Introduction to mmWave Radar

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Recognitions to Peter Aberl and Sandeep Rao

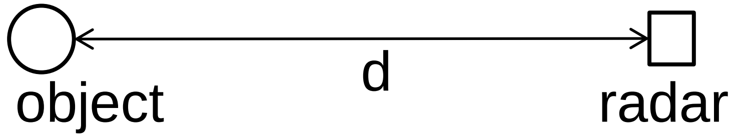
Agenda

- FMCW Radar Overview
- FMCW Radar Signal Processing
- TI mmWave sensor portfolio

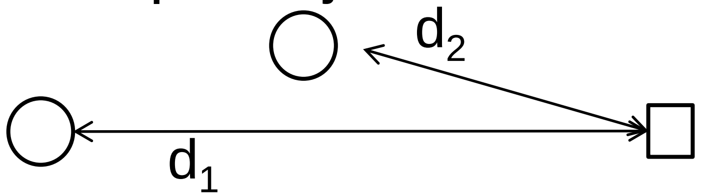
FMCW Radar Overview

Questions

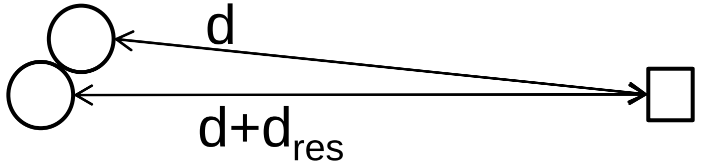
- How does the radar estimate the range of an object?



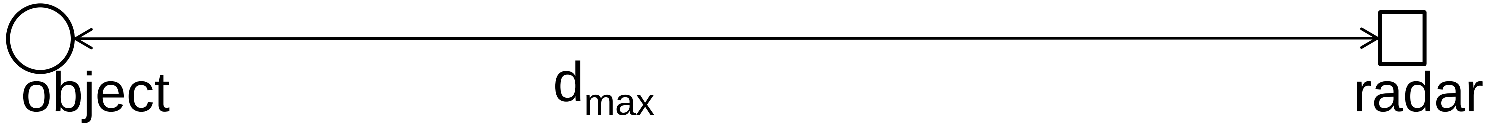
- What if there are multiple objects?



- How close can two object get and still be resolved as two objects?



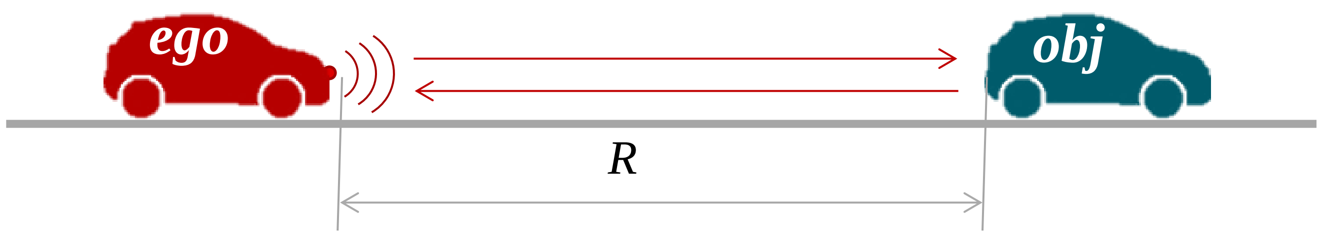
- What determines the furthest distance a radar can see?



Primary Radar Principles

Radar = Radio detection and ranging

- Distance to Object = Time of Flight



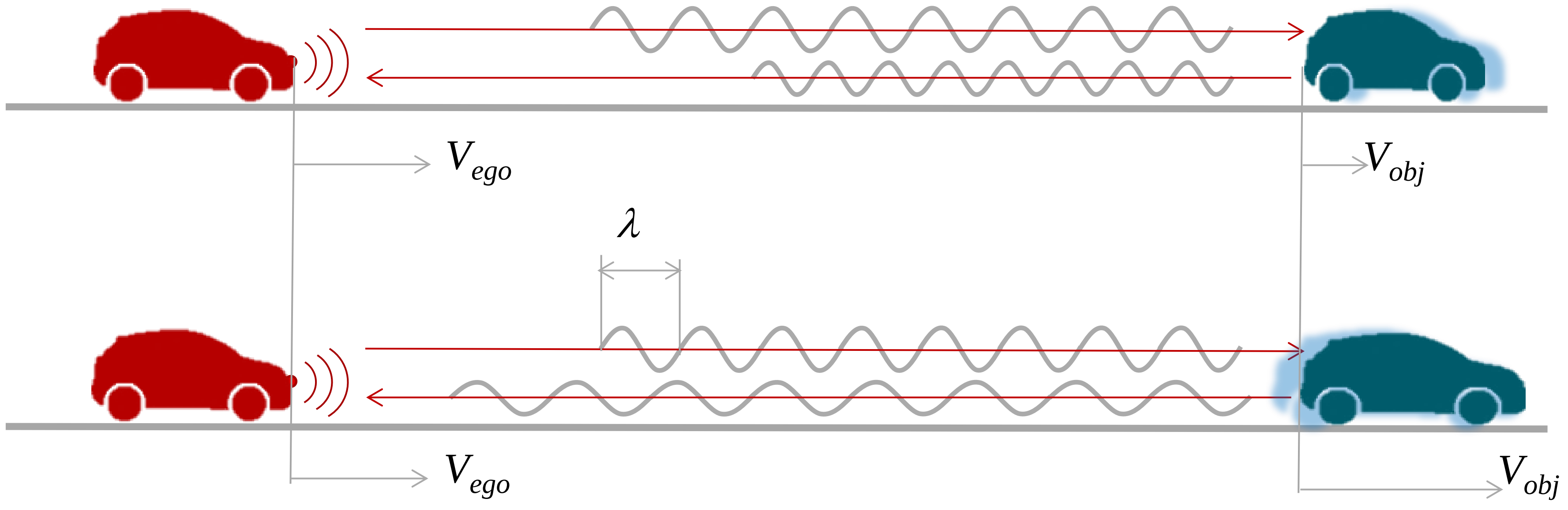
Speed of Light

Range = Distance

$$R = \frac{c}{2} \cdot t_{pd}$$

Propagation Delay TX→RX

- Relative Velocity of Object = Doppler Effect



Relative Speed

Doppler Shift

$$V_{rel} = V_{ego} - V_{obj} = \frac{\lambda \cdot f_D}{2}$$

Wave-length

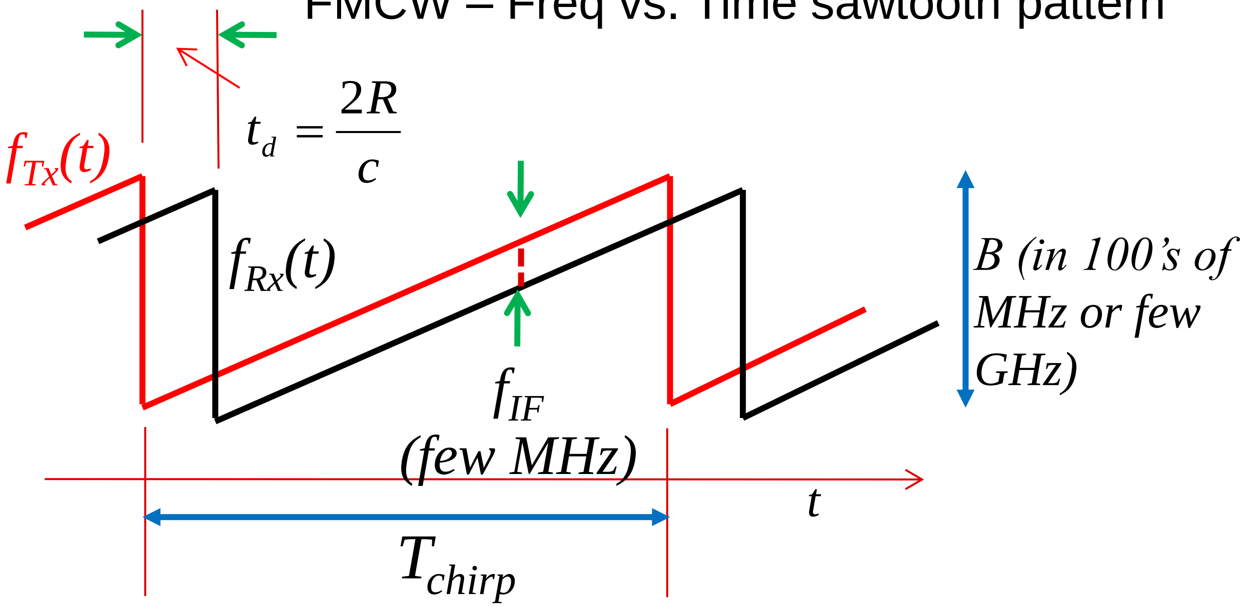
FMCW Radar Overview (1/2)

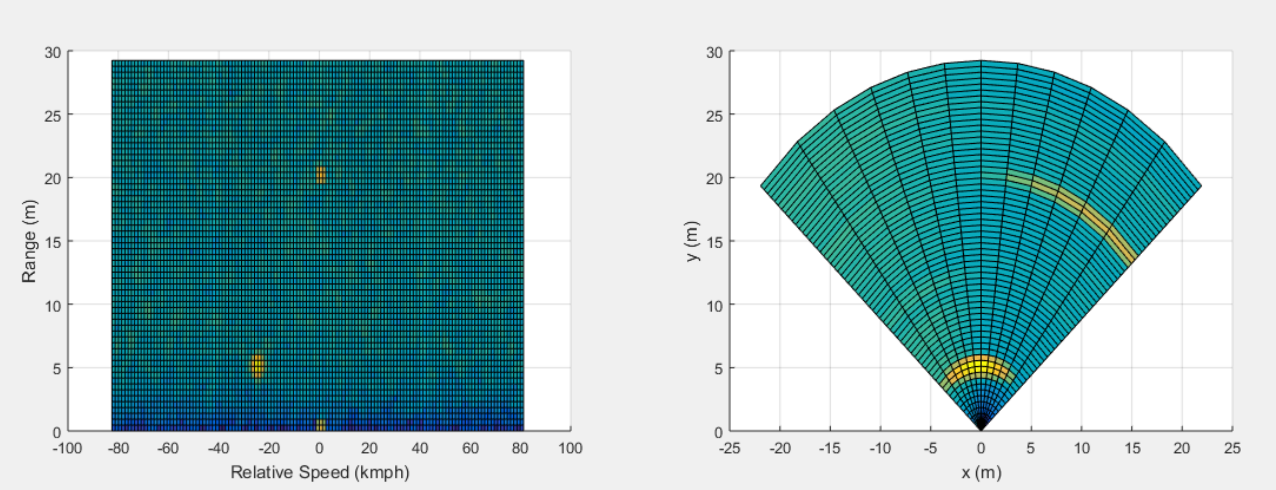
- FMCW: Frequency Modulated Continuous Wave is becoming the most commonly used scheme in automotive radar today
  - Linear FMCW: TX signal has frequency changing linearly with time (i.e., chirp signal)

- Key benefits of FMCW radar
  - Ability to sweep wide RF bandwidth (GHz) while keeping IF bandwidth small (MHz)
  - Better range resolution. RF sweep bandwidth of 2 GHz can achieve 7.5cm range resolution, while IF bandwidth can still be <15MHz
  - Lower peak power requirement, compared to pulsed radar

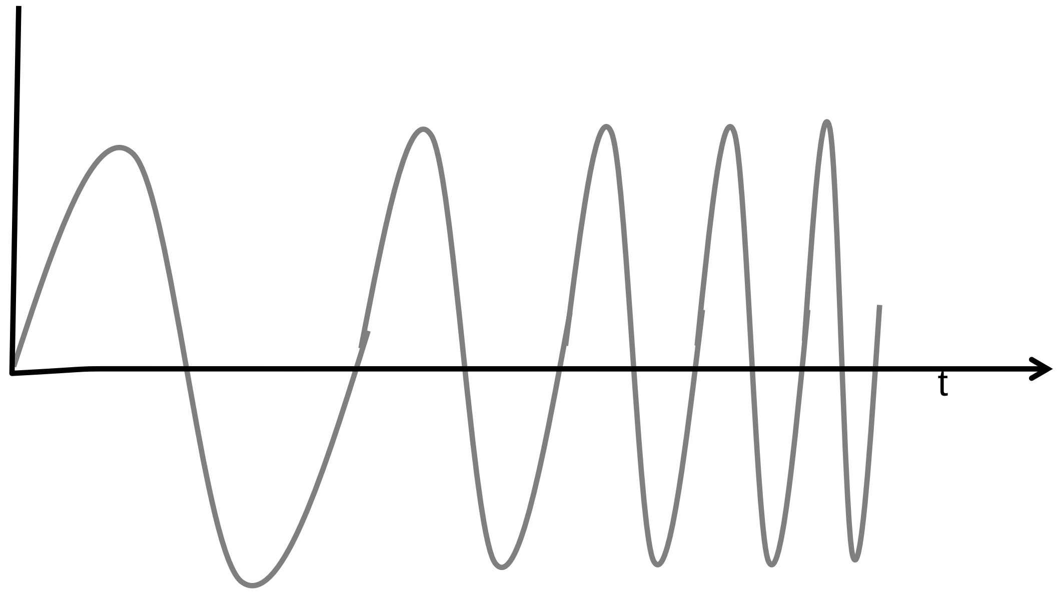
- Factors that determine performance
  - Range precision ∝ RF (sweep) Bandwidth
  - Velocity precision ∝ Dwell (frame) time
  - Angle precision ∝ Number of Tx,Rx

