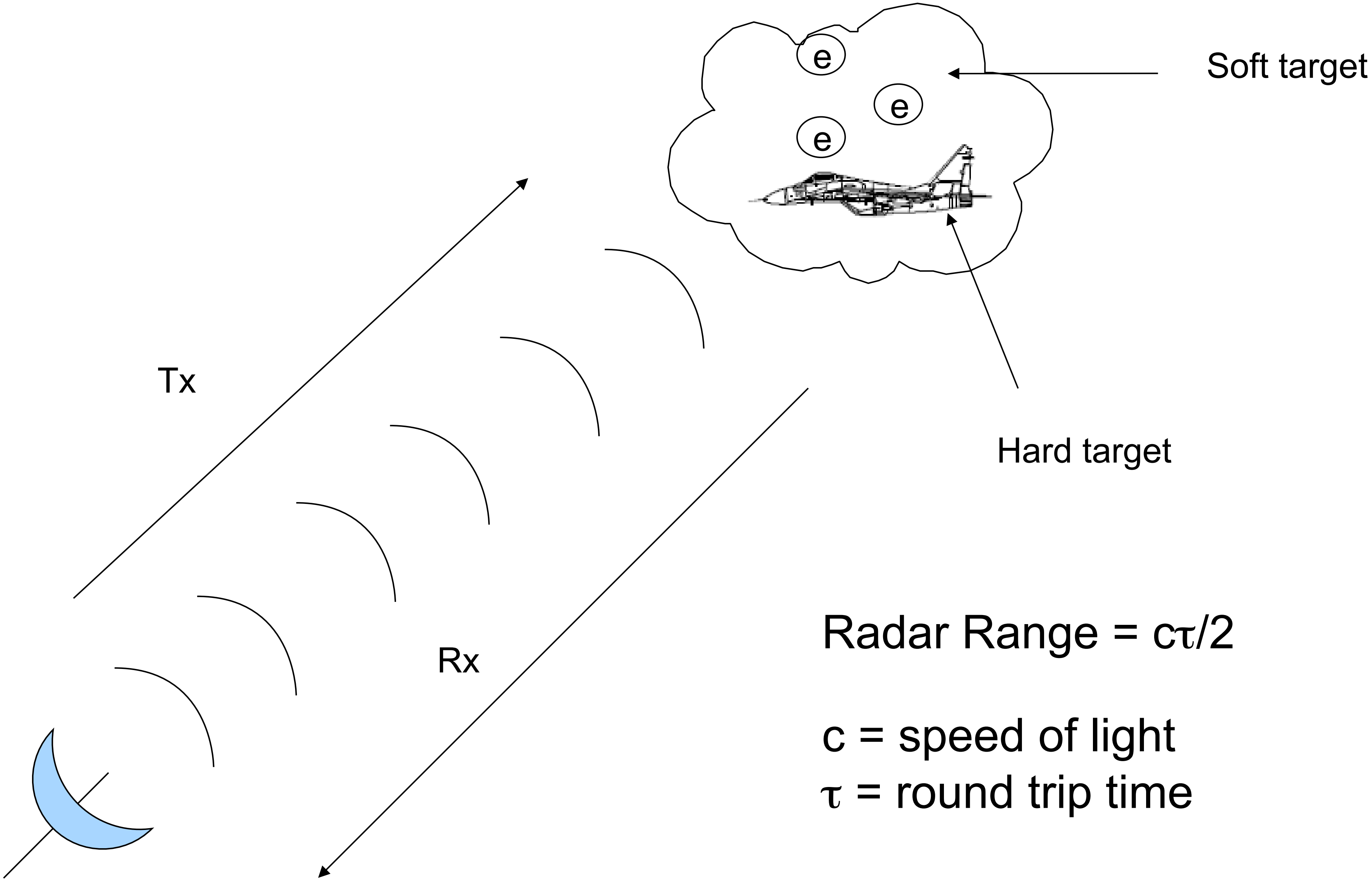
RAdio Detection And Ranging



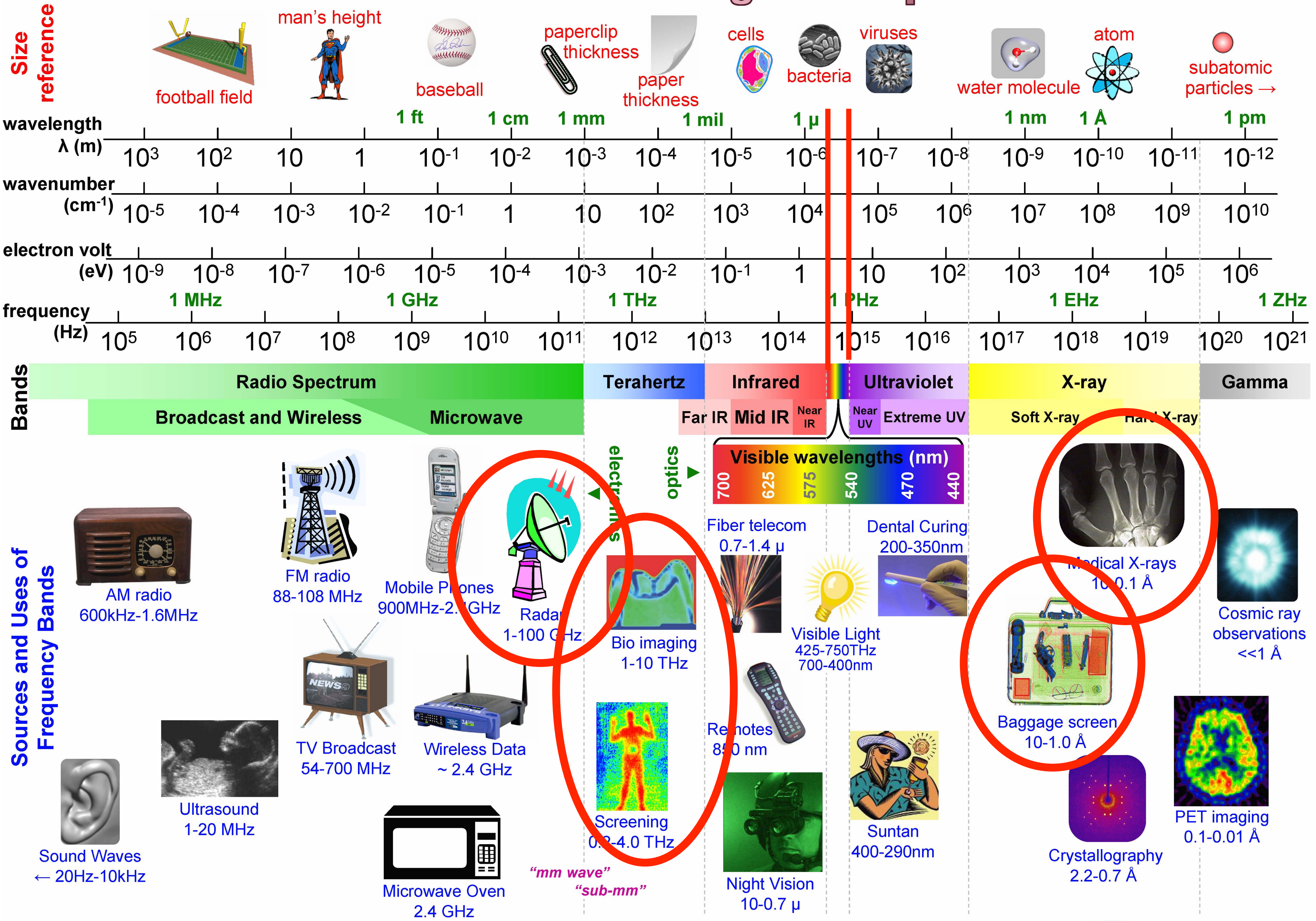
Radar Range = $c\tau/2$

c = speed of light
τ = round trip time

Outline - Radar Basics

- Electromagnetic spectrum
- Radio Waves and Propagation
- Radar fundamentals
  - Radar equation
  - Range Resolution and pulsed radars
- Doppler

Chart of the Electromagnetic Spectrum



Size reference

football field · man's height · baseball · paperclip thickness · paper thickness · cells · bacteria · viruses · water molecule · atom · subatomic particles →

wavelength λ (m): 1 ft · 1 cm · 1 mm · 1 mil · 1 μ · 1 nm · 1 Å · 1 pm

10^{3} 10^{2} 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}

wavenumber (cm⁻¹)

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}

electron volt (eV)

10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

frequency (Hz): 1 MHz · 1 GHz · 1 THz · 1 PHz · 1 EHz · 1 ZHz

10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}

Bands

Radio Spectrum · **Terahertz** · **Infrared** · **Ultraviolet** · **X-ray** · **Gamma**

Broadcast and Wireless · **Microwave** · **Far IR** · **Mid IR** · **Near IR** · **Near UV** · **Extreme UV** · **Soft X-ray** · **Hard X-ray**

electronics ◀ · ▶ optics

Visible wavelengths (nm): 700 · 625 · 575 · 540 · 470 · 440

Sources and Uses of Frequency Bands

Sound Waves
← 20Hz-10kHz

Ultrasound
1-20 MHz

AM radio
600kHz-1.6MHz

FM radio
88-108 MHz

TV Broadcast
54-700 MHz

Mobile Phones
900MHz-2.4GHz

Wireless Data
~ 2.4 GHz

Microwave Oven
2.4 GHz

Radar
1-100 GHz

"mm wave"

"sub-mm"

Bio imaging
1-10 THz

Screening
0.2-4.0 THz

Fiber telecom
0.7-1.4 μ

Remotes
850 nm

Night Vision
10-0.7 μ

Visible Light
425-750THz
700-400nm

Dental Curing
200-350nm

Suntan
400-290nm

Medical X-rays
10-0.1 Å

Baggage screen
10-1.0 Å

Crystallography
2.2-0.7 Å

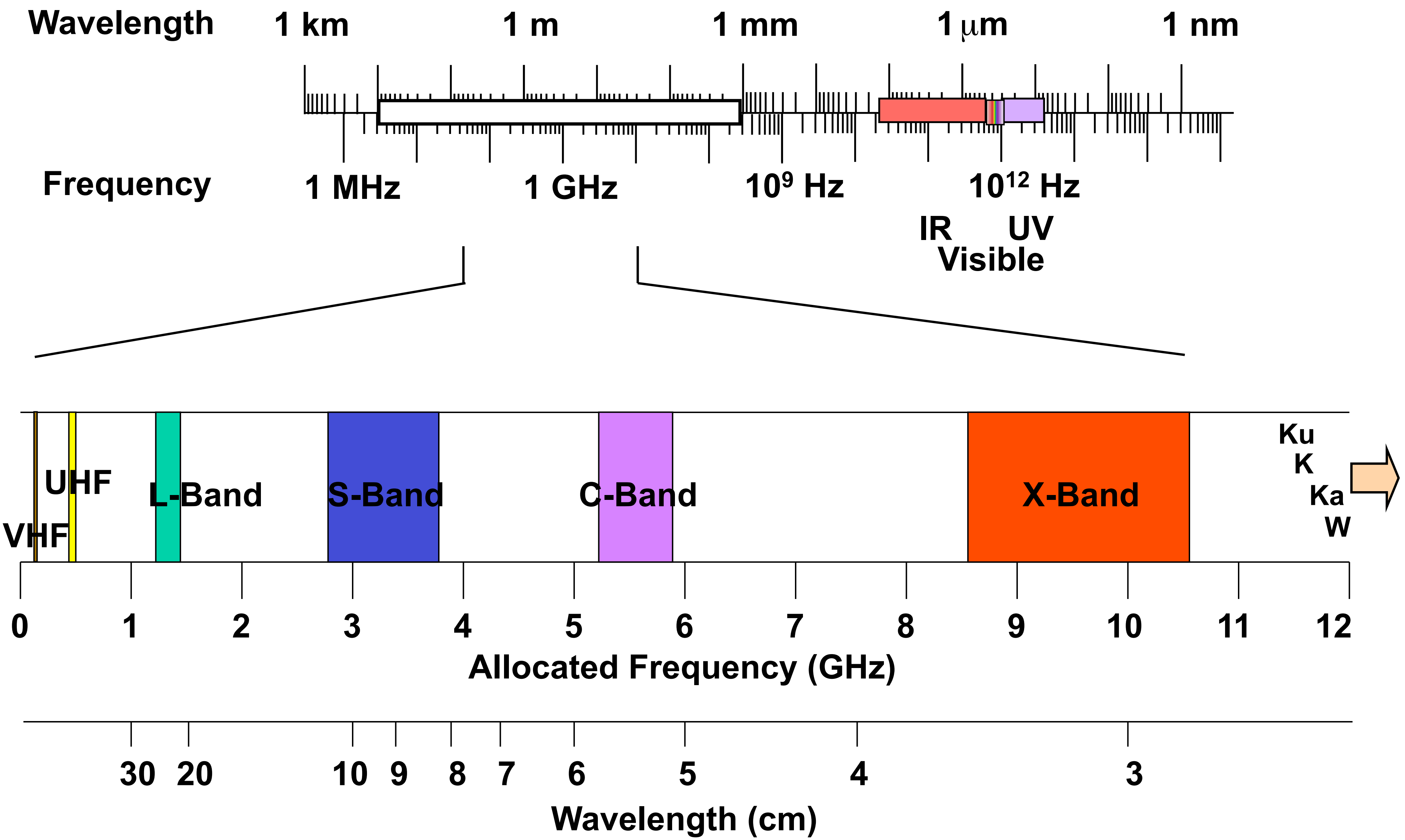
PET imaging
0.1-0.01 Å

Cosmic ray observations
<<1 Å

$\lambda = 3\times10^{8}/\text{freq} = 1/(\text{wn}*100) = 1.24\times10^{-6}/\text{eV}$

SURA Southeastern Universities Research Association ®

Radar Frequency Bands



The Arecibo Observatory

William E. Gordon Telescope

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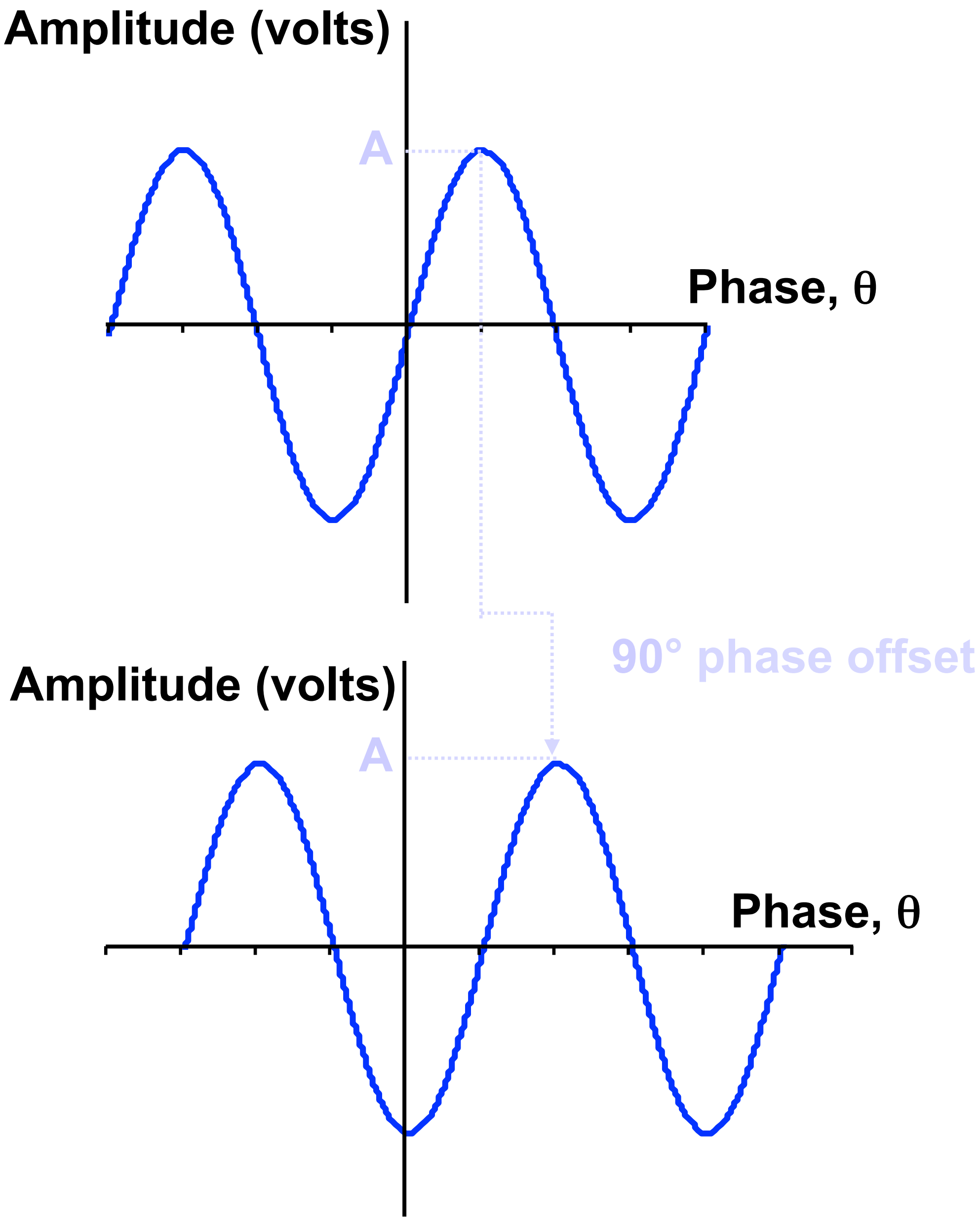
Properties of Waves

