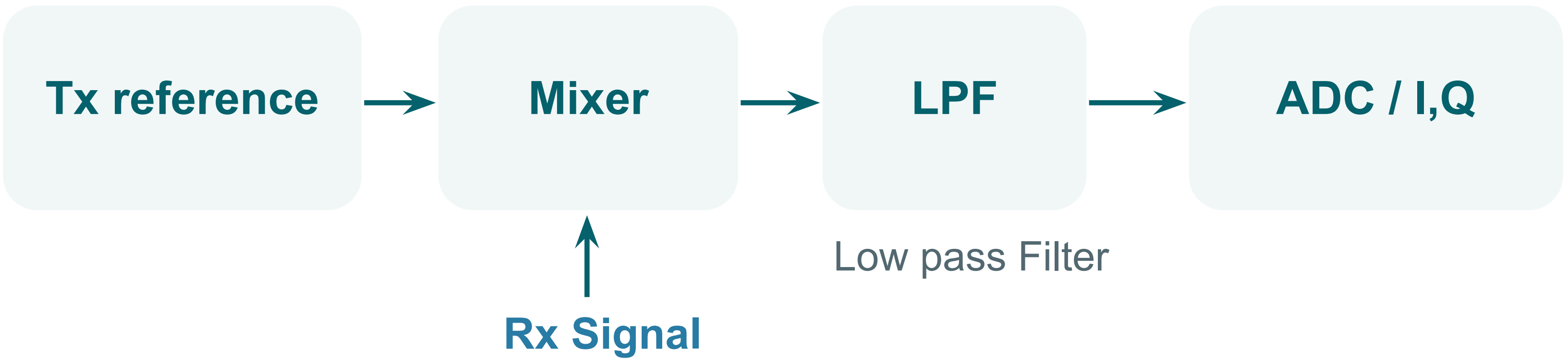
Example height: 200 m

Round-trip delay: 1.33 μs

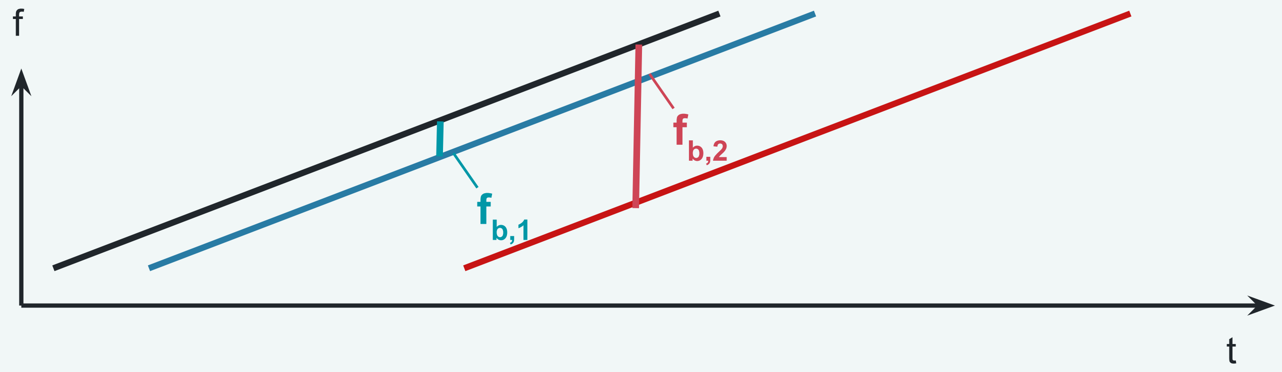
Instead of measuring the time delay, we measure the tone to derive the range from FMCW radar



Dechirping happens before ADC sampling



Closer the target
Lower the beat frequency
Slower the sample rate we need to get range

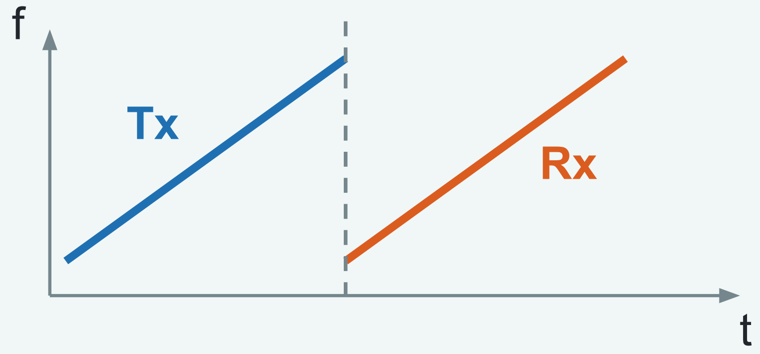


Max sample rate constrained the max range

What are other constraints to measure the max range?

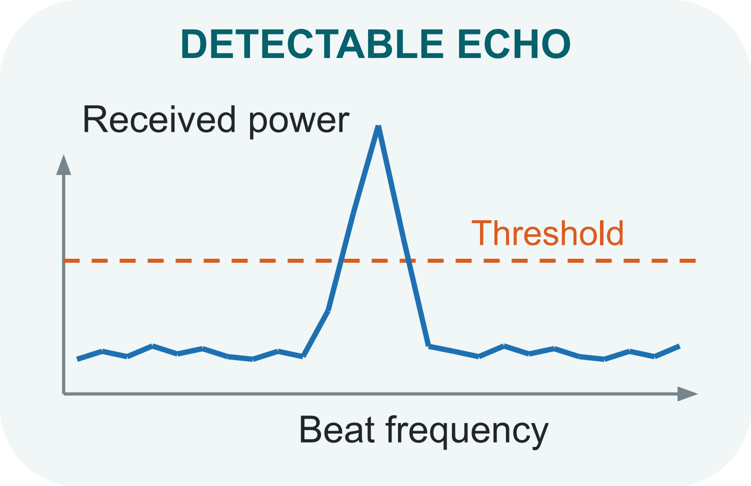
It relate with the max time delay that overlap with the Tx chirp