FMCW – Freq vs. Time sawtooth pattern

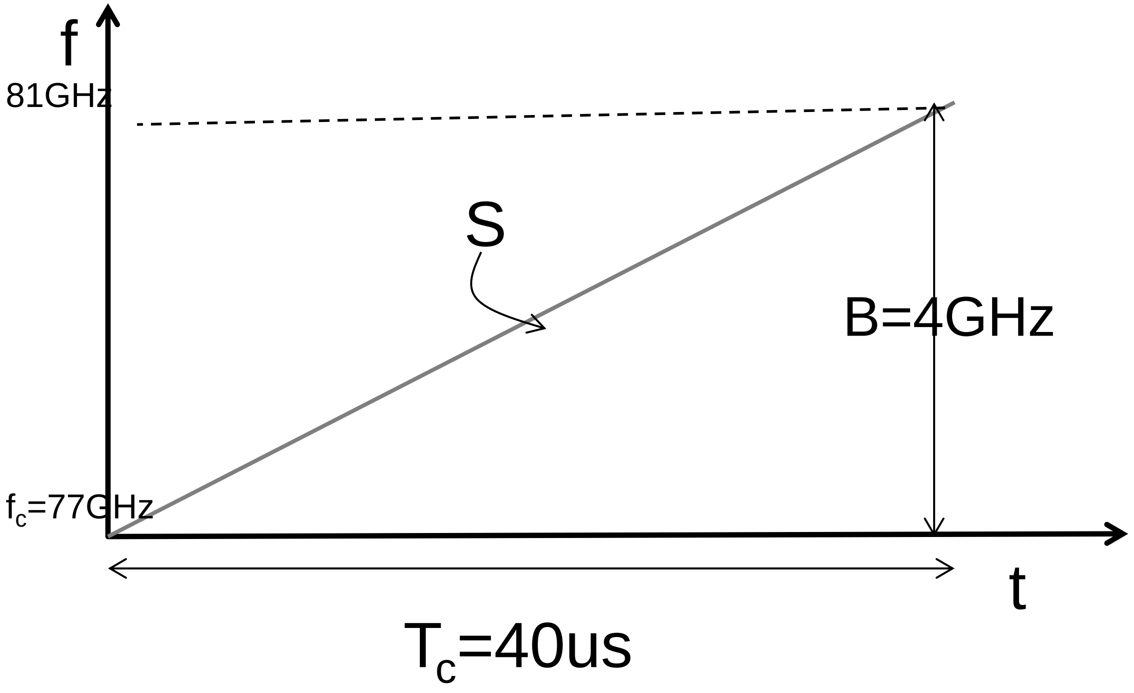




FMCW Radar Overview (2/2)



An FMCW radar transmits a signal called a “chirp”. A chirp is a sinusoid whose frequency increases linearly with time, as shown in the Amplitude vs time (or ‘A-t’ plot) here.



- A frequency vs time plot (or ‘f-t plot’) is a convenient way to represent a chirp.
- A chirp is characterized by a start frequency (f_c), Bandwidth(B) and duration (T_c).
- The Slope (S) of the chirp defines the rate at which the chirp ramps up. In this example the chirp is sweeping a bandwidth of 4GHz in 40us which corresponds to a Slope of 100MHz/us

An Example of FMCW Radar – 1Tx/1Rx

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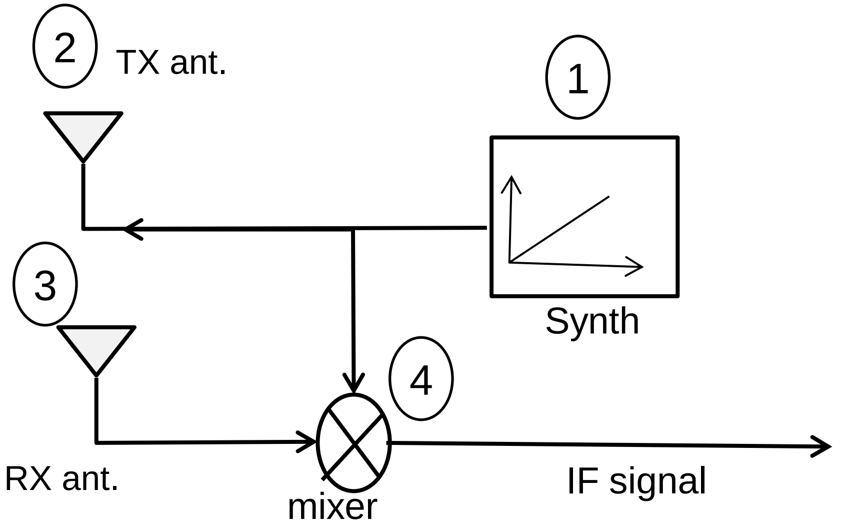
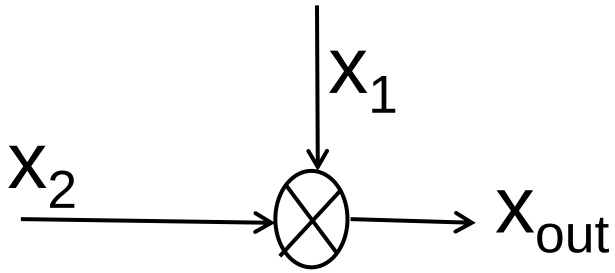


1. A synthesizer (synth) generates a chirp
2. The chirp is transmitted by the TX antenna
3. The chirp is reflected off an object and the reflected chirp is received at the RX antenna.
4. The RX signal and TX signal are 'mixed' and the resulting signal is called an 'IF signal'. We'll analyze the IF signal in more detail in the next slide

What is a mixer?



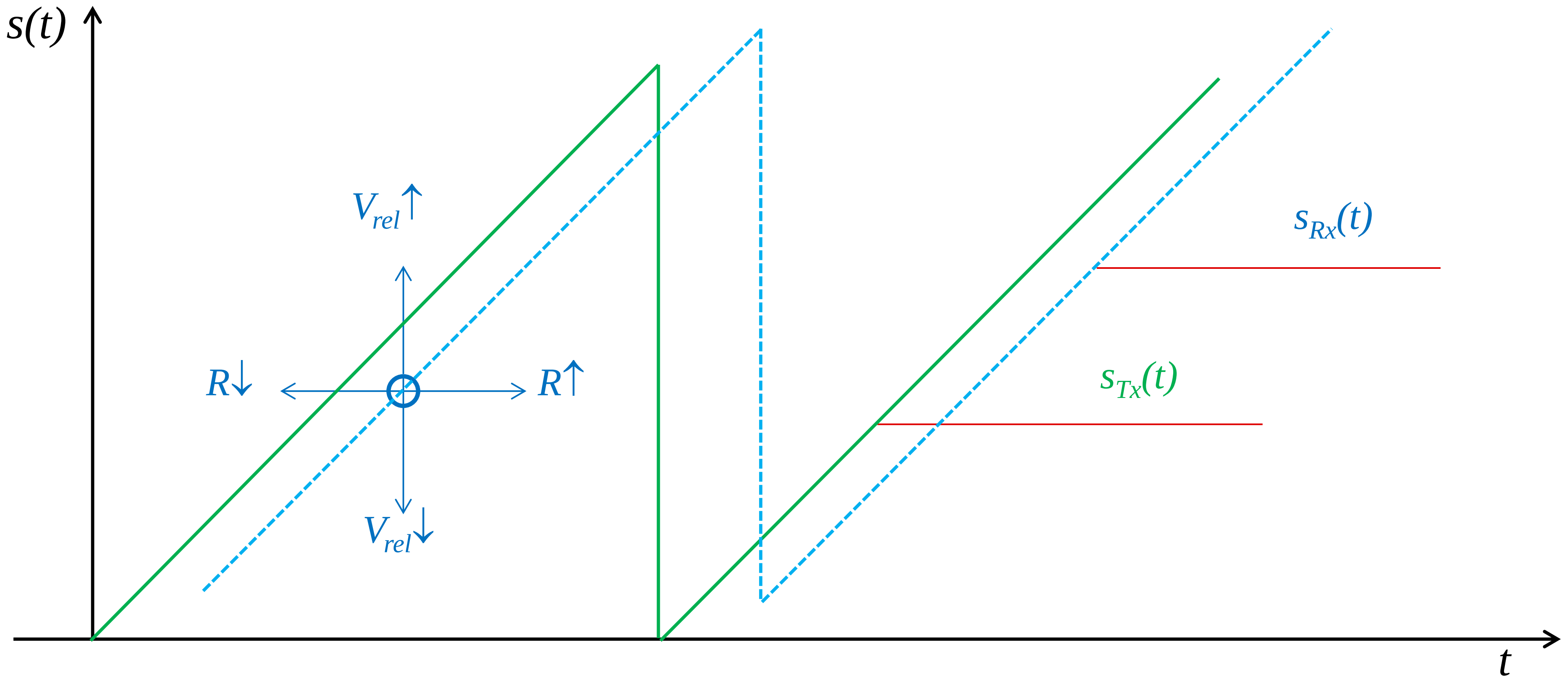
A mixer is a 3 port device with 2 inputs and 1 output. For our purposes, a mixer can be modelled as follows. For two sinusoids x1 and x2 input at the two input ports, the output is a sinusoid with:

- Instantaneous frequency equal to the difference of the instantaneous frequencies of the two input sinusoids.
- Phase equal to the difference of the phase of the two input sinusoids

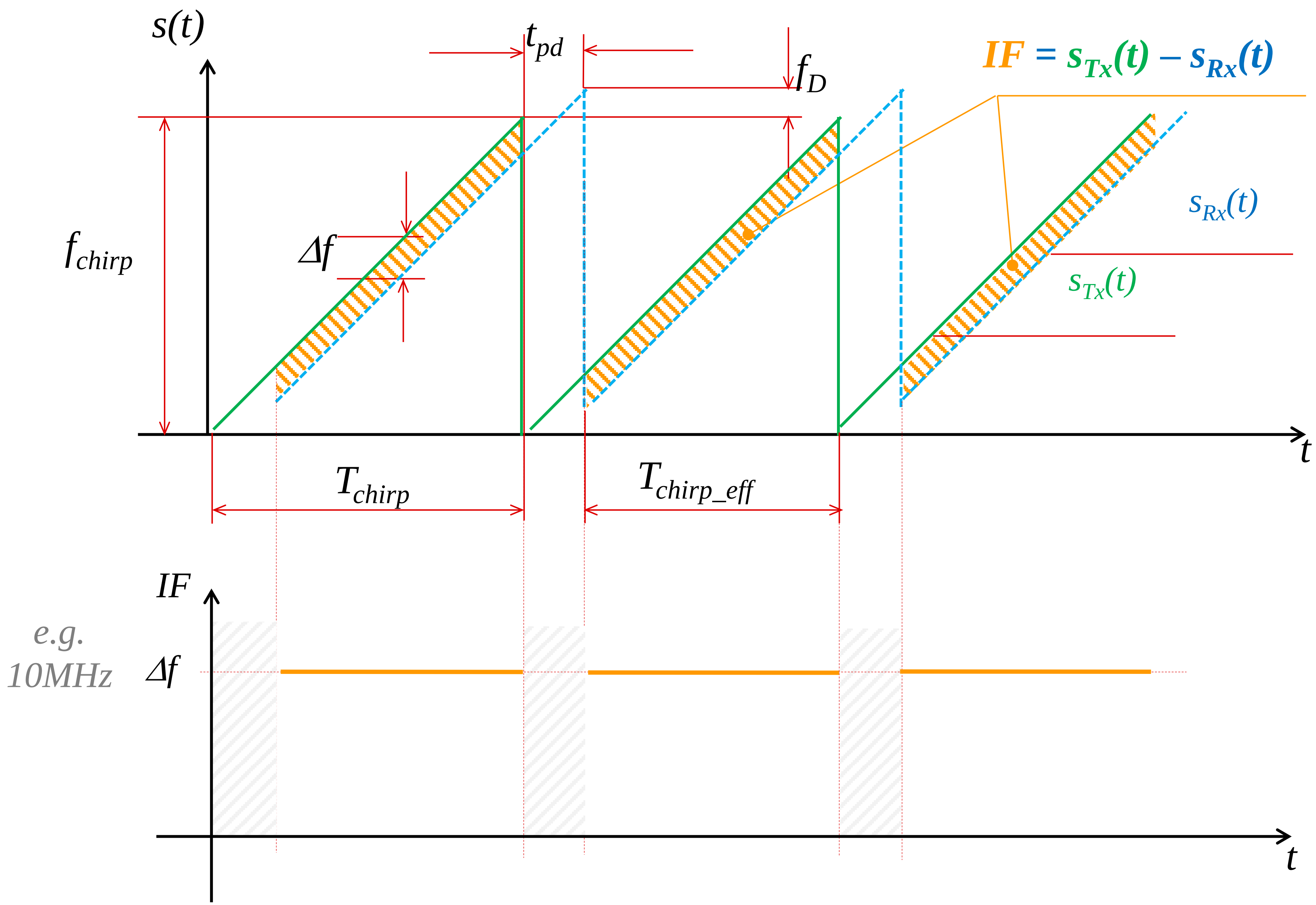
$$x_1 = \sin[w_1 t + \phi_1)]$$
$$x_2 = \sin[w_2 t + \phi_2)]$$

$$x_{out} = \sin[(w_1 - w_2)t + (\phi_1 - \phi_2)]$$

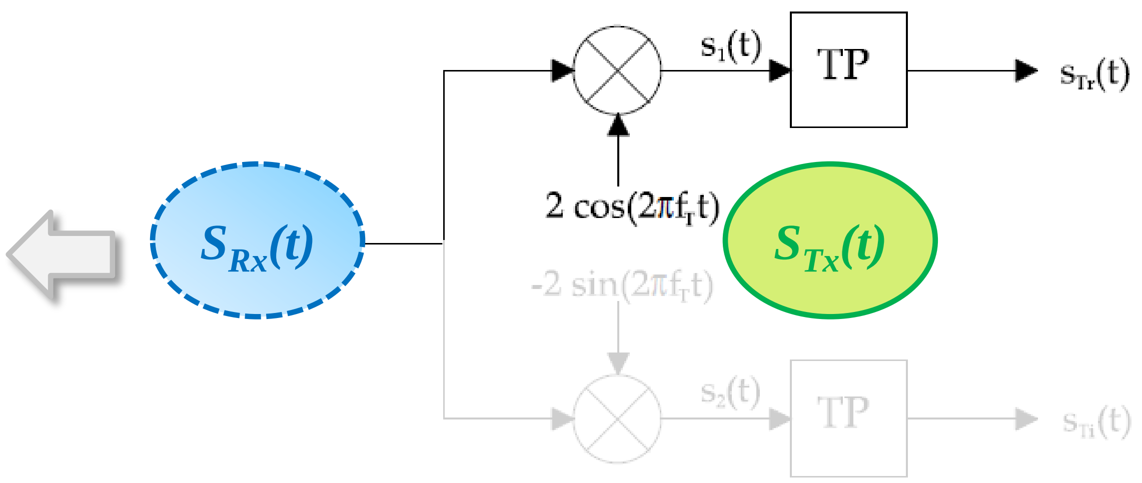
FMCW summary



FMCW intermediate frequency (IF)



