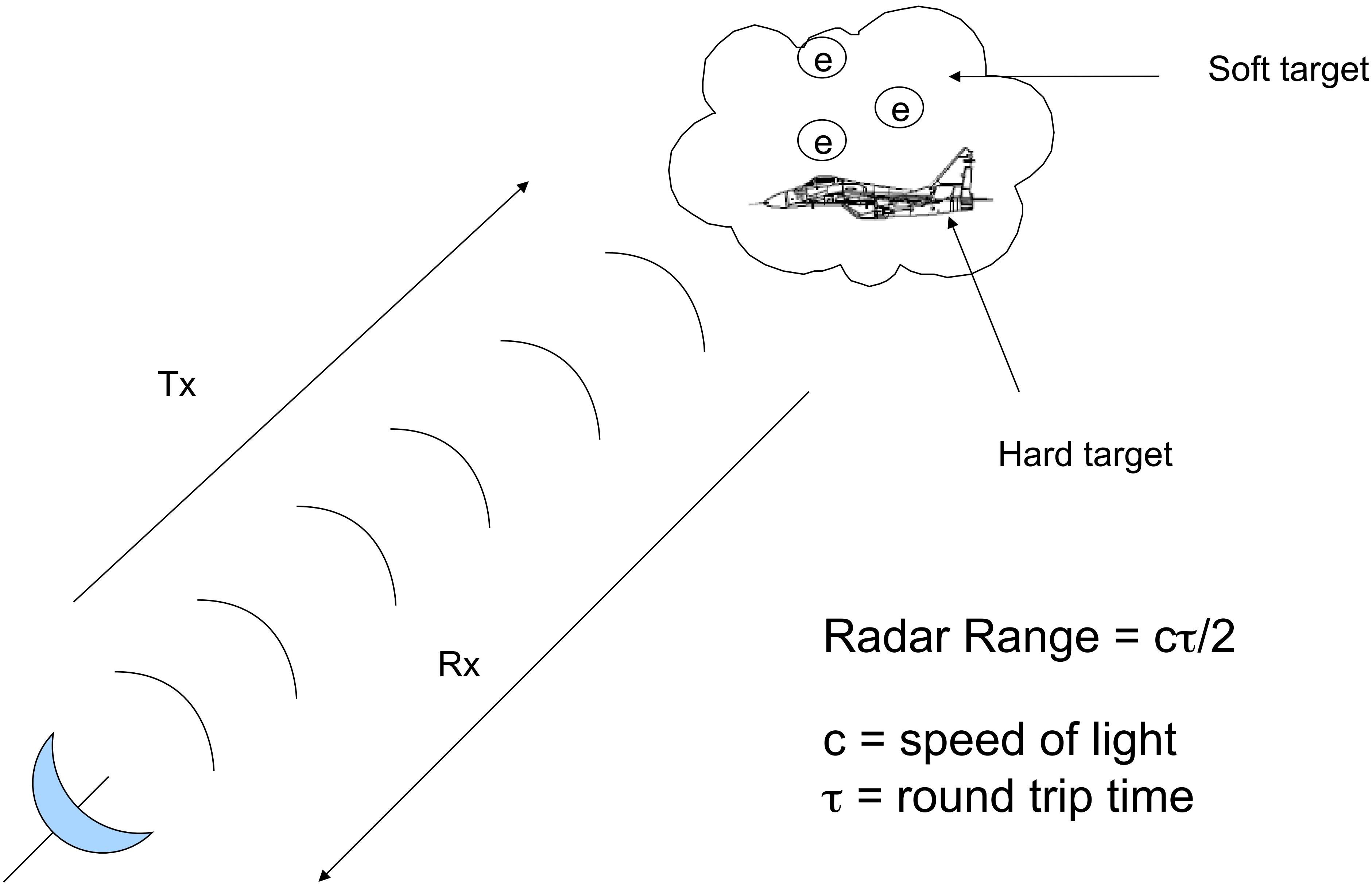
RAdio Detection And Ranging



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

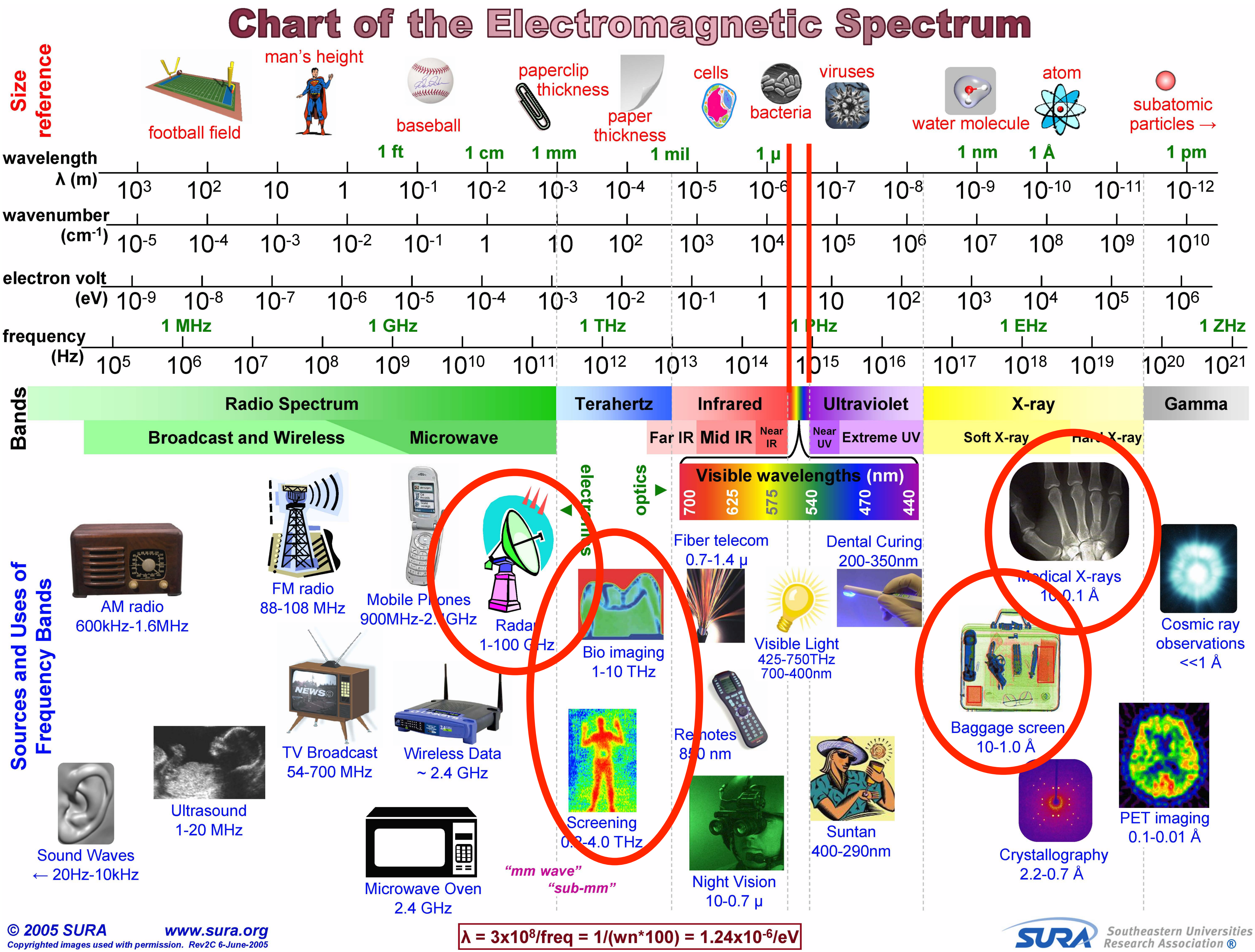


Chart of the Electromagnetic Spectrum
Size reference
football field
man's height
baseball
paperclip thickness
paper thickness
cells
bacteria
viruses
water molecule
atom
subatomic particles →
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10³ 10² 10 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
wavenumber (cm⁻¹)
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰
electron volt (eV)
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵ 10⁶
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹
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
Visible wavelengths (nm)
700 625 575 540 470 440
electronics
optics
Sources and Uses of Frequency Bands
AM radio 600kHz-1.6MHz
FM radio 88-108 MHz
Mobile Phones 900MHz-2.4GHz
Radar 1-100 GHz
Bio imaging 1-10 THz
Fiber telecom 0.7-1.4 μ
Dental Curing 200-350nm
Medical X-rays 10-0.1 Å
Cosmic ray observations <<1 Å
Visible Light 425-750THz 700-400nm
Baggage screen 10-1.0 Å
TV Broadcast 54-700 MHz
Wireless Data ~ 2.4 GHz
Remotes 850 nm
Ultrasound 1-20 MHz
Screening 0.2-4.0 THz
Suntan 400-290nm
PET imaging 0.1-0.01 Å
Sound Waves ← 20Hz-10kHz
Microwave Oven 2.4 GHz
"mm wave"
"sub-mm"
Night Vision 10-0.7 μ
Crystallography 2.2-0.7 Å
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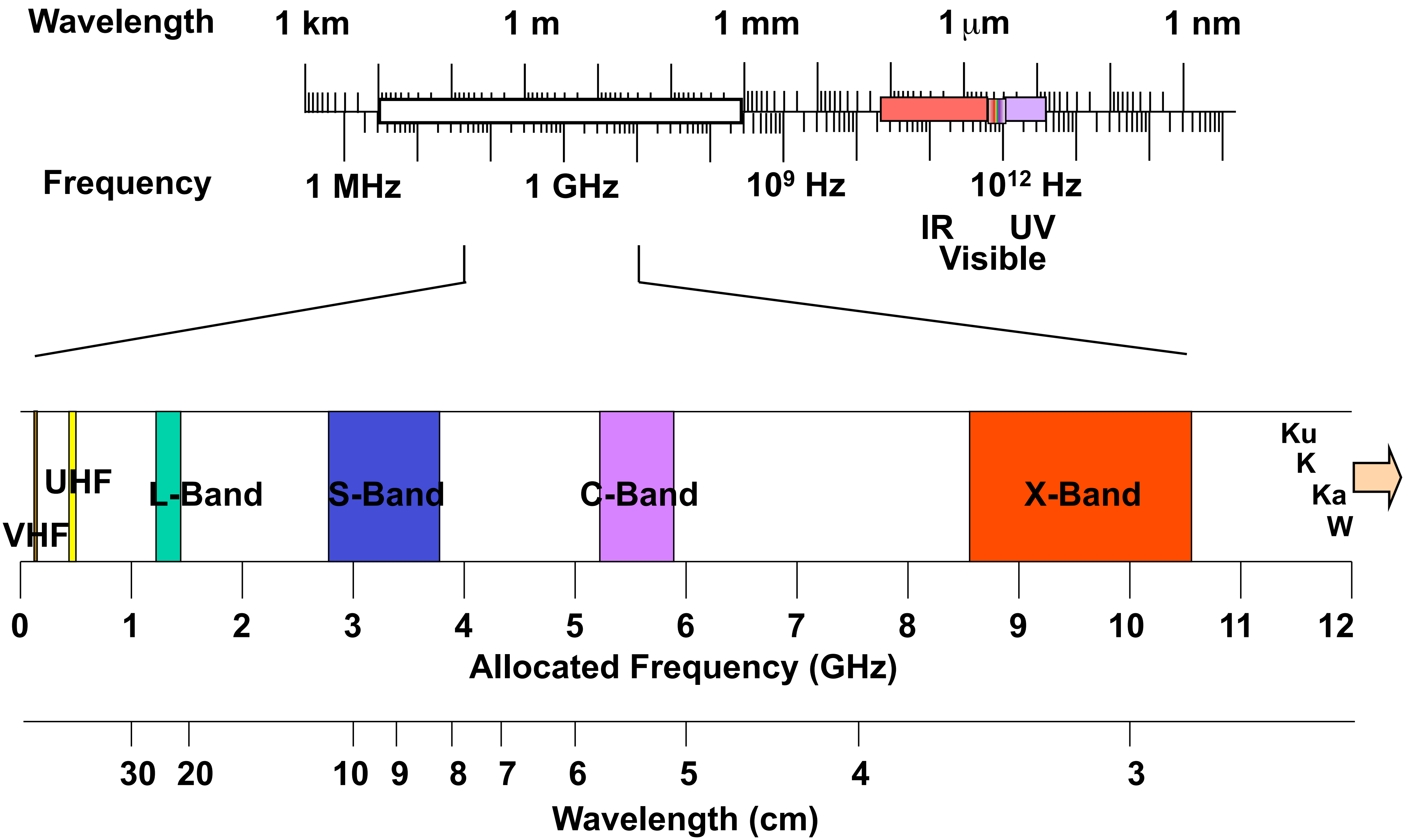
λ = 3x10⁸/freq = 1/(wn*100) = 1.24x10⁻⁶/eV
SURA Southeastern Universities Research Association ®

Radar Frequency Bands



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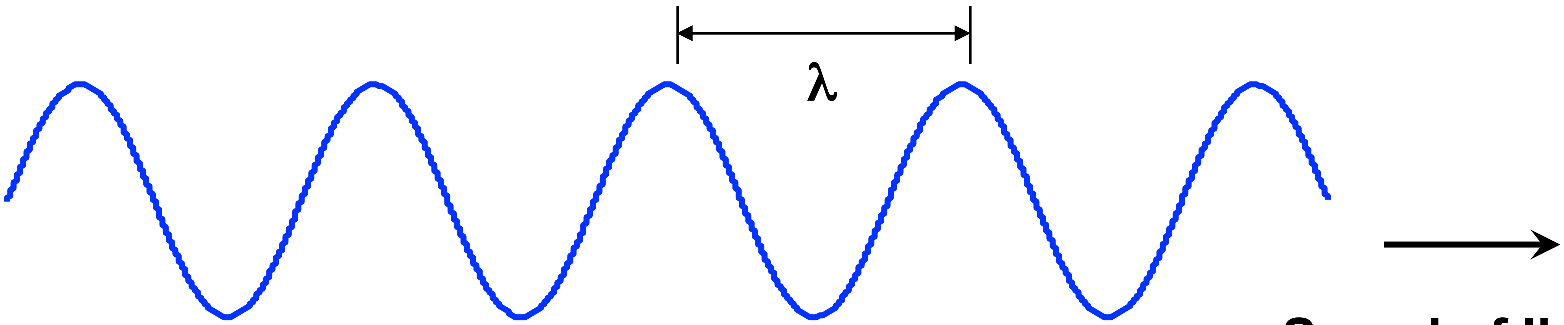
Properties of Waves