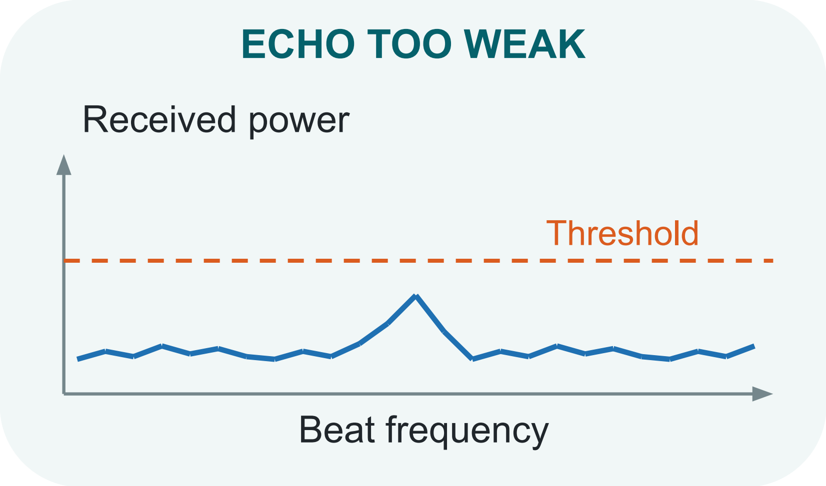
THE TIMING BOUNDARY



We need an overlapping interval to measure the beat tone

Max range also relates to the power of reflect signal



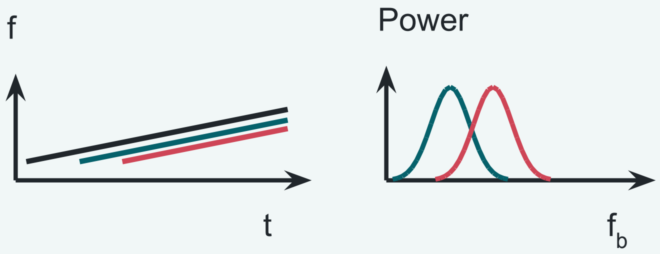


More transmit power or a stronger reflection helps

How close can two targets be?

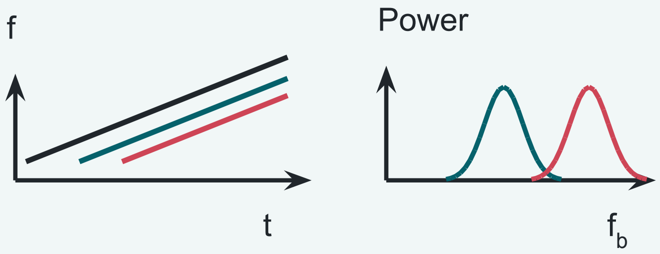
Range resolution: the minimum range separation we can distinguish.

SMALL B



Small beat-frequency gap

LARGE B

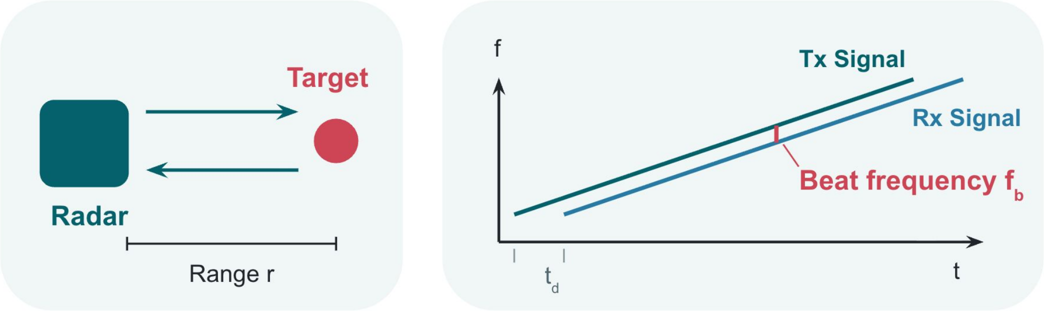


Larger beat-frequency gap

Larger B → steeper S → greater beat-frequency separation

Deriving the Range Resolution

Let's rearrange the beat frequency equation



$t_d = 2r/c$ $\quad$ $f_b = St_d$

$$f_b = S2r/c = (2S/c)r$$

Deriving the Range Resolution

Convert frequency resolution into range resolution.

1 Range → frequency gap

Two nearby targets

$$|f_{b,2} - f_{b,1}| = (2S/c)|r_2 - r_1|$$

2 At the resolution limit

Frequency resolution ≈ $1/T_s$

$$1/T_s = (2S/c)\,\Delta r$$

3 Solve for Δr

Use $S = B/T_s$

$$\Delta r = c/(2ST_s) = c/(2B)$$

Larger bandwidth → finer range resolution

Δr: range resolution c: speed of light S: sweep slope
T_s: observation time $B = ST_s$: observed bandwidth Nominal resolution.

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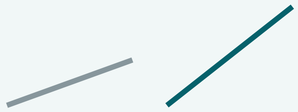
Configuration changes the sampled signal

Connect each setting to the physical pattern it changes.

RANGE



Spatial

DOPPLER

Temporal

ANGLE

Spatial

Spatial controls

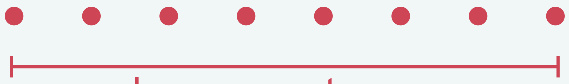
Ranges depend on bandwidth; directions depend on aperture.