Mixer to extract IF



FMCW – Doppler range resolution

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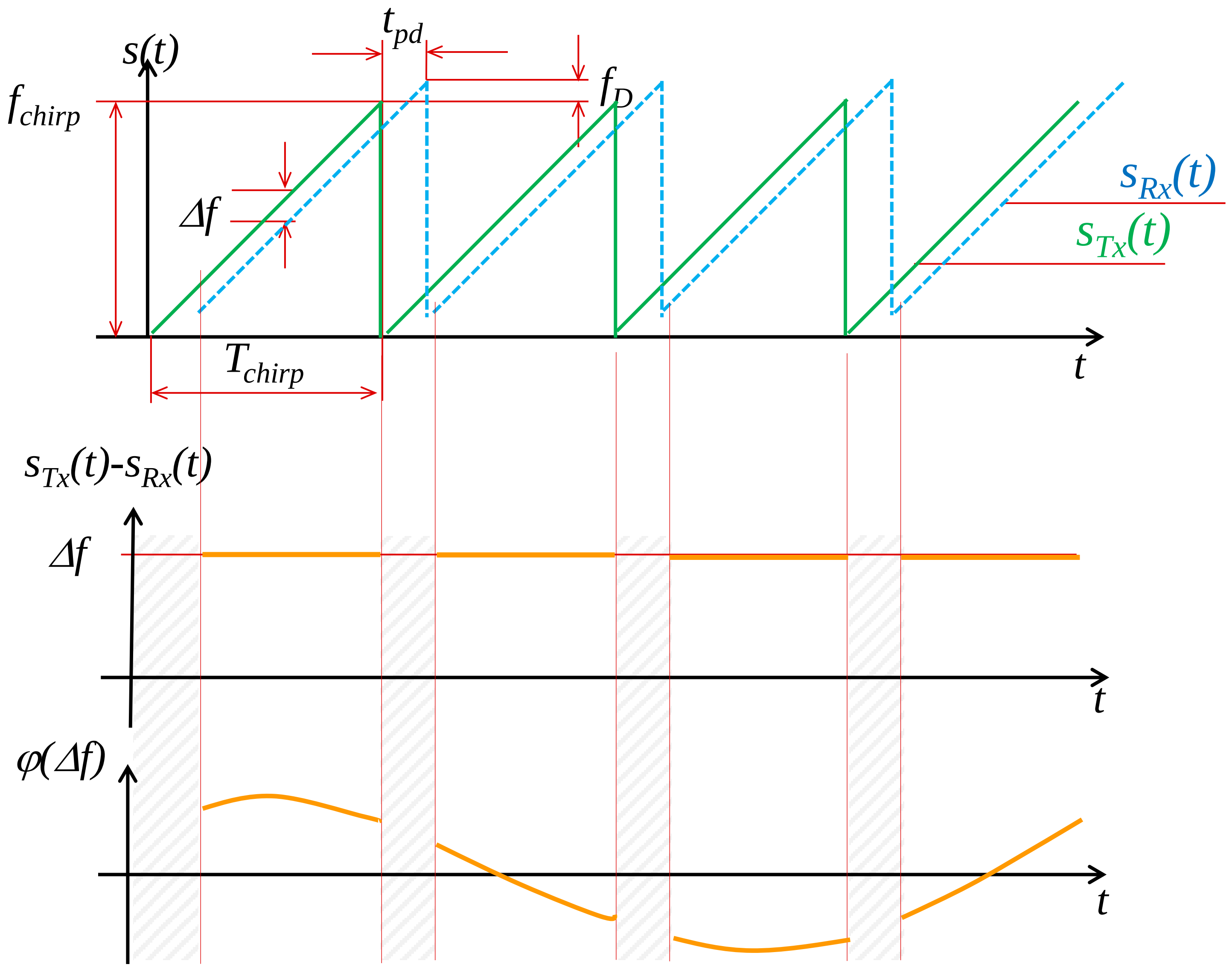
- T_{chirp} *in 10's of μs* → *quasi stationary environment per frame*

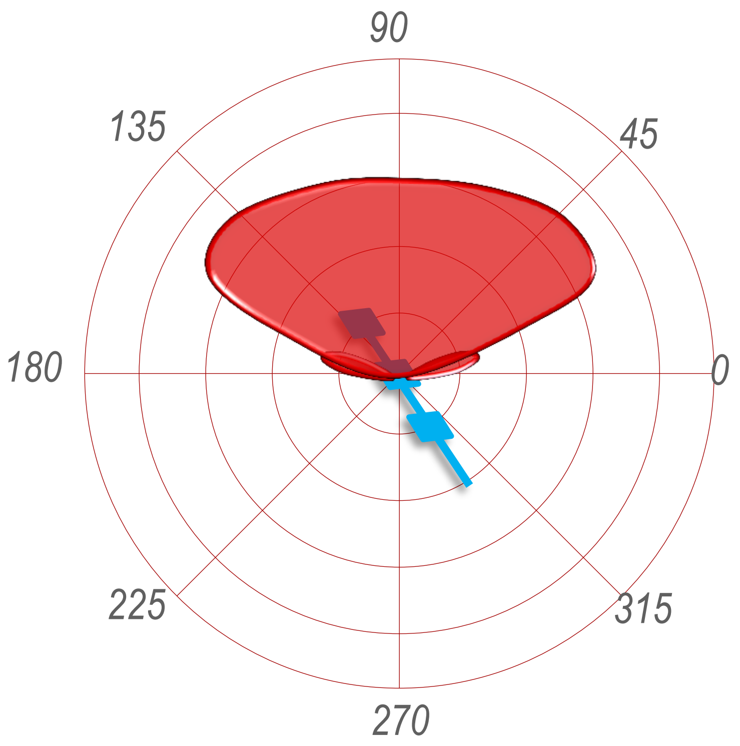


Δf → FFT → Object Range

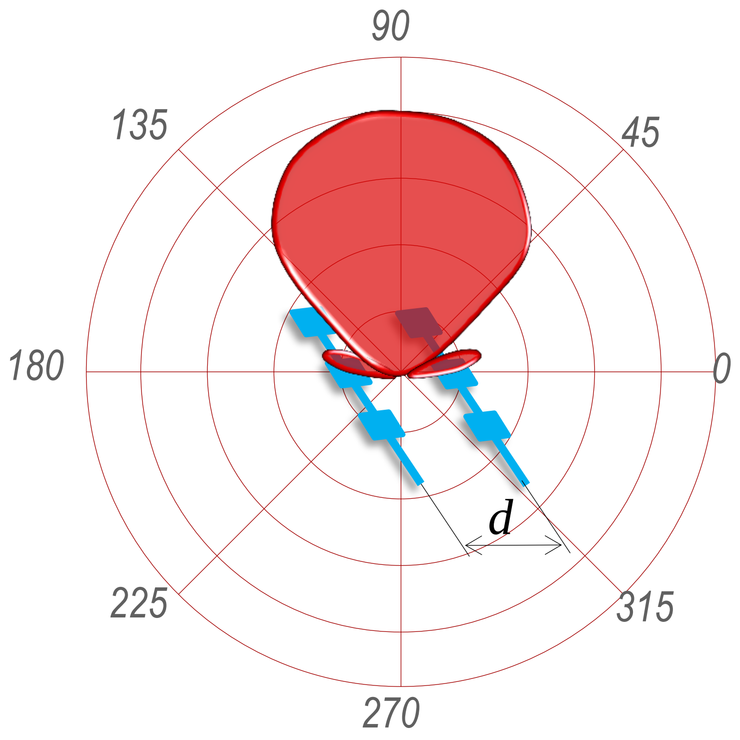
φ → f_D → FFT → Relative Velocity

Linear patch antenna array examples

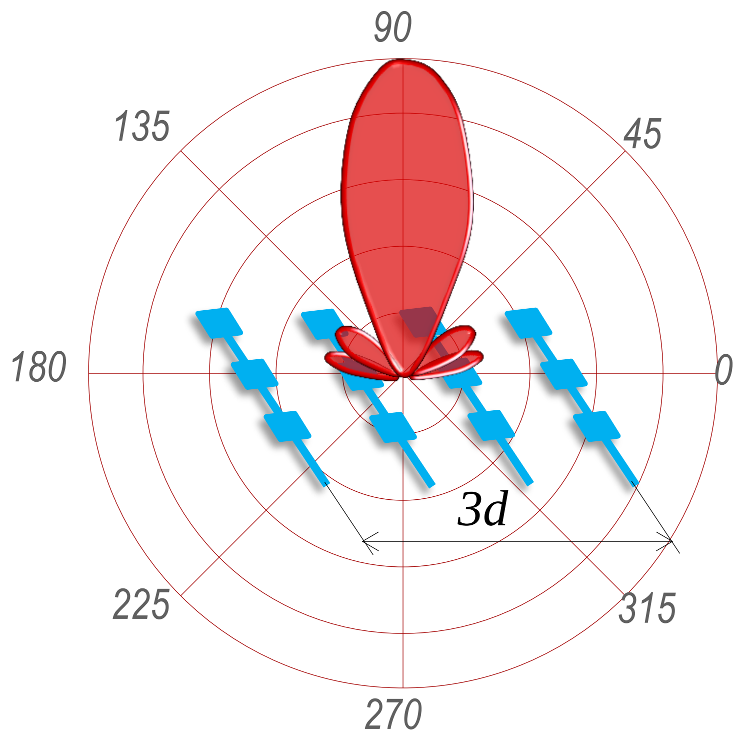
Linear patch antenna



Linear patch antenna array, 2 elements



Linear patch antenna array, 4 elements



→ More Antenna elements for better angular resolution and higher antenna gain

Disadvantages:

- Reduced “Field of View”
- more PCB space for antenna patches

Angle of arrival of an object

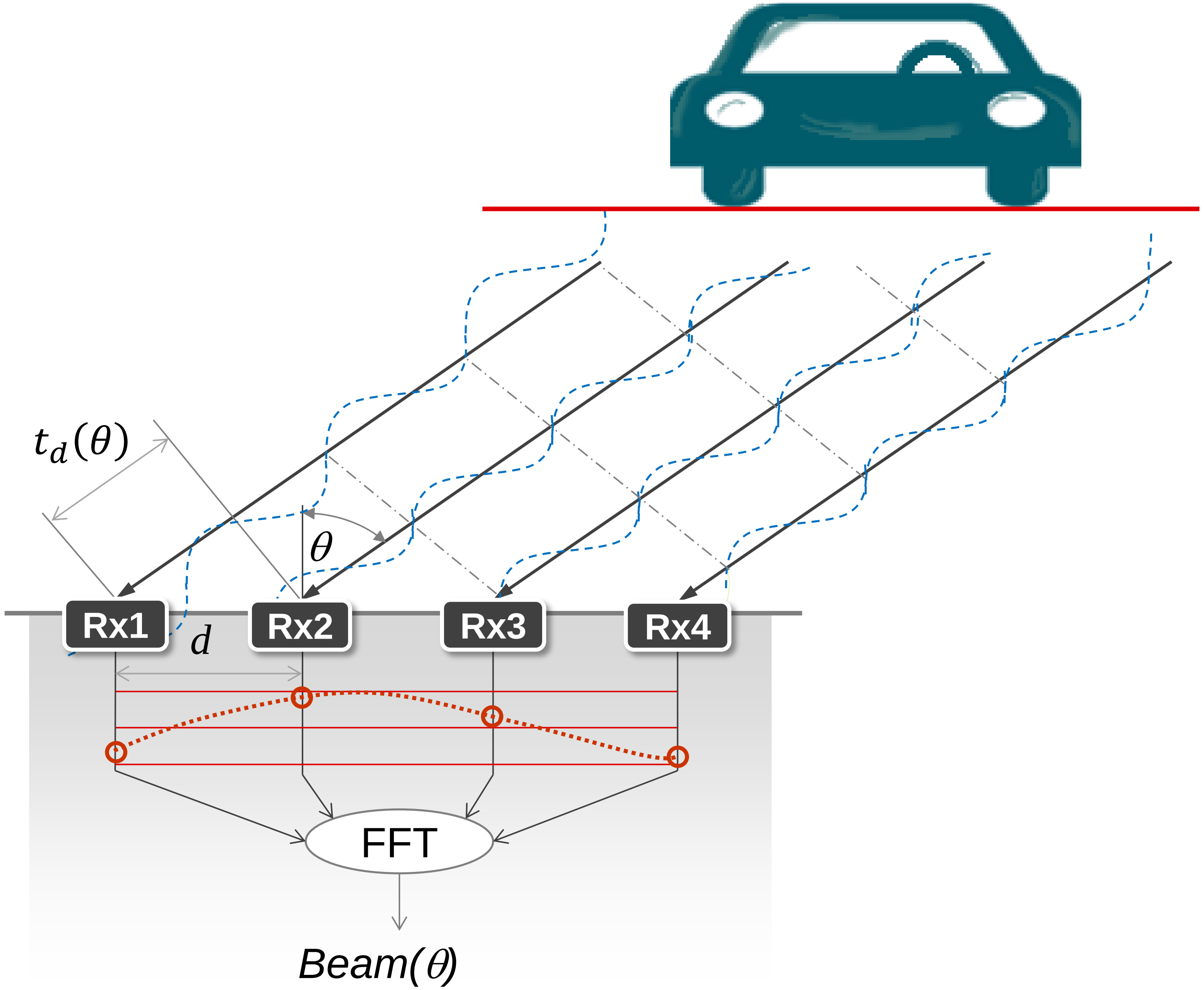
Digital beam forming / steering
with Linear Antenna Array