Phase and Amplitude

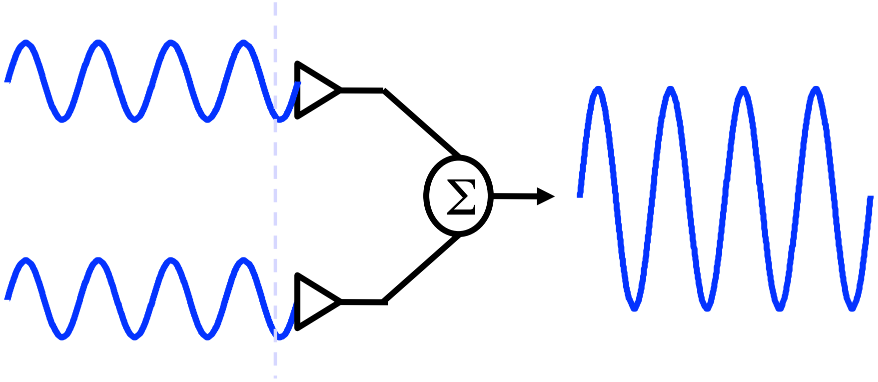


$$A\sin(\theta)$$

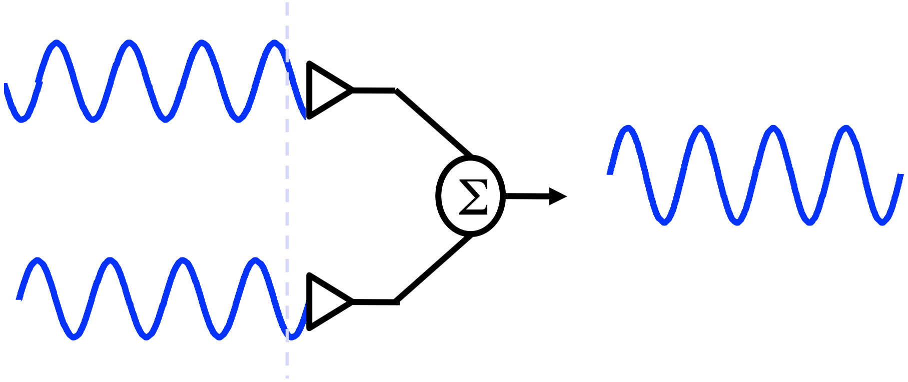
$$A\sin(\theta - 90^{o})$$

Properties of Waves

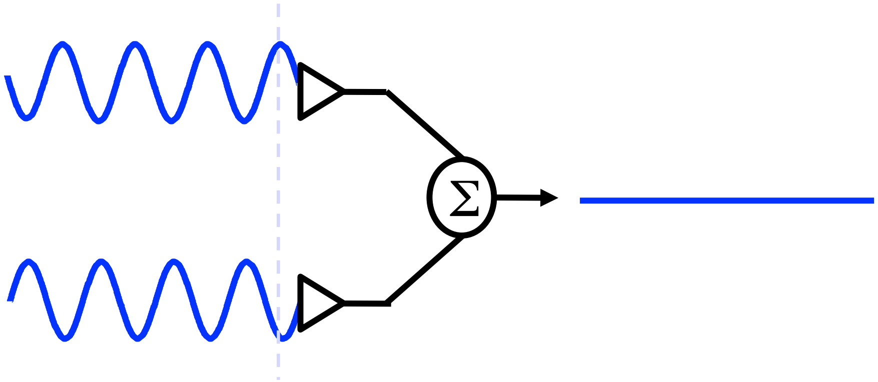
Constructive vs. Destructive Addition



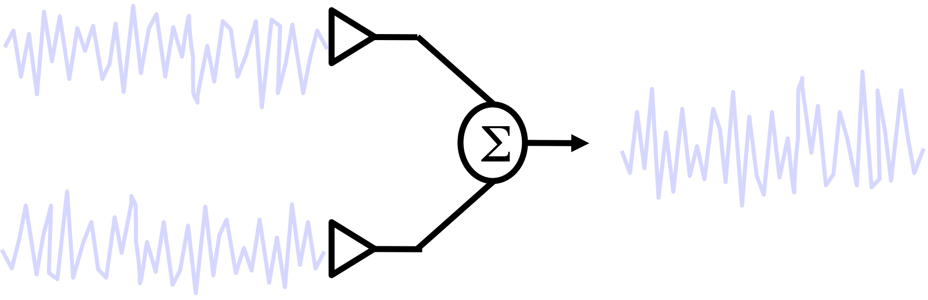
Constructive
(in phase)



Partially Constructive
(somewhat out of phase)



Destructive
(180° out of phase)



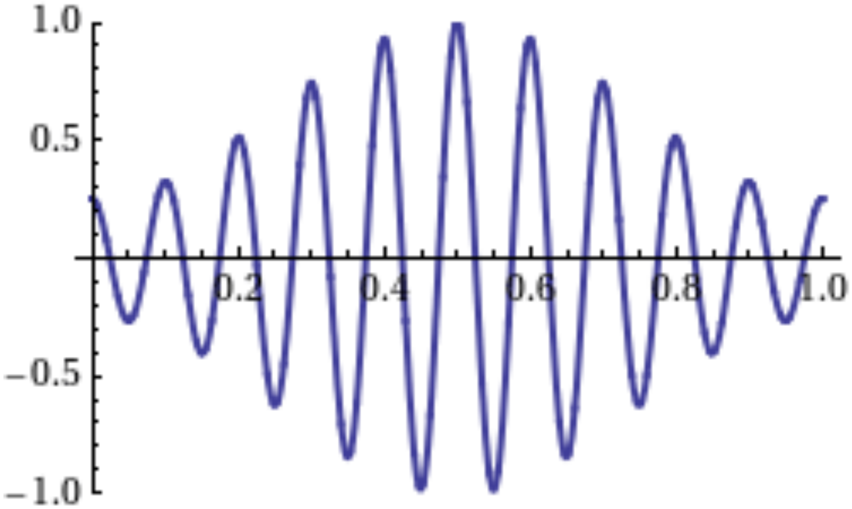
Non-coherent signals
(noise)

Phase Velocity, Group Velocity, Index of Refraction

$$v_{\mathrm{p}} = \frac{\omega}{k}$$

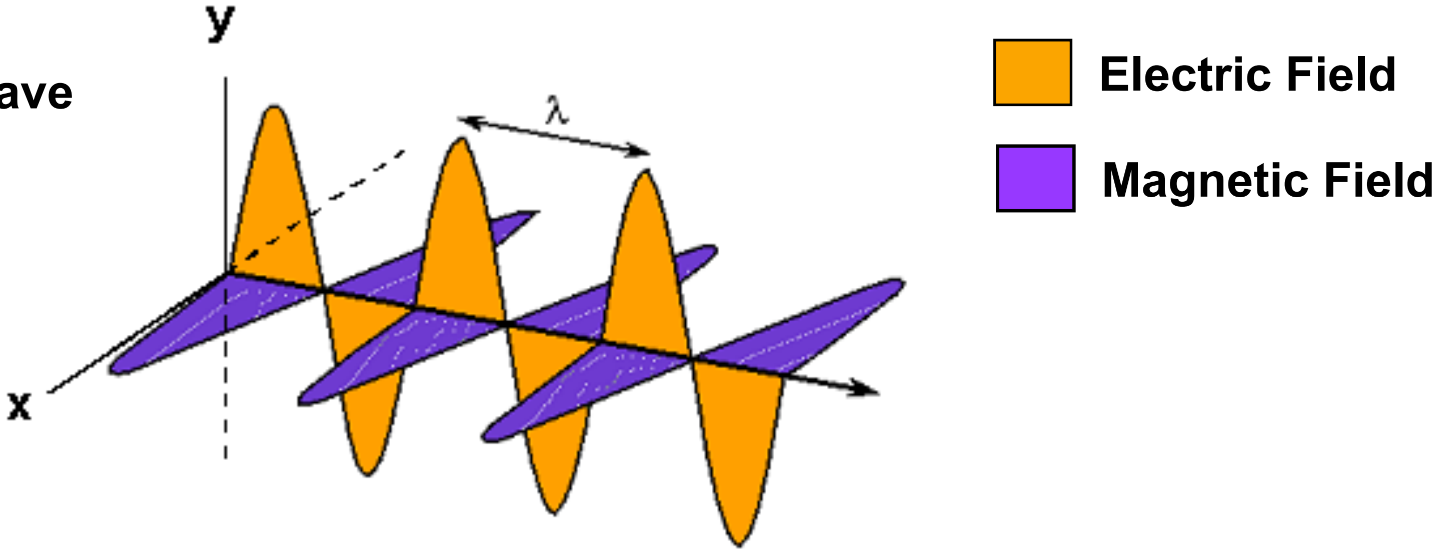
$$v_g \equiv \frac{\partial \omega}{\partial k}$$

$$n = \frac{c}{v_{\mathrm{p}}}.$$

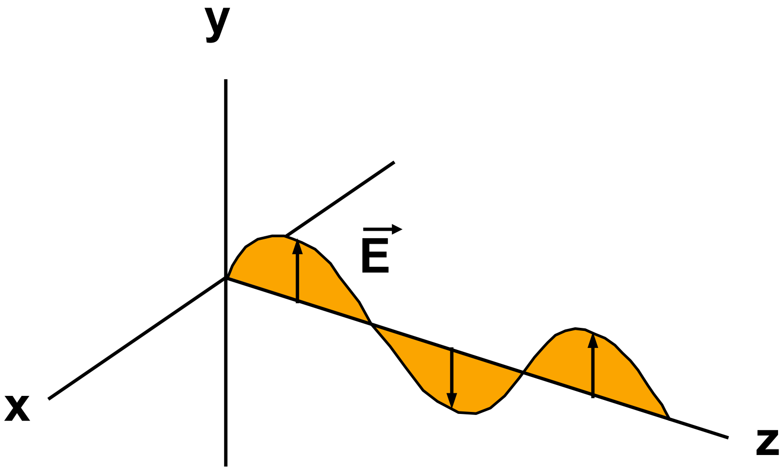


Polarization

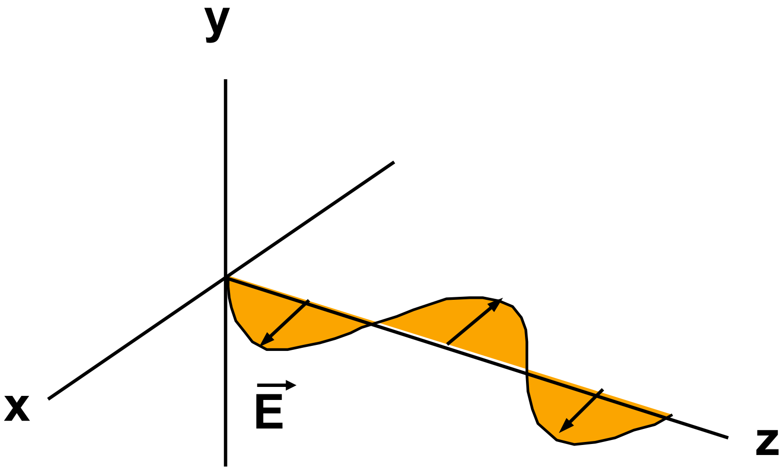
Electromagnetic Wave



Vertical Polarization

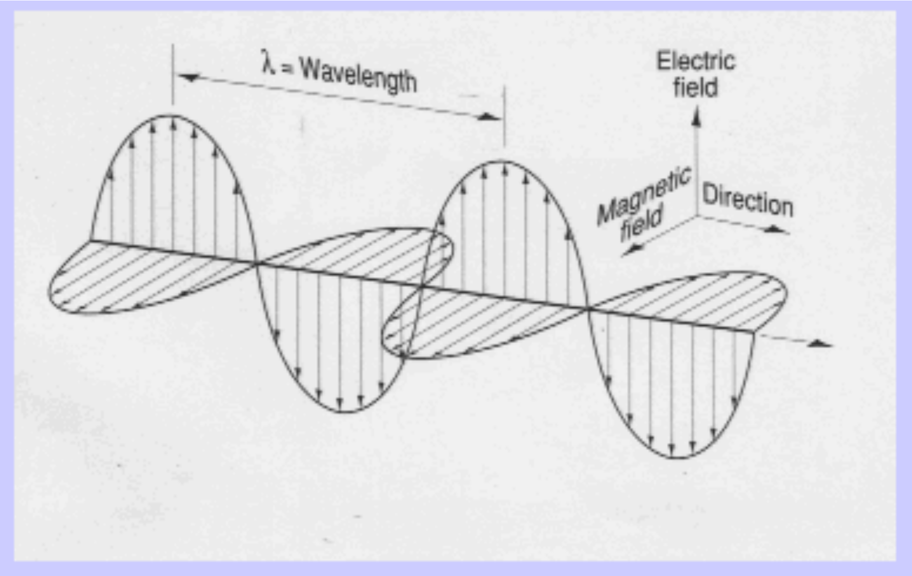


Horizontal Polarization

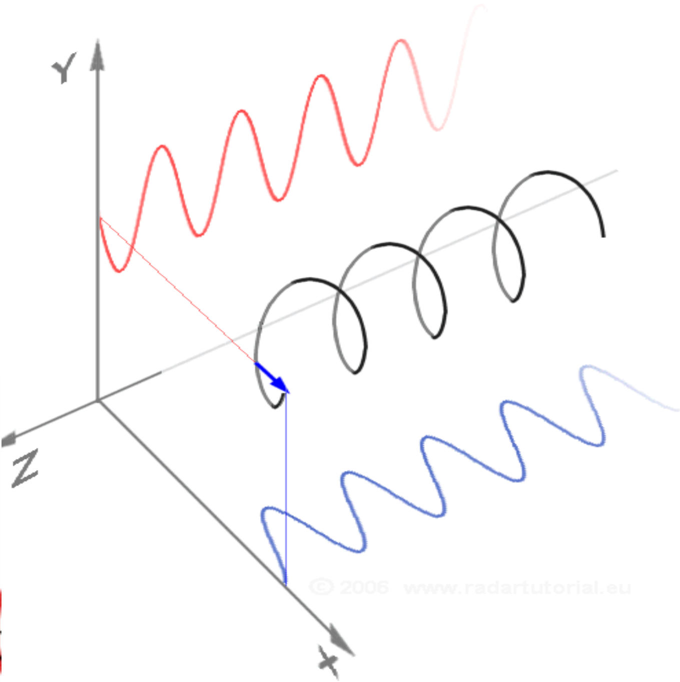


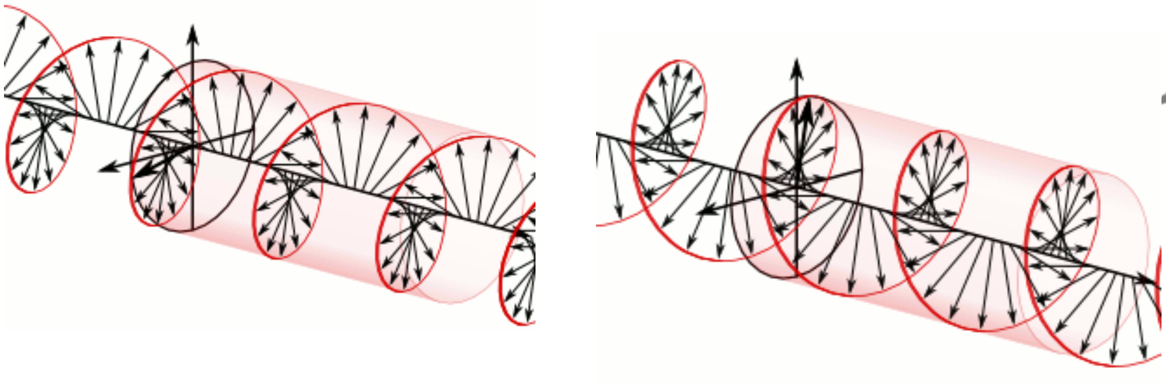
TEM Waves: *Transverse electromagnetic (TEM) modes*