RANGE

$$\Delta r = c/(2B)$$

ANGLE

$$\Delta(\sin\theta) \approx \lambda/(N_a\, d)$$



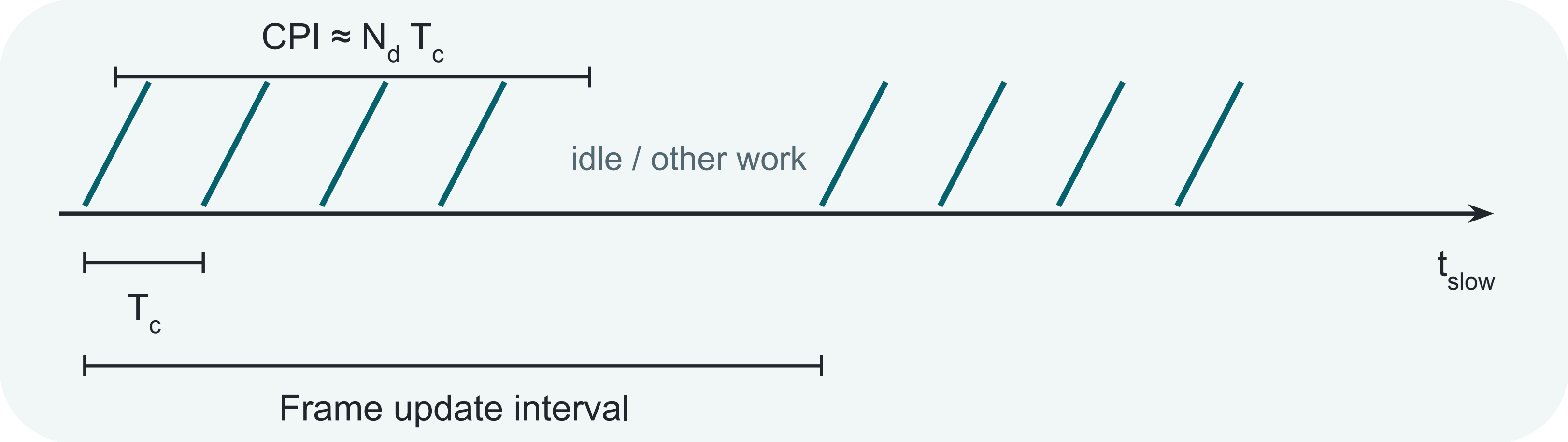
Larger aperture →
finer detail

B ↑ → better range **Aperture ↑ → better angle**

N_a: #antenna d: Antenna spacing λ: Wavelength

Temporal controls

Doppler depends on the way we spawn the chirps



$$v_{max} = \lambda/(4T_c) \qquad \Delta v = \lambda/(2CPI)$$

TI Radar Configuration

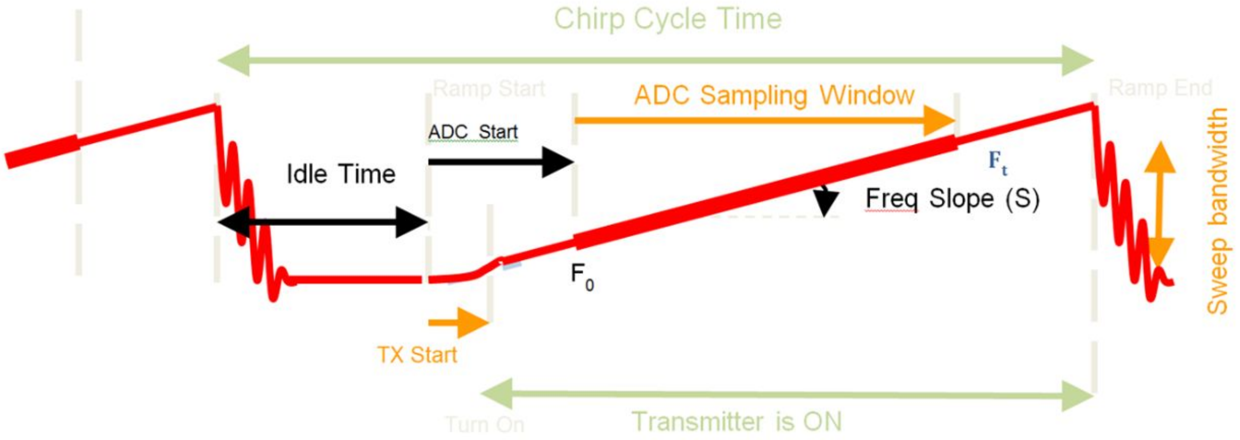


Figure 1. Typical FMCW Chirp

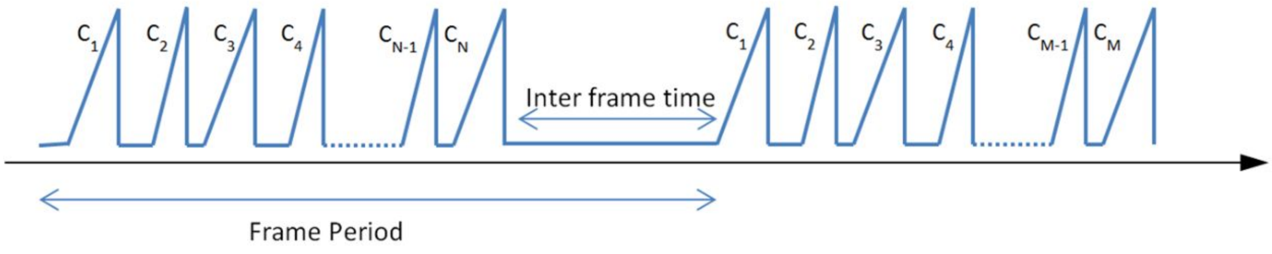


Figure 2. Typical Frame Structure

```
frequency: 77.0 GHz
idle_time: 20.0 µs
adc_start_time: 3.0 µs
ramp_end_time: 136.25 µs
tx_start_time: 1.0 µs
freq_slope: 29.35 MHz/µs
adc_samples: 512 samples
sample_rate: 4000 ksps
frame_length: 1 #chirps/frame
frame_period: 0.625 s
```