Relationship Between Frequency and Wavelength



Speed of light, c

c= 3×10^8 m/sec

= 300,000,000 m/sec

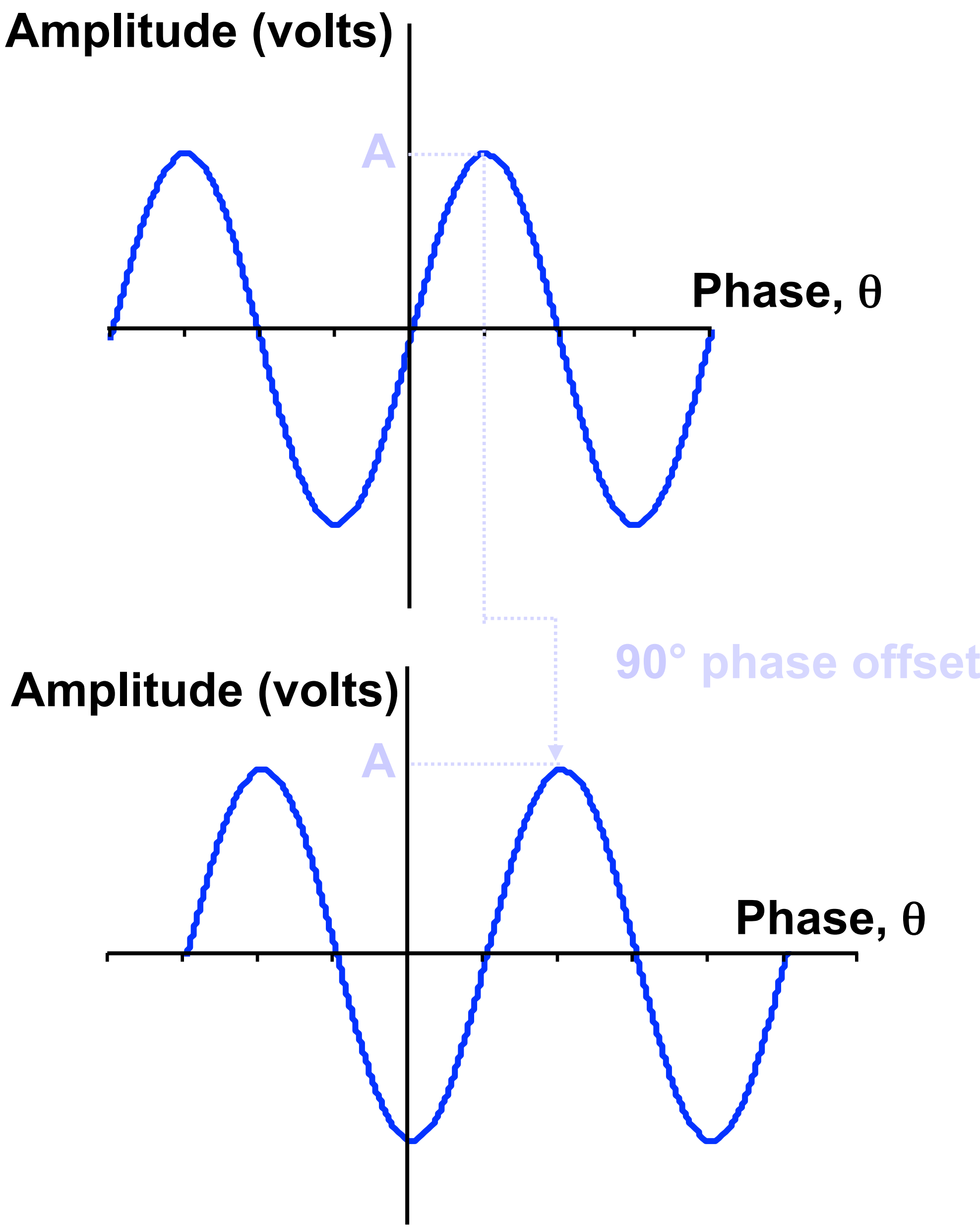
$$\text{Frequency (1/s)} = \frac{\text{Speed of light (m/s)}}{\text{Wavelength } \lambda \text{ (m)}}$$

Examples:

Frequency	Wavelength
100 MHz	3 m
1 GHz	30 cm
3 GHz	10 cm
10 GHz	3 cm

Properties of Waves

Phase and Amplitude

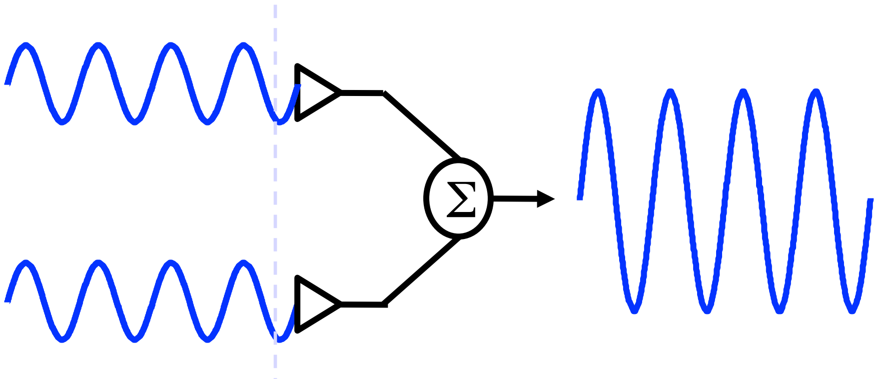


$A \sin(\theta)$

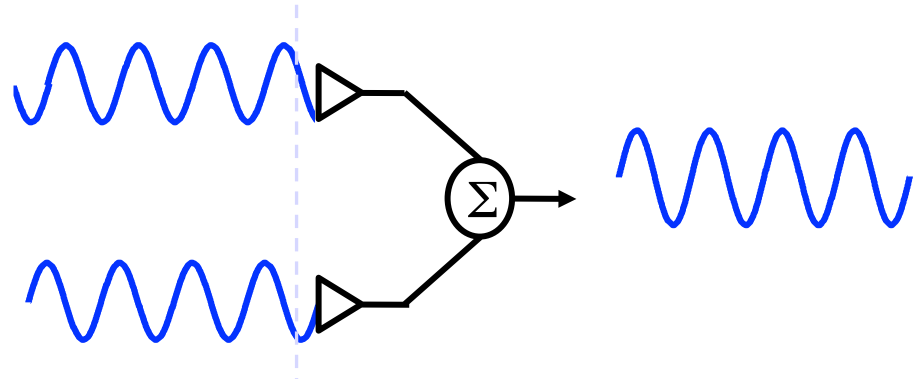
$A \sin(\theta - 90^o)$

Properties of Waves

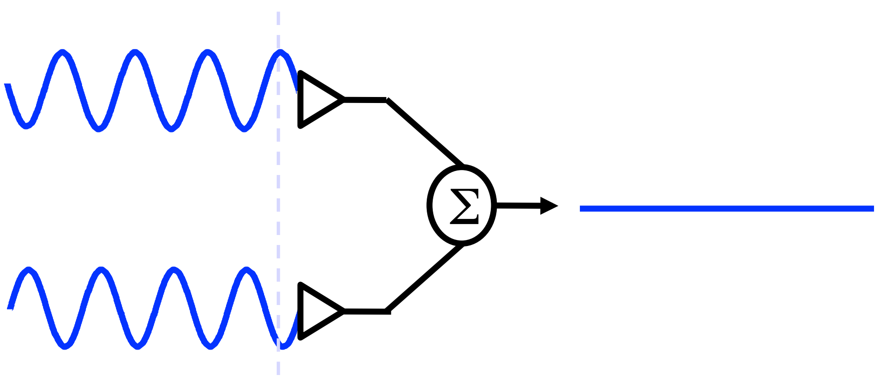
Constructive vs. Destructive Addition



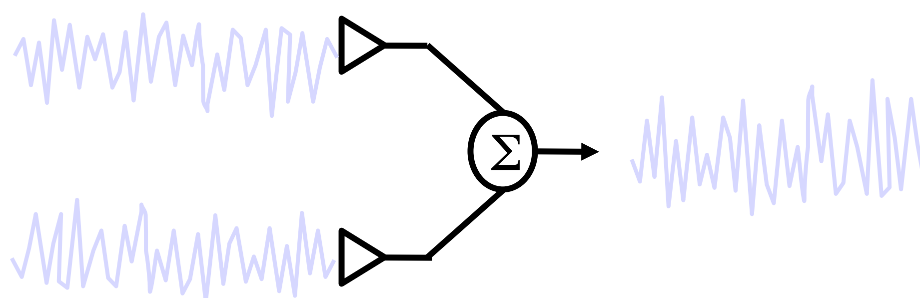
Constructive
(in phase)



Partially Constructive
(somewhat out of phase)



Destructive
(180° out of phase)



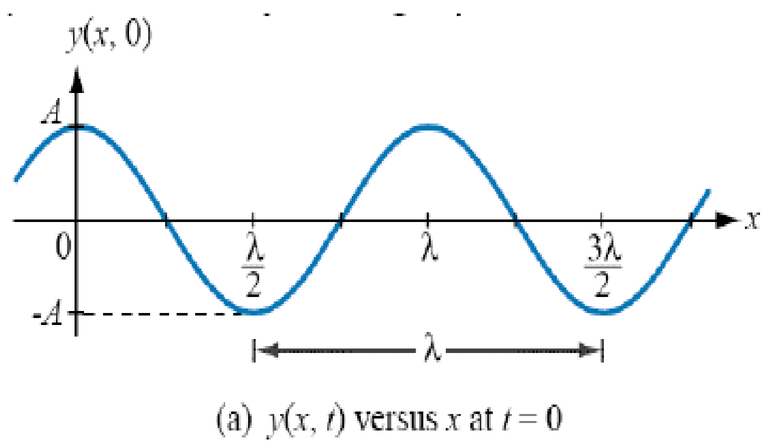
Non-coherent signals
(noise)

Radio Waves

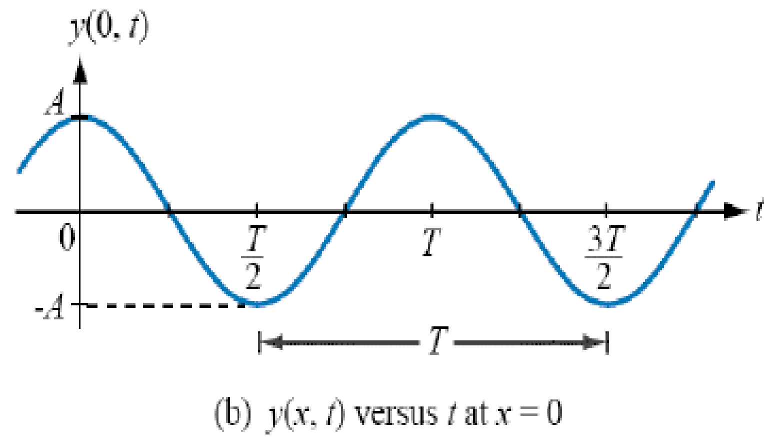
$$y(x, t) = A\cos(\omega t - kx + \phi_o)$$

Angular Frequency
$\omega = 2\pi f = 2\pi/T$

Wavenumber
$k = 2\pi/\lambda$



(a) y(x, t) versus x at t = 0



(b) y(x, t) versus t at x = 0

Wave phase velocity
$c = f\lambda = \omega/k = 3\text{x}10^8\ m/s$

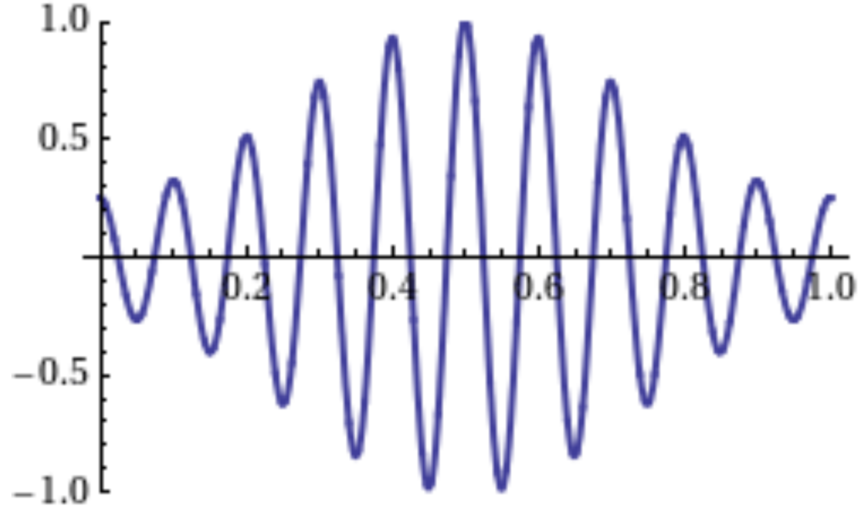
$$\textbf{Frequency (1/s)} = \frac{\textbf{Speed of light (m/s)}}{\textbf{Wavelength l (m)}}$$

Phase Velocity, Group Velocity, Index of Refraction

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

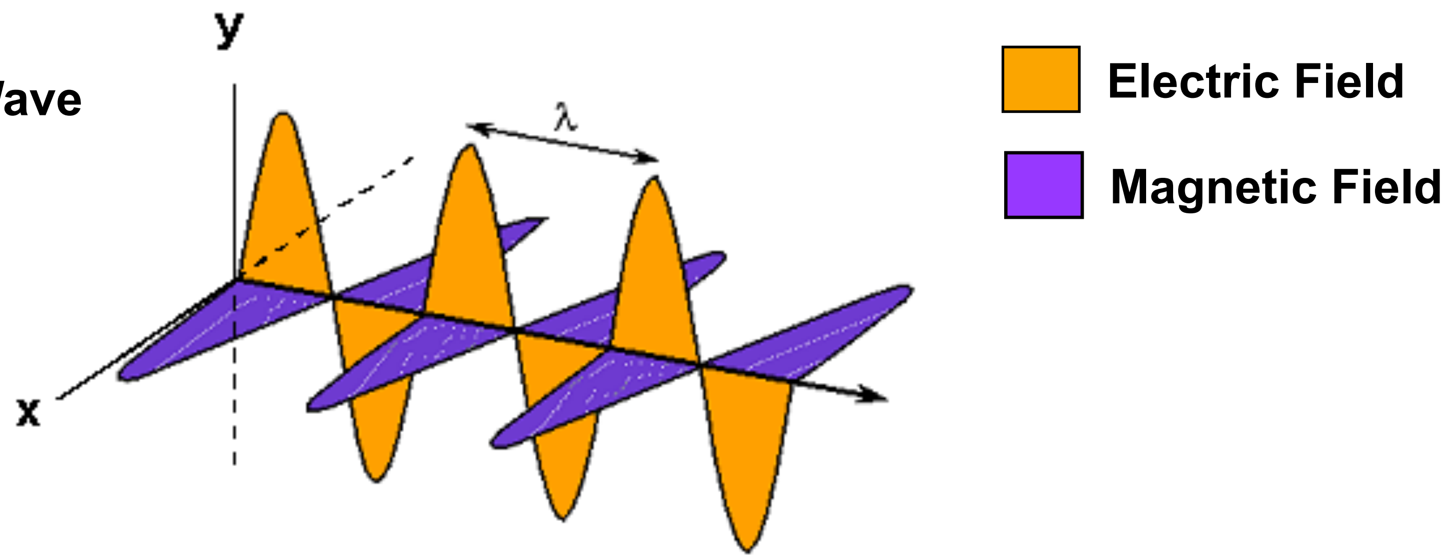
$$v_g \equiv \frac{\partial \omega}{\partial k}$$