neither electric nor magnetic field in the direction of propagation



Electromagnetic waves in free space propagate in TEM mode





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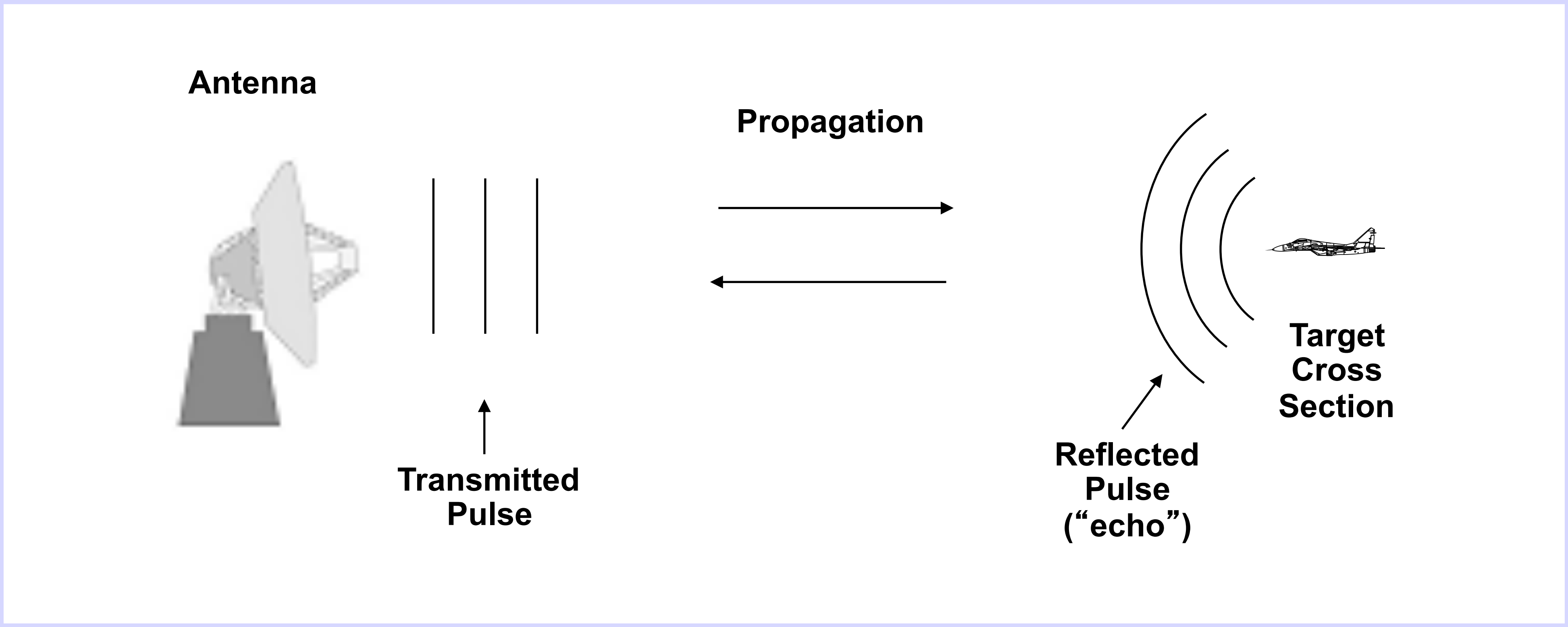
RADAR

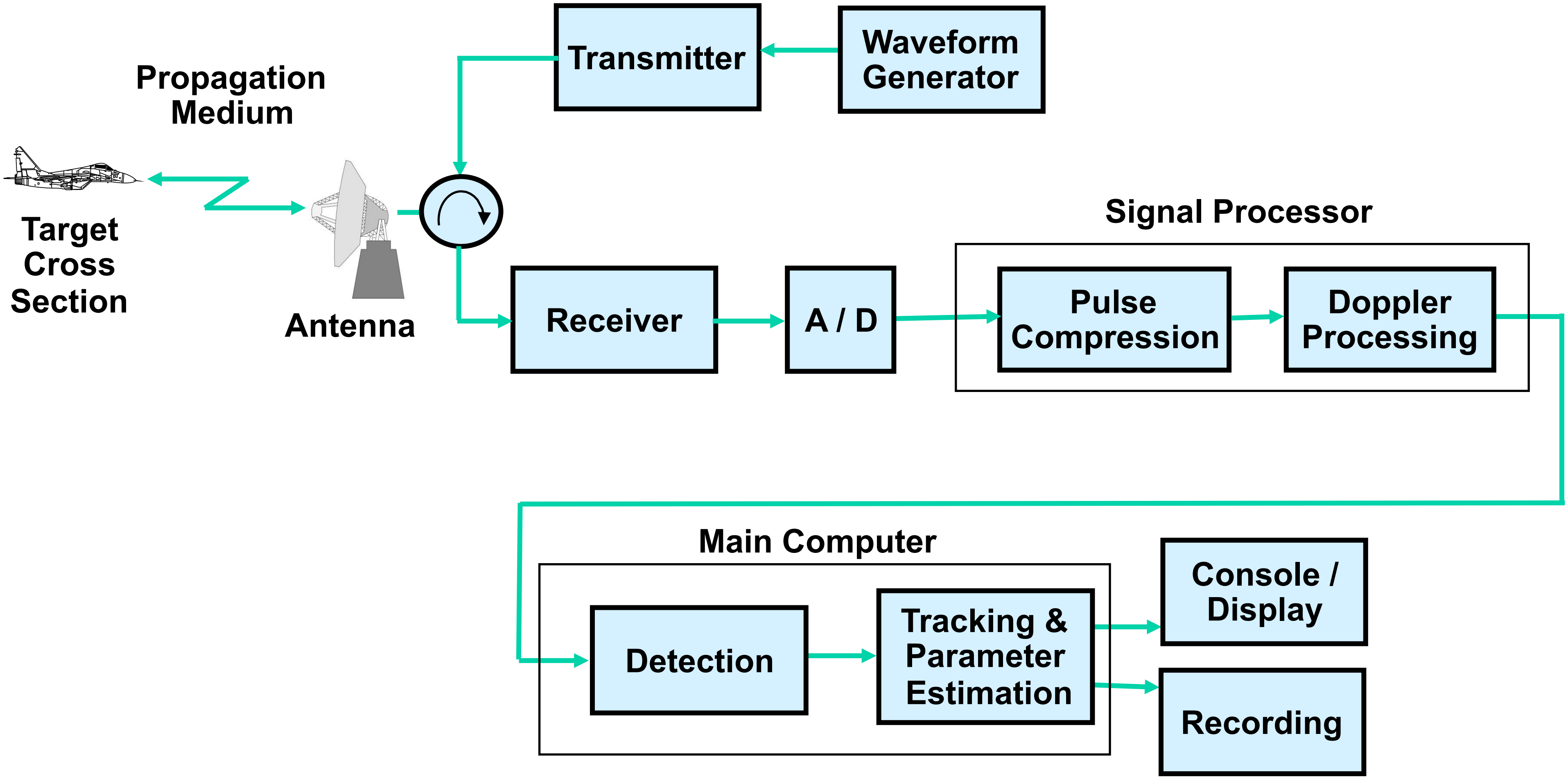
RAdio Detection And Ranging



Radar observables:

- Target range
- Target angles (azimuth & elevation)
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)

Radar Block Diagram



Propagation Medium

Target Cross Section

Antenna

Transmitter

Waveform Generator

Receiver

A / D

Signal Processor

Pulse Compression

Doppler Processing

Main Computer

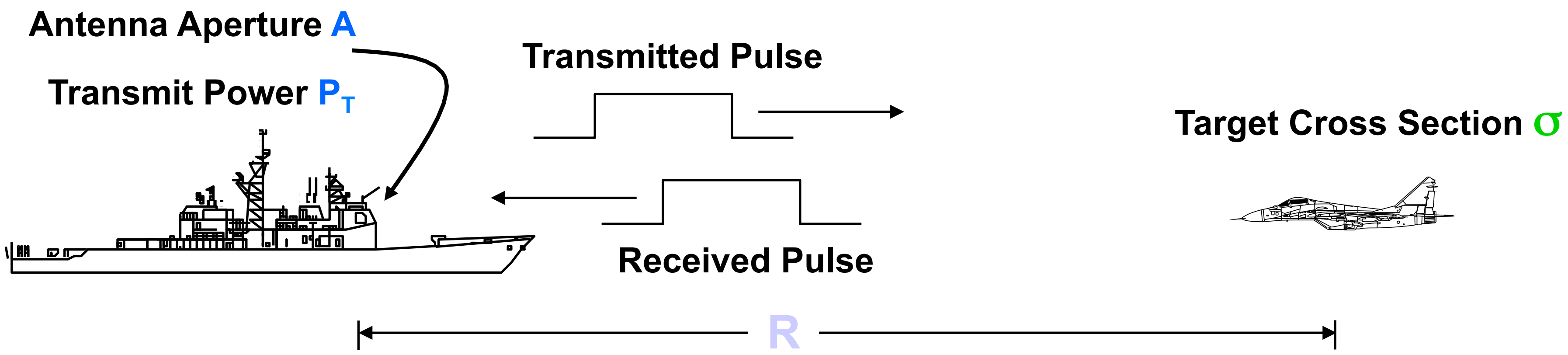
Detection

Tracking & Parameter Estimation

Console / Display

Recording

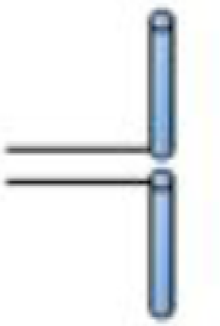
Radar Range Equation



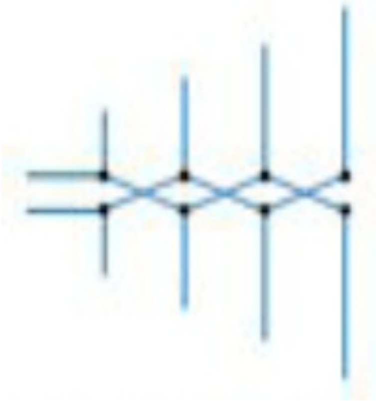
$$\text{Received Signal Energy} = \overset{\text{Transmit Power}}{\left[P_T \right]} \overset{\text{Transmit Gain}}{\left[\frac{4\pi A}{\lambda^2} \right]} \overset{\text{Spread Factor}}{\left[\frac{1}{4\pi R^2} \right]} \overset{\text{Losses}}{\left[\frac{1}{L} \right]} \overset{\text{Target RCS}}{\left[\sigma \right]} \overset{\text{Spread Factor}}{\left[\frac{1}{4\pi R^2} \right]} \overset{\text{Receive Aperture}}{\left[A \right]} \overset{\text{Dwell Time}}{\left[\tau \right]}$$

Antennas

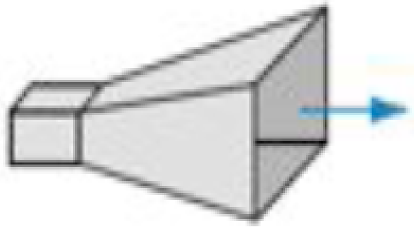
Most basic form of antennas – a wire element with a time varying current flowing in it



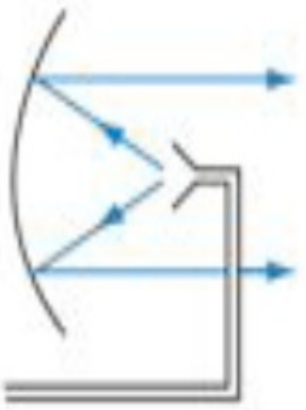
Dipole antenna



Log Periodic



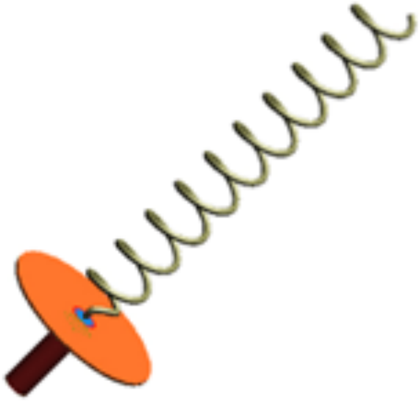
Horn antenna



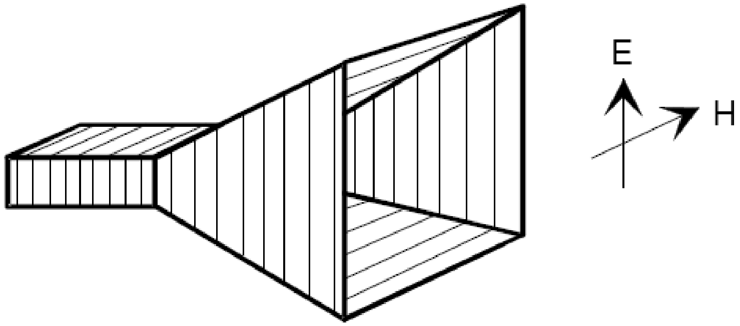
Parabolic dish
Reflector antenna

Antennas

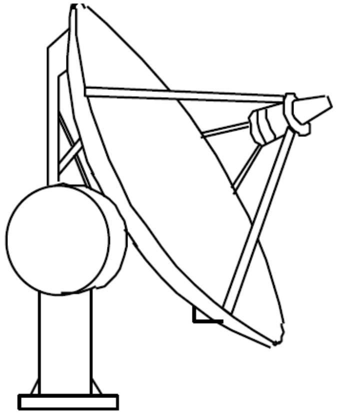
- Four primary functions of an antenna for radar applications
  - Impedance transformation (free-space intrinsic impedance to transmission-line characteristic impedance)
  - Propagation-mode adapter (free-space fields to guided waves)
  - Spatial filter (radiation pattern – direction-dependent sensitivity)
  - Polarization filter (polarization-dependent sensitivity)