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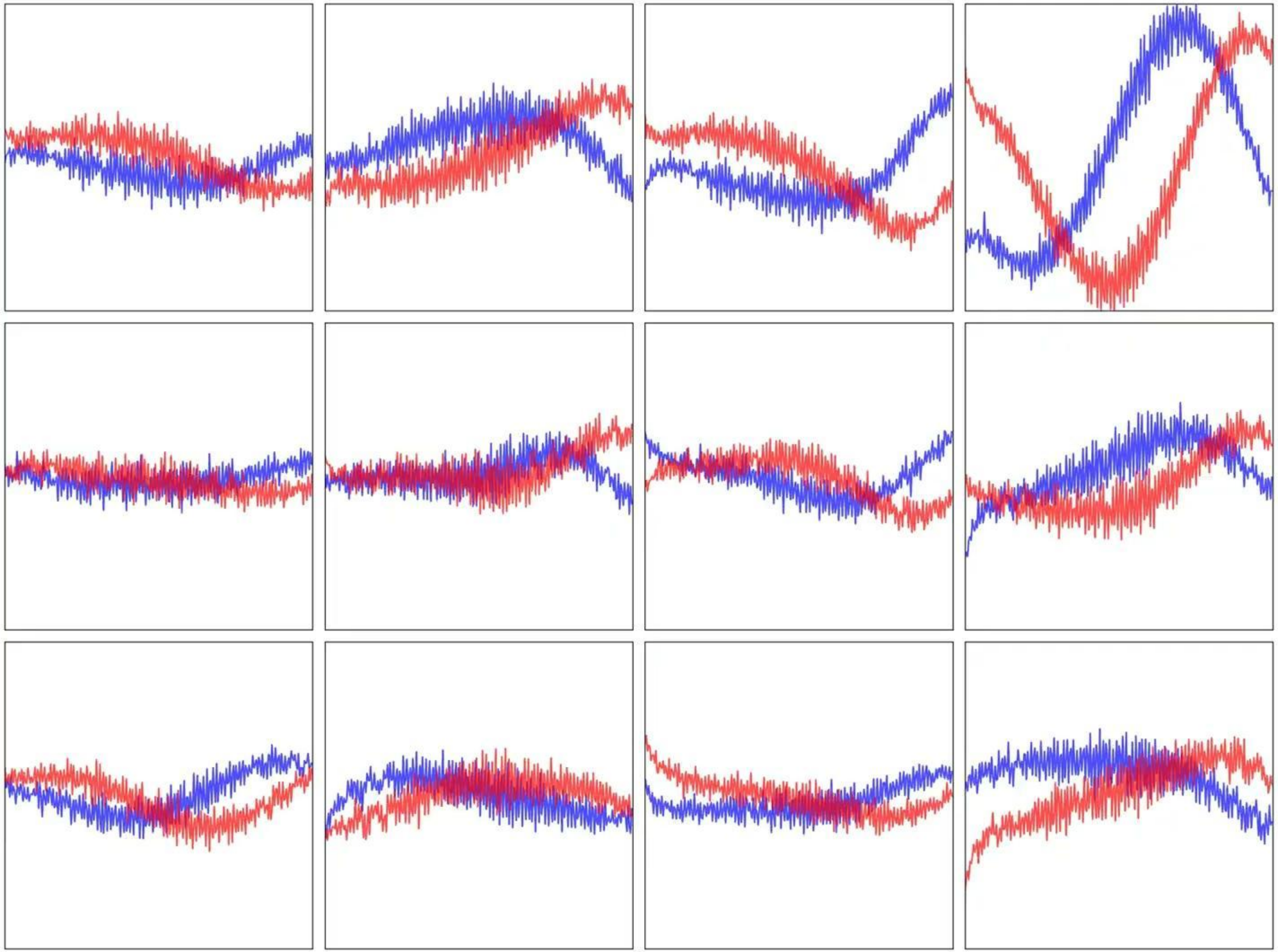
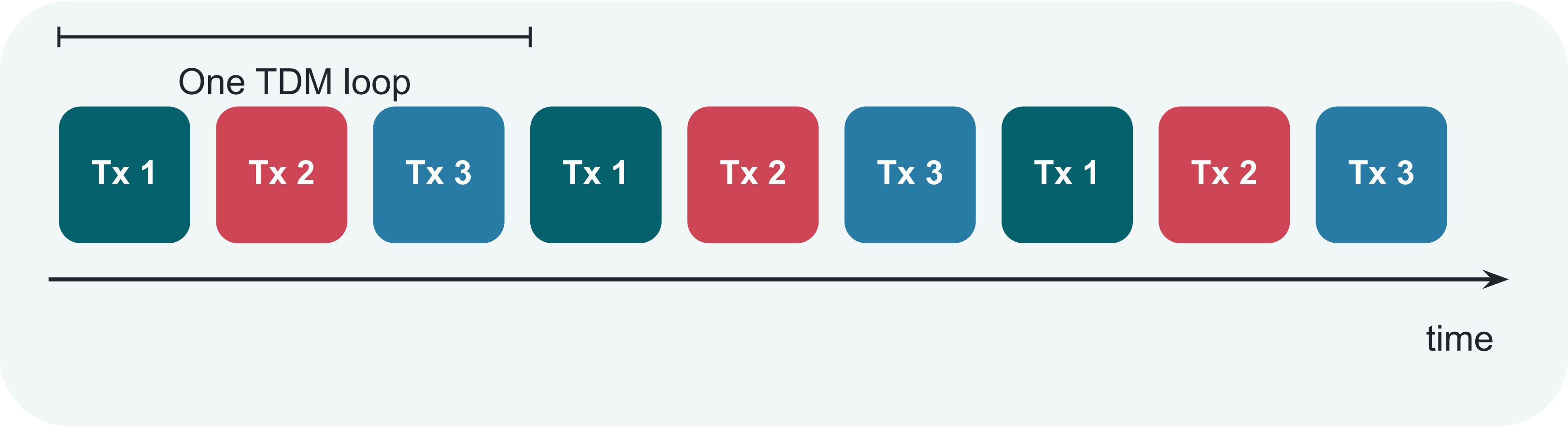


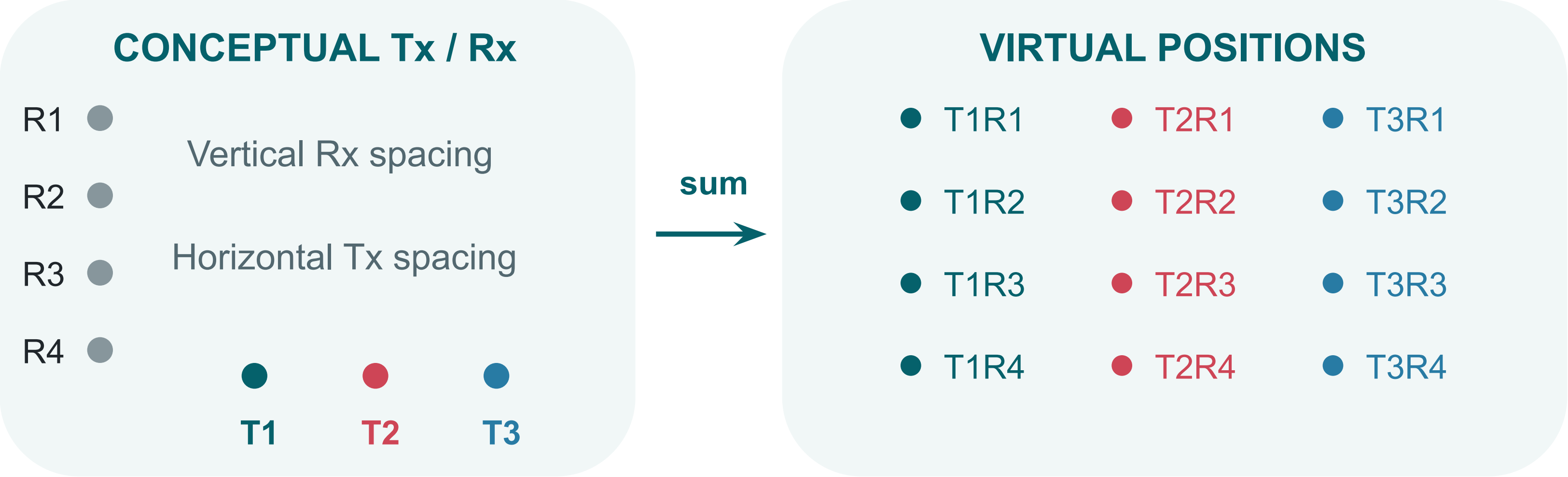
Time Division Multiplexing (TDM) separates transmitters in time

Each Tx/Rx pair is measured in its own transmitter's time slot.