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

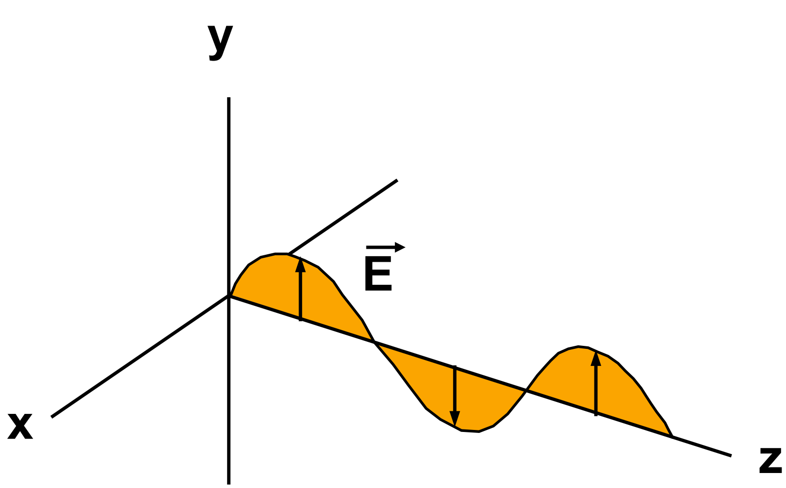


Polarization

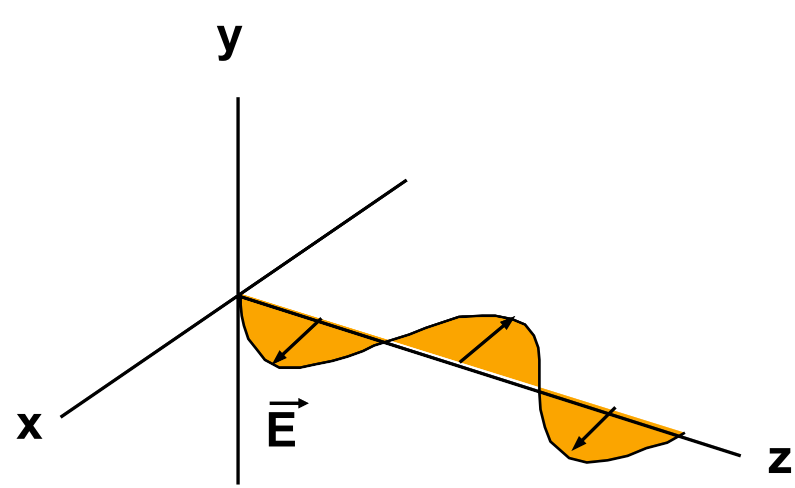
Electromagnetic Wave



Vertical Polarization

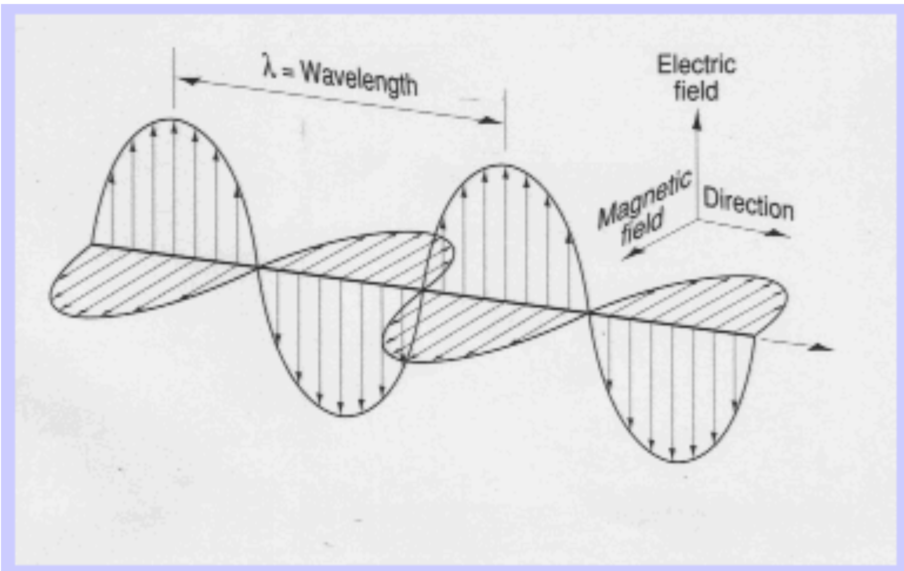


Horizontal Polarization

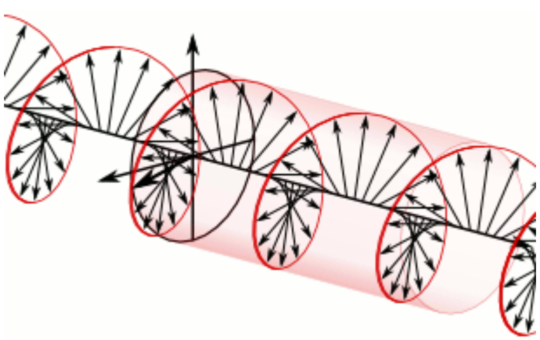


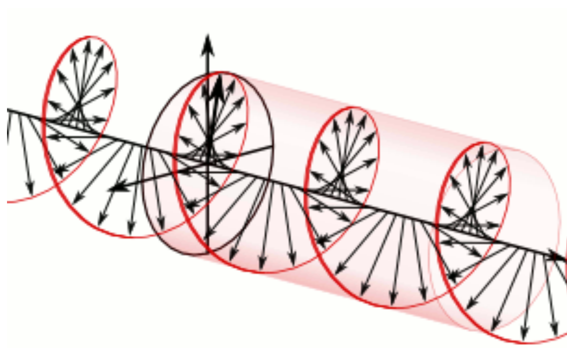
TEM Waves: *Transverse electromagnetic (TEM) modes*

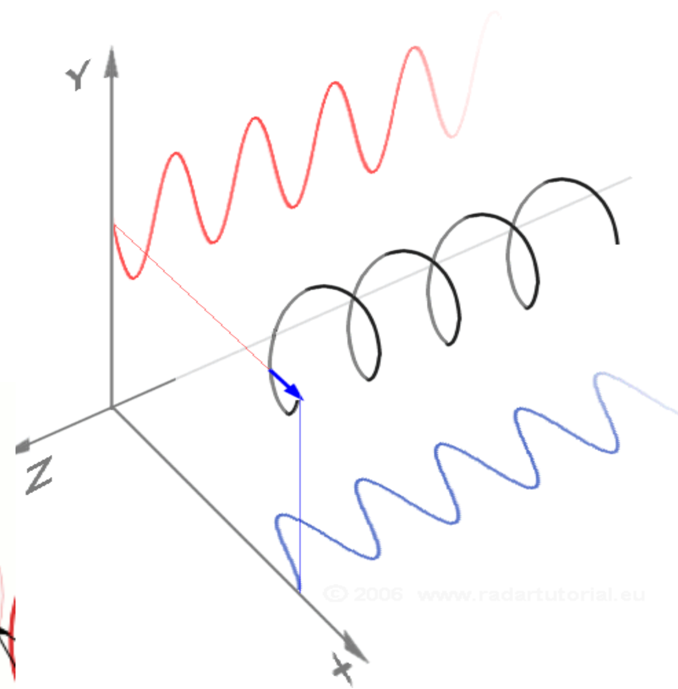
neither electric nor magnetic field in the direction of propagation



Electromagnetic waves in free space propagate in TEM mode







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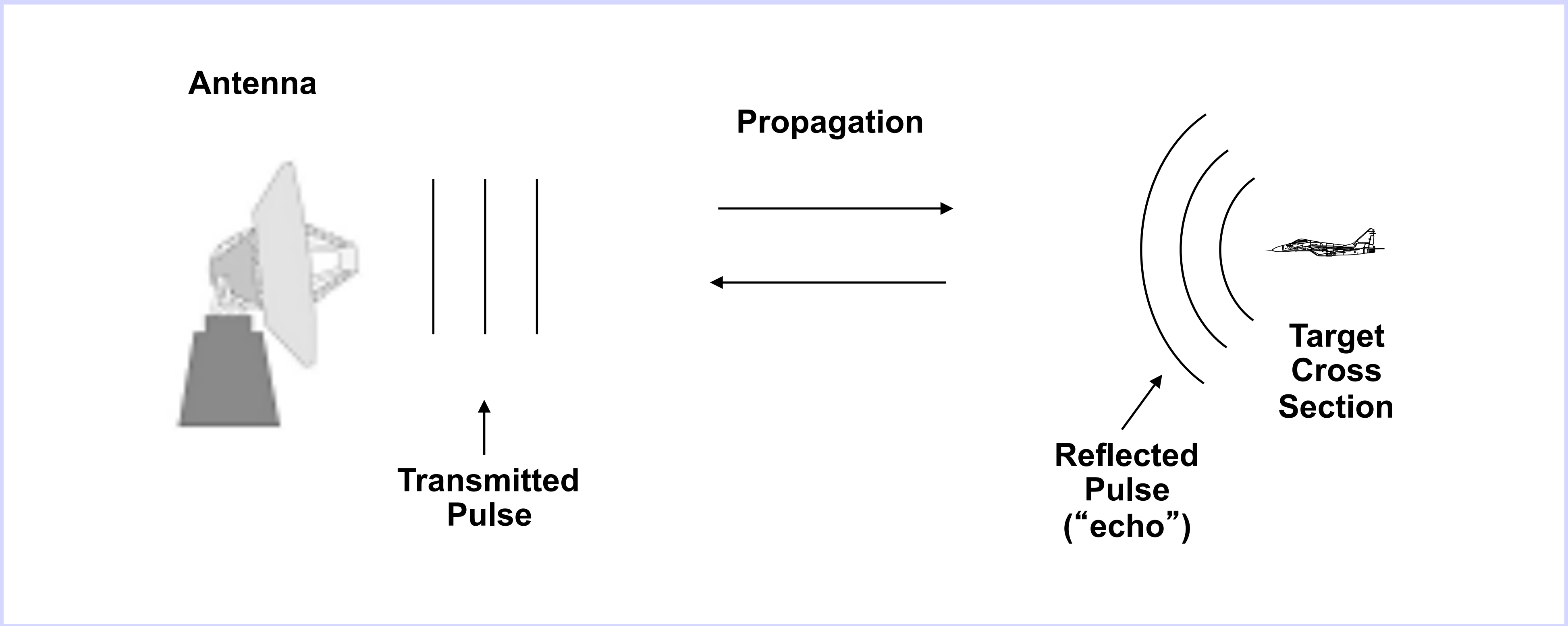
RADAR

RAdio Detection And Ranging

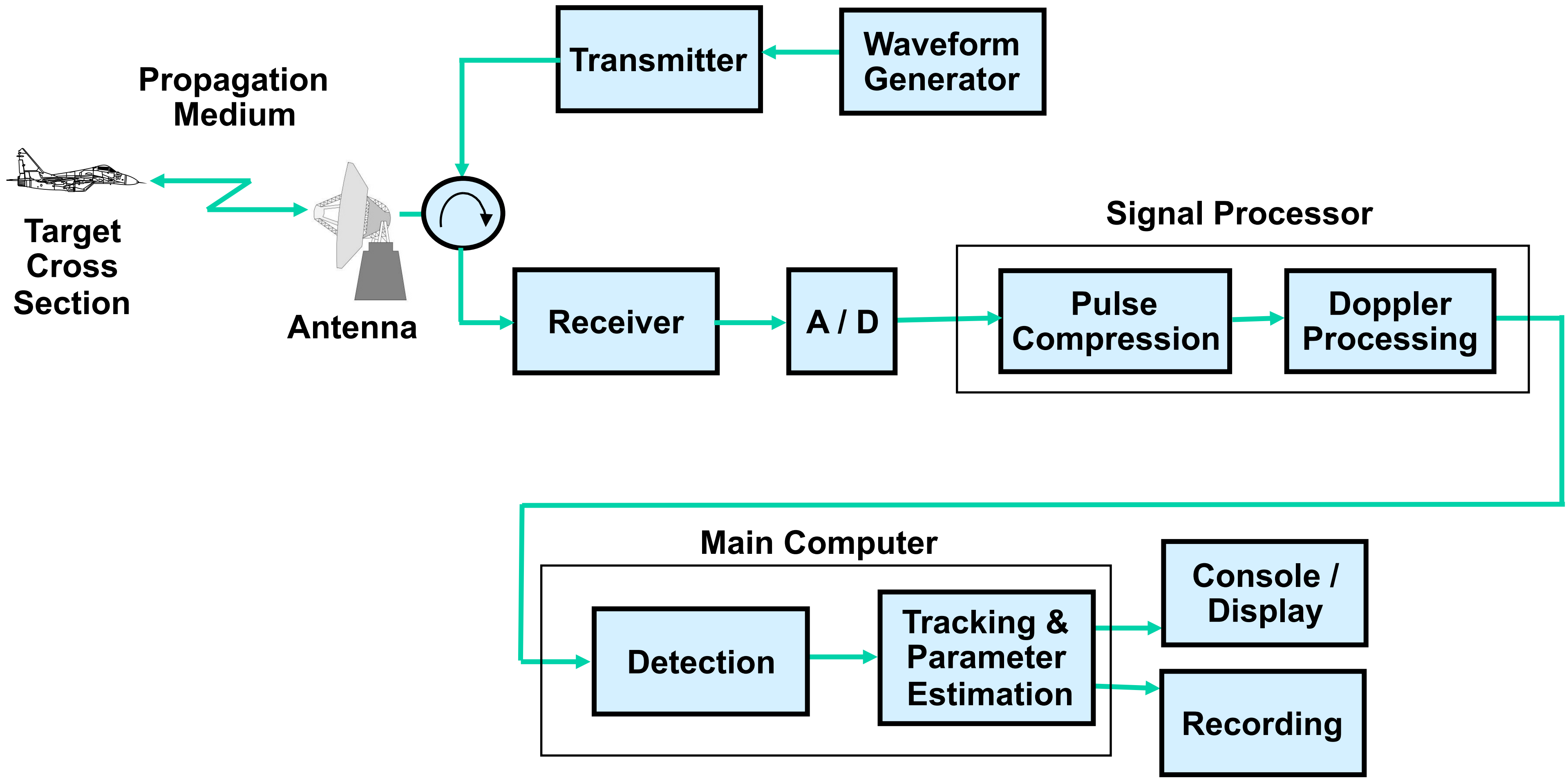


Radar observables:

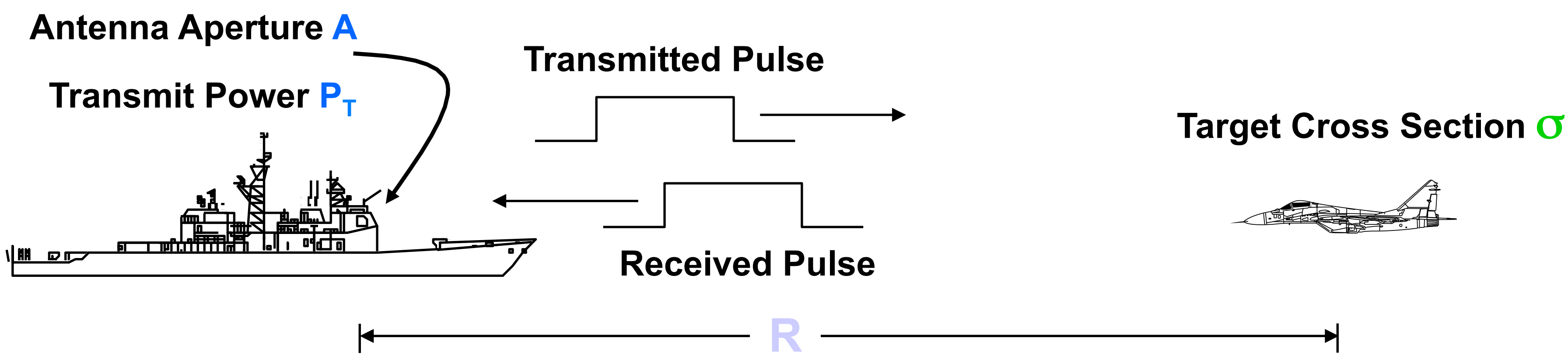
- Target range
- Target angles (azimuth & elevation)
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)