Helical antenna



Horn antenna



Parabolic reflector antenna

Impedance transformer

- Intrinsic impedance of free-space, $\eta_o \equiv E/H$ is

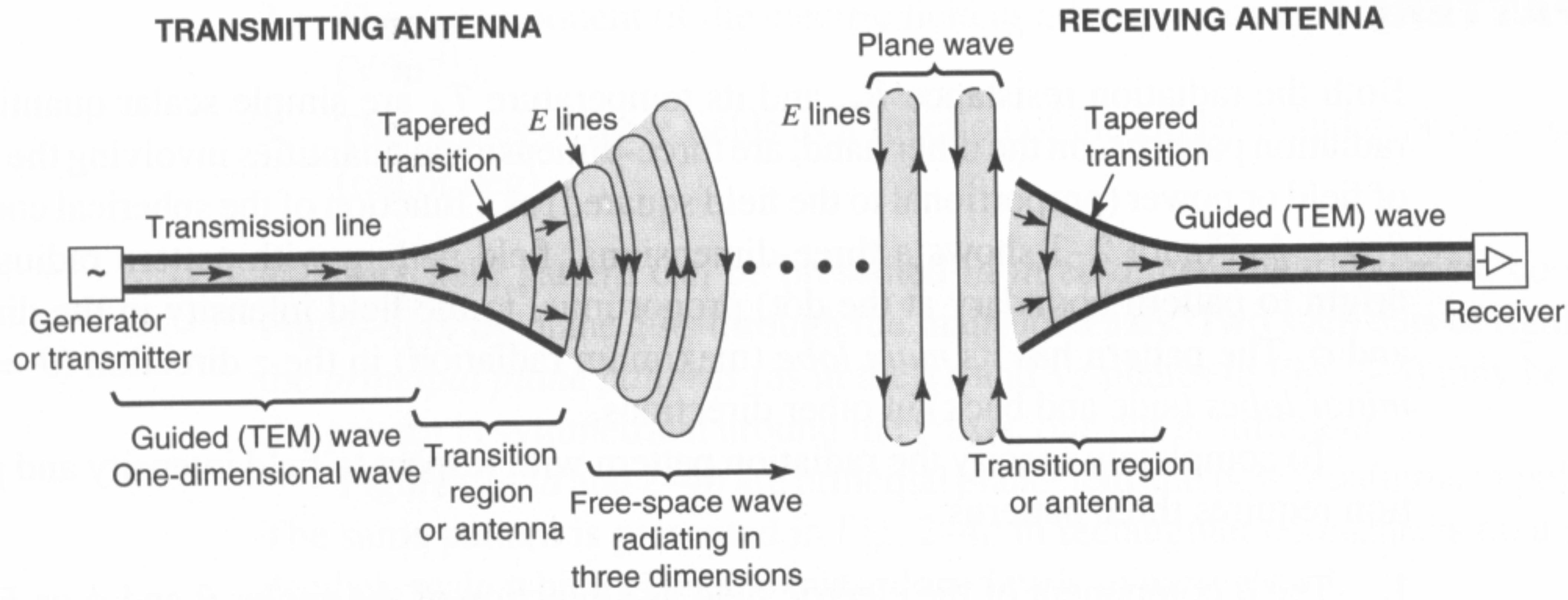
$$\eta_0 = \sqrt{\mu_0/\varepsilon_0} = 120\,\pi \cong 376.7\,\Omega$$

- Characteristic impedance of transmission line, $Z_o = V/I$
- A typical value for Z_o is $50\ \Omega$.

- Clearly there is an impedance mismatch that must be addressed by the antenna.

Propagation-mode adapter

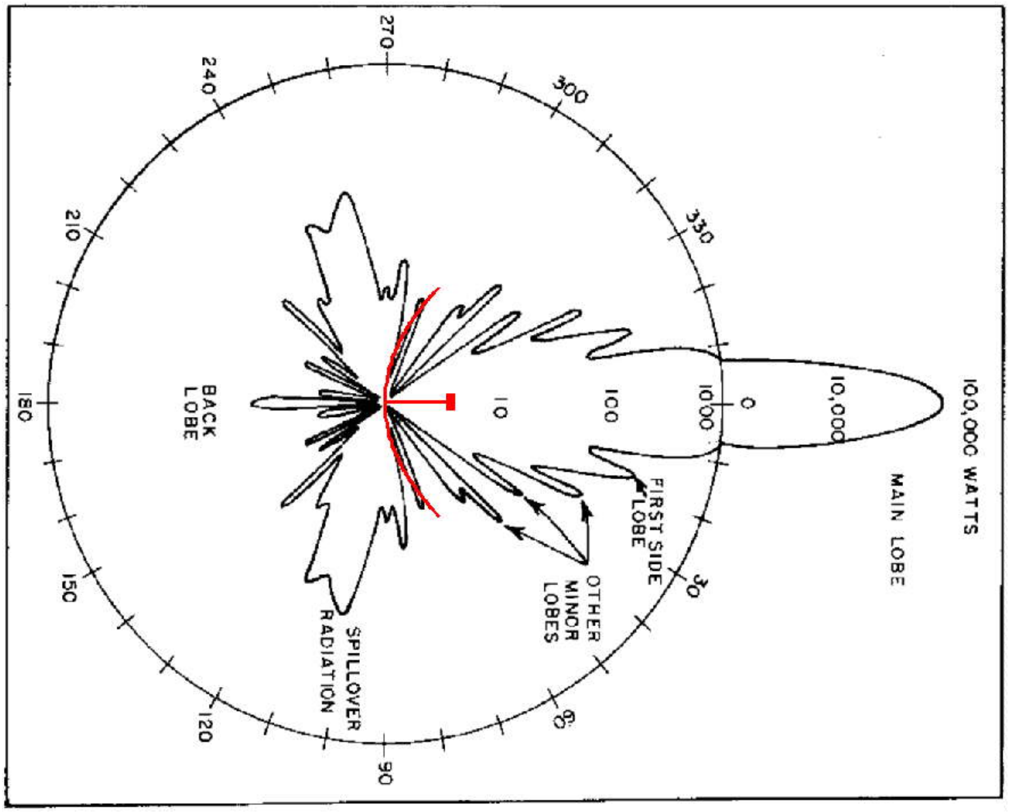
- During both transmission and receive operations the antenna must provide the transition between these two propagation modes.



Spatial filter

- Antennas have the property of being more sensitive in one direction than in another which provides the ability to spatially filter signals from its environment.

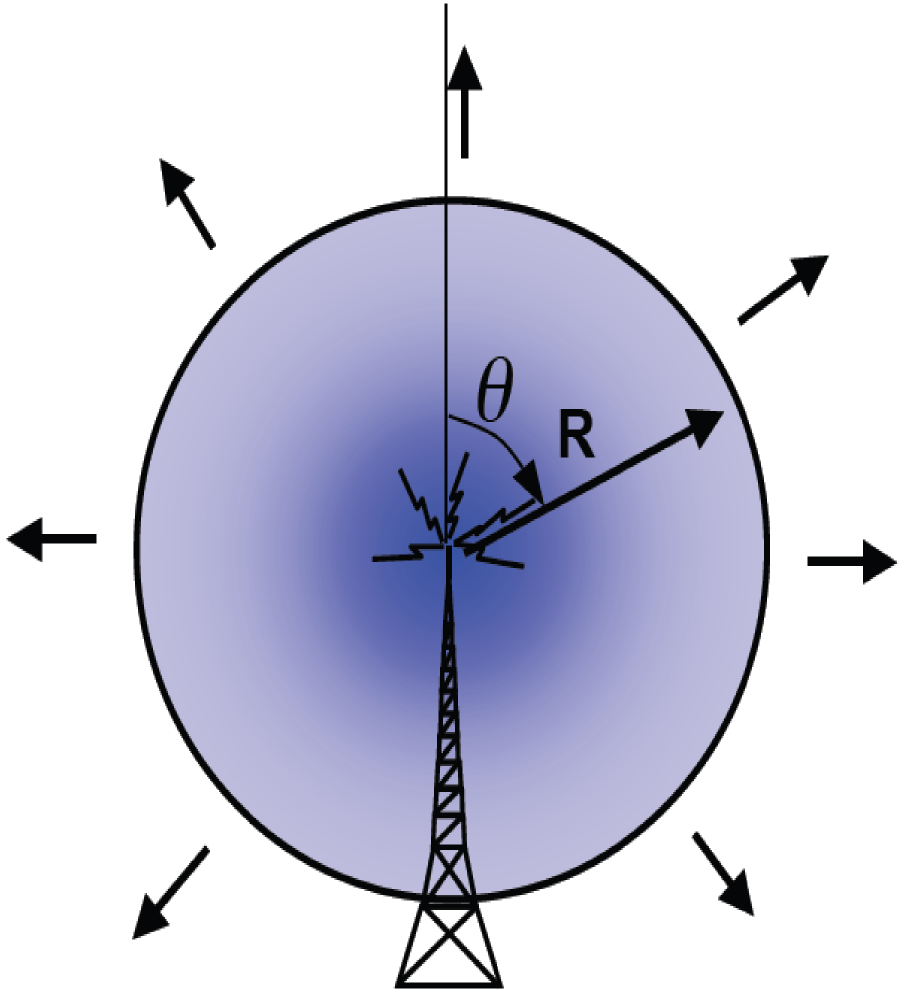
Directive antenna.



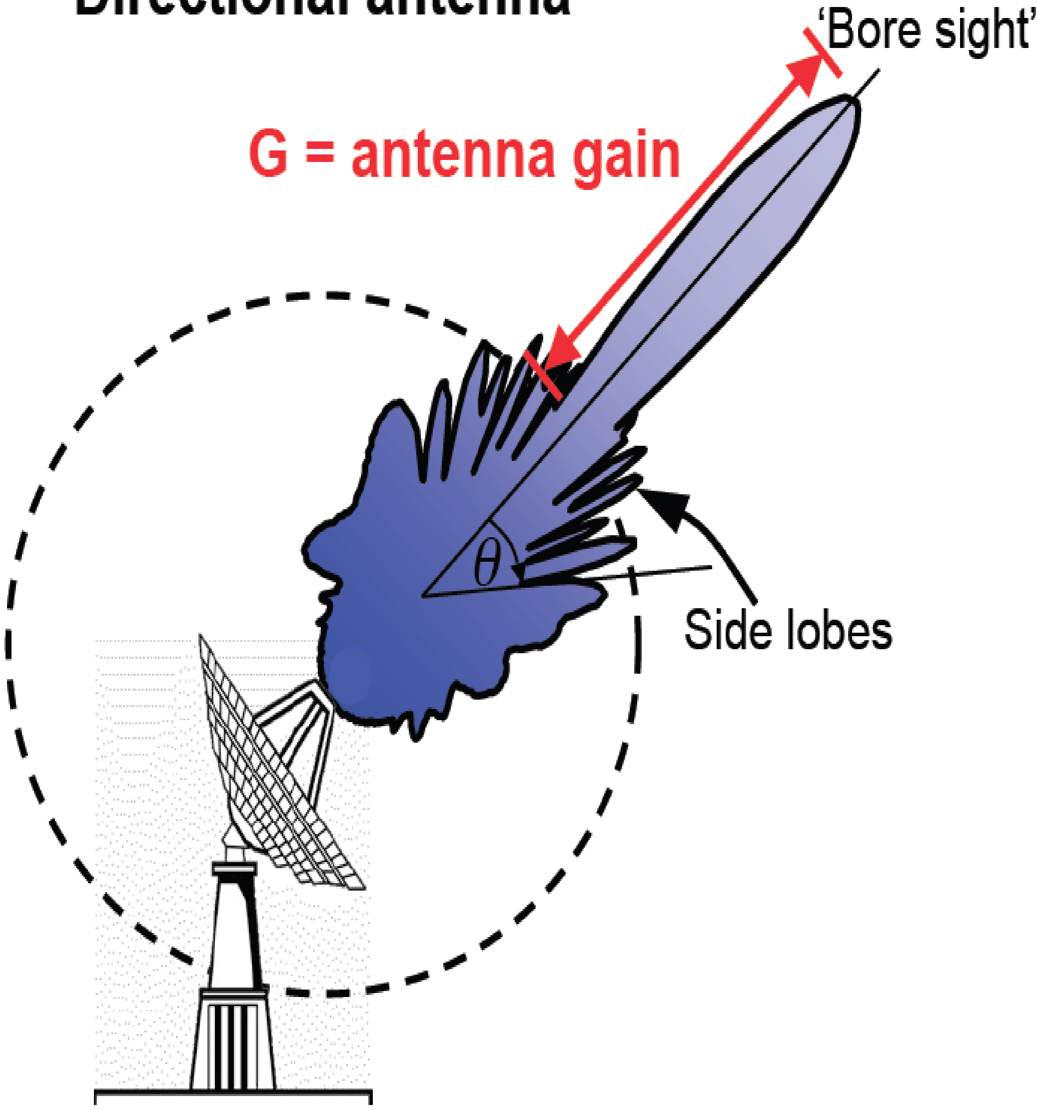
Radiation pattern of directive antenna.

Radiation Pattern – Antenna Gain

Isotropic antenna



Directional antenna



Polarization filter

Antennas have the property of being more sensitive to one polarization than another. This provides the ability to filter signals based on its polarization.