→ Can be applied to TX,
RX (see below) or both directions

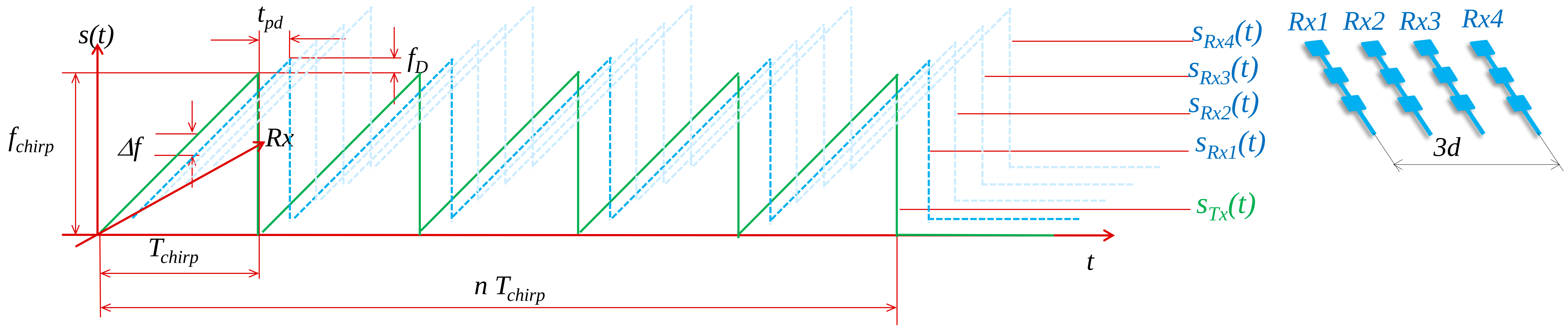
$$t_d(\theta) = \frac{d}{c} \cdot \sin(\theta)$$

Phase difference $\omega(Rx_n) - \omega(Rx_{n-1})$

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

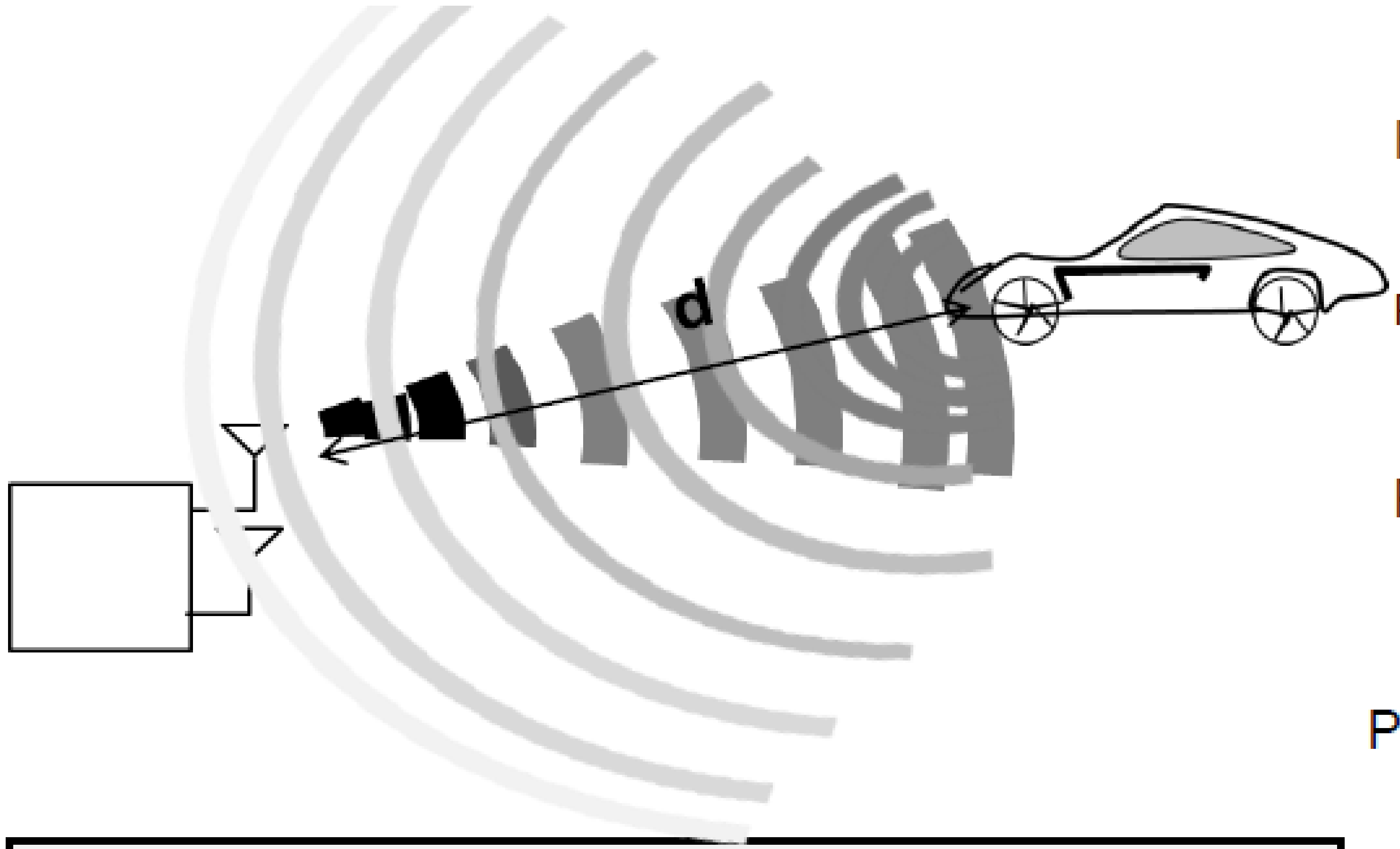


FMCW – equations



	Range R	*Rel. velocity V*	*Angel of arrival θ*
Generic	$R = \frac{c}{2} \cdot \frac{T_{chirp}}{f_{chirp}} \cdot \Delta f$	$V = \frac{\lambda \cdot f_D}{2}$	$\theta = sin^{-1}\left(\frac{\lambda\Delta\omega}{2\pi d}\right)$
Resolution	$\Delta R = \frac{c}{2} \cdot \frac{1}{f_{chirp}}$	$\Delta V = \frac{\lambda}{2 \cdot n \cdot T_{chirp}}$	$\Delta\theta = \frac{\lambda}{N \cdot d \cdot cos(\theta)}$
Maximum unambiguous	$R_{max} = \frac{c \cdot T_{chirp}}{f_{chirp}} \cdot F_{ADC\_SR}$	$V_{max} = \frac{\lambda}{4 \cdot T_{chirp}}$	$\theta_{max} = sin^{-1}\left(\frac{\lambda}{2d}\right)$

The Radar Range Equation



Radiated Power Density$= \frac{P_t G_{TX}}{4\pi d^2} \; W/m^2$

Power reflected by object $= \frac{P_t G_{TX} \sigma}{4\pi d^2} \; W$

Power density at RX ant$= \frac{P_t G_{TX} \sigma}{(4\pi)^2 d^4} \; W/m^2$

Power captured at RX ant $= \frac{P_t G_{TX} \sigma A_{RX}}{(4\pi)^2 d^4}$ W

$= \frac{P_t G_{TX} \sigma G_{RX} \lambda^2}{(4\pi)^3 d^4}$ W

$$A_{RX} = \frac{G_{RX}\lambda^2}{4\pi}$$

P_t: Output power of device

$G_{TX/RX}$: TX/RX Antenna Gain

σ: Radar Cross Section of the Target (RCS)

A_{RX}: Effective aperture area of RX antenna

The Radar Range Equation

$$SNR = \frac{\sigma P_t G_{TX} G_{RX} \lambda^2 T_{meas}}{(4\pi)^3 d^4 kTF}$$

Total measurement time (NT_c)

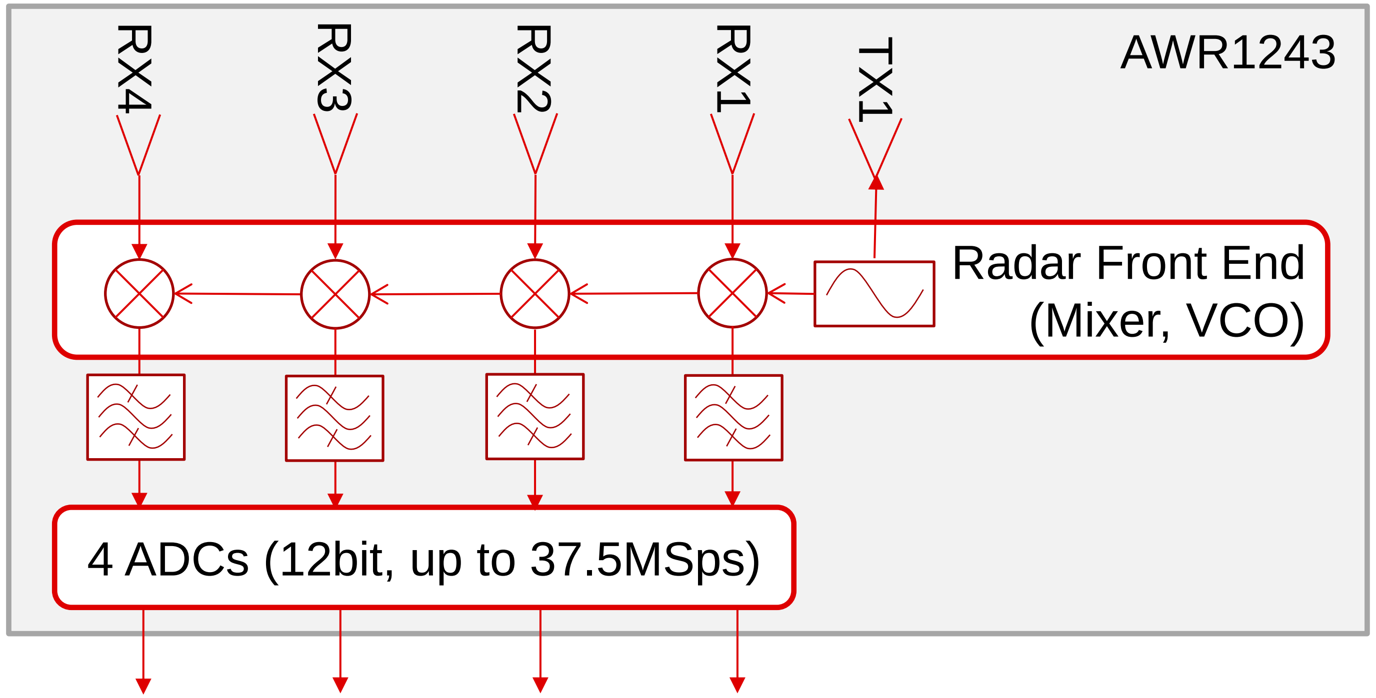
Thermal noise at the reciever (k=Boltzman constant, T=Antenna temperature)

- There is a minimum SNR (SNR_{min}) that is required for detecting an target.
  - Choice of SNR_{min} is trade-off between probability of missed detections and probability of false alarms. Typical numbers are in the 15dB-20dB range.
- Given an SNR_{min}, the maximum distance that can be seen by the radar can be computed as:

$$d_{max} = \left(\frac{\sigma P_t G_{TX} G_{RX} \lambda^2 T_{meas}}{(4\pi)^3 SNR_{min} kTF}\right)^{\frac{1}{4}}$$