Demonstrate radar

Radar Block Diagram



Radar Range Equation

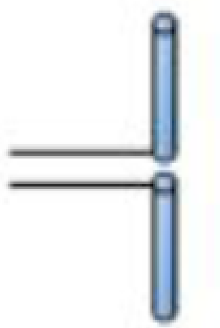


	Transmit Power	Transmit Gain	Spread Factor	Losses	Target RCS	Spread Factor	Receive Aperture	Dwell Time
Received Signal Energy =	$[P_T]$	$\left[\frac{4\pi A}{\lambda^2}\right]$	$\left[\frac{1}{4\pi R^2}\right]$	$\left[\frac{1}{L}\right]$	$[\sigma]$	$\left[\frac{1}{4\pi R^2}\right]$	$[A]$	$[\tau]$

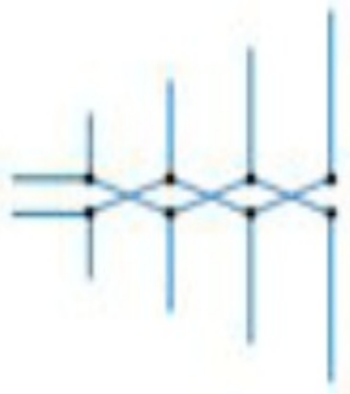
$$\text{Received Signal Energy} = [P_T]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L}\right][\sigma]\left[\frac{1}{4\pi R^2}\right][A][\tau]$$

Antennas

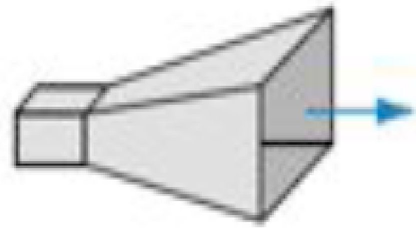
Most basic form of antennas – a wire element with a time varying current flowing in it



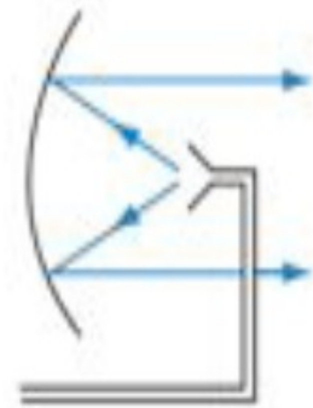
Dipole antenna



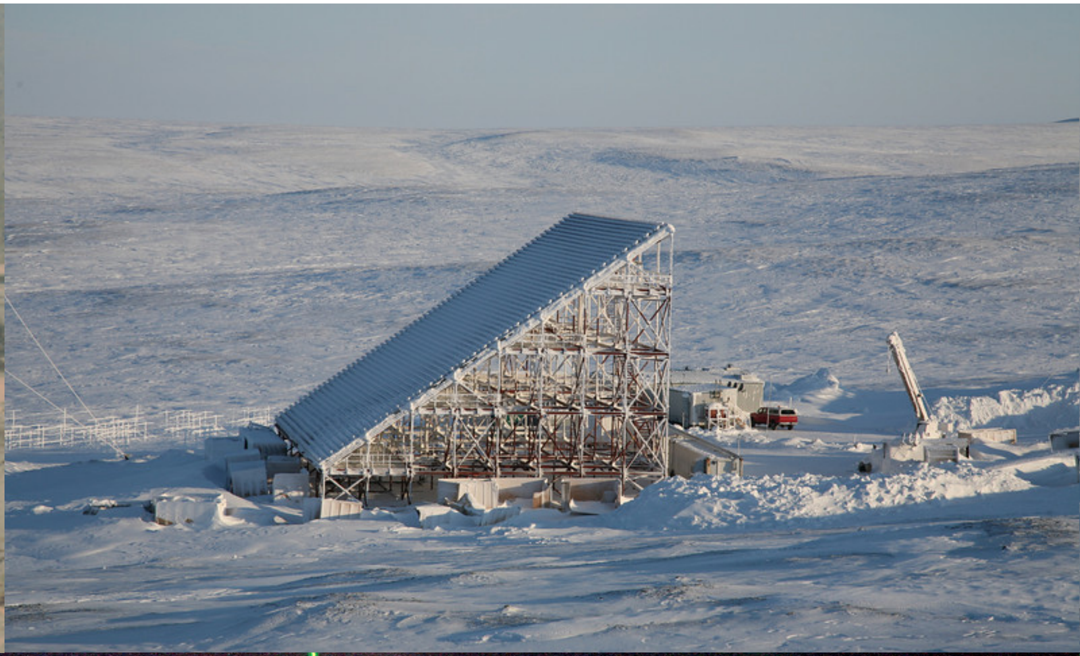
Log Periodic



Horn antenna

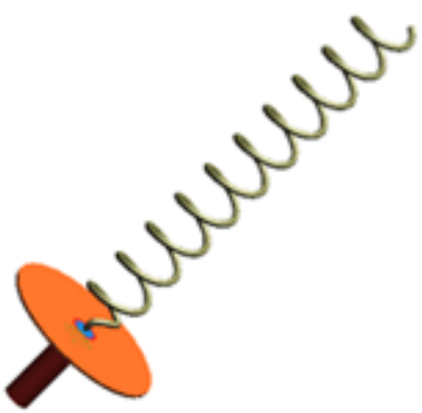


Parabolic dish Reflector antenna

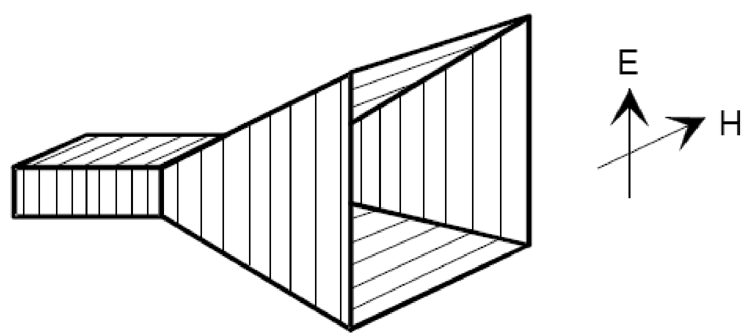


Antennas

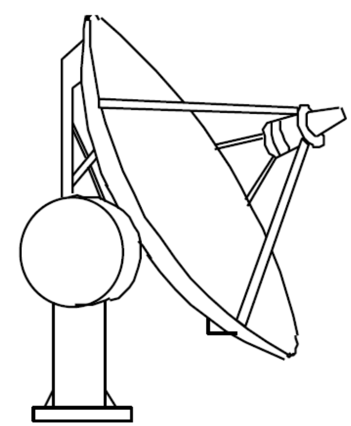
- Four primary functions of an antenna for radar applications
  - Impedance transformation (free-space intrinsic impedance to transmission-line characteristic impedance)
  - Propagation-mode adapter (free-space fields to guided waves)
  - Spatial filter (radiation pattern – direction-dependent sensitivity)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

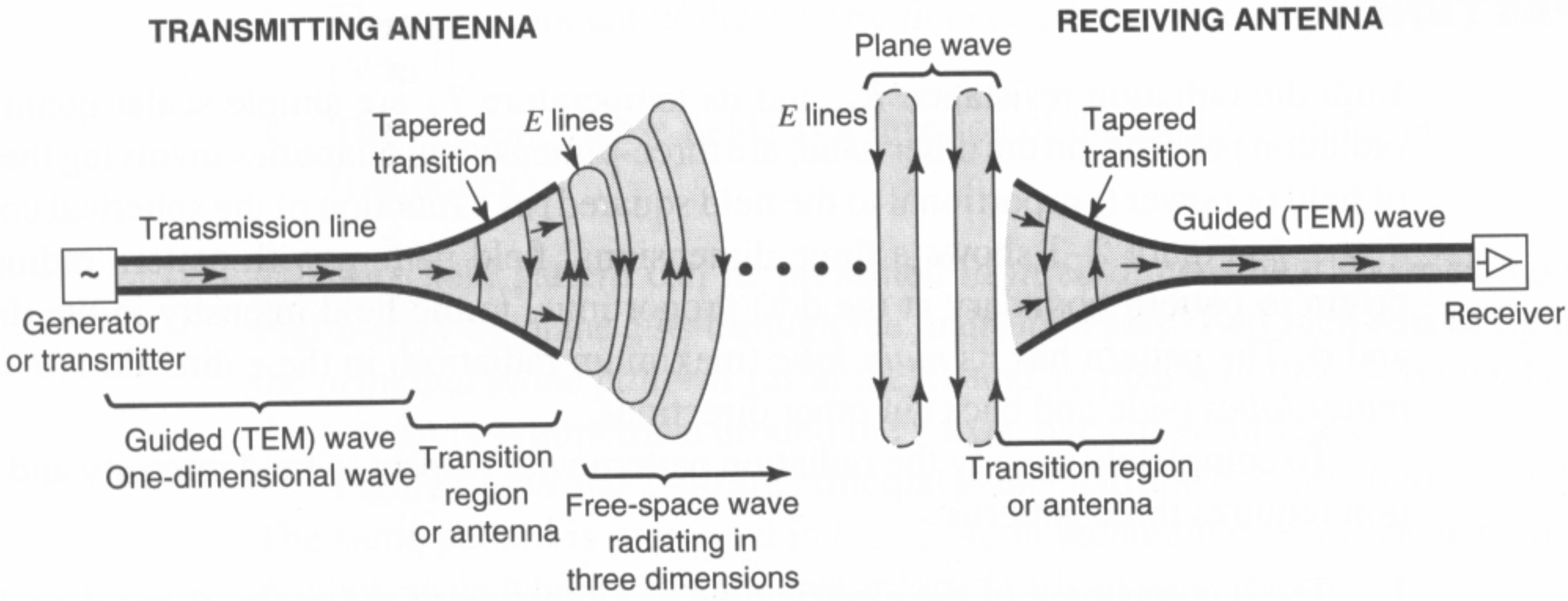
$$\eta_0 = \sqrt{\mu_0/\varepsilon_0} = 120\,\pi \cong 376.7\,\Omega$$

- 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

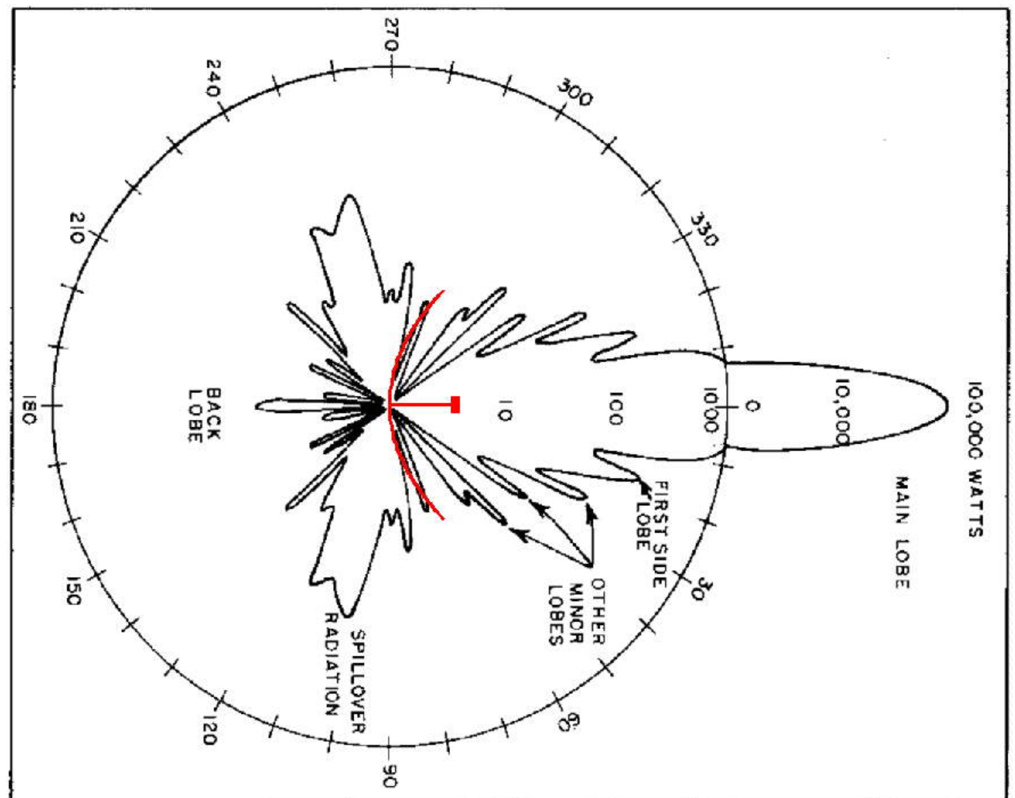
- During both transmission and receive operations the antenna must provide the transition between these two propagation modes.