Example: Satellite tracking receive on both right-circular and left-circular

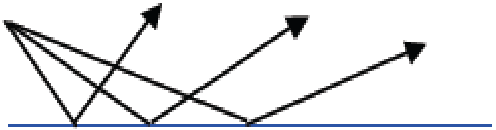
Propagation Medium - Losses

Radio waves are affected by the medium they propagate in. Effects dependent on the refractive index of the medium and wave frequency

Radio waves are also reflected off of the surface

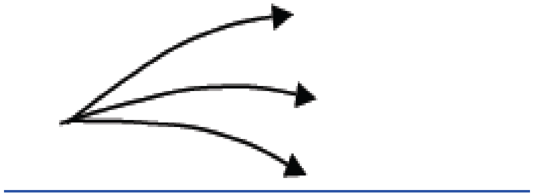
- **Atmospheric attenuation**

- **Reflection off of earth's surface**



- **Over-the-horizon diffraction**

- **Atmospheric refraction**

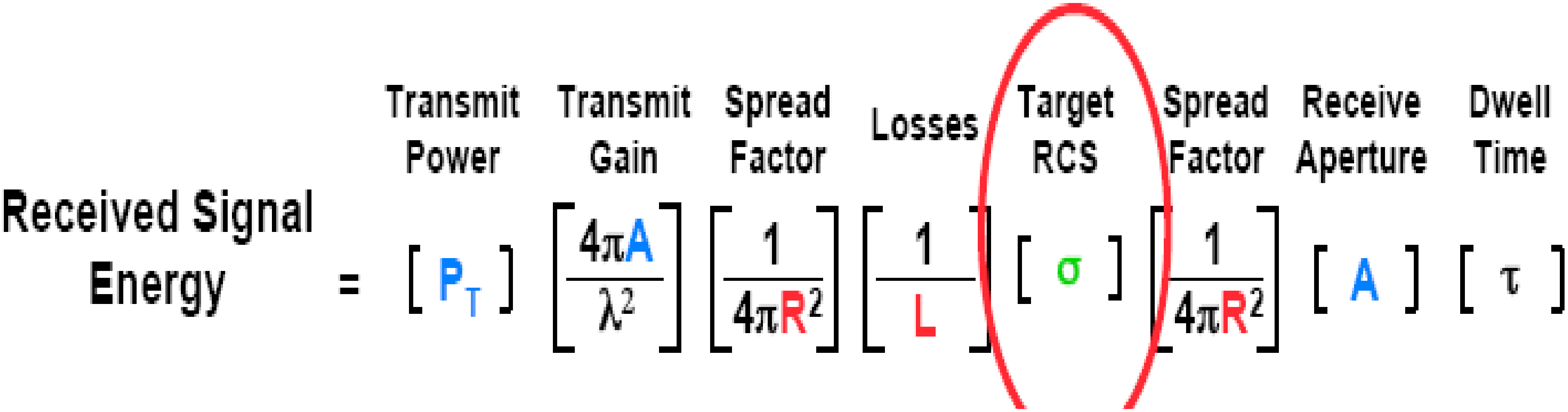


Attenuation usually measured in dB

$$\text{SNR dB} = 10\log_{10}\frac{\mathit{signal\ power}}{\mathit{noise\ power}}$$

dB value	times by
+30 dB	1000
+20 dB	100
+3 dB	2
-10 dB	0.1
-20 dB	0.01

Radar equation



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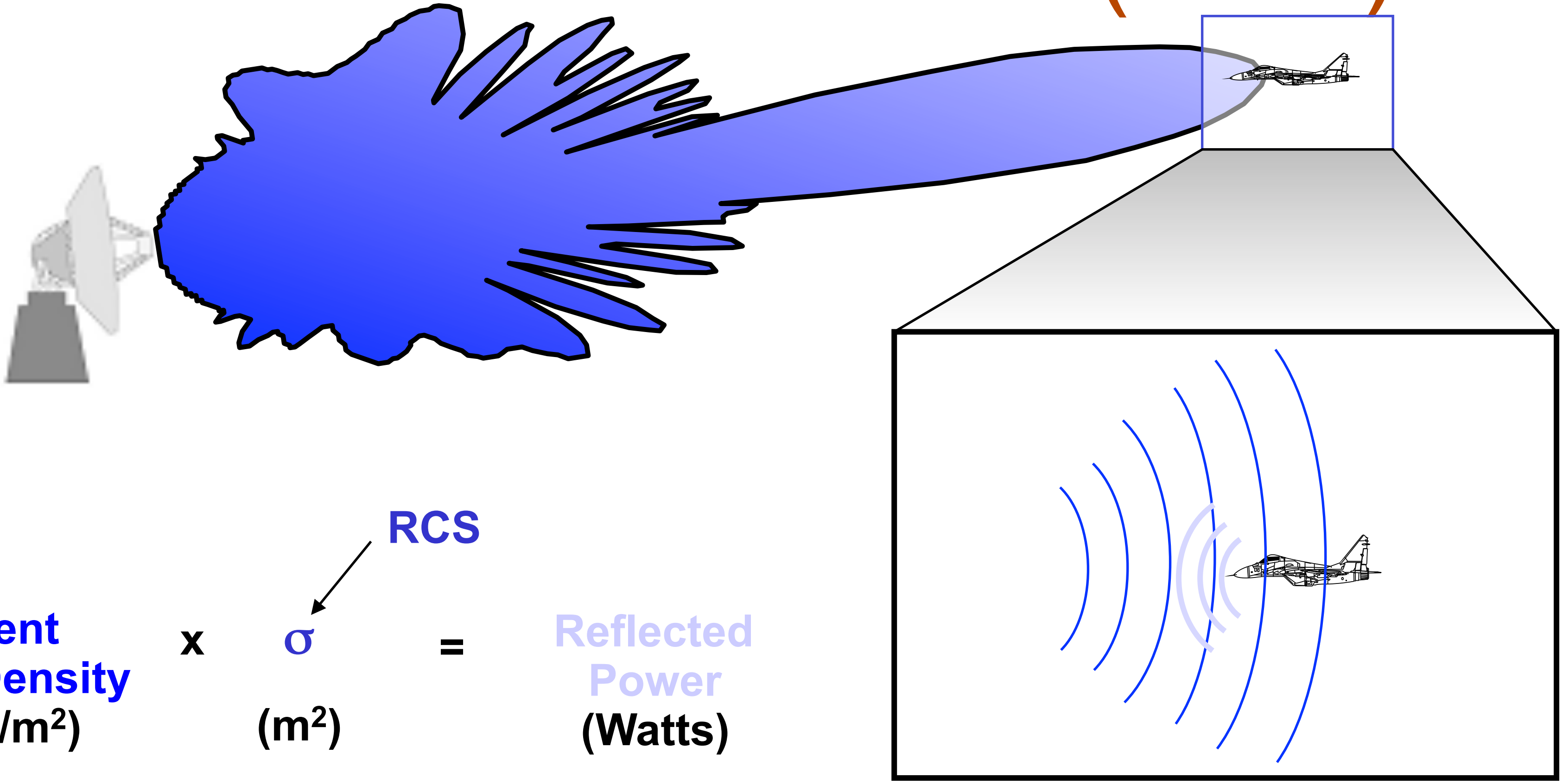
Radar cross section tells us about the target properties

It is the effective target cross section as seen by the radar

Radar Cross Section (RCS)



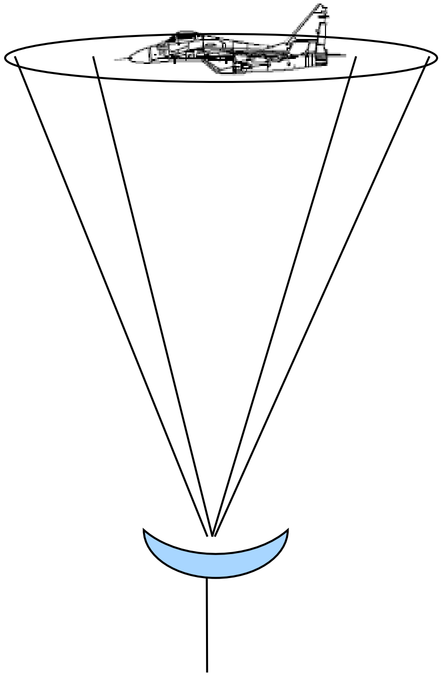
RCS

Incident Power Density (Watts/m^2) x σ (m^2) = **Reflected Power** (Watts)

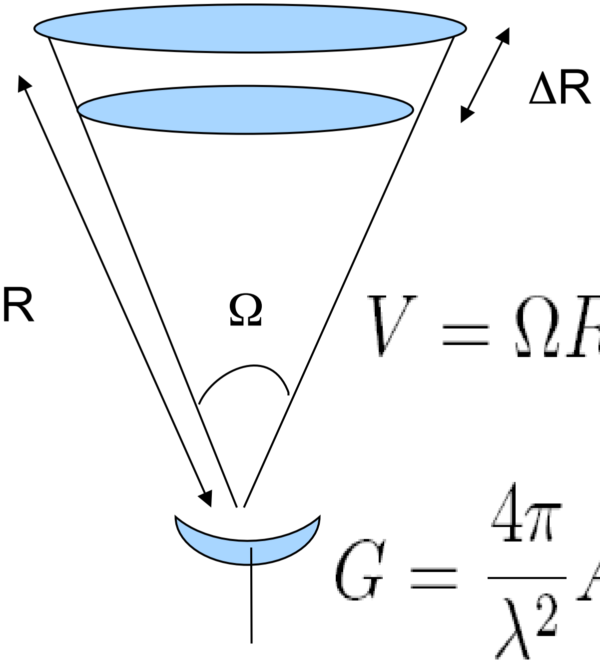
Radar Cross Section (RCS, or s) is the *effective* cross-sectional area of the target as seen by the radar

measured in m^2, or dBm^2

Hard targets vs. Soft targets



vs.



$$V = \Omega R^2 \,\Delta R$$

$$G = \frac{4\pi}{\lambda^2} A = \frac{4\pi}{\Omega}$$

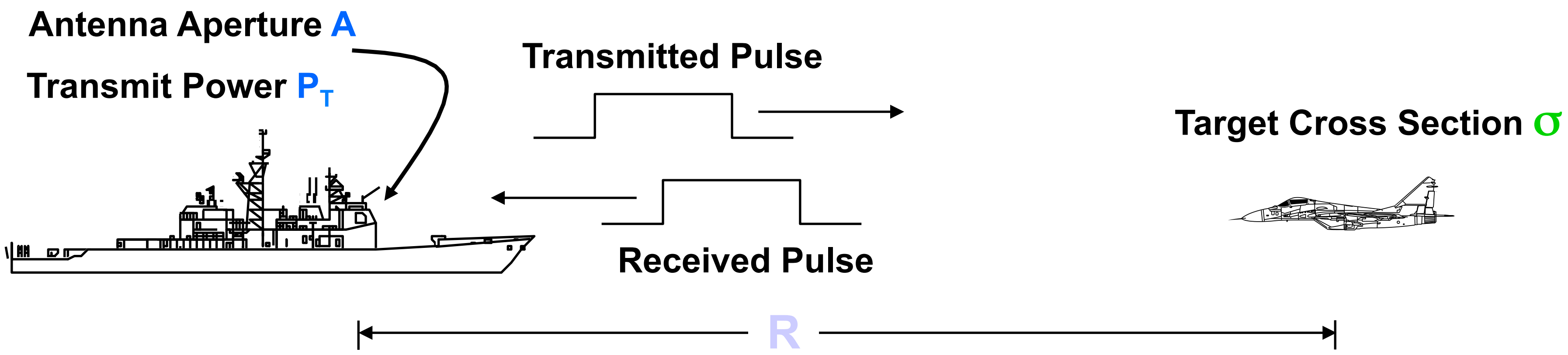
$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

$$P_r = \frac{P_t A \sigma_v \Delta R}{4\pi R^2}$$

Volume scattering - Ionosphere

- Volume scattering cross section σ_v has area/ volume units
- Signal is proportional to range resolution
- What about the ionosphere ?
- Cross section of a single electron = 10^{-28} m^2
- Cross section of a bunch of electrons in a 10 km^3 volume in the ionosphere assuming electron density = 10^{12} /m^3, is $10^{10} \times 10^{12} \times 10^{-28} = 10^{-6}$ m^2 !!)
- **CAN be measured by an incoherent scatter radar.**

Radar Range Equation



Antenna Aperture A

Transmit Power P_T

Transmitted Pulse

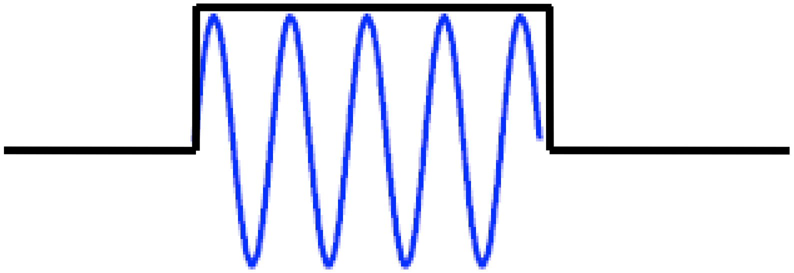
Target Cross Section σ

Received Pulse

R

$$\text{Received Signal Energy} = \overset{\text{Transmit Power}}{\left[\, P_T \,\right]} \overset{\text{Transmit Gain}}{\left[\frac{4\pi A}{\lambda^2}\right]} \overset{\text{Spread Factor}}{\left[\frac{1}{4\pi R^2}\right]} \overset{\text{Losses}}{\left[\frac{1}{L}\right]} \overset{\text{Target RCS}}{\left[\, \sigma \,\right]} \overset{\text{Spread Factor}}{\left[\frac{1}{4\pi R^2}\right]} \overset{\text{Receive Aperture}}{\left[\, A \,\right]} \overset{\text{Dwell Time}}{\left[\, \tau \,\right]}$$

What the radar transmits: Pulses and waves

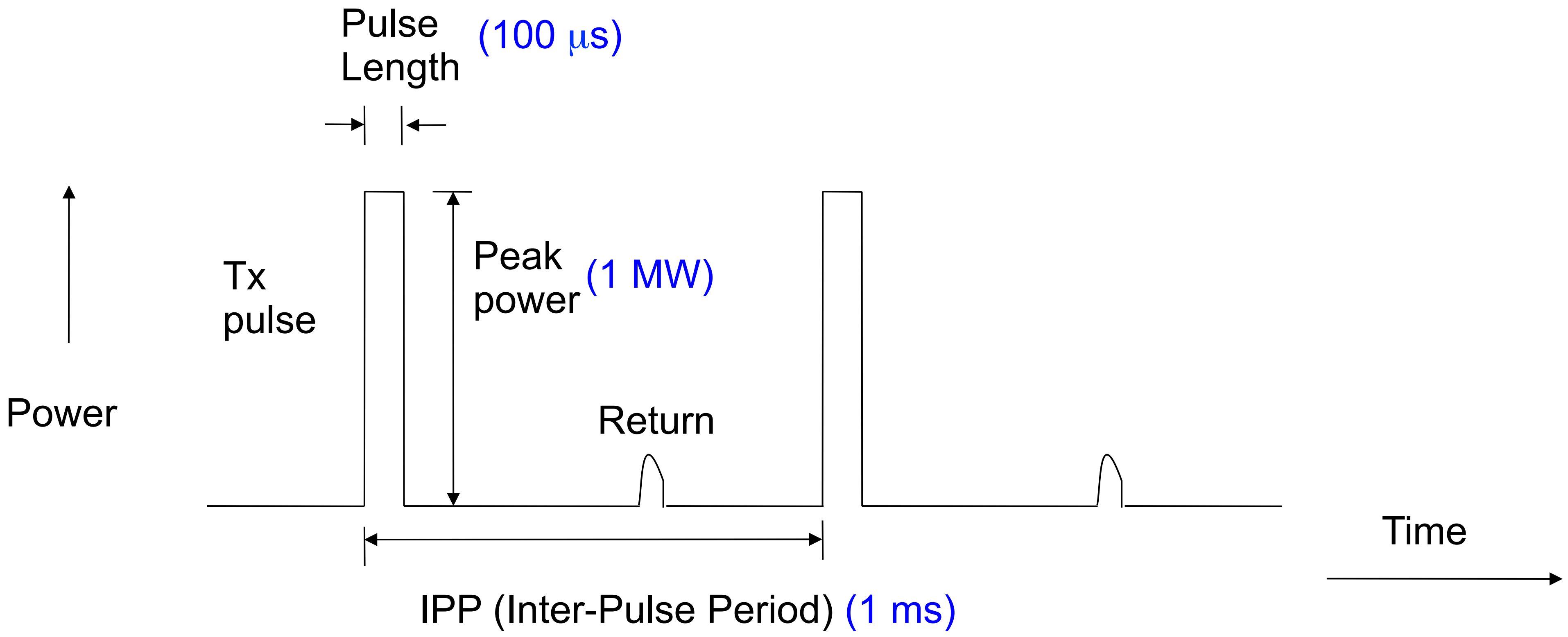


Cycles in a pulse.

PFISR frequency = 449 MHz
Long pulse length = 480 μs
# of cycles = 215520 !