A 2-D virtual array measures two directions

Each virtual position is the sum of one Tx and one Rx position.

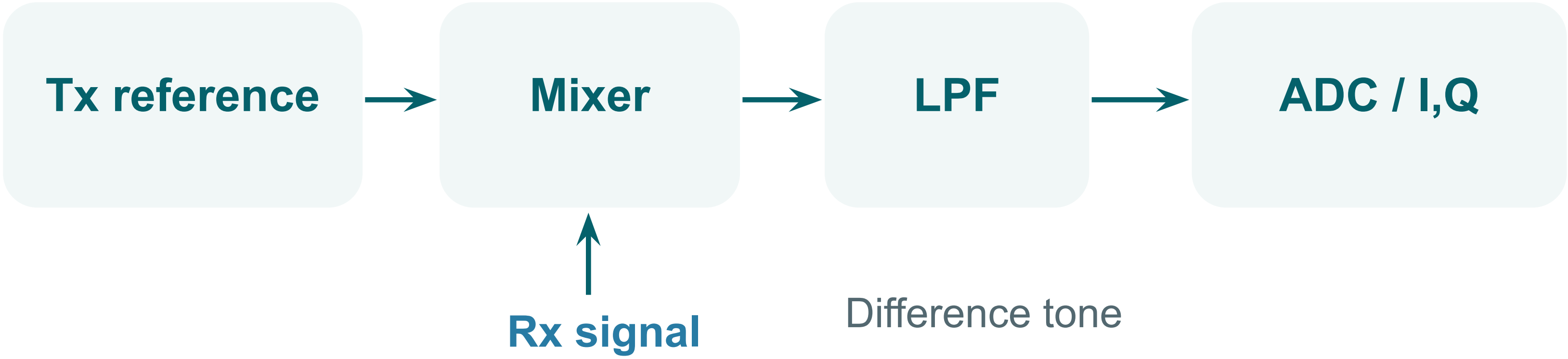


$p_m = p_i^{Tx} + p_j^{Rx}$ **3 × 4 = 12 virtual channels**

p denotes an antenna's position

FMCW Receiver Signal Chain

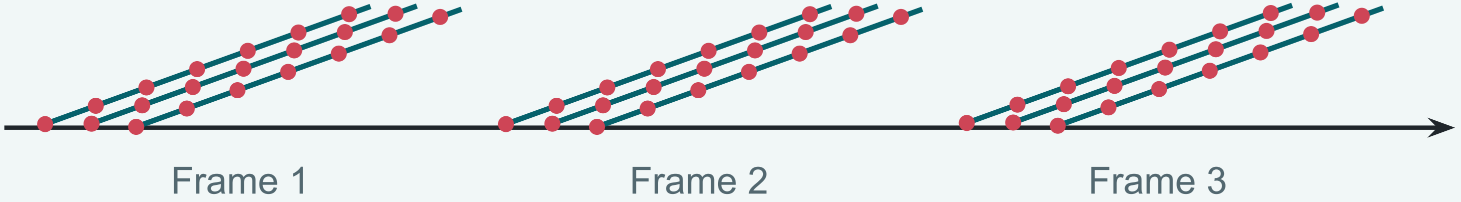
The analog receiver retains the beat frequency signal



Map the samples to the data dimensions

One frame contains doppler chirp loops, antenna pairs, and fast-time samples.

x_{IF}[frame, n_d, tx, rx, n]