Spatial filter

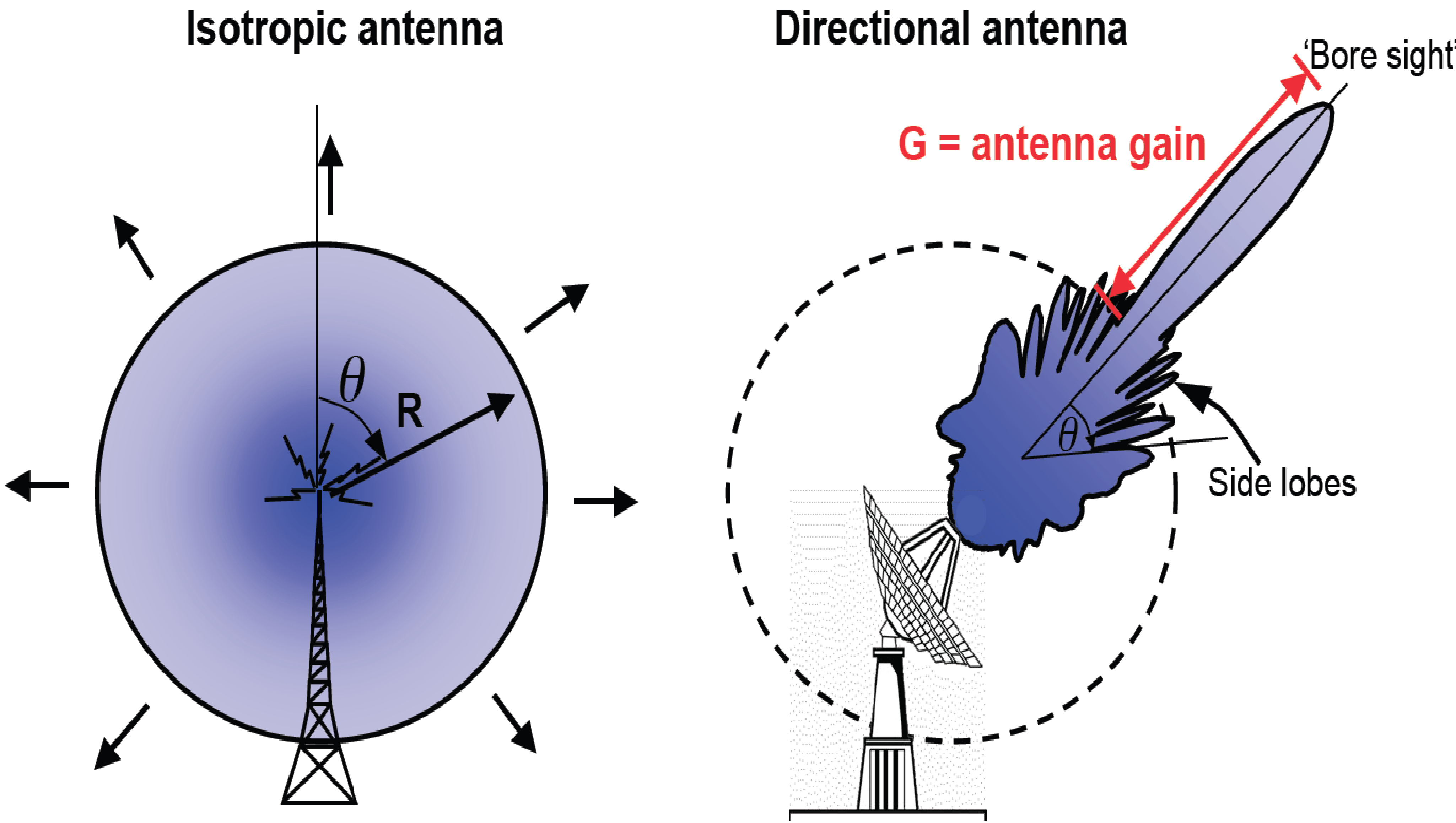
- Antennas have the property of being more sensitive in one direction than in another which provides the ability to spatially filter signals from its environment.

Directive antenna.



Radiation pattern of directive antenna.

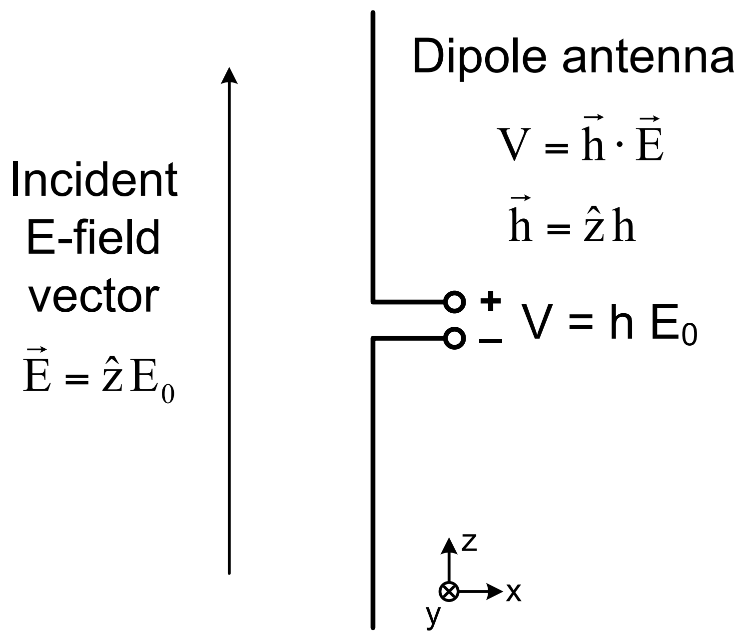
Radiation Pattern – Antenna Gain

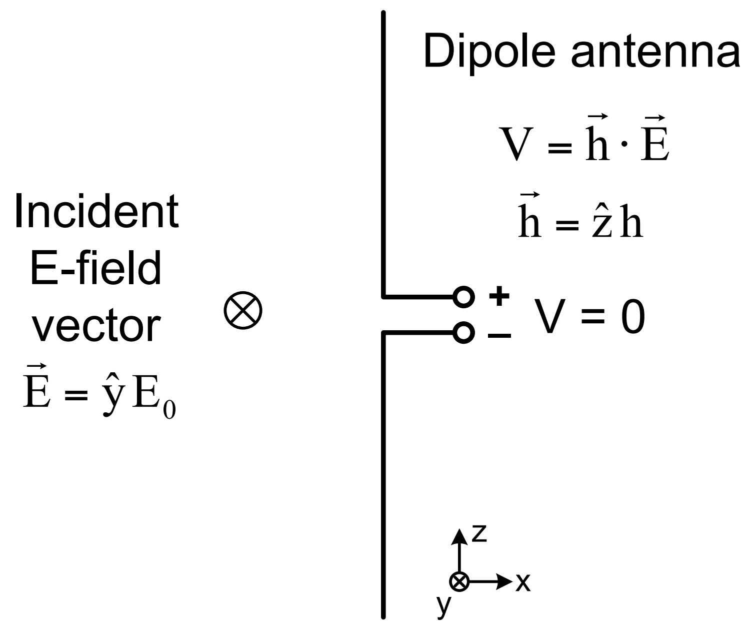


Write equation for Gain on blackboard

Polarization filter

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





In this example, h is the antenna's effective height whose units are expressed in meters.

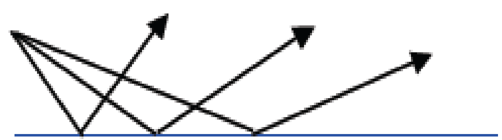
Propagation Medium - Losses

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

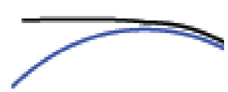
Radio waves are also reflected off of the surface

- **Atmospheric attenuation**

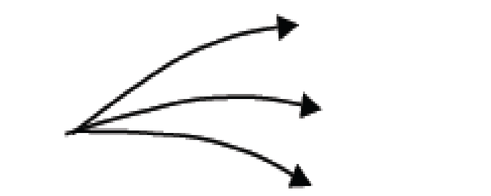
- **Reflection off of earth's surface**



- **Over-the-horizon diffraction**



- **Atmospheric refraction**



Attenuation usually measured in dB

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

Example:

Factor of:	**Scientific Notation**	**dB**
10	10^1	**10**
100	10^2	**20**
1000	10^3	**30**
⋮		
1,000,000	10^6	**60**

Radar equation

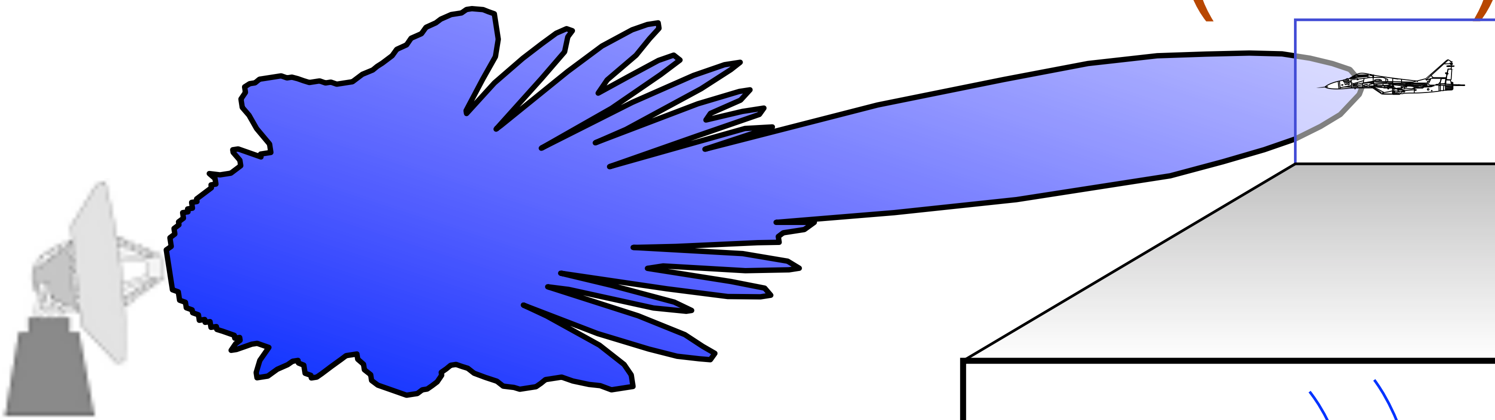
	Transmit Power	Transmit Gain	Spread Factor	Losses	Target RCS	Spread Factor	Receive Aperture	Dwell Time
Received Signal Energy =	$[P_T]$	$\left[\frac{4\pi A}{\lambda^2}\right]$	$\left[\frac{1}{4\pi R^2}\right]$	$\left[\frac{1}{L}\right]$	$[\sigma]$	$\left[\frac{1}{4\pi R^2}\right]$	$[A]$	$[\tau]$

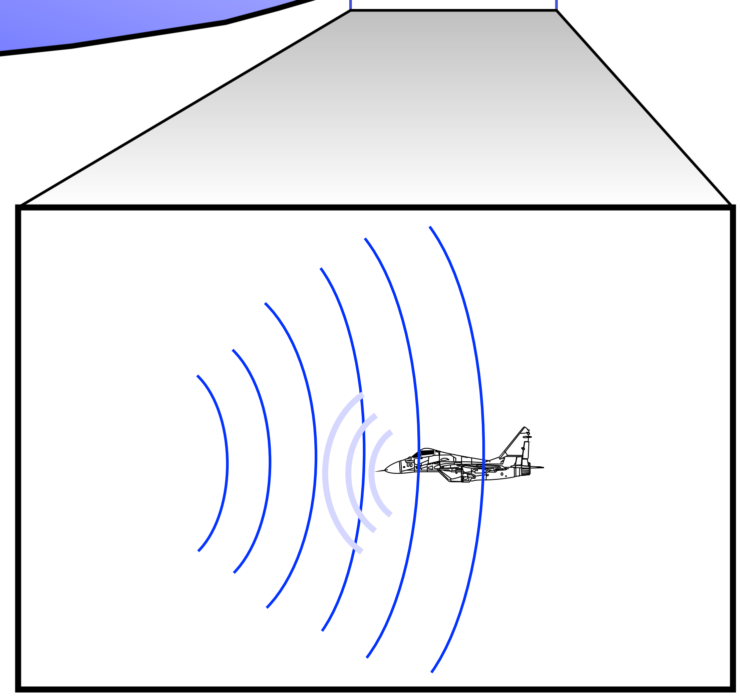
$$\text{Received Signal Energy} = [P_T]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L}\right][\sigma]\left[\frac{1}{4\pi R^2}\right][A][\tau]$$

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)





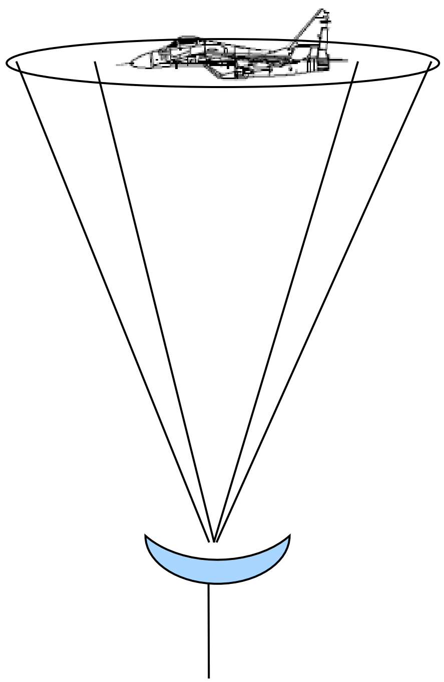
RCS

Incident Power Density (Watts/m²) x σ (m²) = **Reflected Power** (Watts)

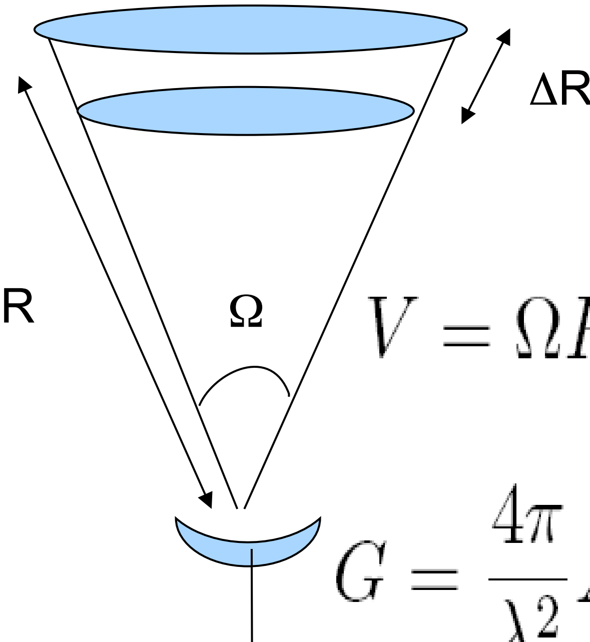
Radar Cross Section (RCS, or s) is the *effective* cross-sectional area of the target as seen by the radar

measured in m², or dBm²

Hard targets vs. Soft targets



vs.



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

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

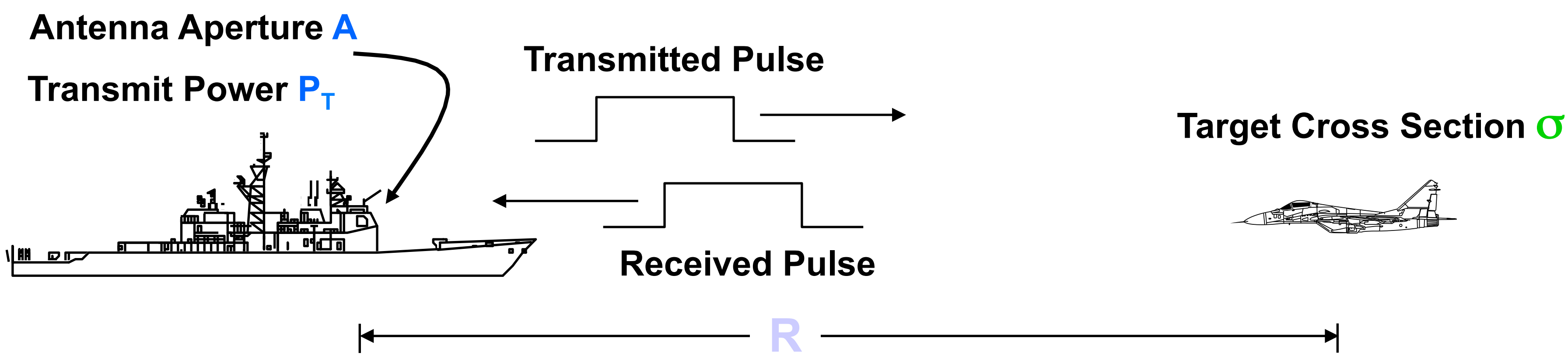
$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

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

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, which is why we are here.