Radar waveforms modulate the waves with on-off sequence

Pulsed Radar



Duty cycle = Pulse Length/IPP (10%)
Average power = Peak power x Duty cycle (100 kW)
PRF (Pulse Repetition Frequency) = 1/IPP (1kHz)

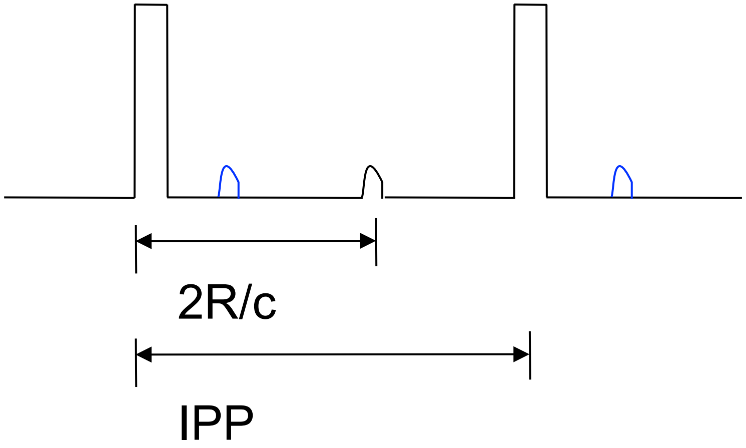
Duty cycle for a CW (continuous wave) radar 100%

Range Resolution

Range resolution is set by pulse length

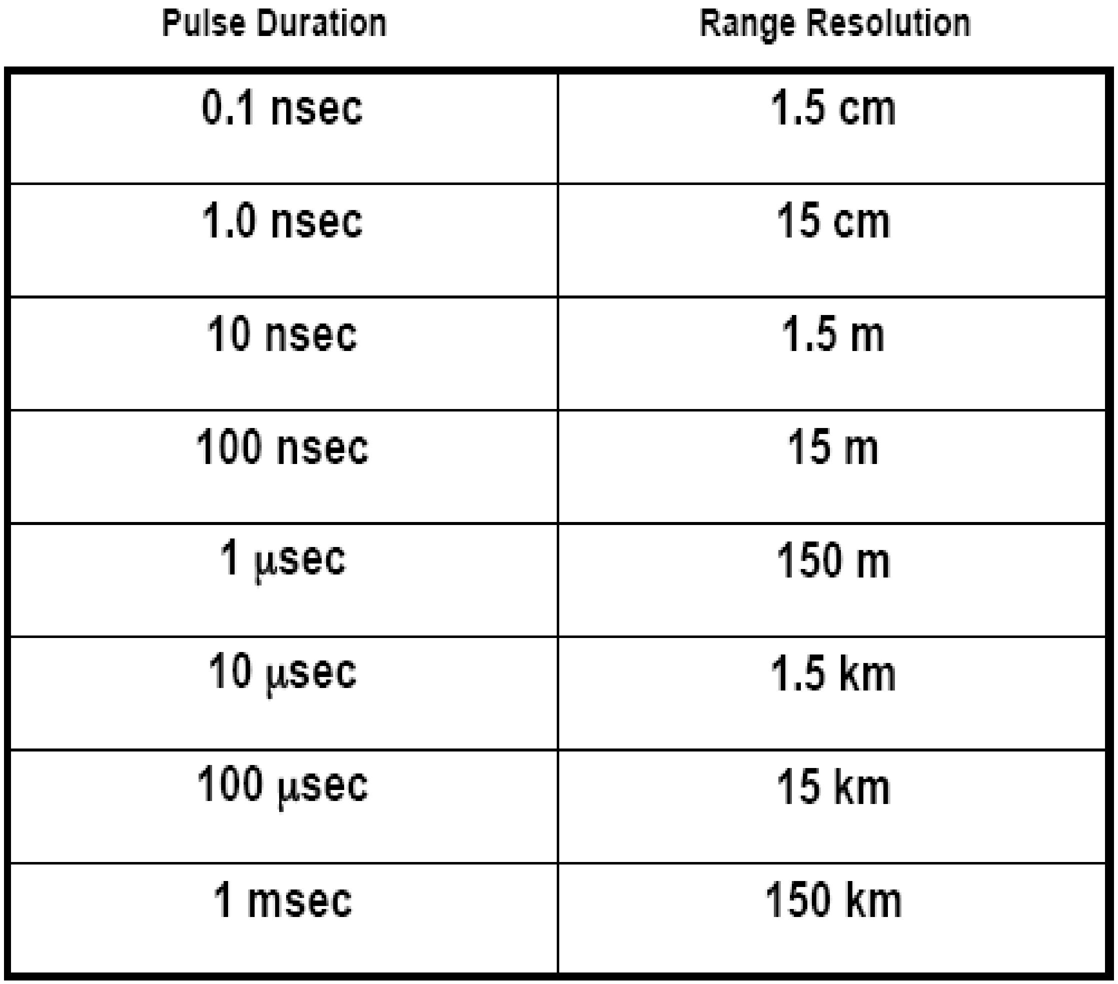
Pulse length = τ_p , Range resolution = $c\tau_p/2$ for a single target.

Maximum unambiguous range



MUR = c*IPP/2

Pulse duration vs. Range resolution

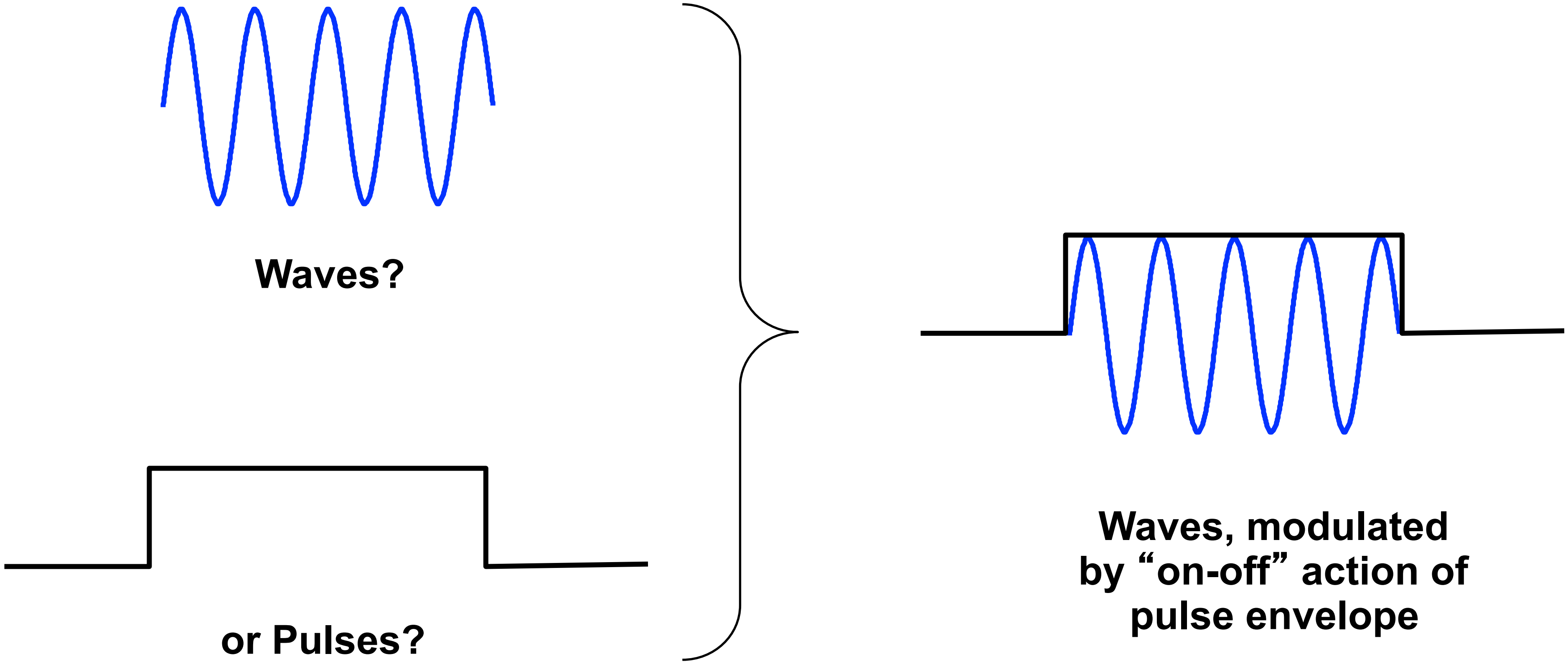


Pulse Duration	Range Resolution
0.1 nsec	1.5 cm
1.0 nsec	15 cm
10 nsec	1.5 m
100 nsec	15 m
1 μsec	150 m
10 μsec	1.5 km
100 μsec	15 km
1 msec	150 km

What is a typical F region ISR pulselength?

Radar Waveforms

What do radars transmit?



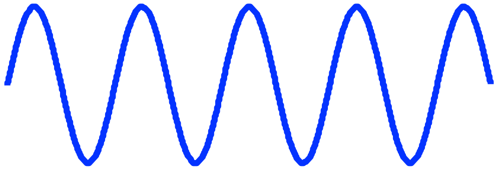
Waves?

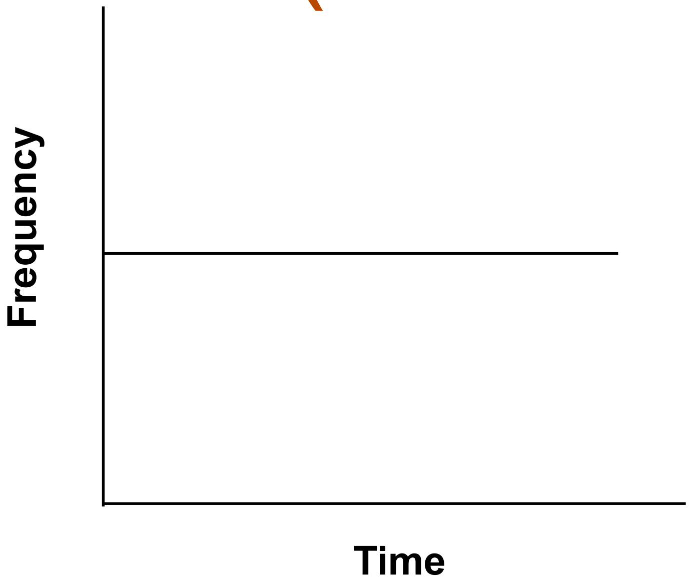
or Pulses?

Waves, modulated by “on-off” action of pulse envelope

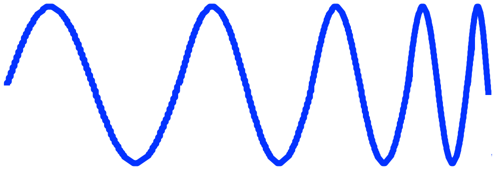
Radar Waveforms (cont’d.)

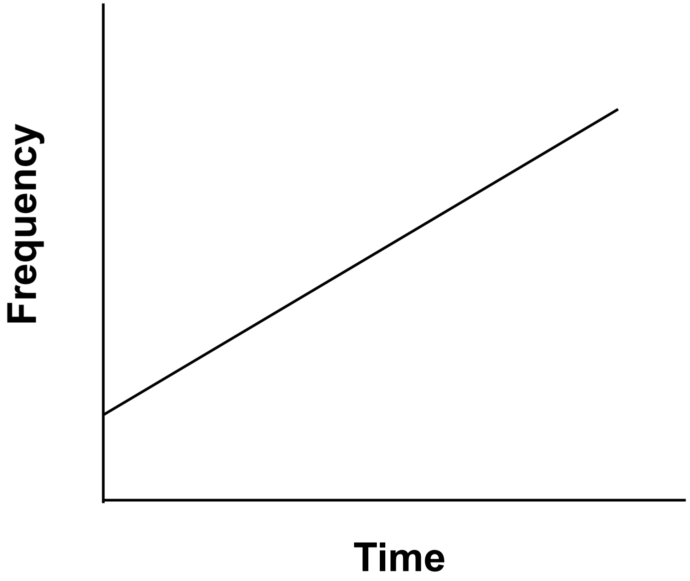
Pulse at single frequency





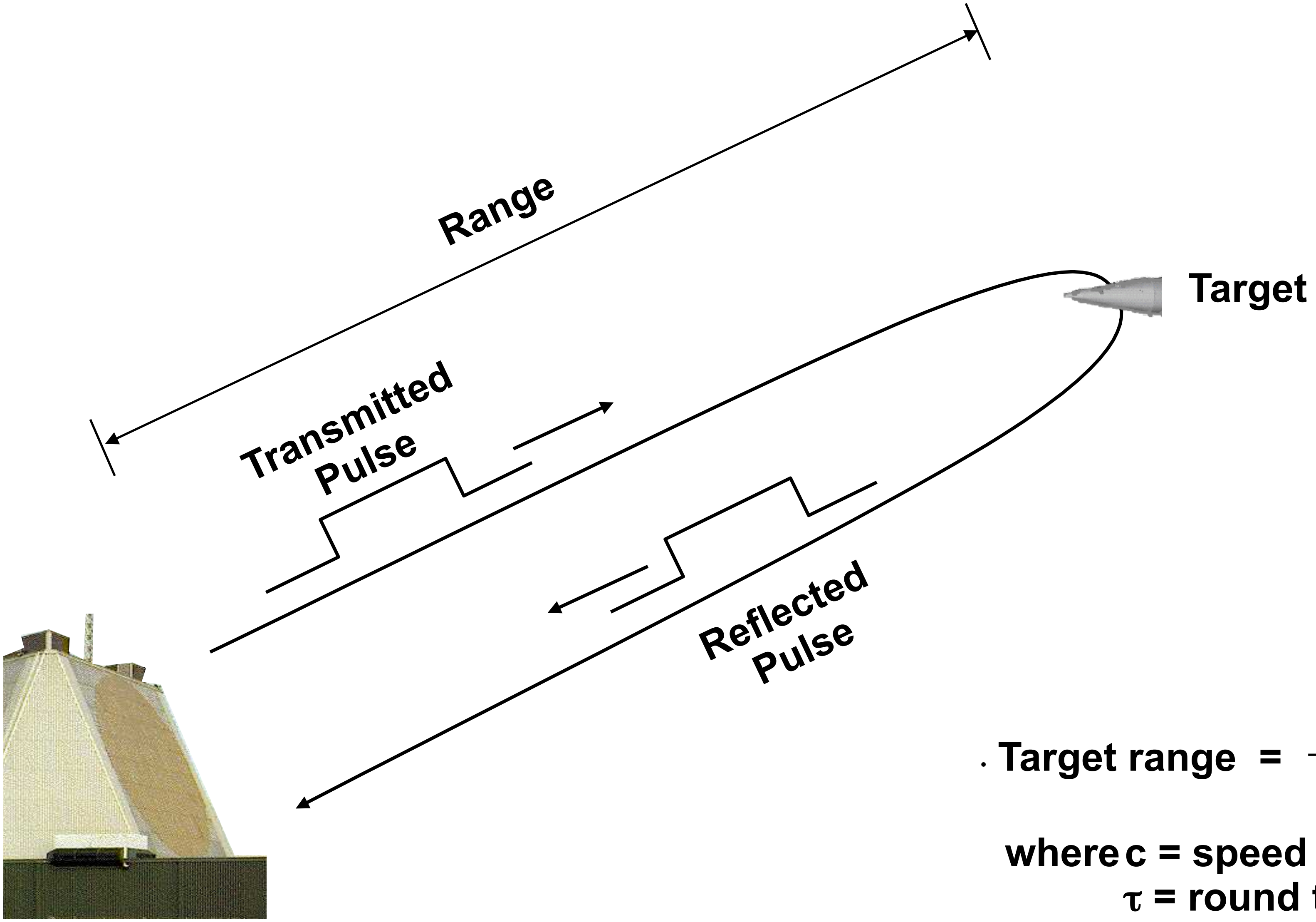
Pulse with changing frequency





Linear Frequency-Modulated (LFM) Waveform

Radar Range Measurement



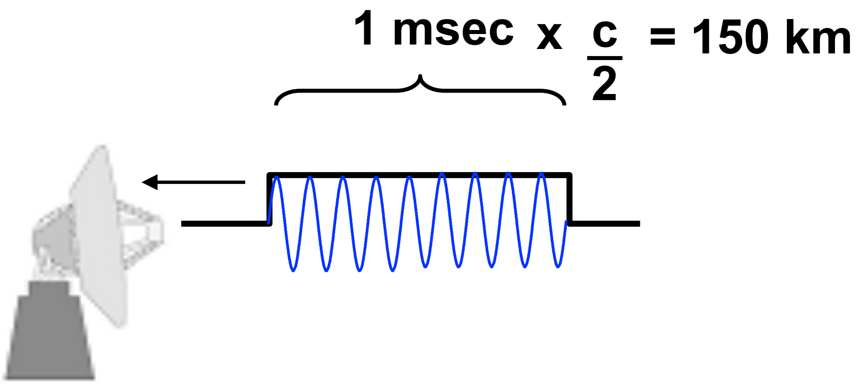
- Target range $= \frac{c\tau}{2}$

where c = speed of light
τ = round trip time

Signal Processing

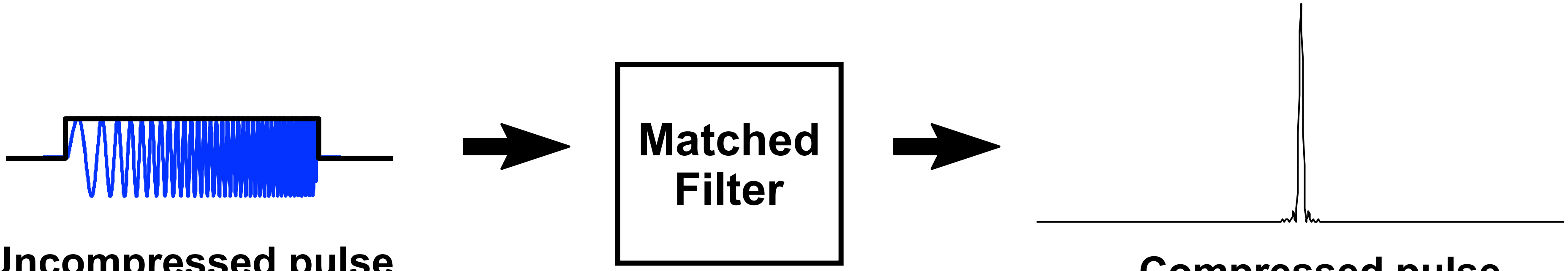
Pulse Compression

Problem: Pulse can be very long; does not allow accurate range measurement



$$1\text{ msec} \times \frac{c}{2} = 150\text{ km}$$

Solution: Use pulse with changing frequency and signal process using "matched filter"