n: samples within one chirp

n_d: chirps within one frame

Apply FFT at different axis gives us target information

RANGE FFT

Across n
ADC samples

→

DOPPLER FFT

Across n_d
Same Tx/Rx pair

→

ANGLE FFT

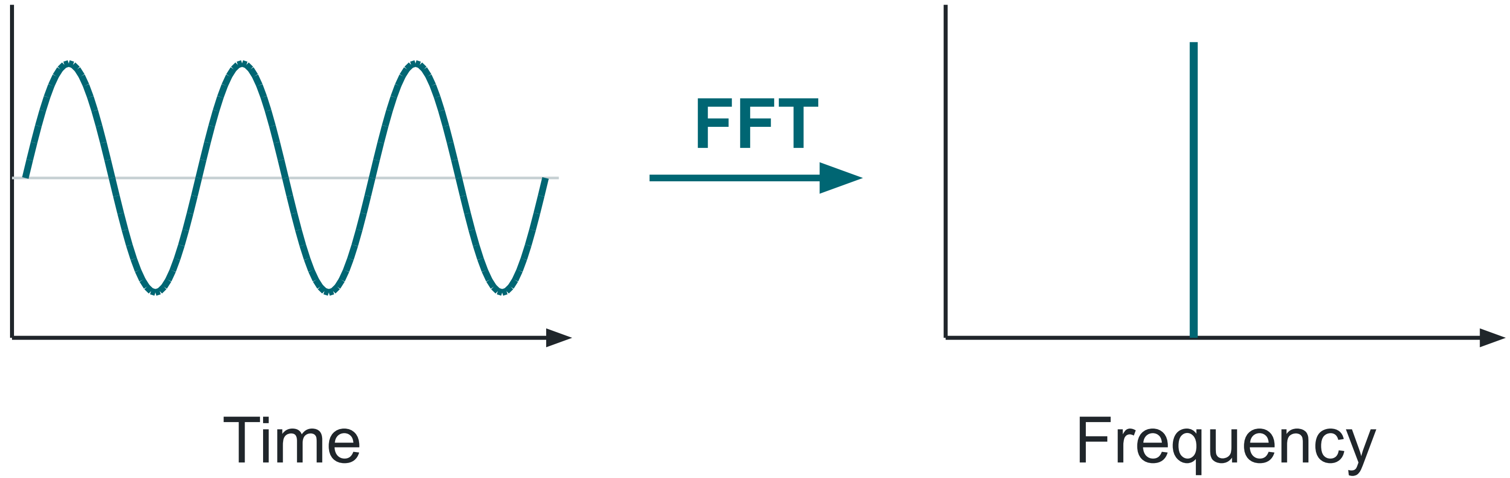
Across virtual
antenna positions

Select range bins

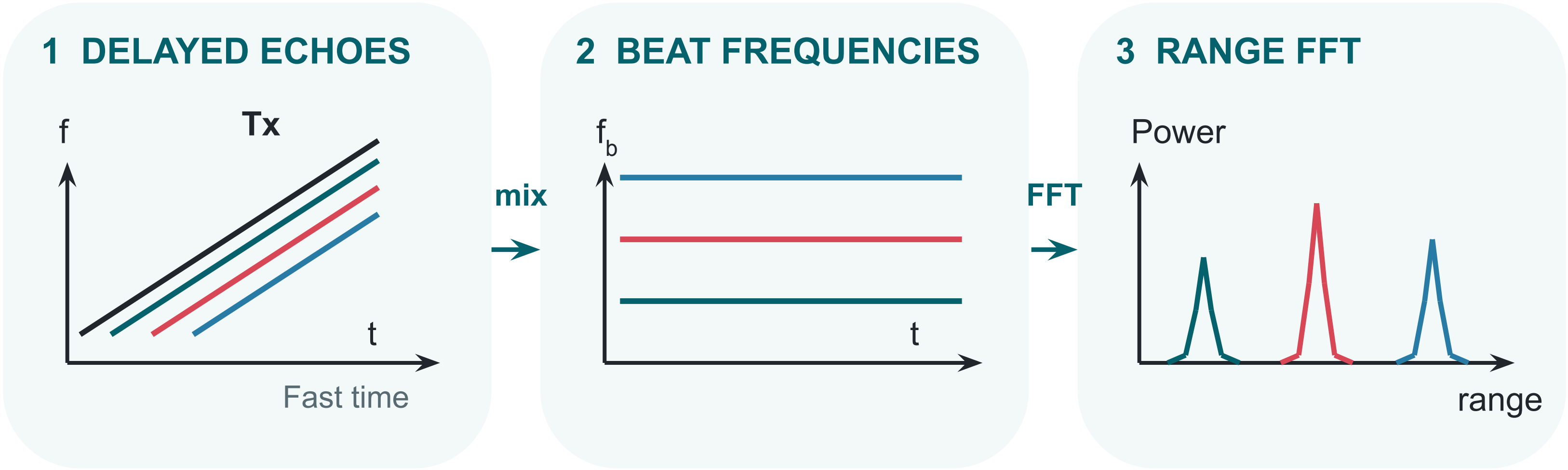
Signed velocity bins

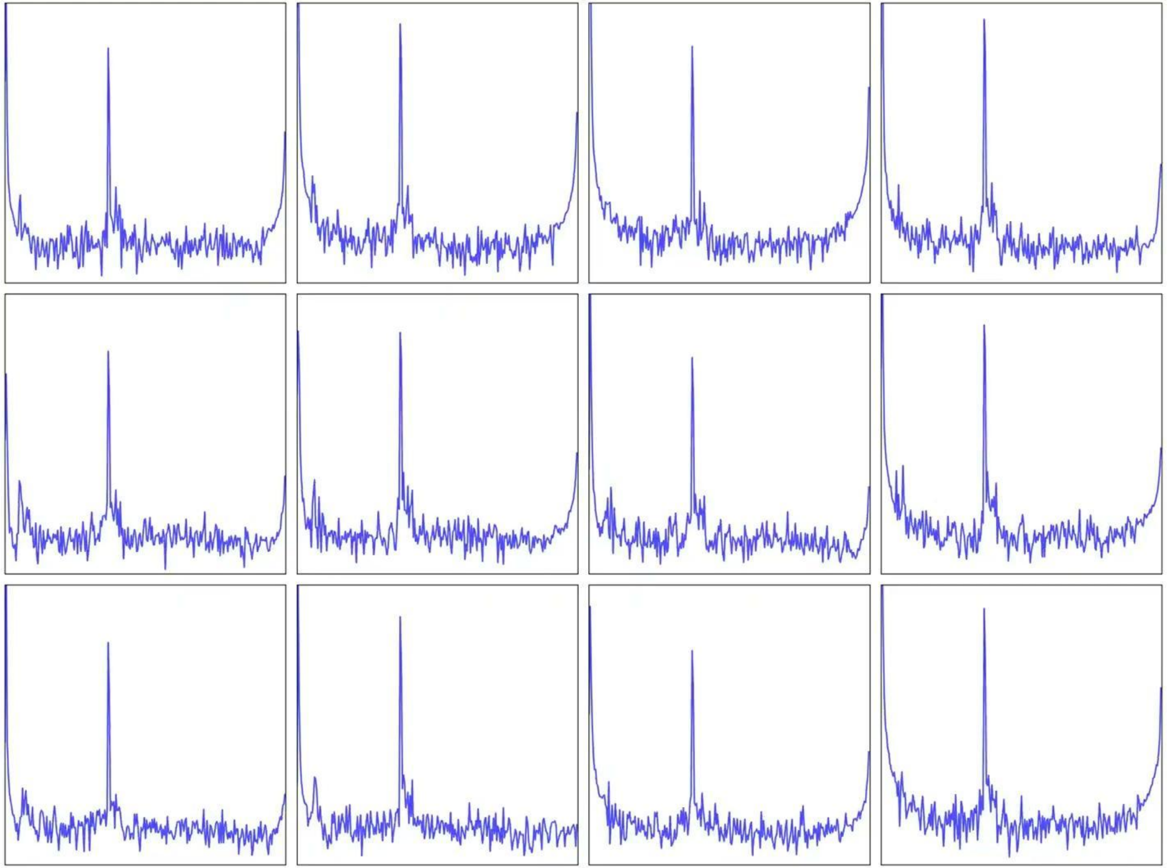
Signed directions

How FFT help to derive the range



Different beat frequencies = different ranges



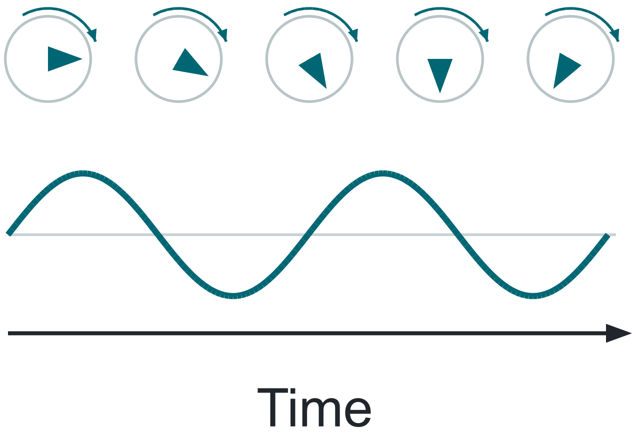


How FFT helps for angle and doppler

The FFT detects frequencies, which basically is the period change of phase

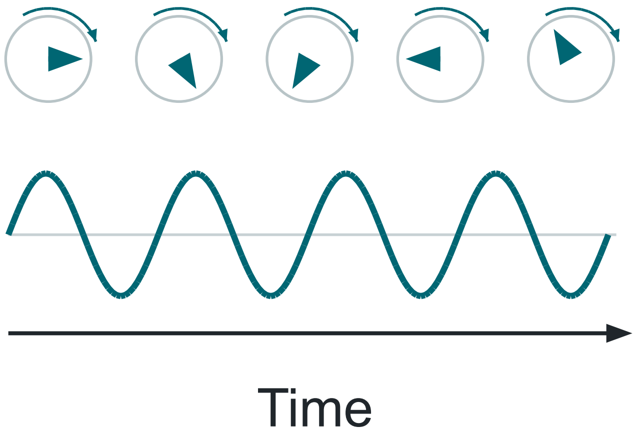
Slow phase change

Lower frequency

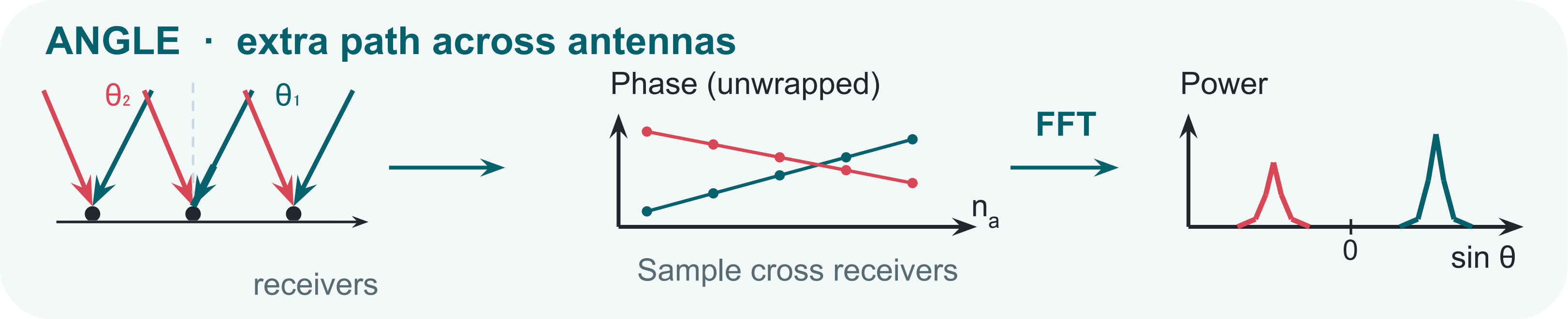


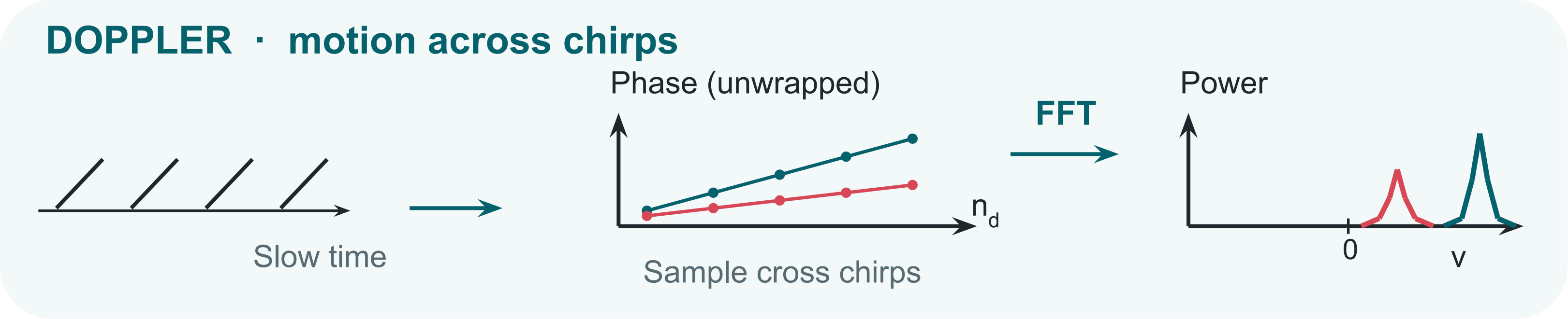
Fast phase change

Higher frequency

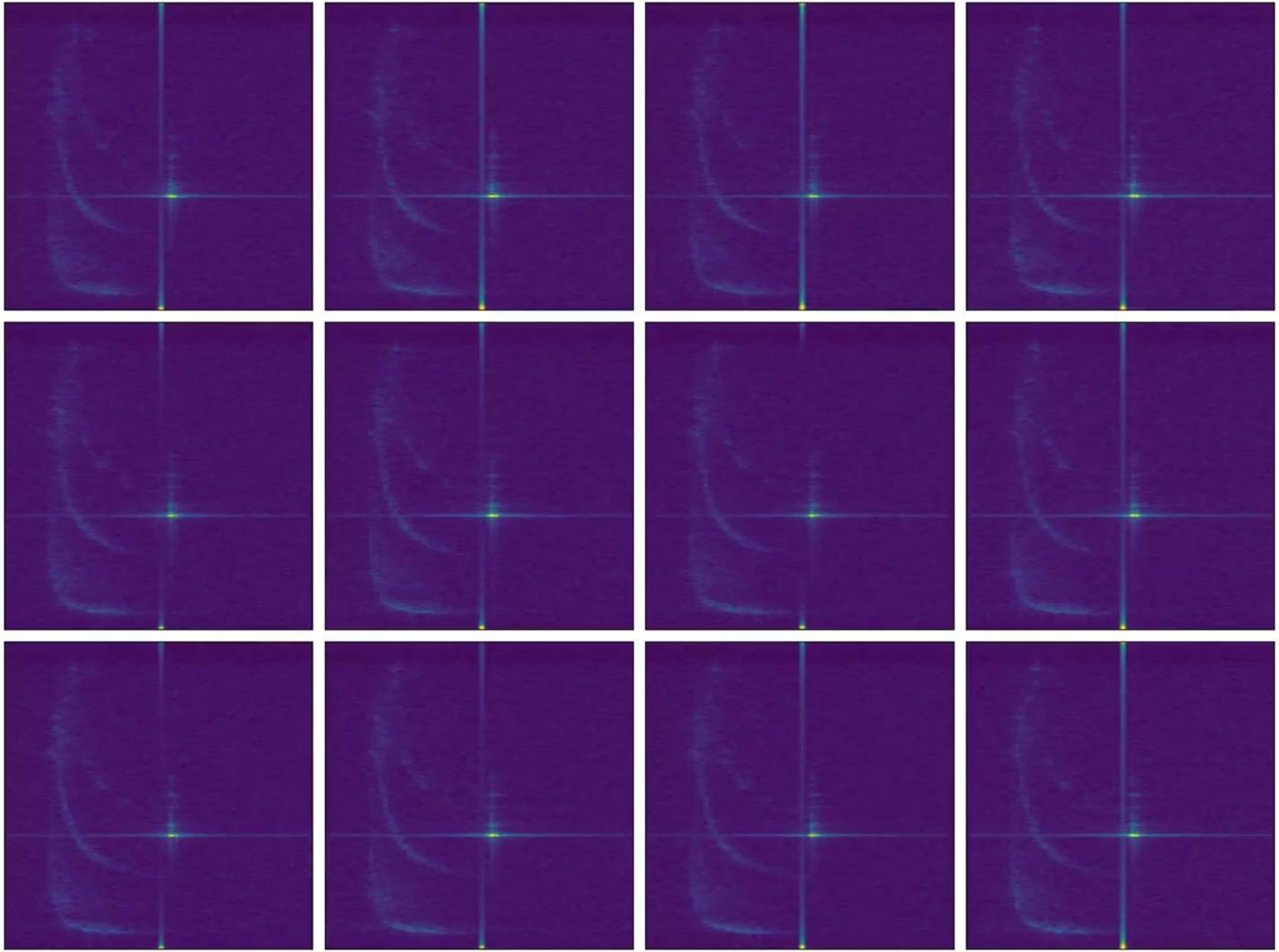