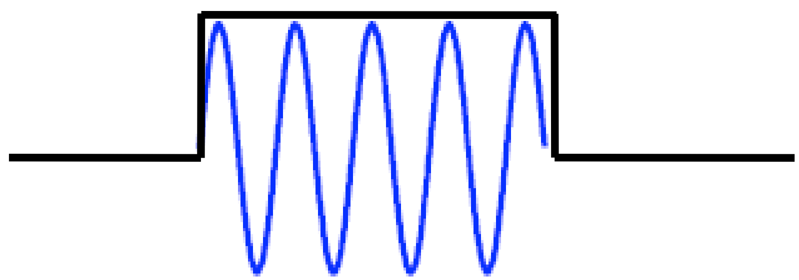
Radar Range Equation



Received Signal Energy	=	Transmit Power	Transmit Gain	Spread Factor	Losses	Target RCS	Spread Factor	Receive Aperture	Dwell Time

$$\text{Received Signal Energy} = \left[P_T \right] \left[\frac{4\pi A}{\lambda^2} \right] \left[\frac{1}{4\pi R^2} \right] \left[\frac{1}{L} \right] \left[\sigma \right] \left[\frac{1}{4\pi R^2} \right] \left[A \right] \left[\tau \right]$$

What the radar transmits: Pulses and waves

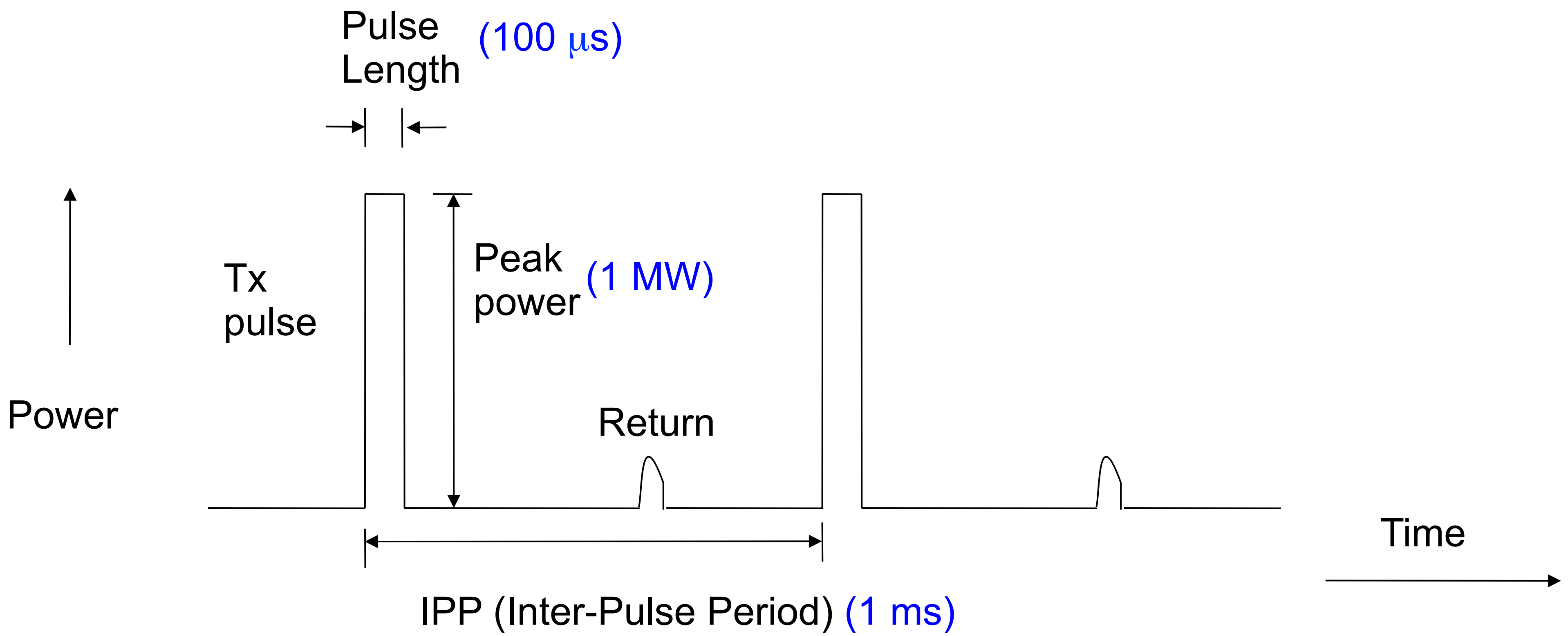


Cycles in a pulse.

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)

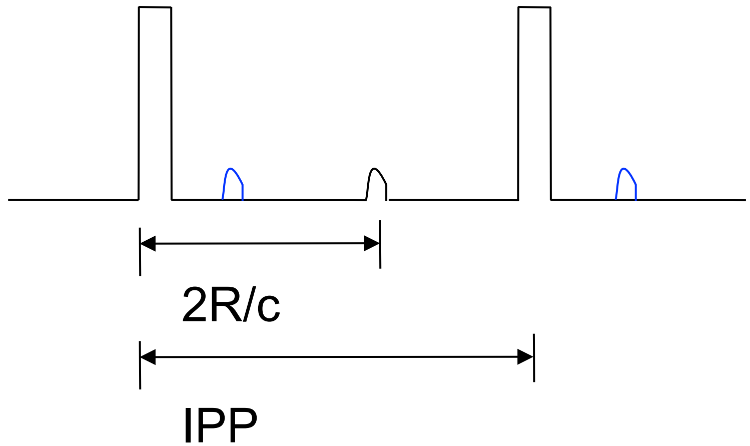
Duty cycle for a CW (continuous wave) radar 100%

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

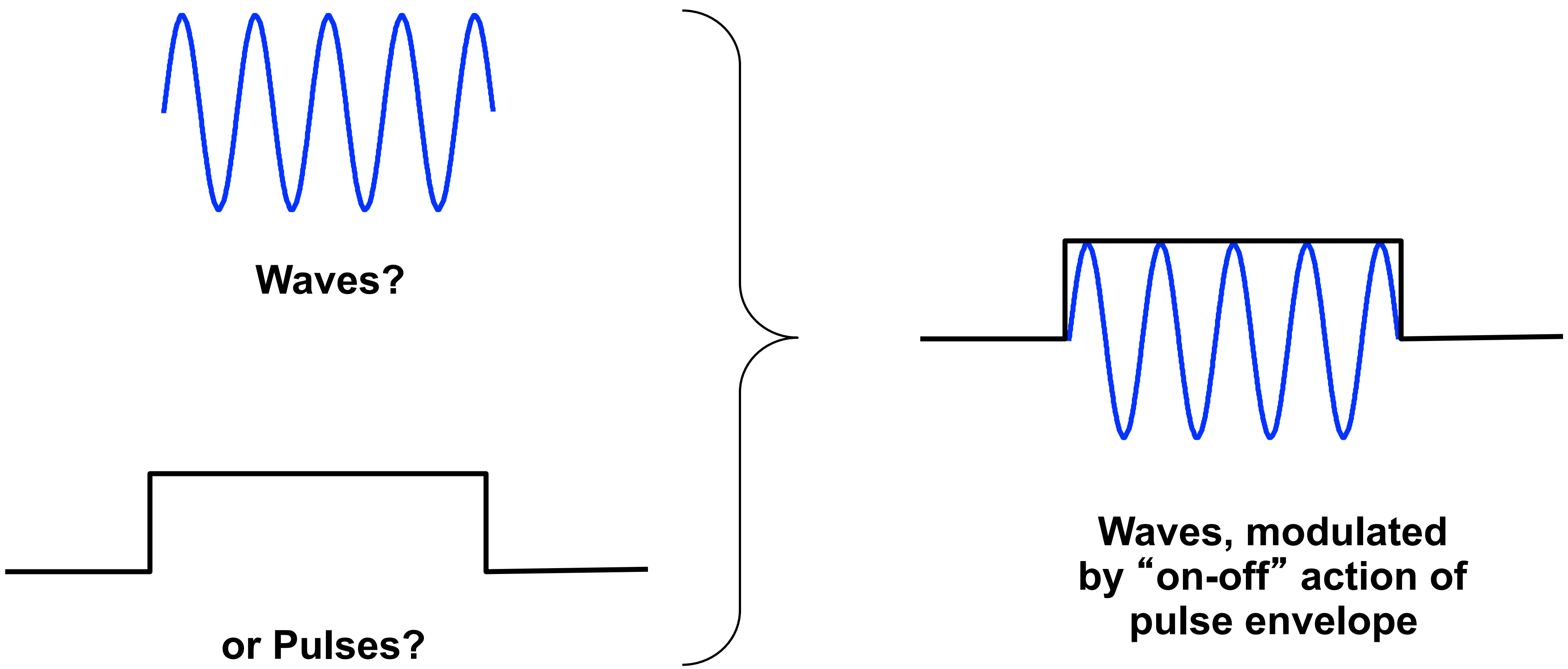
Pulse duration vs. Range resolution

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?

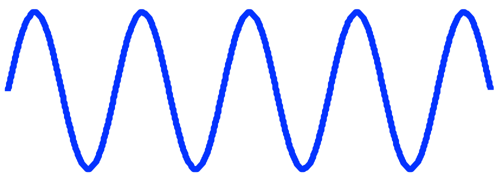
Radar Waveforms

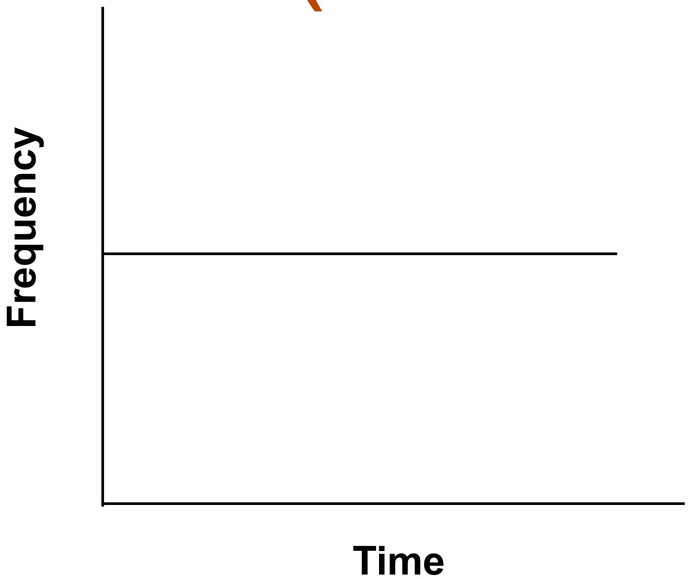
What do radars transmit?



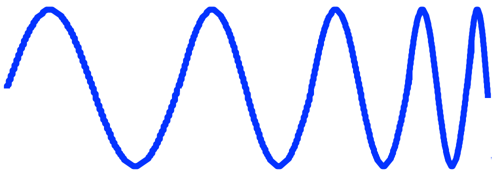
Radar Waveforms (cont' d.)

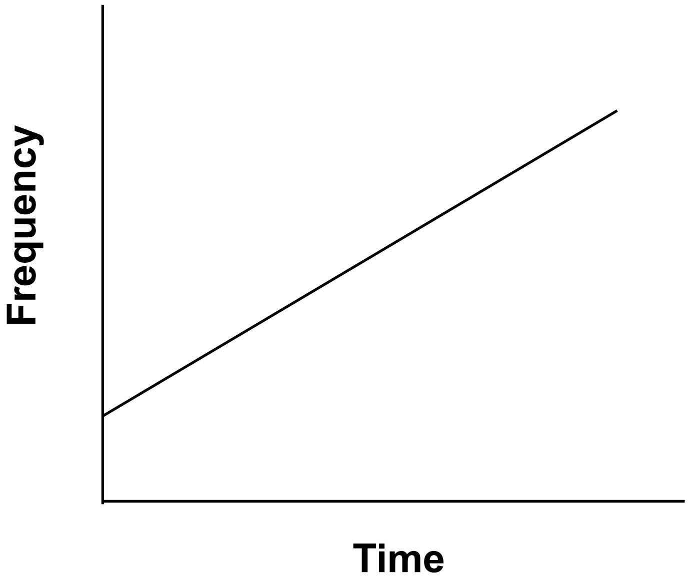
Pulse at single frequency





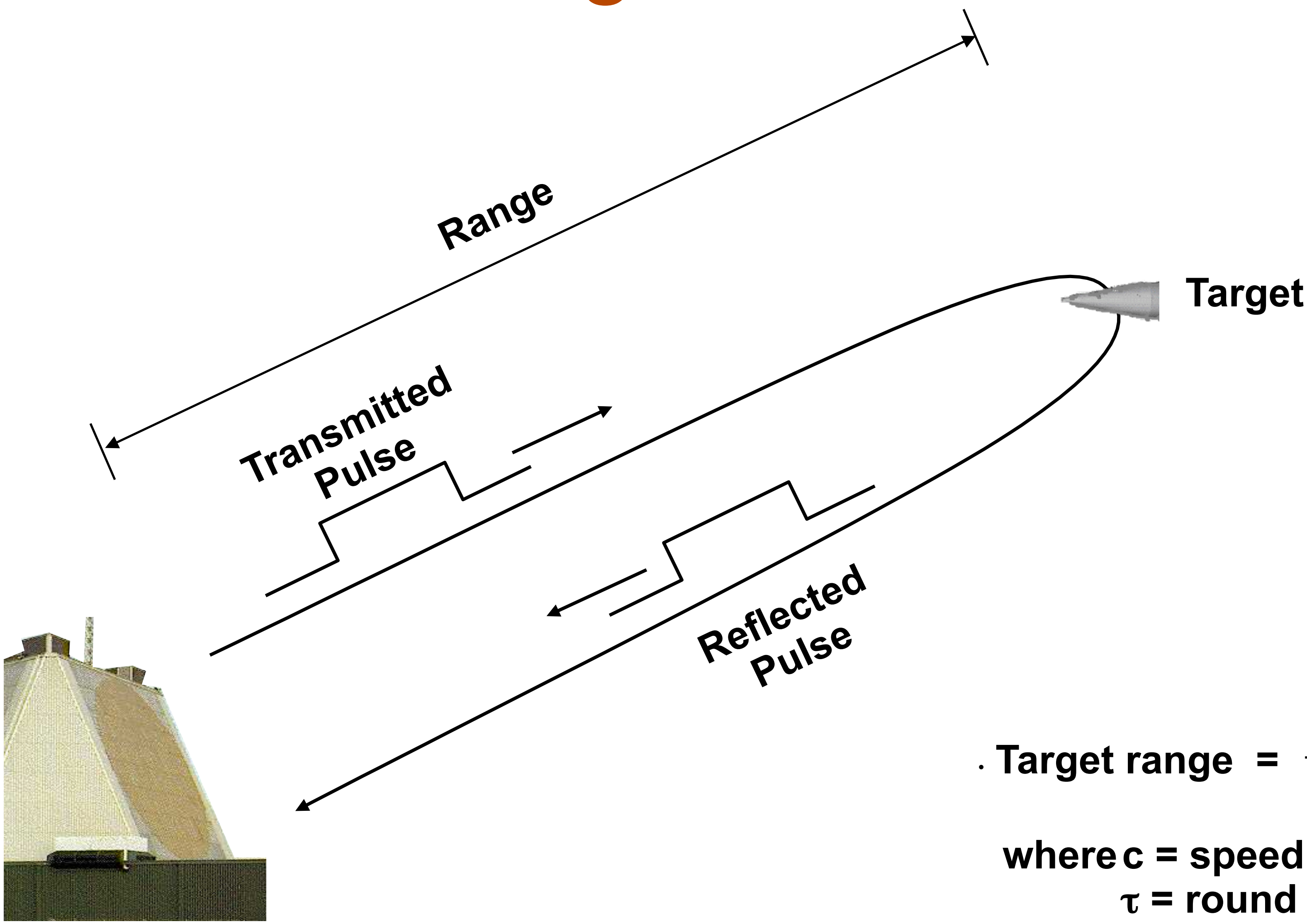
Pulse with changing frequency





Linear Frequency-Modulated (LFM) Waveform

Radar Range Measurement



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

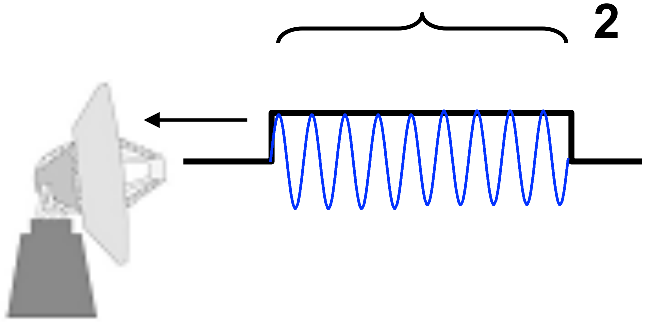
where c = speed of light
τ = round trip time