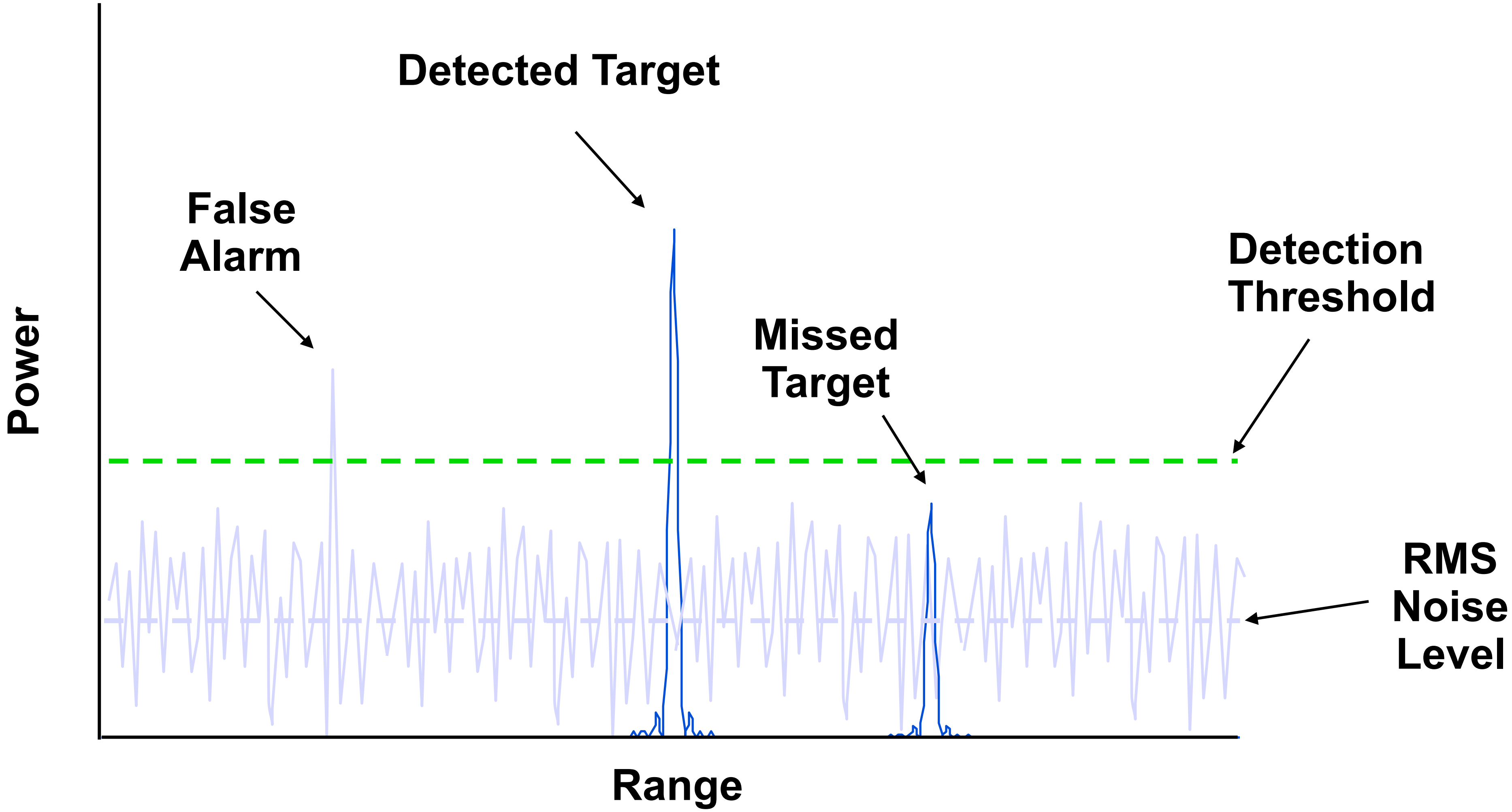


Uncompressed pulse

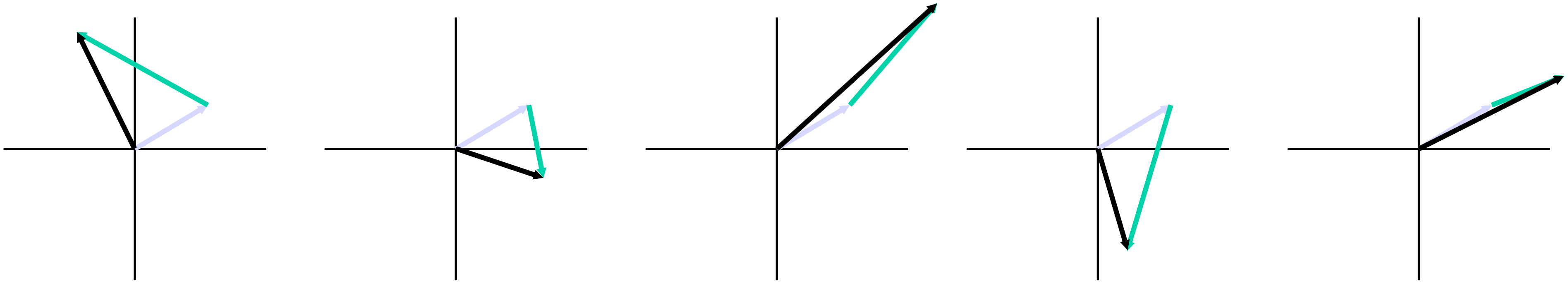
Matched Filter

Compressed pulse

Detection of Signals in Noise



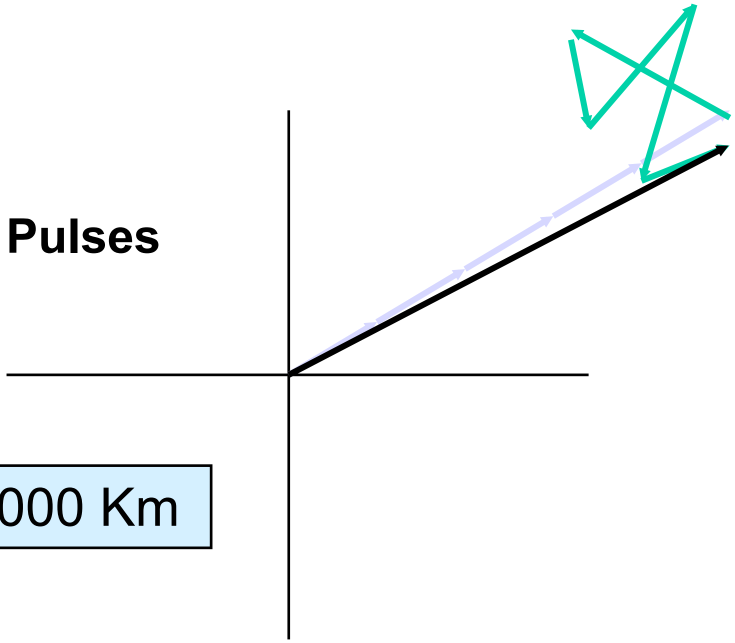
Coherent Integration



Pulse 1 **Pulse 2** **Pulse 3** **Pulse 4** **Pulse 5**

- Coherent target returns
- Noise samples at low SNR
- Resultant signal

Coherently Integrated Pulses



Deep space targets at 30,000 – 40,000 Km

Outline - Radar Basics

- Electromagnetic spectrum
- Radio Waves and Propagation
- Radar fundamentals
  - Radar equation
  - Range Resolution and pulsed radars
- Doppler and Doppler Radars

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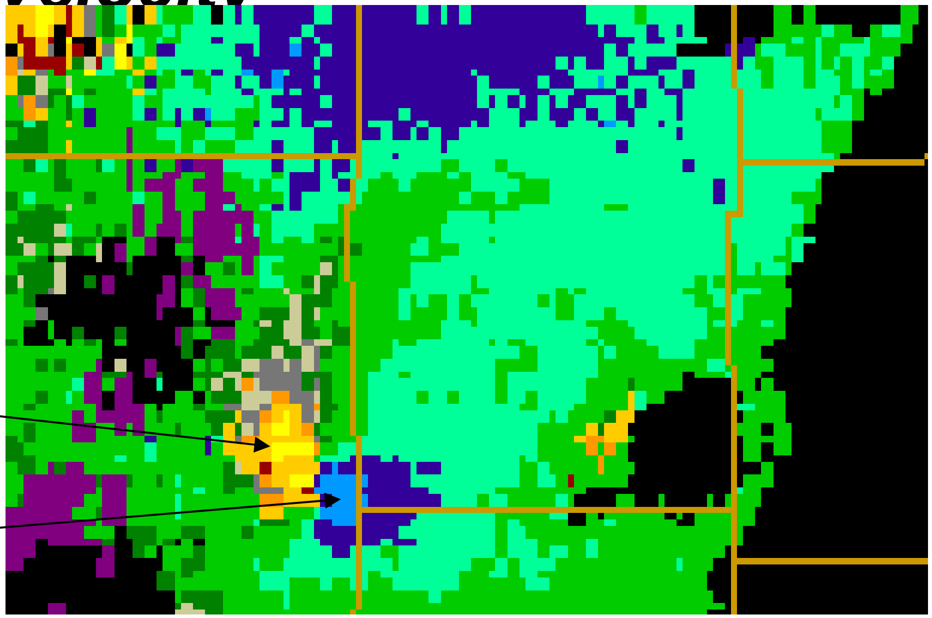
AMISR Summer School 2013

Sign conventions

The Doppler frequency is negative (lower frequency, red shift) for objects receding from the radar

The Doppler frequency is positive (higher frequency, blue shift) for objects approaching the radar

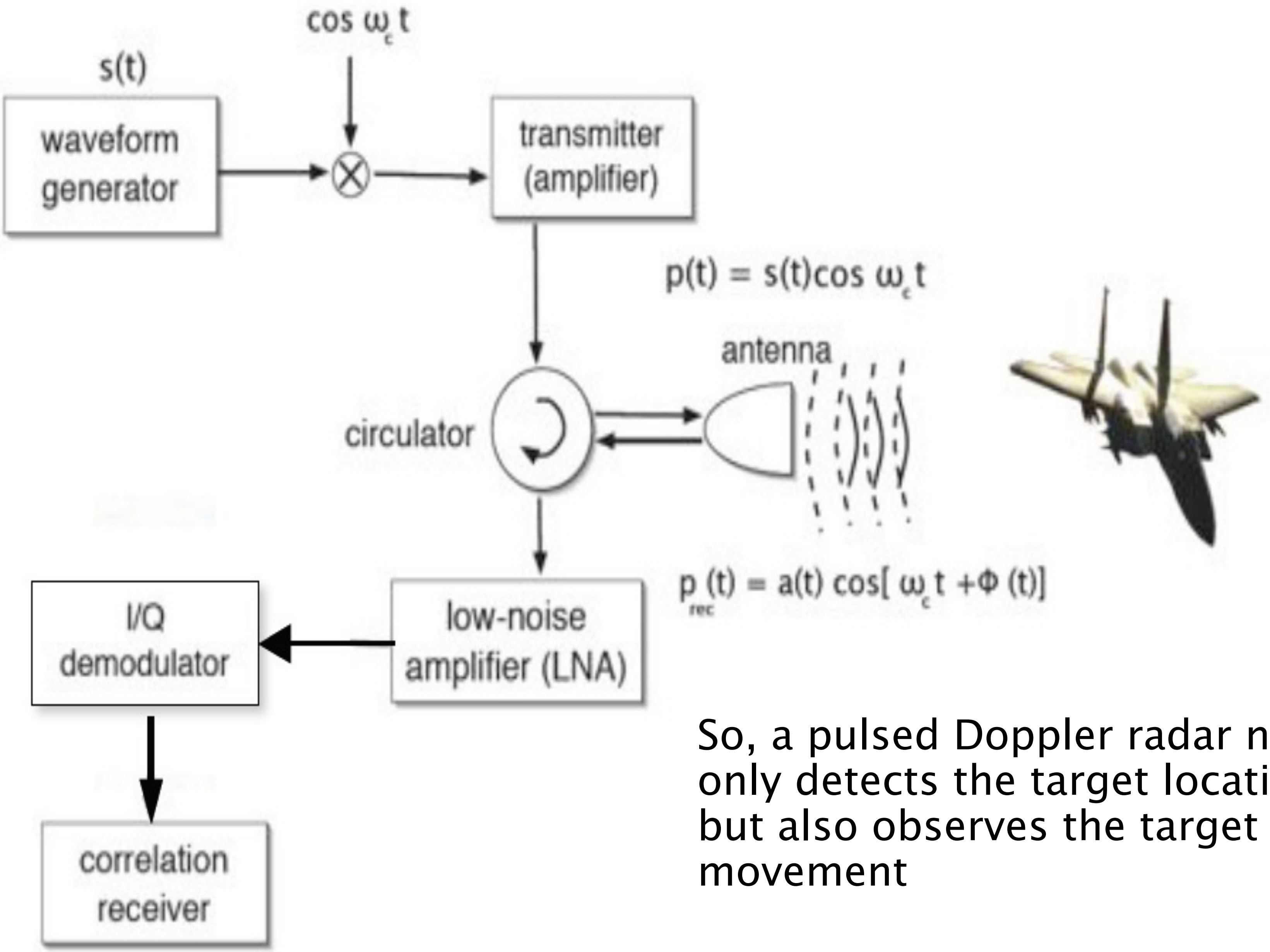
These "color" shift conventions are typically also used on radar displays of Doppler velocity