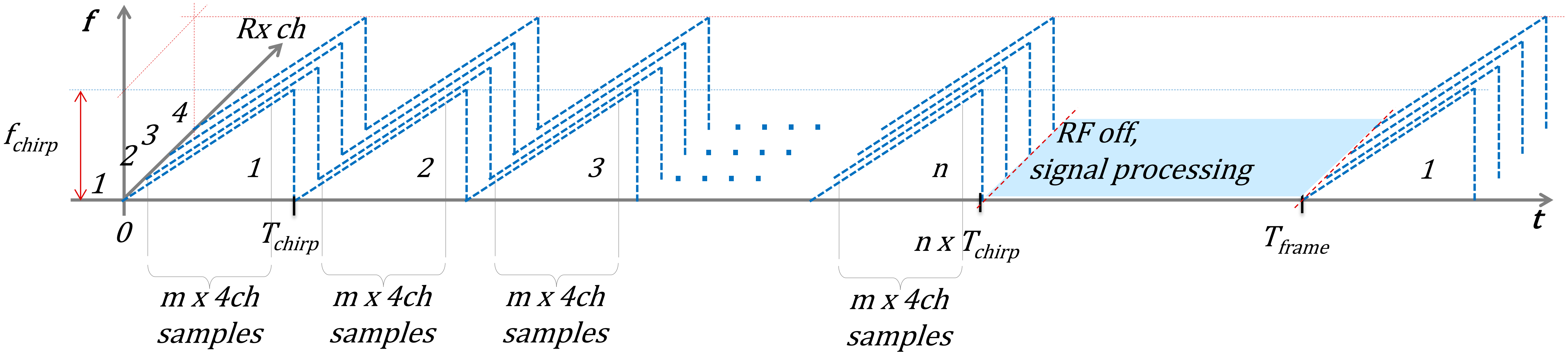
FMCW Radar Signal Processing

1. How to capture data



$$Duty\ Cycle = DC = \frac{n \cdot Tchirp\text{郝}}{Tframe}$$

DC(typ.) ~ 30 ... 70 %



2. How to determine range

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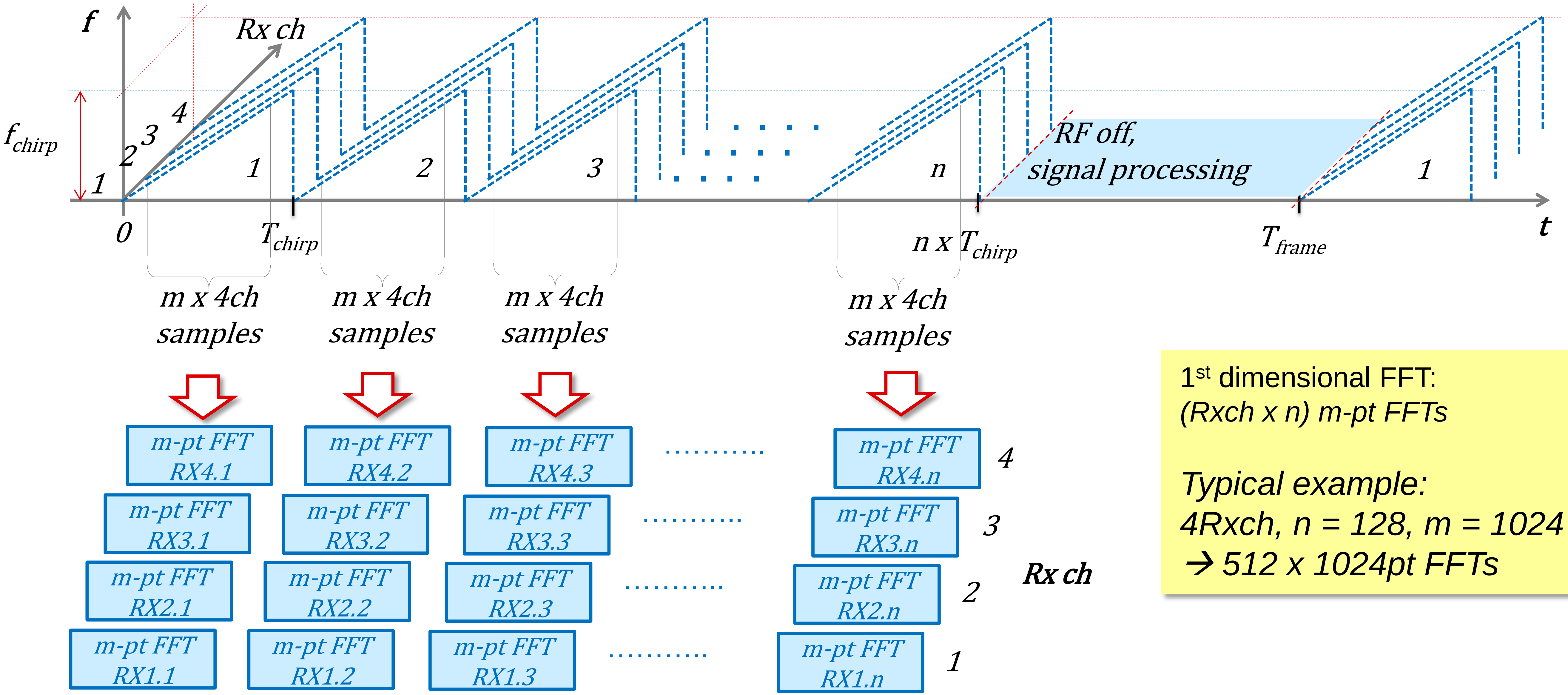
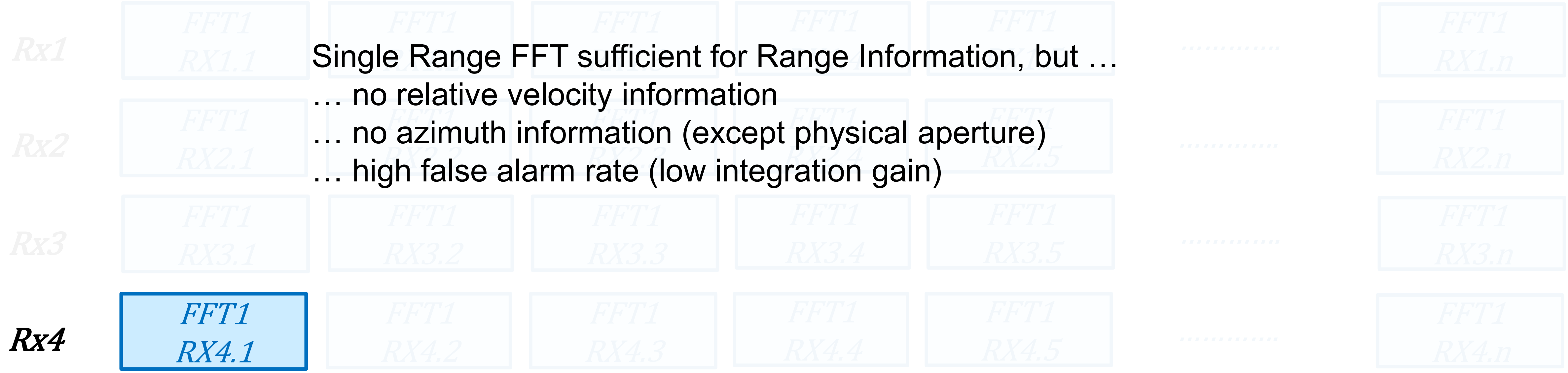


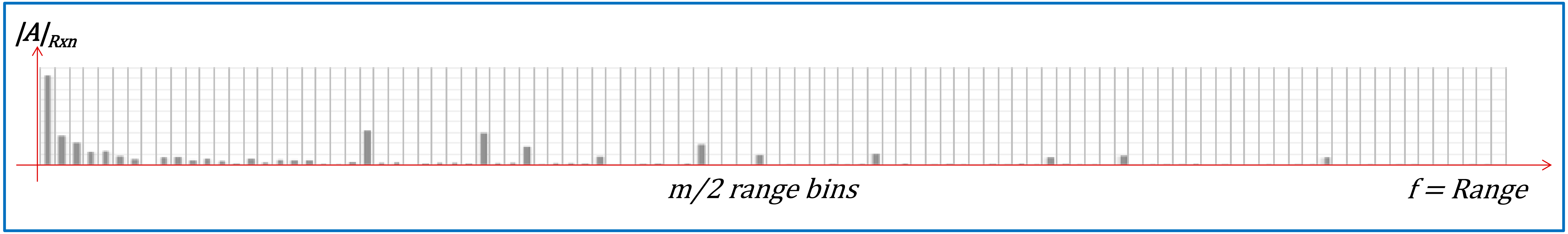
1st dimensional FFT:
(Rxch x n) m-pt FFTs

Typical example:
4Rxch, n = 128, m = 1024 (real)
→ 512 x 1024pt FFTs

2. Why so many range FFTs?

Single Range FFT sufficient for Range Information, but …
… no relative velocity information
… no azimuth information (except physical aperture)
… high false alarm rate (low integration gain)





3. How to determine velocity in 2 steps

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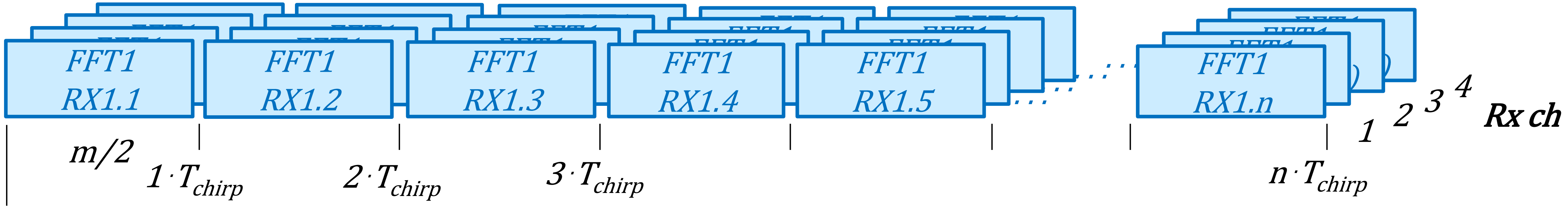
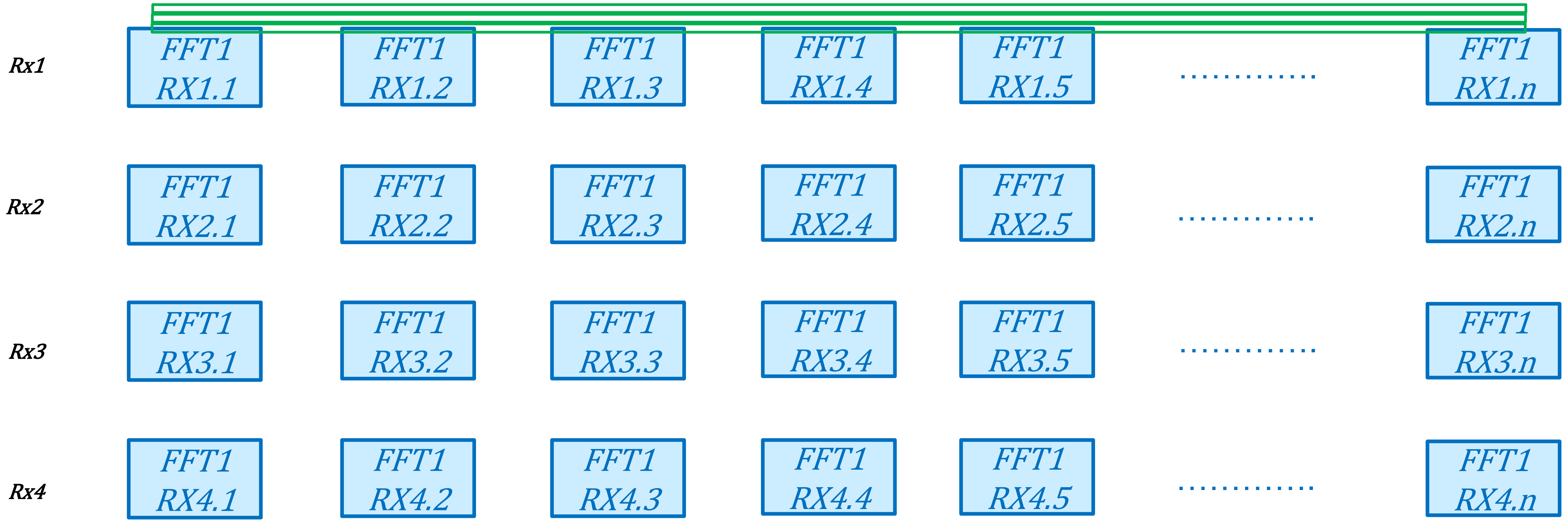
a. Resorting of range FFT results
b. Doppler FFT