FFT separates the periods of phase change





T_c: same-Tx repeat   Angle row: one uniform axis of a 2-D array



In pseudo code

```
Input: IQ[frame, loop, antenna, sample]

rangeFFT   = FFT(IQ, axis=sample)

dopplerFFT = FFT(rangeFFT, axis=loop)
dopplerFFT = FFTSHIFT(dopplerFFT, axis=loop)

angleFFT   = FFT(dopplerFFT, axis=antenna)
angleFFT   = FFTSHIFT(angleFFT, axis=antenna)
```

Phase in chirp signal

Think phase as distance, then frequency is the velocity and frequency slope is acceleration

Tx $x_{Tx}(t) = A \exp\{j(2\pi f_0 t + \pi S t^2)\}$

Rx Same phase, evaluated at time $t - t_d$

IF $x_{IF}(t) = x_{Tx}(t)\, x_{Rx}^*(t)$

$$\varphi_{IF}(t) = 2\pi f_0 t_d + 2\pi S t_d t - \pi S t_d^2$$

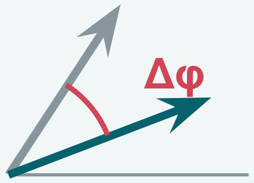
Small motion changes the measured phase

RANGE-DEPENDENT PHASE