Signal Processing

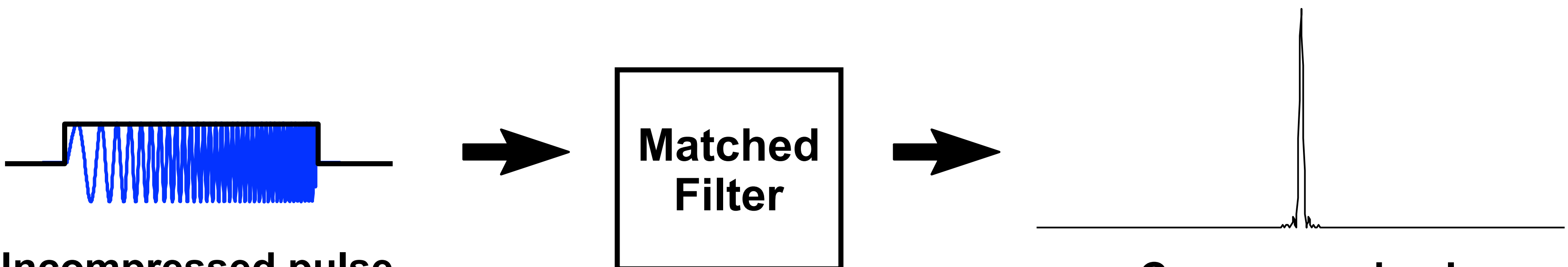
Pulse Compression

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

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

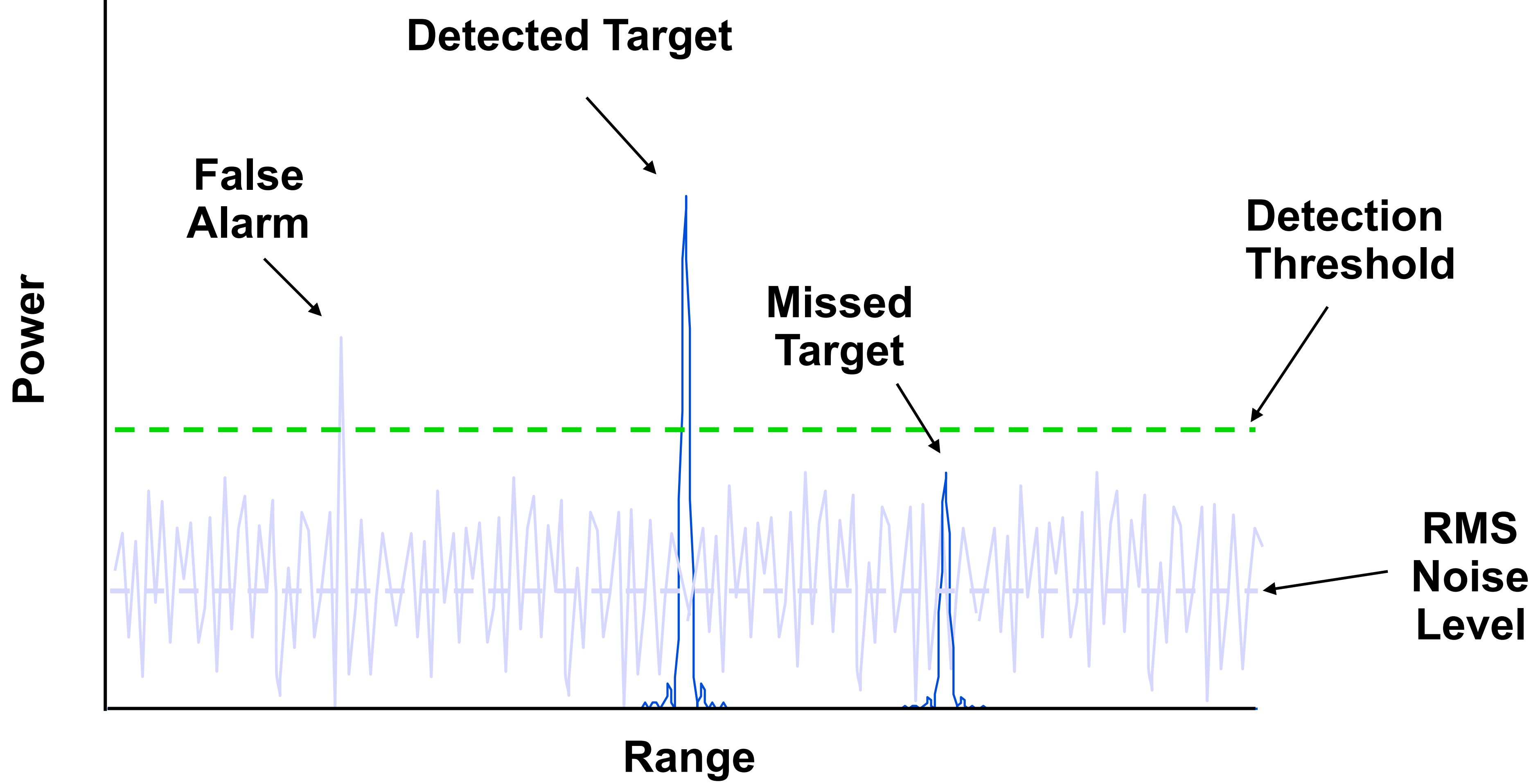


Solution: Use pulse with changing frequency and signal process using “matched filter”

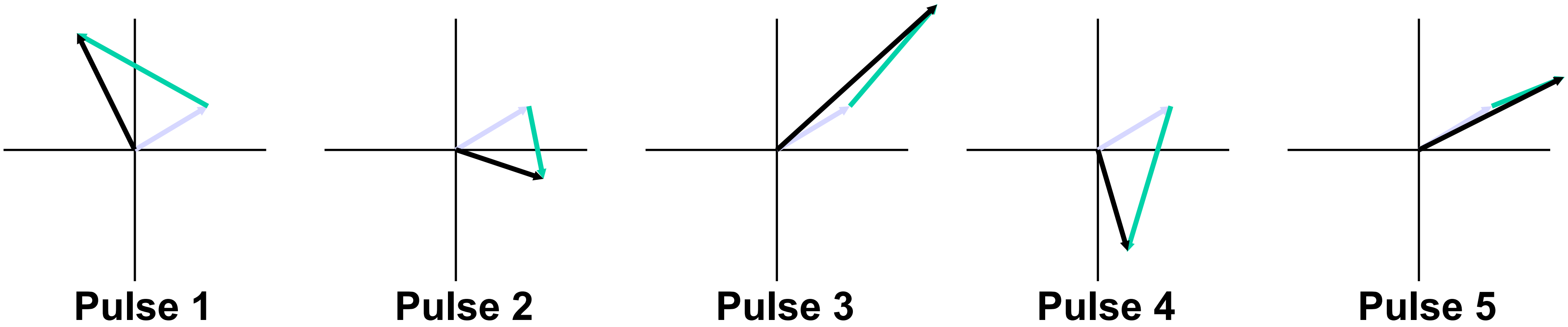


Uncompressed pulse **Compressed pulse**

Detection of Signals in Noise

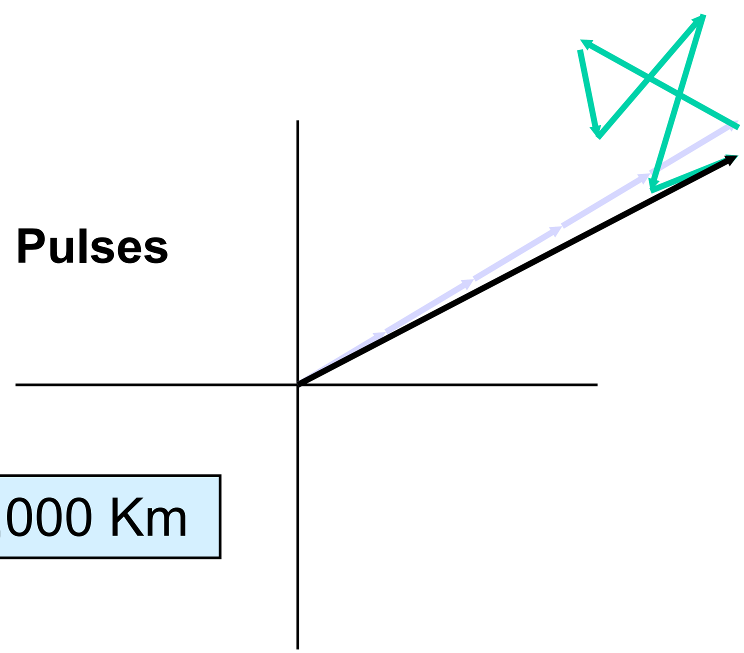


Coherent Integration



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

Coherently Integrated Pulses

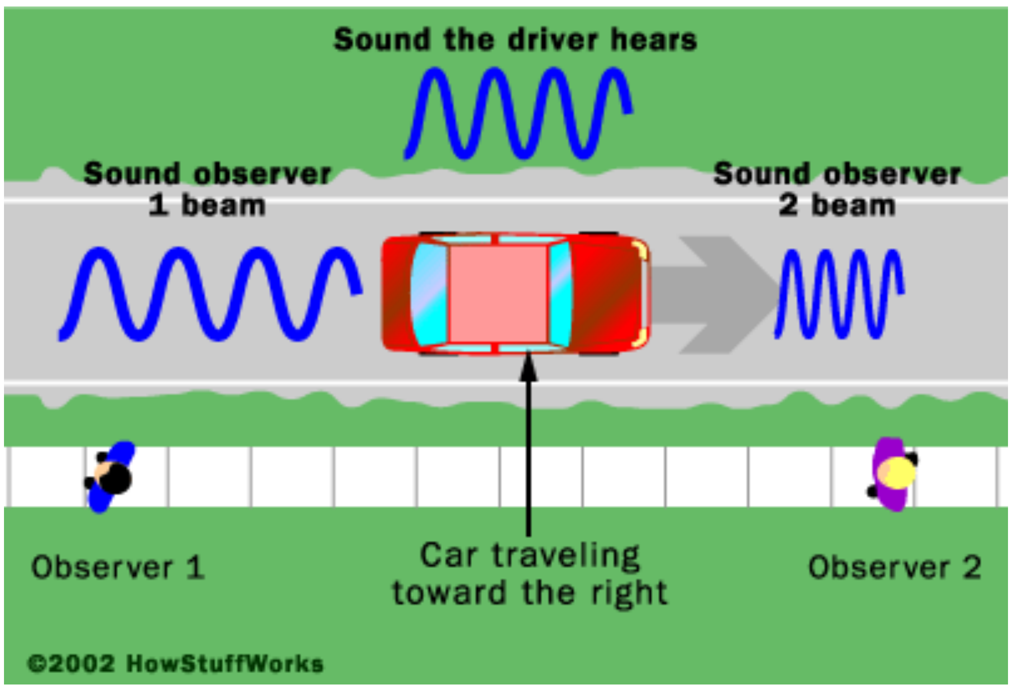


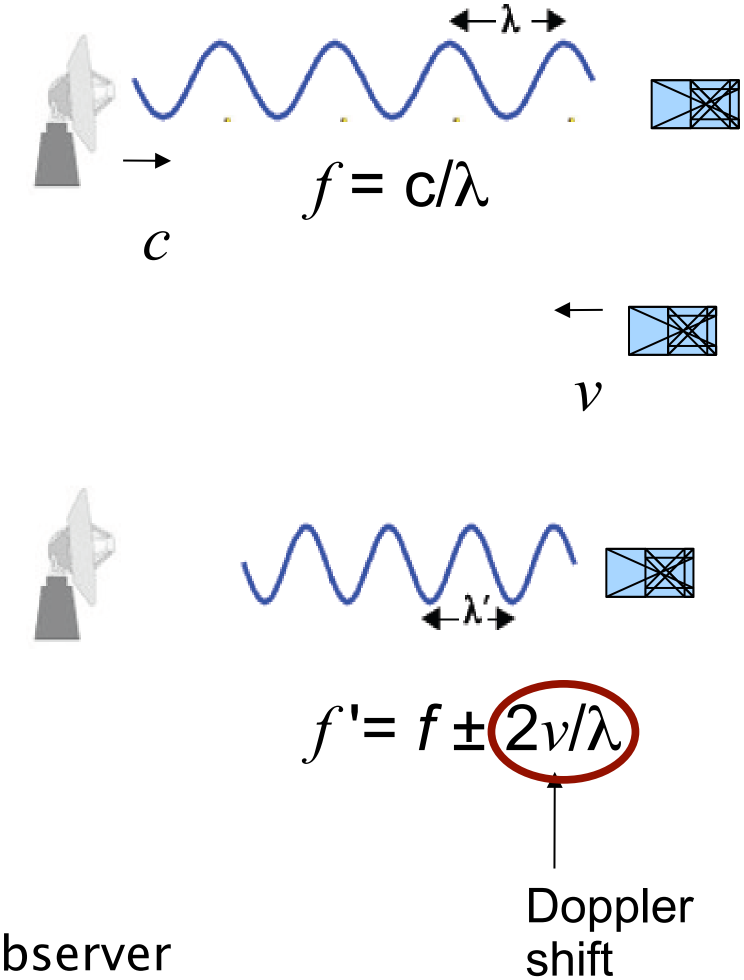
Deep space targets at 30,000 – 40,000 Km