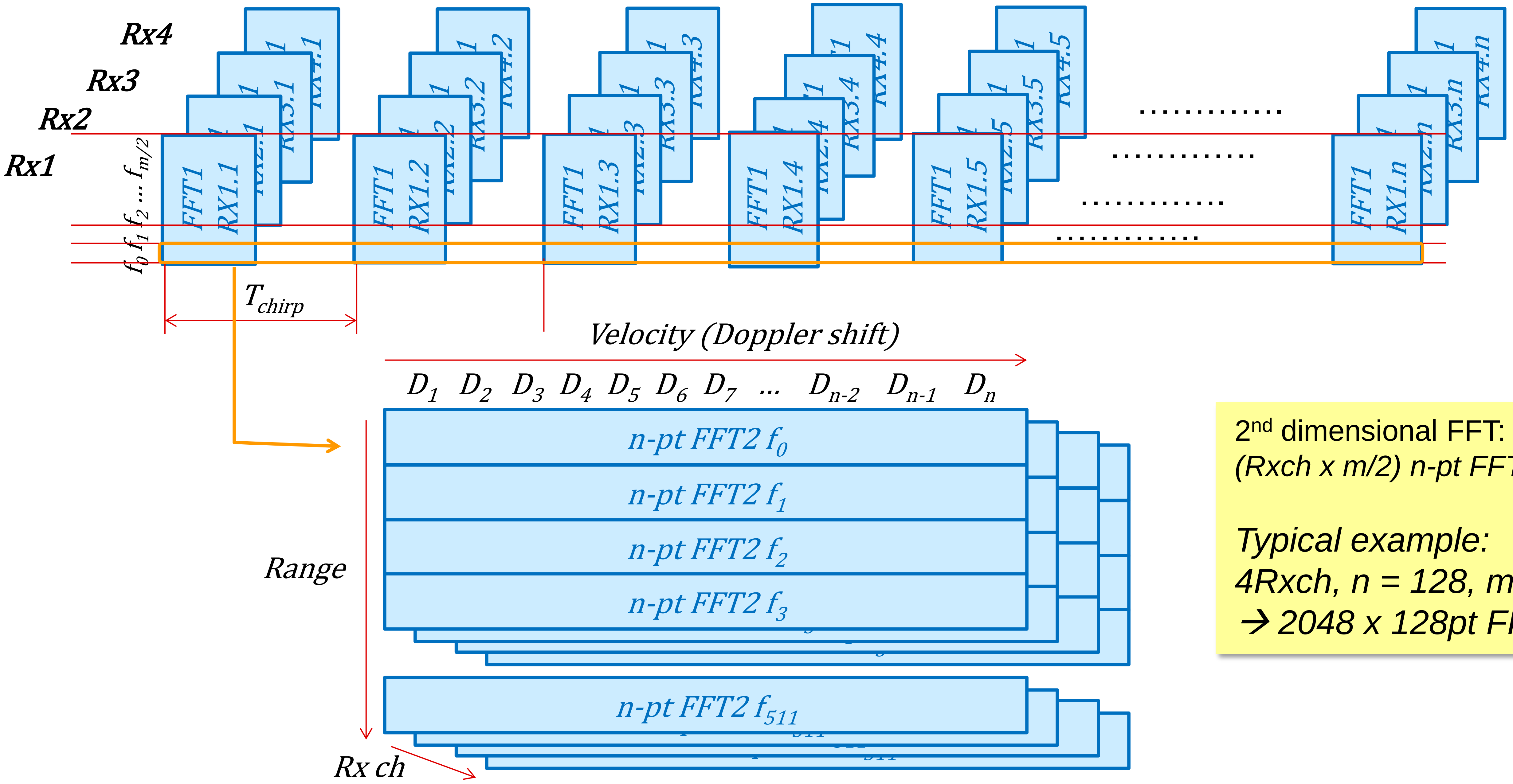
Resorting of range FFT for Doppler FFT



Same frequency bin = same range = same target



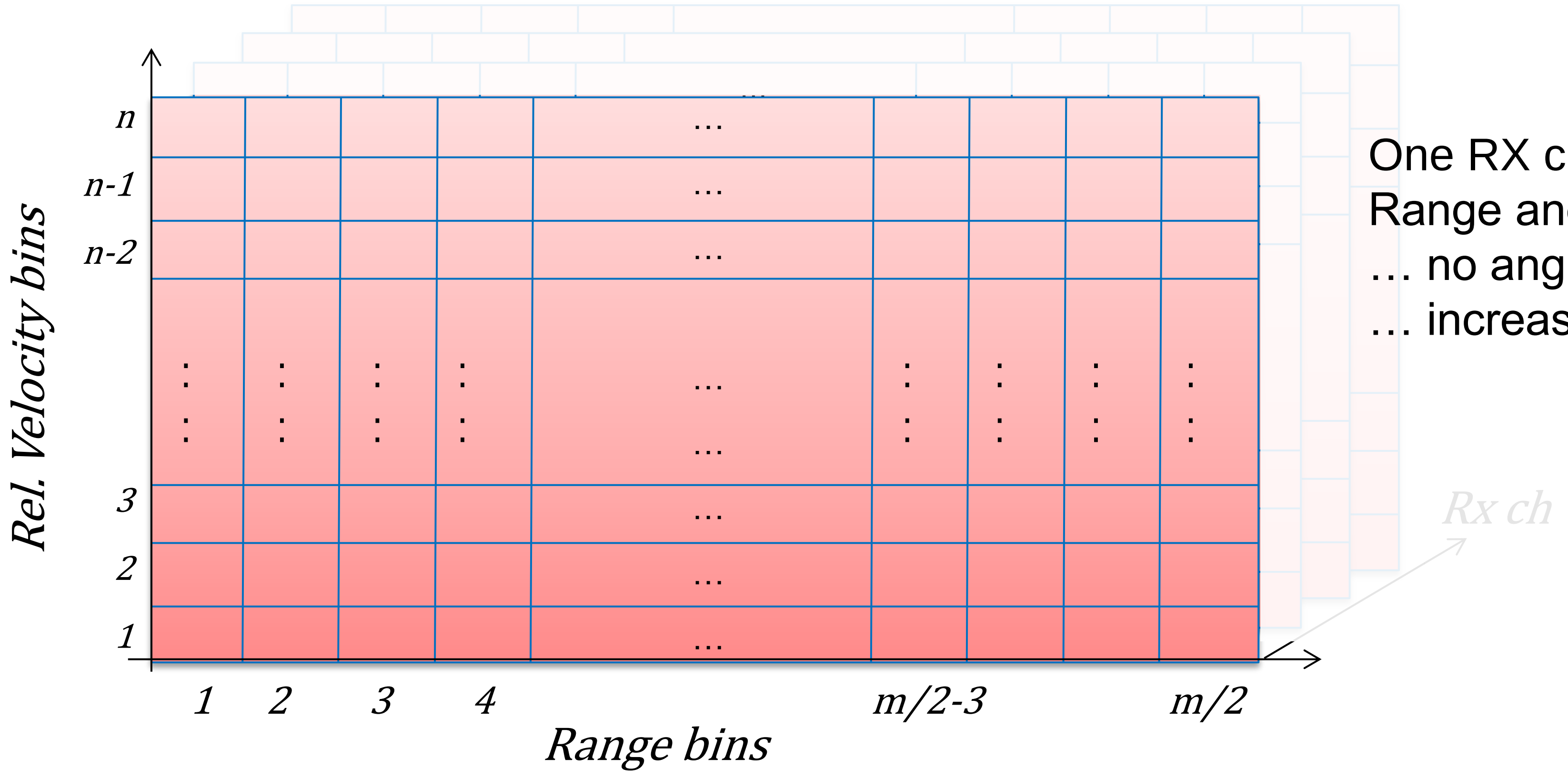
Doppler FFT to determine relative velocity



2nd dimensional FFT:
(Rxch x m/2) n-pt FFTs

Typical example:
4Rxch, n = 128, m = 1024 (real)
→ 2048 x 128pt FFTs

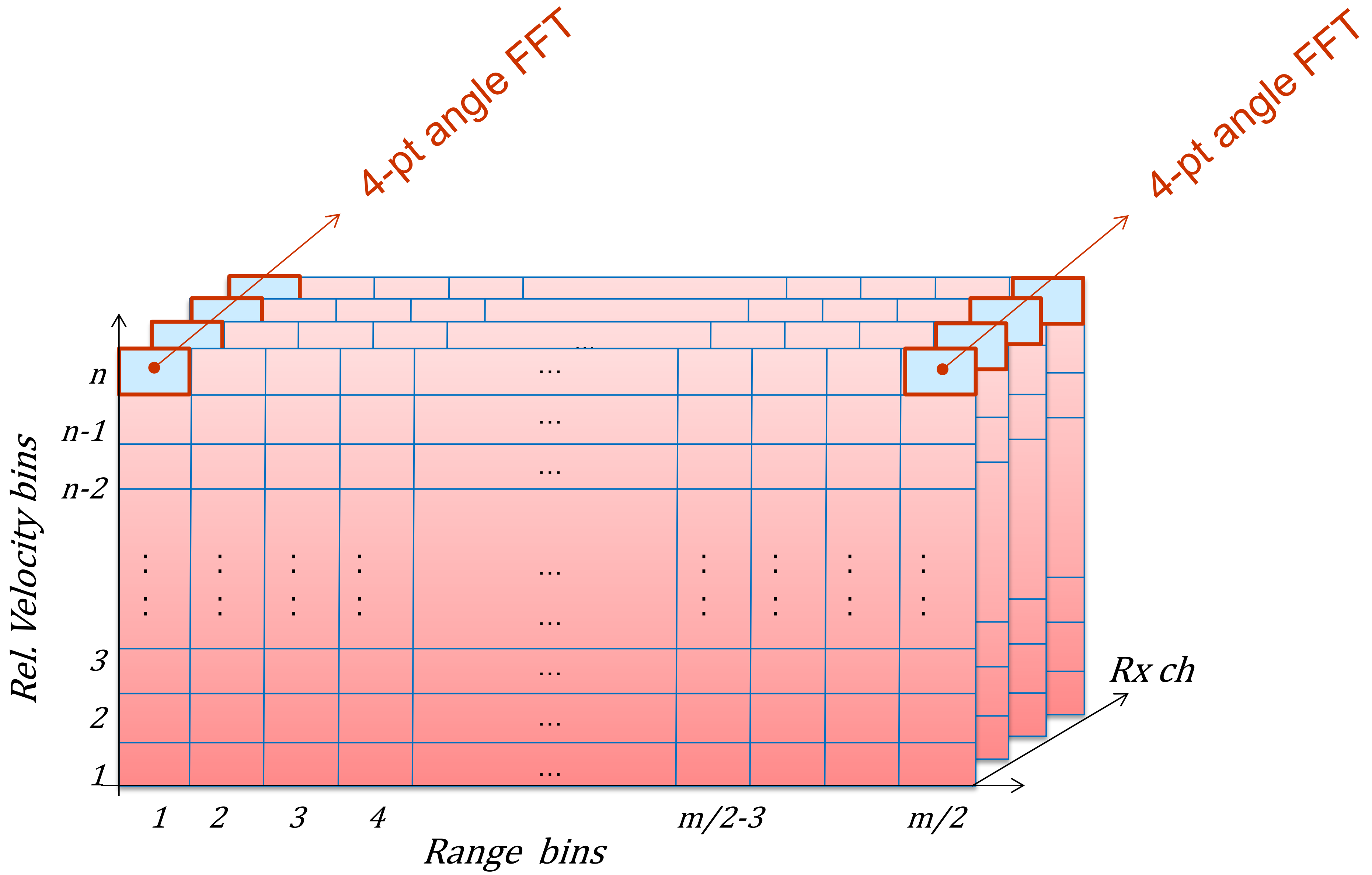
Range–Doppler 2D arrays, what's next?

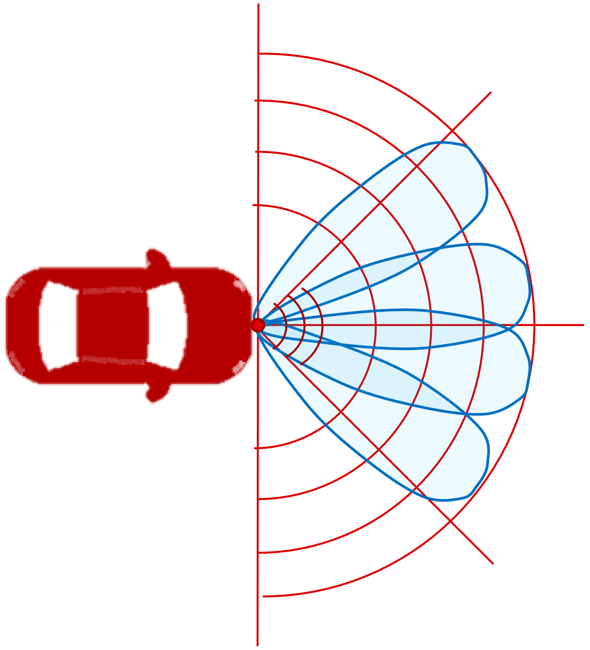


One RX channel sufficient for
Range and Velocity information, but …
… no angle information
… increased false alarm rate

Additional RX channels for …
… Digital Beam Forming (DBF)

4. How to determine angle

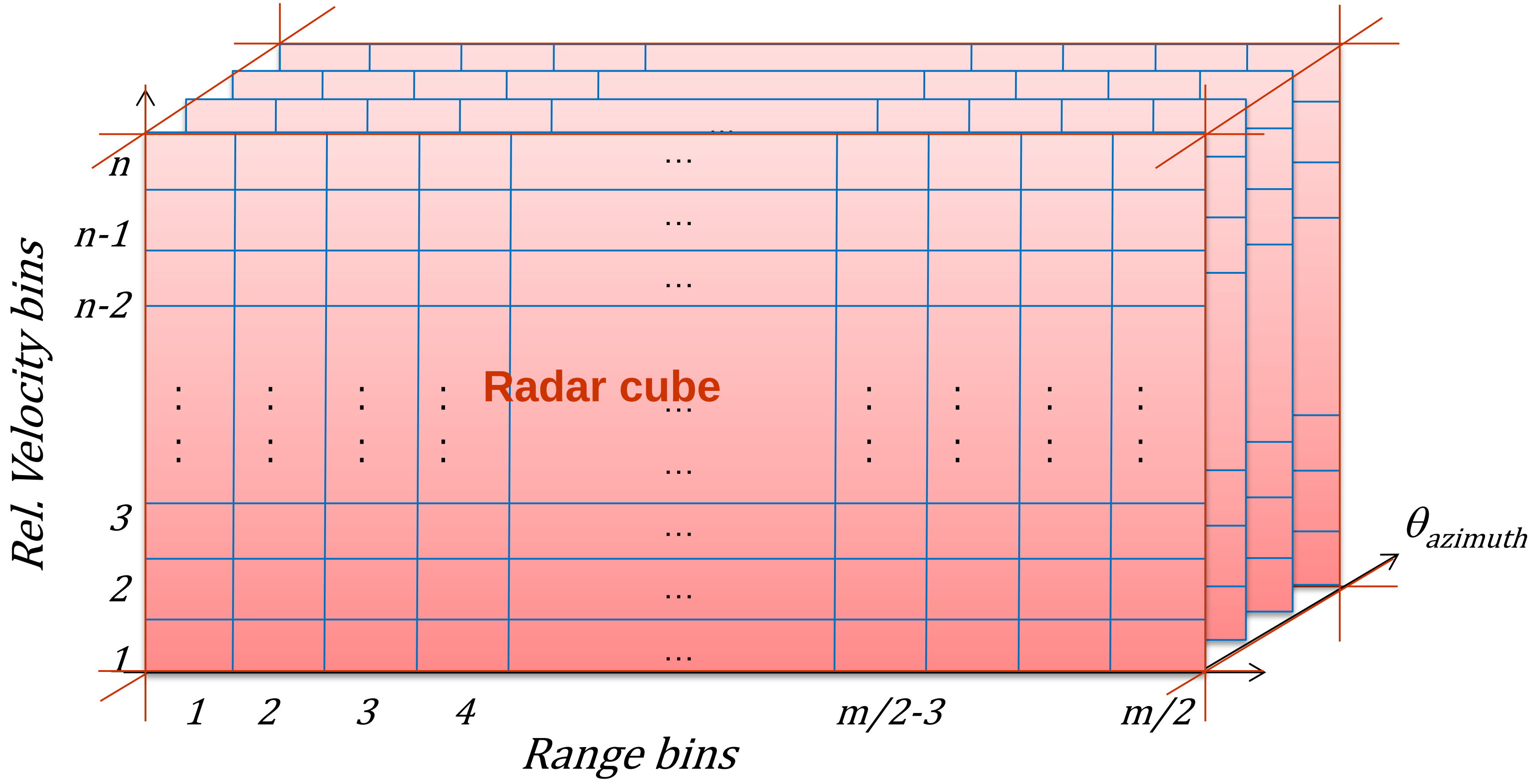




3rd dimensional FFT:
(n x m/2) Rxch-pt FFTs

Typical example:
4Rxch, n = 128, m = 1024 (real)
→ 64k x 4pt FFTs

Range-Doppler arrays after angle FFT



→ Good azimuth angular resolution
→ Wide “Field of View”