$$\begin{aligned}\varphi &= 2\pi f_0 t_d + 2\pi S t_d t - \pi S t_d^2 \\ &\approx 2\pi f_0 t_d \\ &= 2\pi f_0 * 2R/c \\ &= 4\pi r/\lambda\end{aligned}$$

A tiny displacement changes φ

ONE TARGET, TWO INSTANTS

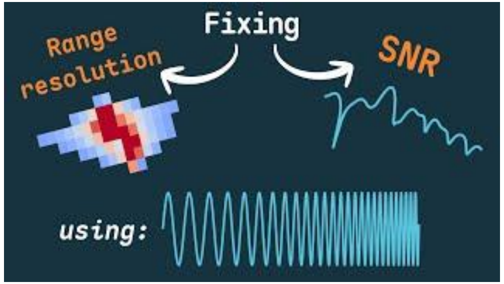


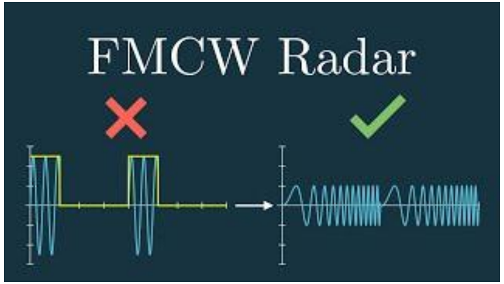
$\Delta\varphi \approx 4\pi\, \Delta r/\lambda$ λ: carrier wavelength

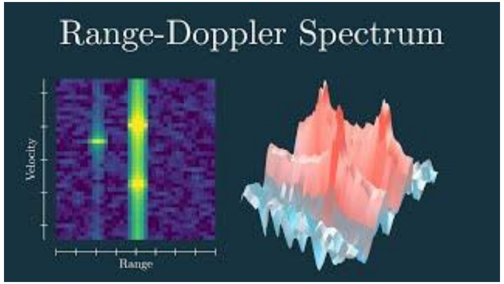
Resources

Links on course website (https://radarml.github.io/18848/)

- FMCW radar cheatsheet
- [TI radar configuration]()
- Videos - Marshall Bruner







Next Class

- A high level introduction to ML
  - If you have not taken an Intro ML course, please read: https://developers.google.com/machine-learning – introduction, linear regression, neural networks (links on class website)
- Some questions we will answer:
  - How much test data should I have?
  - What are the ways to scale an approach?
  - Why is data scaling logarithmic?