Red: Receding from radar

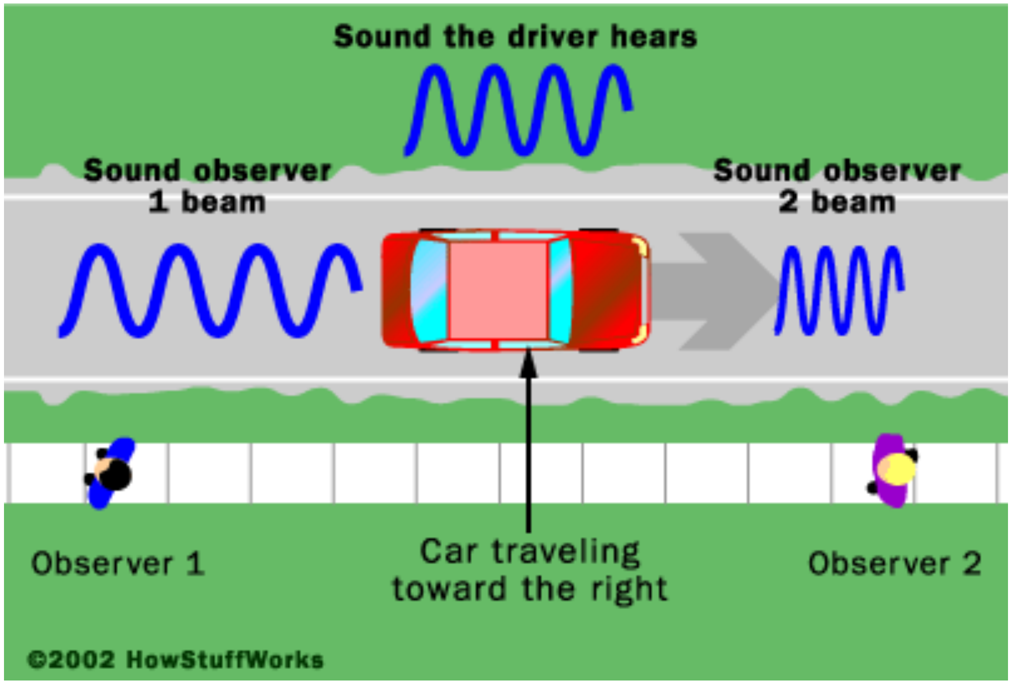
Blue: Toward radar

Pulsed Doppler Radar system



So, a pulsed Doppler radar not only detects the target location, but also observes the target movement

Moving target - Doppler



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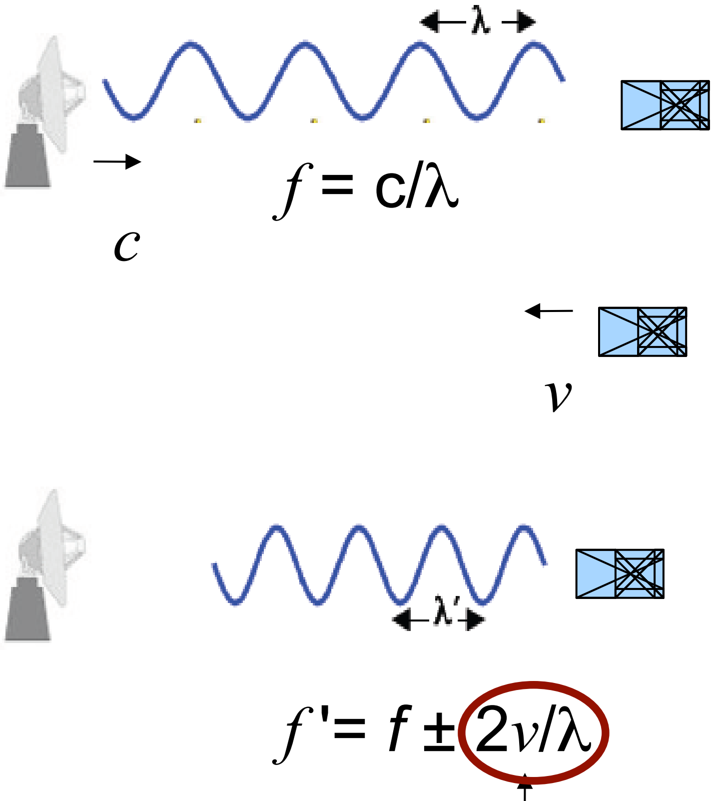


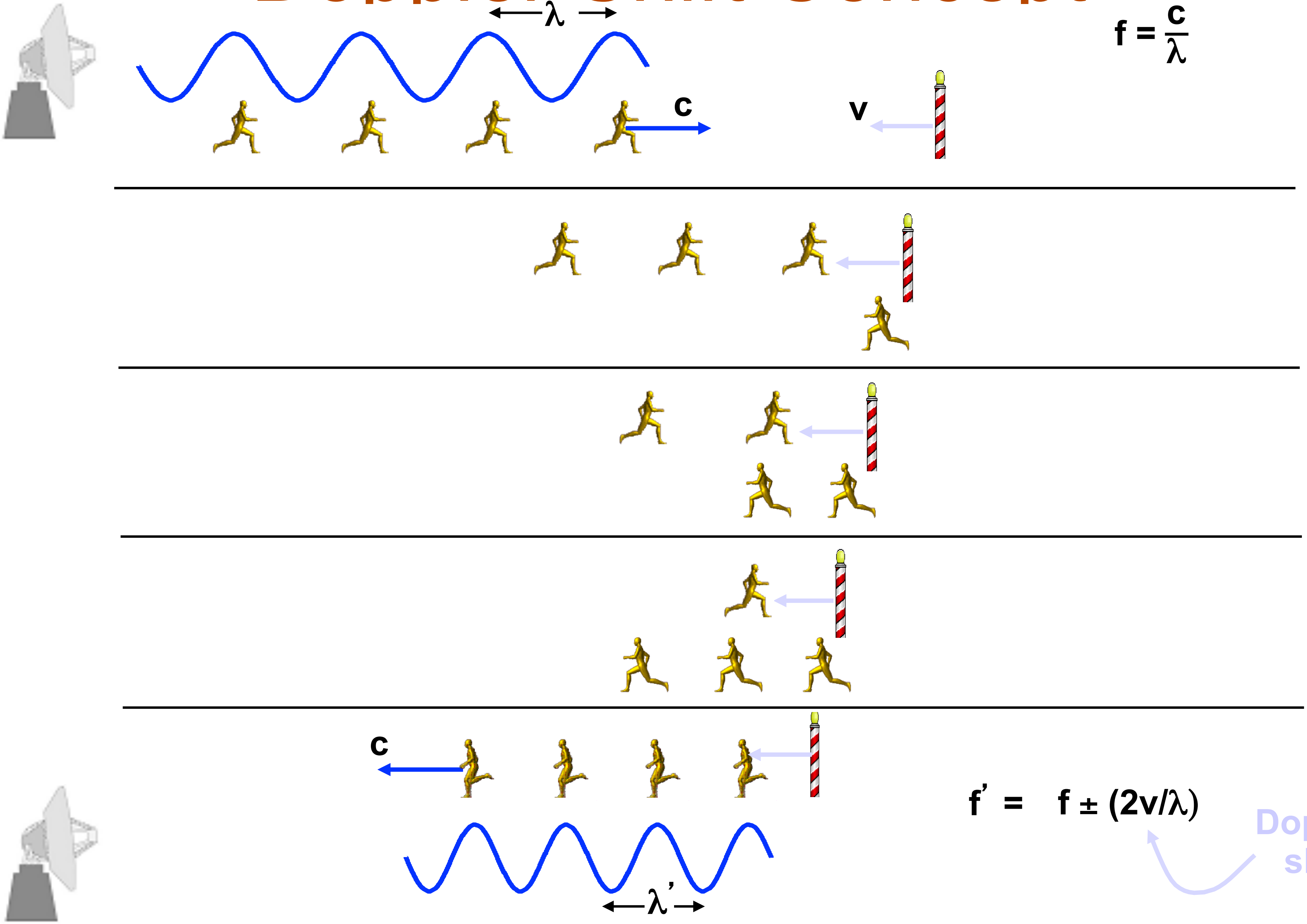
$f = c/\lambda$

$f' = f \pm \underbrace{2v/\lambda}_{\text{Doppler shift}}$

Positive Doppler = target moving **toward** the observer
Negative Doppler = target moving **away** from the observer

Doppler Shift Concept

$$f = \frac{c}{\lambda}$$



$$f' = f \pm (2v/\lambda)$$

Doppler shift

Doppler shift frequency

Tx signal: $\cos(2\pi f_o t)$

Return from a moving target: $\cos[2\pi f_o(t + 2R/c)]$

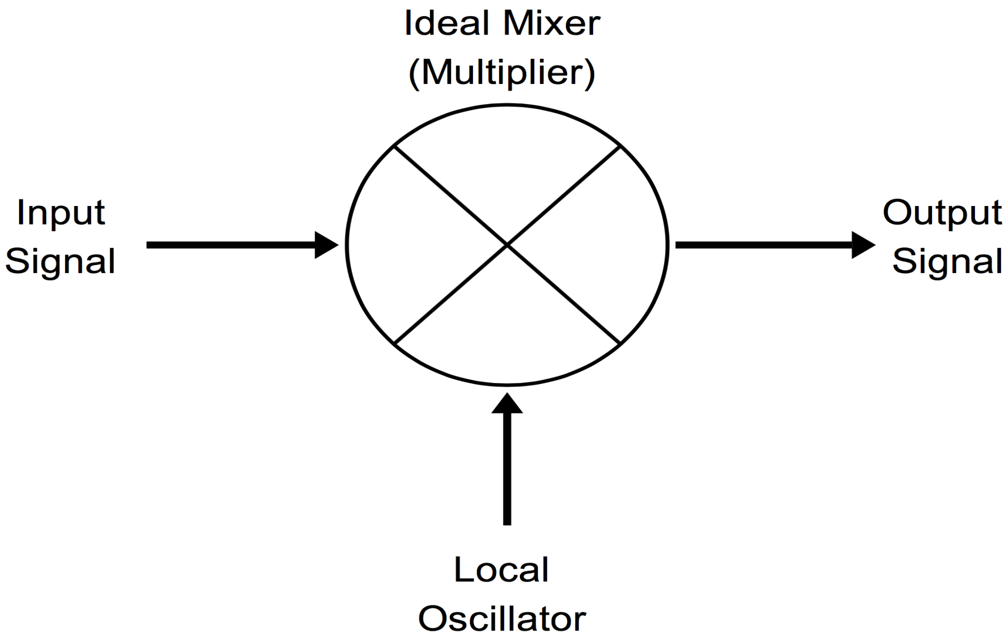
If target is moving with a constant velocity: $R = R_o + v_o t$

then,

Return: $\cos[2\pi(f_o + \boxed{f_o 2 v_o / c})t + 2\pi f_o R_o / c]$

Doppler frequency:
$-2 f_o v_o / c = -2 v_o / \lambda_o$

Mixing to Baseband



Ideal Mixer
(Multiplier)

Input
Signal

Output
Signal

Local
Oscillator

$$\sin u \sin v = \frac{1}{2}\left[\cos(u-v) - \cos(u+v)\right]$$

$$\cos u \cos v = \frac{1}{2}\left[\cos(u-v) + \cos(u+v)\right]$$

$$\sin u \cos v = \frac{1}{2}\left[\sin(u+v) + \sin(u-v)\right]$$

$$\cos u \sin v = \frac{1}{2}\left[\sin(u+v) - \sin(u-v)\right]$$

Resolving Doppler

Tx signal: cos($2\pi f_o$t)
Doppler shifted: cos[$2\pi(f_o + f_D)$t]

Multiply by cos($2\pi f_o$t) -> Low pass filter -> cos($2\pi f_D$t)

BUT, the sign of f_D is lost (cosine is an even function)

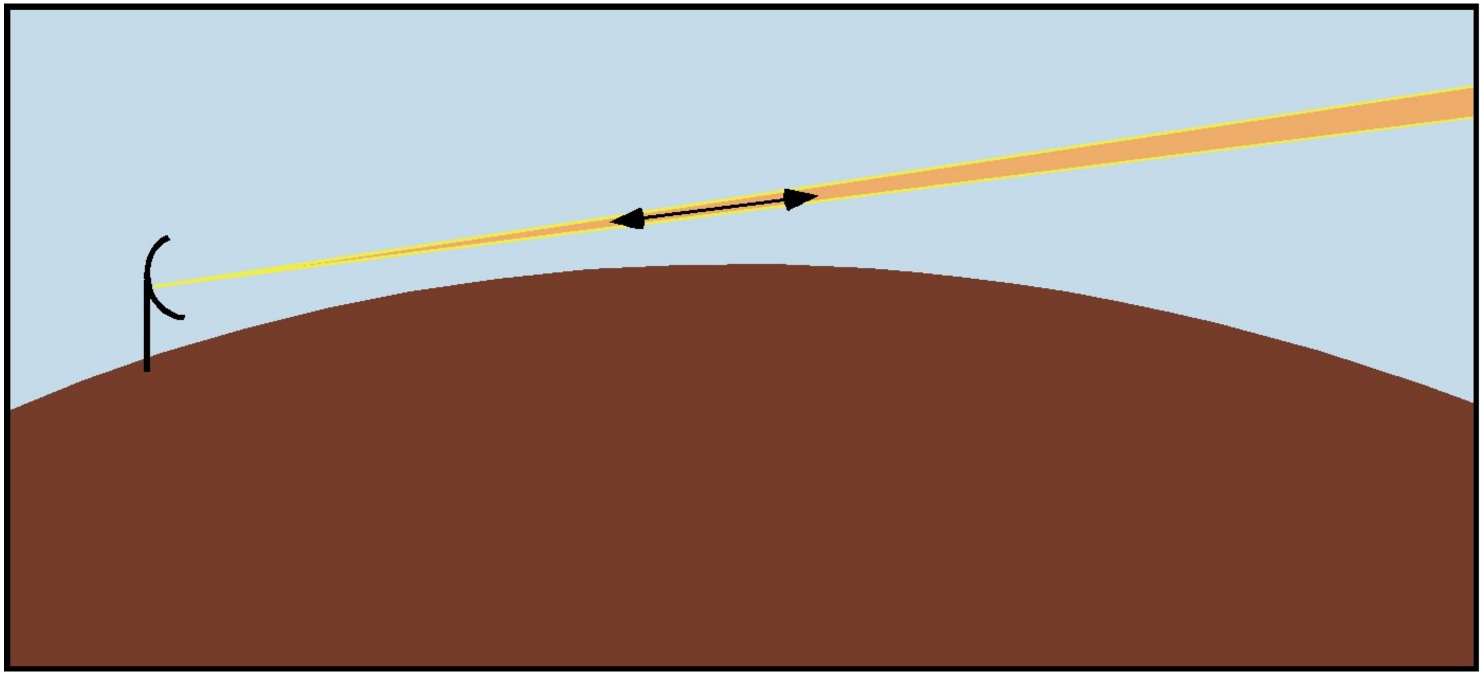
So, instead use
exp($j2\pi f_D$t) = cos($2\pi f_D$t) + $j$sin($2\pi f_D$t)

Generate this signal by mixing cos and sin via two oscillators (same frequency, 90° out of phase)

Components are called I (In phase) and Q (Quadrature): Aexp($j2\pi f_D$t) = $\mathrm{I} + j\mathrm{Q}$

Note that Doppler radars are only sensitive to the radial motion of objects

Air motion is a three dimensional vector: *A Doppler radar can only measure one of these three components – the motion along the beam toward or away from the radar*



Question: how does a steerable dish like Millstone – or a phased array dish like PFISR – determine vector ion velocities?