Radar signal processing summary

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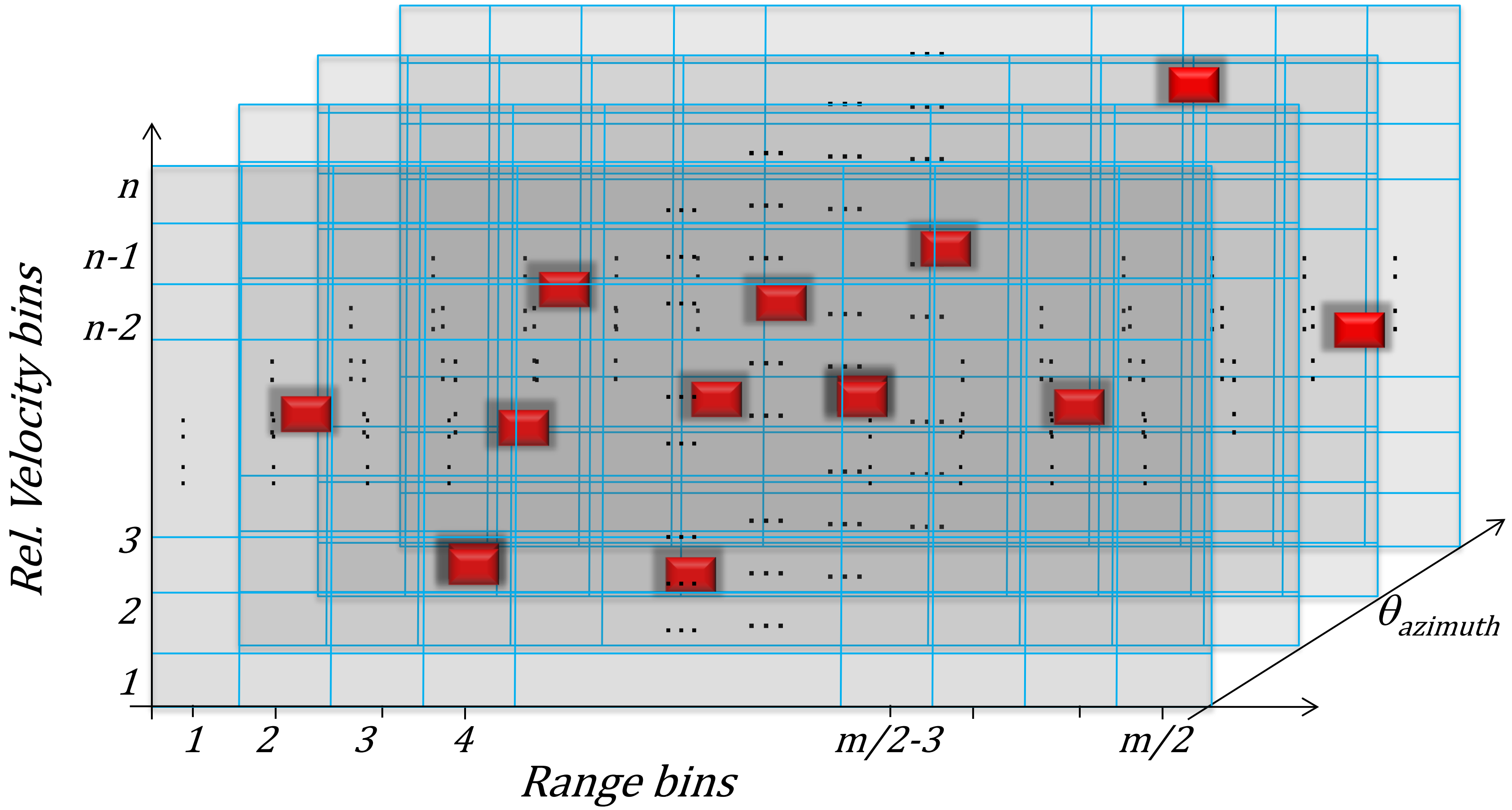
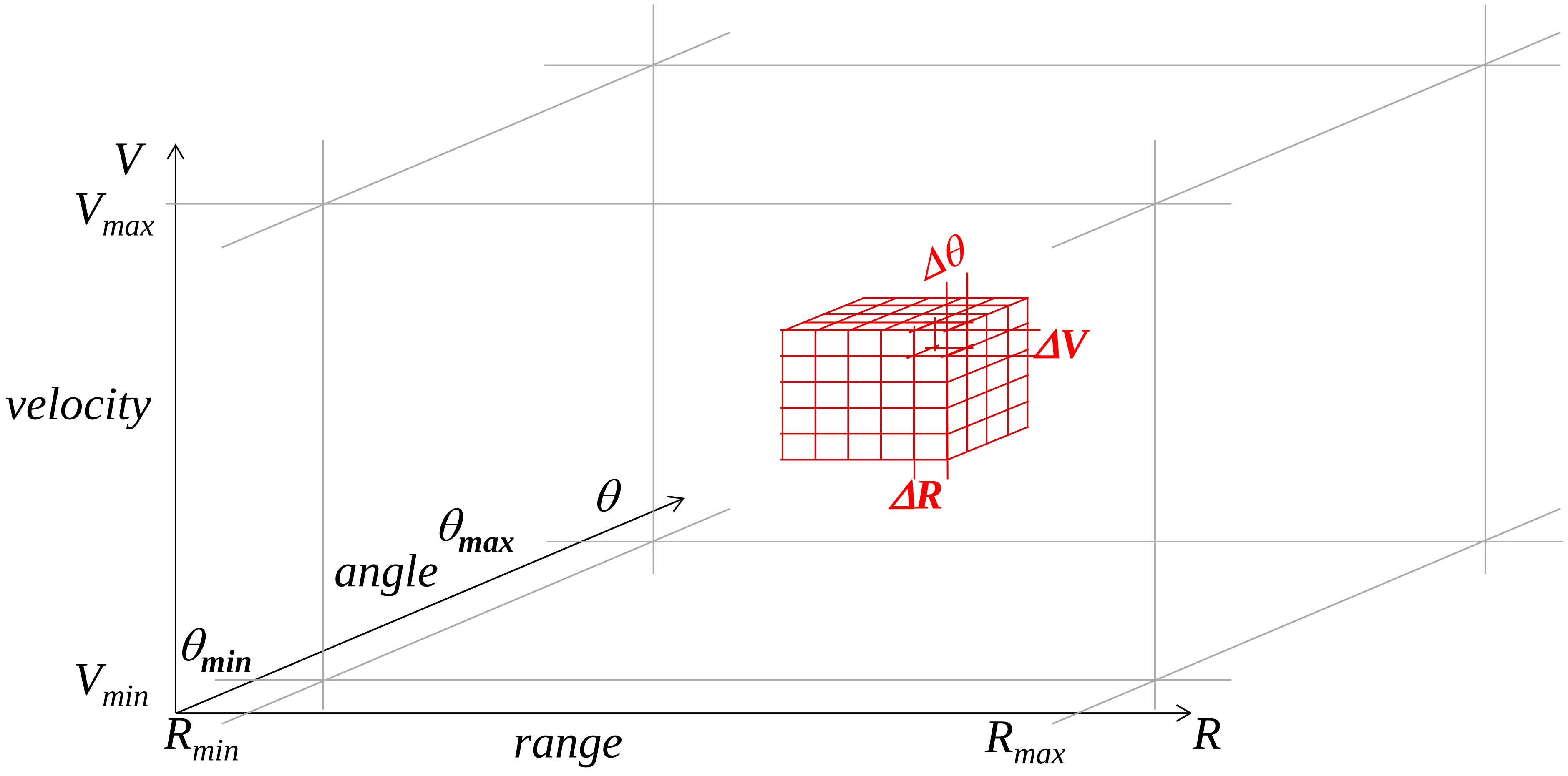


- FFT1
  → Range R
- FFT2
  → relative velocity V
- FFT3
  → Azimuth angle Φ
- Max. Search + OS-CFAR
  → Targets (R, V, Φ)

Radar system performance – radar cube



For best performance

- Large cube, i.e. maximize
  range $[R_{min} ; R_{max}]$
  velocity $[V_{min} ; V_{max}]$
  angle $[\theta_{min} ; \theta_{max}]$
- High Resolution, i.e. minimize
  ΔR, ΔV and $\Delta \theta$

Radar cube size and resolution defines memory foot print → cost impact

Multi-Mode Radar: short range and mid range cubes to reduce total cube size

What you learned in this section

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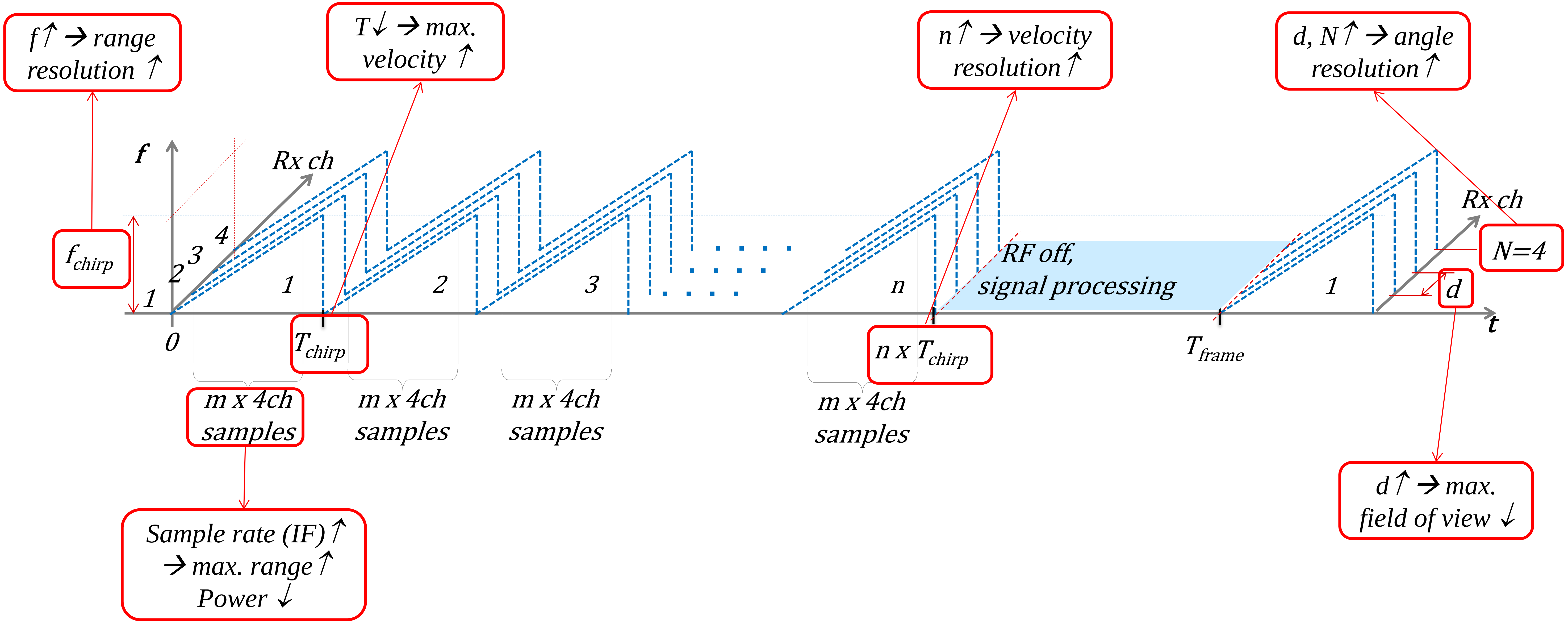
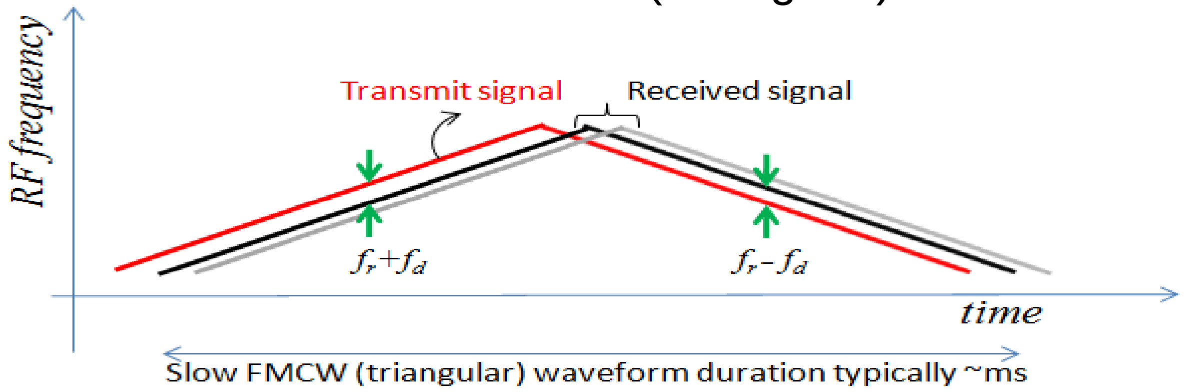
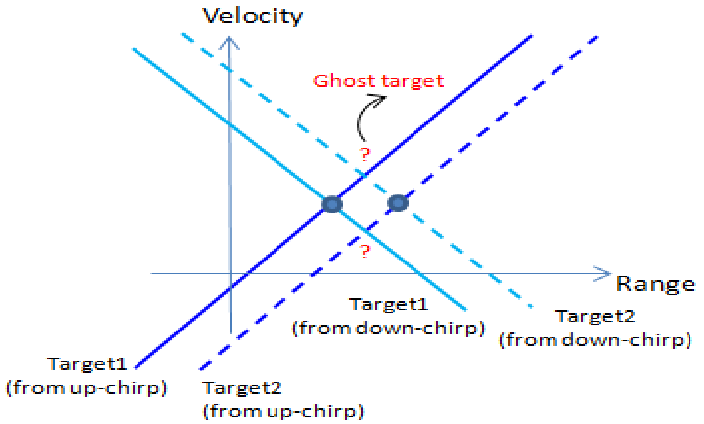


Advantages of Fast FMCW modulation

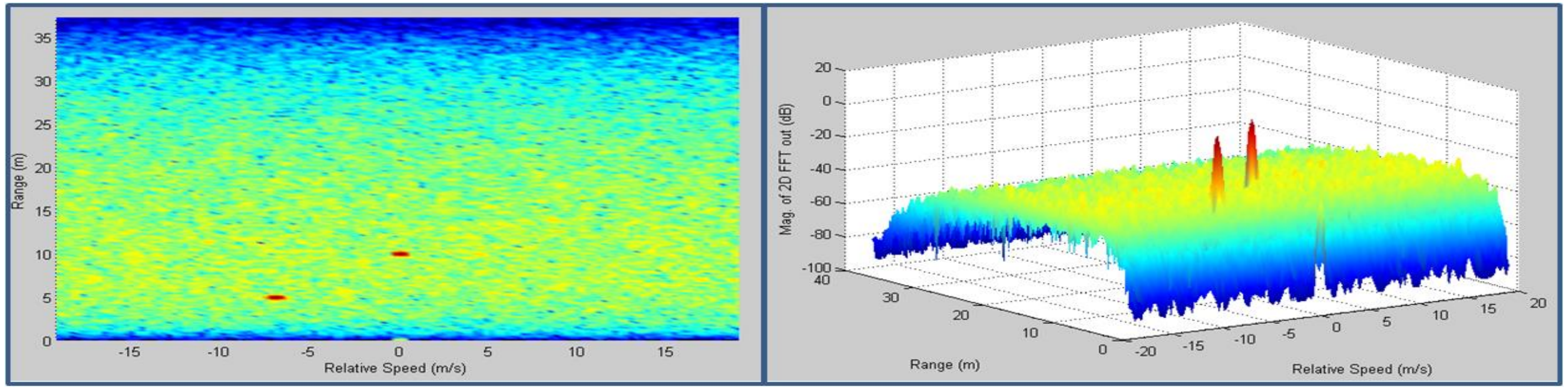
- Slow FMCW (Triangular) waveform used in many legacy systems
  – Chirp duration in ms, instead of us
- Slow FMCW has advantage of low DSP MIPS requirement
  – No two-dimensional FFT processing
- However, it suffers from ambiguity issues
  – No elegant way of getting range-doppler image
- Fast FMCW (Sawtooth) waveform is preferred in newer systems
- Fast FMCW has ability to provide range-doppler two dimensional image of objects

Slow (Triangular) FMCW





Fast (sawtooth) FMCW



Why mm-wave?

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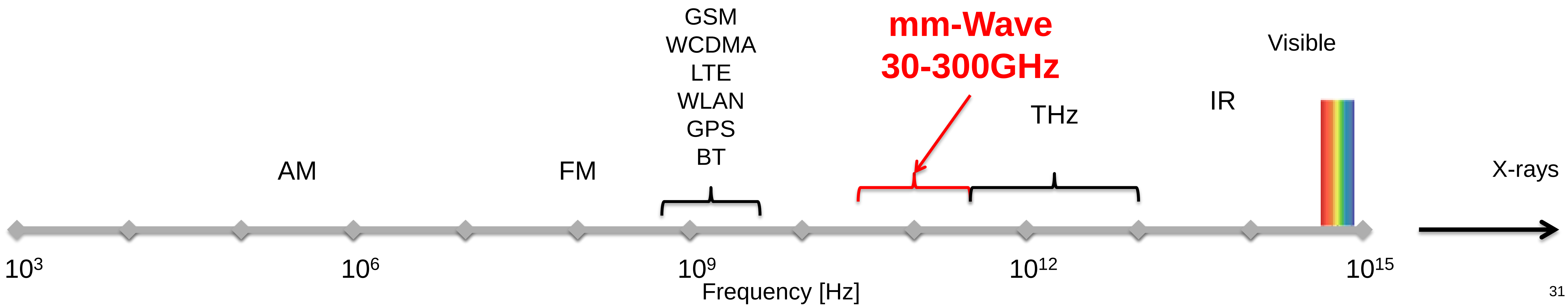
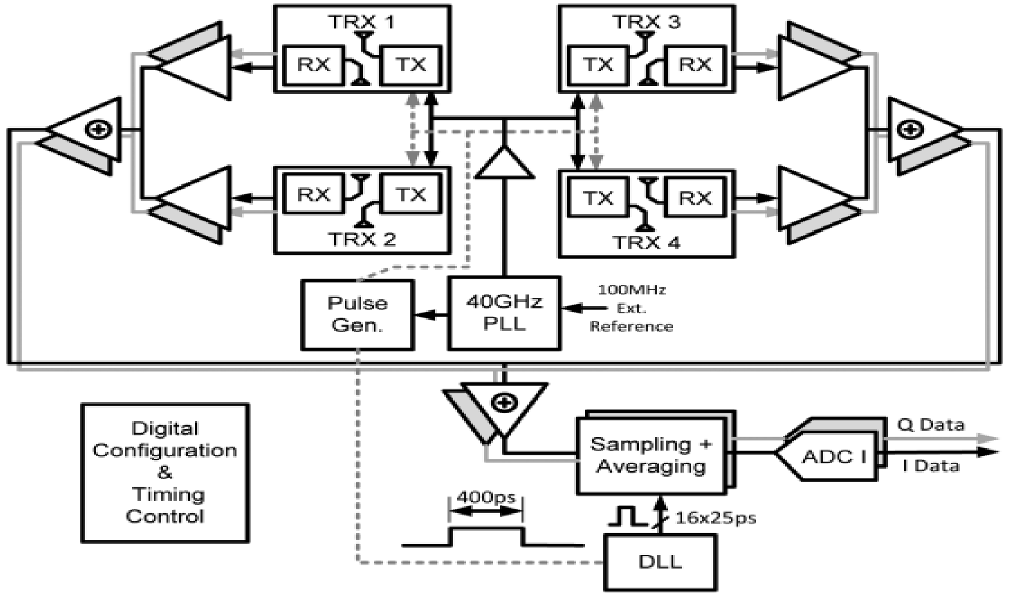
Property	Microwave	mm-Wave	IR/Visible Light
Generation	Electronic	Electronic	Optics
Spatial resolution	~cm – m	~mm – cm	um
Coupling (antenna) size	PCB	Package	Package
Propagation Through Walls, Boxes, etc.	Yes	Yes	No

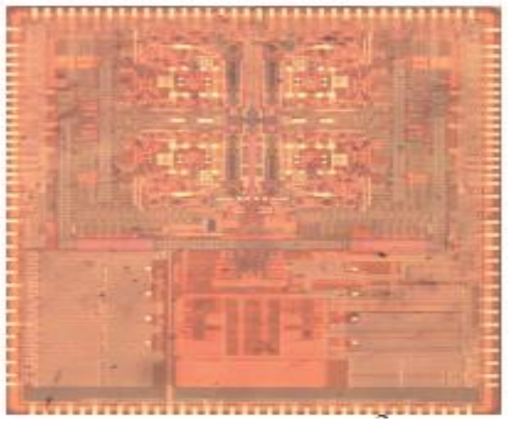


TI mmWave Sensors Portfolio

TI History with High Frequency CMOS

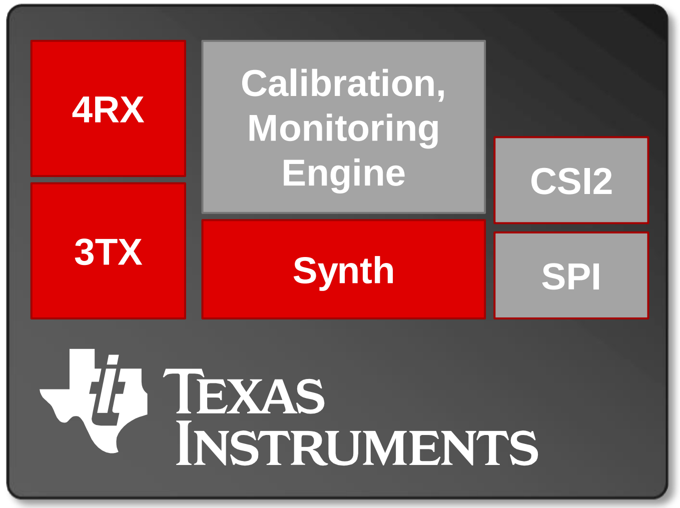
- TI high-frequency CMOS RF technology is backed by years of research
- 160GHz nano-radar 2x2 TRX – Kilby Labs project
  - Pulsed radar transceiver with packaged antenna array in 65nm CMOS
    - Vijay Rentala, et. al., “160GHz Pulsed Transmitter with Packaged Antenna Array in 65nm CMOS” , 2013 Symposium on VLSI circuits
    - Brian Ginsburg, et. al., “A 160 GHz Pulsed Radar Transceiver in 65 nm CMOS”, IEEE Journal of Solid State Circuits, 2014





76 – 81 GHz mmWave Sensors

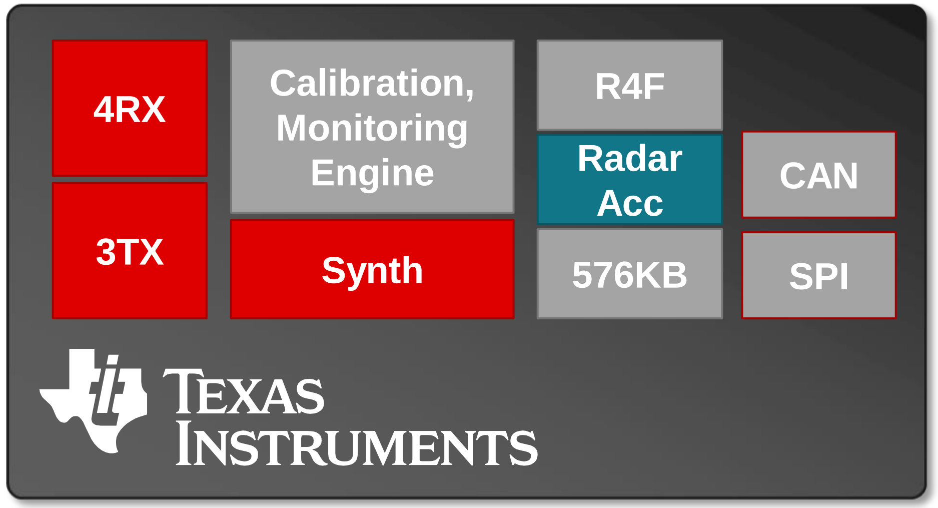
AWR1243



Radar Sensor

- **Use Cases**
  - – Imaging Radar Sensor
    - 2x or 4x AWR12 (cascade) + External DSP
  - – MRR and LRR
- **ASIL-B**

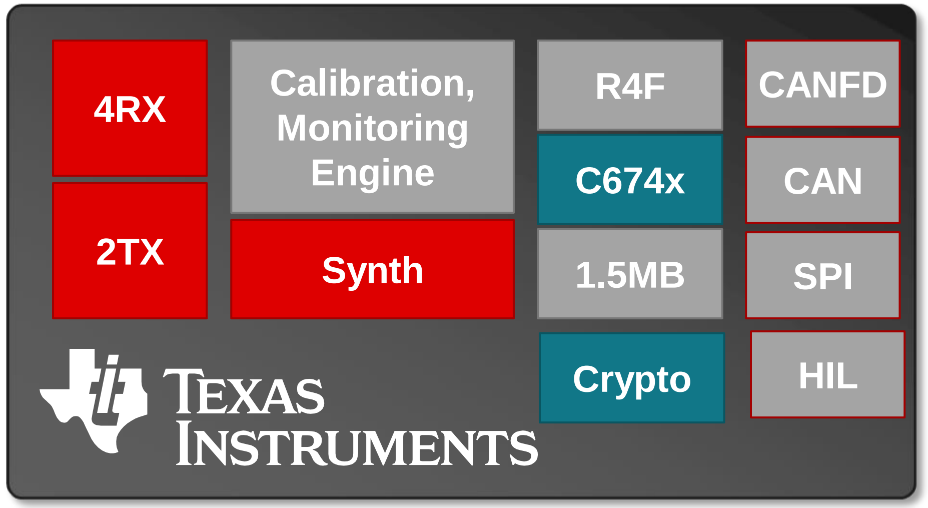
AWR1443



Radar Sensor + HW Accelerator

- **Use Cases**
  - – Entry-level Single-chip Radar
    - Proximity warning
  - – Free space sensor in and around the vehicle
  - – Occupant detection, driver monitoring

AWR1642



Radar Sensor + DSP

- **Use Cases**
  - – USRR Single Chip Radar
    - 160 Degree, 40m
  - – SRR Single chip Radar
    - 120m Cross traffic Alert
- **ASIL-B**

Delivering the most precise sensors in CMOS
Enabling Level 2 and above

Ultra high resolution

Wide RF BW, Chirp linearity

Higher range and velocity

Wide IF BW

Intelligent

Built-in Self monitoring & calibration
Complex baseband

Multi mode

Long-/Mid-/Short-/Ultra-short- range

Small

Single chip, cost optimized BOM, lower power

Auto-friendly package

Reliability, mass production

mmWave Sensing Applications

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Automotive

Highway Pilot

Front NCAP applications

Rear NCAP applications

Body and Chassis sensors

Beyond Automotive

Level Probing

Precision Measurement

Vibration Monitoring

Building Automation

Occupancy Sensing

Gesture Recognition

Traffic Monitoring

Perimeter Surveillance

Vital Sign Monitoring

Factory Automation

Drones

Industrial Transport & Robots

Texas Instruments