Outline - Radar Basics

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

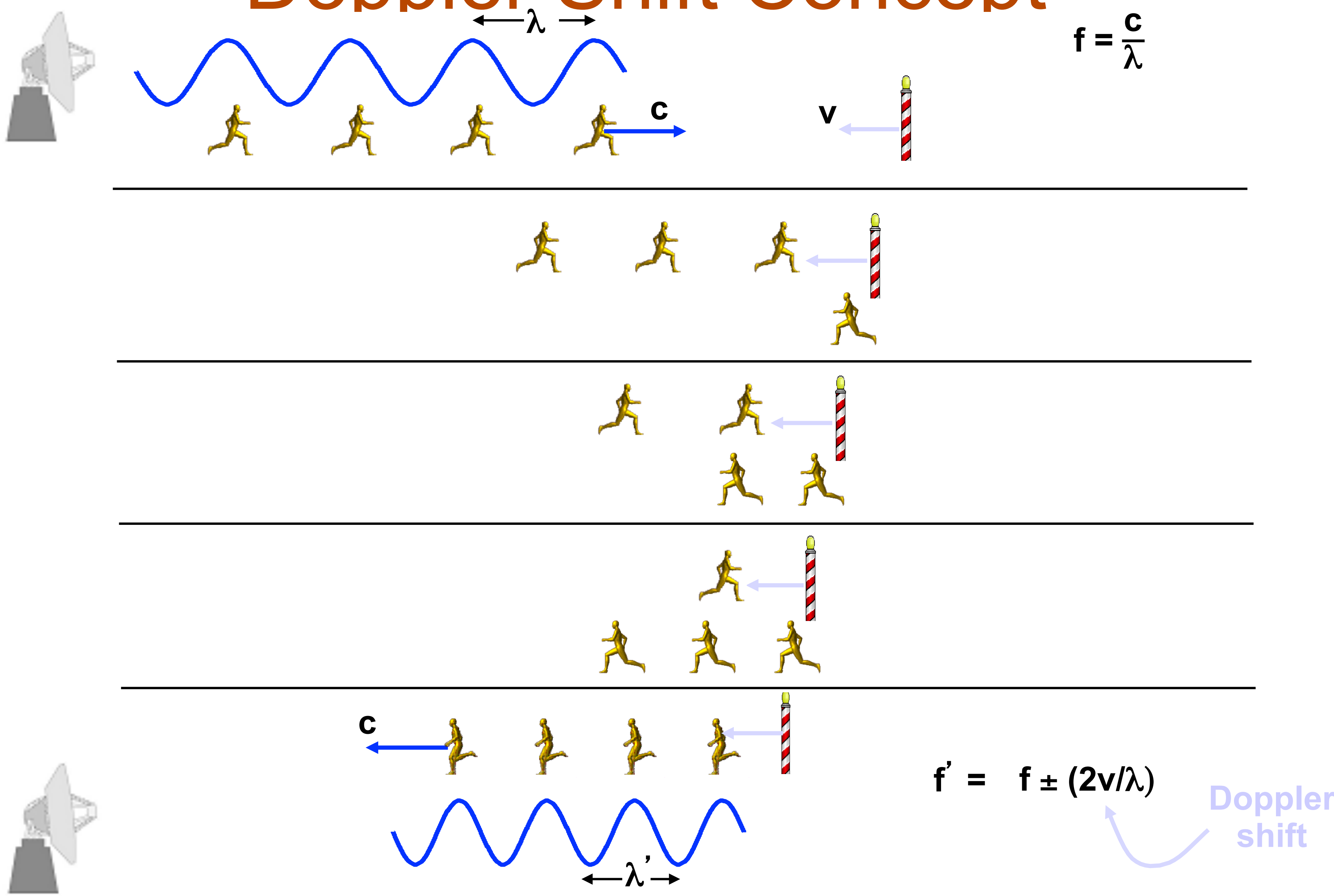
Moving target - Doppler





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

Doppler Shift Concept



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

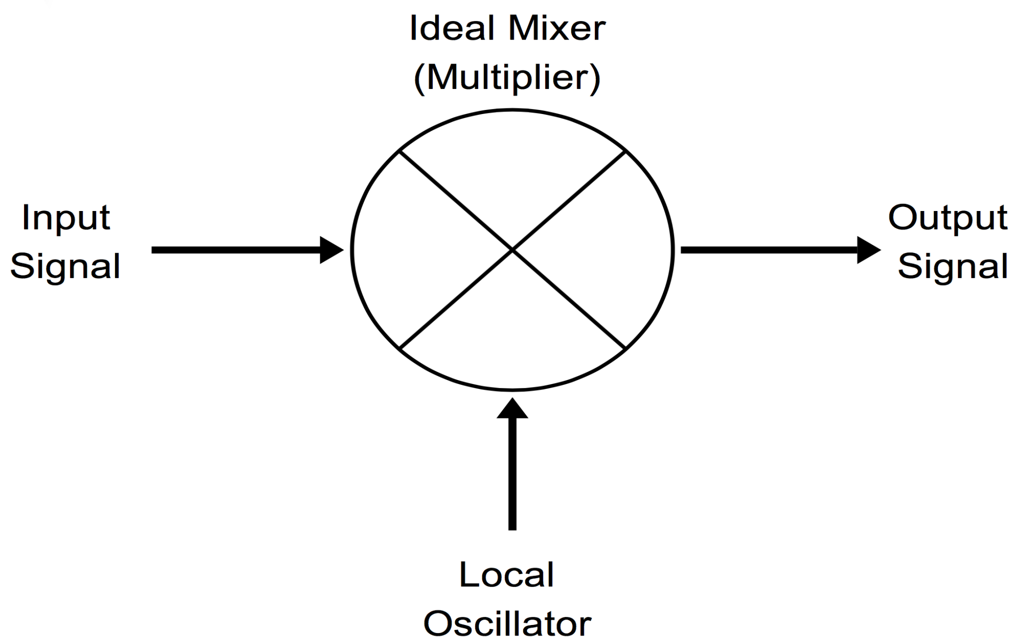
Doppler frequency:
$-2f_o v_o/c = -2v_o/\lambda_o$

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 -> $\cos(2\pi f_D t)$

Mixing to Baseband



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

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

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

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

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 -> $\cos(2\pi f_D t)$

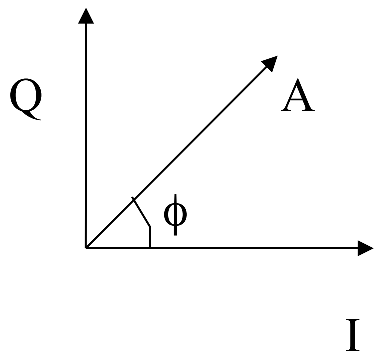
BUT, the sign of f_D is lost (cosine is an even function)

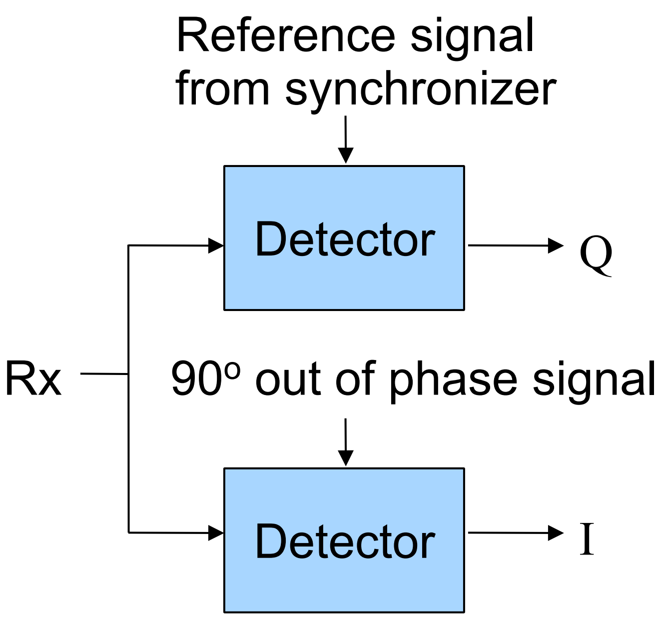
So, instead use
$\exp(j2\pi f_D t) = \cos(2\pi f_D t) + j\sin(2\pi f_D t)$

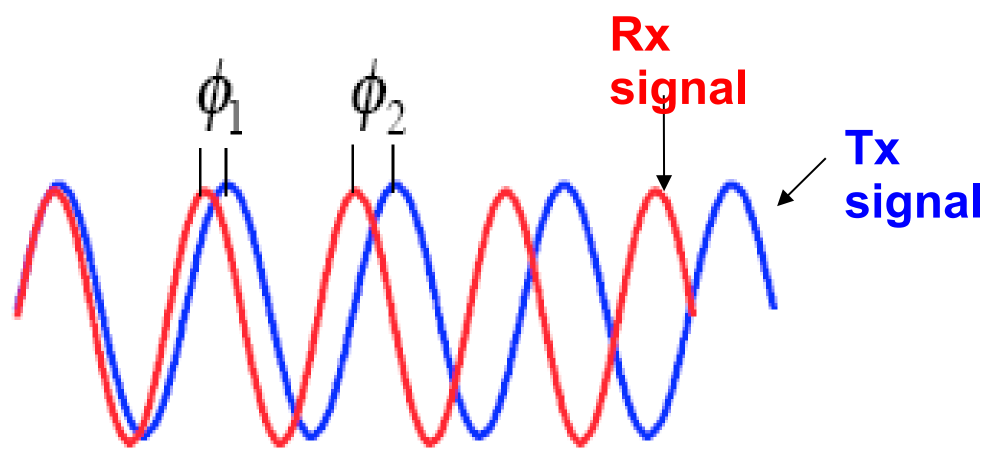
Generate this signal by mixing cos and sin via two oscillators (same frequency, 90° out of phase)

Components are called I (In phase) and Q (Quadrature): $A\exp(j2\pi f_D t) = I + jQ$

I/Q Demodulation

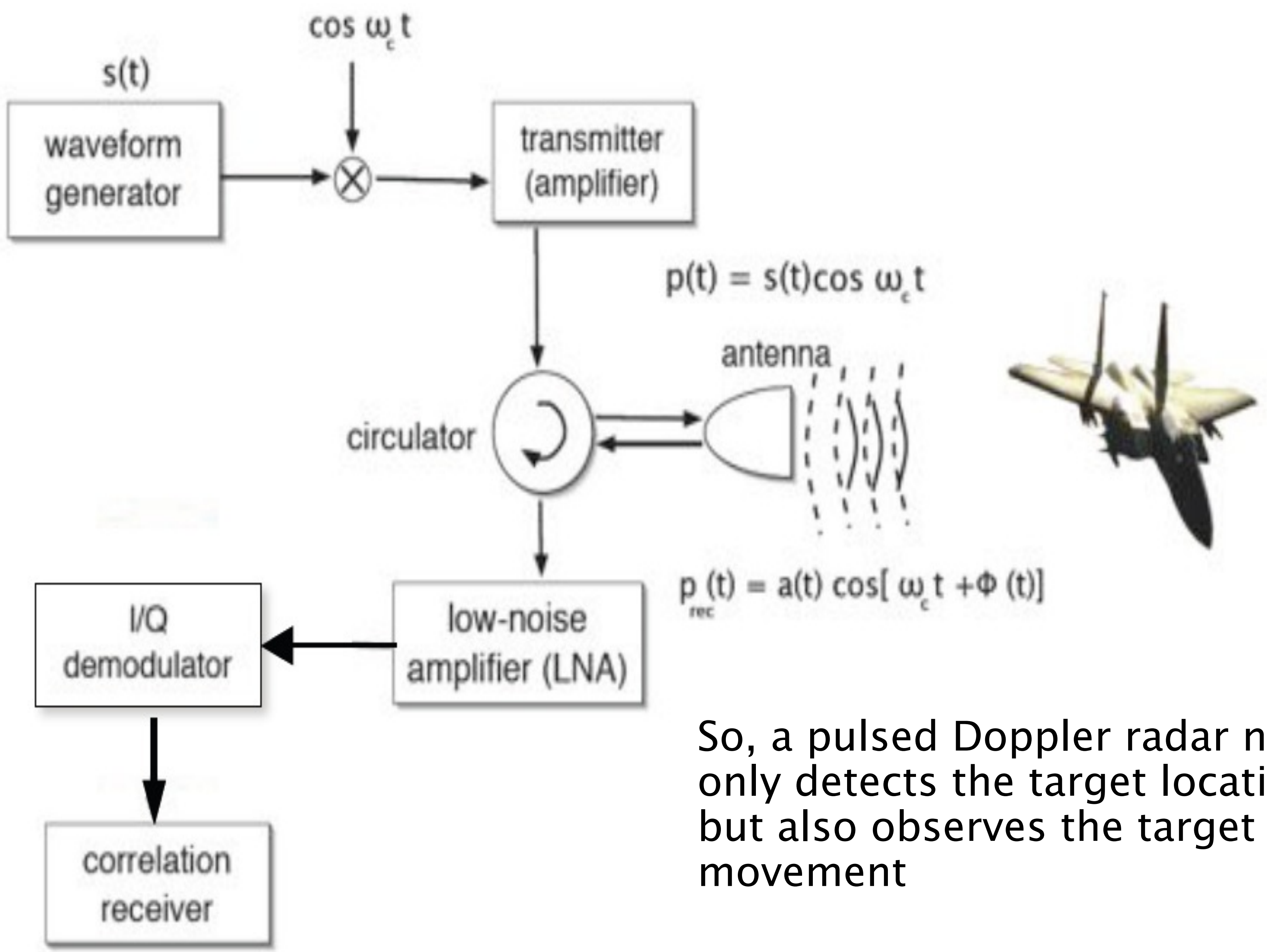






The Doppler frequency shows up as a pulse-to-pulse phase shift

Pulsed Doppler Radar system



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

Determining the Doppler Spectrum

1. Doppler spectrum is measured at a particular range gate (e.g. at $r = \dfrac{c\Delta t}{2}$)

2. Must process a <u>time series of discrete samples</u> of echo $E_r(t)$ at intervals of the pulse period T_r

3. Analyze the sampled signal using (fast) Fourier Transform methods:

$$E(mT_r) = \frac{1}{M}\sum_{m=0}^{M-1} F(kf_0)\cos\left[2\pi k f_0 m T_r\right]$$

M = # of samples
f_0 = frequency resolution

$$F(kf_0) = \sum_{m=0}^{M-1} E_r(mT_r)\cos\left[2\pi k f_0 m T_r\right]$$

4. Frequency components (radial velocities) occur at discrete intervals, with M intervals separated by intervals of $1/MT_r = f_D$

Spectrum analysis (FS)

Fourier series (FS)

The coefficients c(i) contain the time domain information and are evaluated as

$$c(n) = \frac{1}{P}\int_{-P/2}^{P/2} y(t)e^{-j2\pi n f_o t}\,dt$$

P is the period of the wave

The FS is often expressed in trigonometric form as

$$y(t) = a(0)/2 + \sum_{n=1}^{\infty} a(n)\cos(2\pi n f_o t) + b(n)\sin(2\pi n f_o t)$$

$$a(0) = \frac{2}{P}\int_{-P/2}^{P/2} y(t)\,dt$$

$$a(m) = \frac{2}{P}\int_{-P/2}^{P/2} y(t)\cos(2\pi m f_o t)\,dt$$

$$b(m) = \frac{2}{P}\int_{-P/2}^{P/2} y(t)\sin(2\pi m f_o t)\,dt$$

m is any integer greater than zero

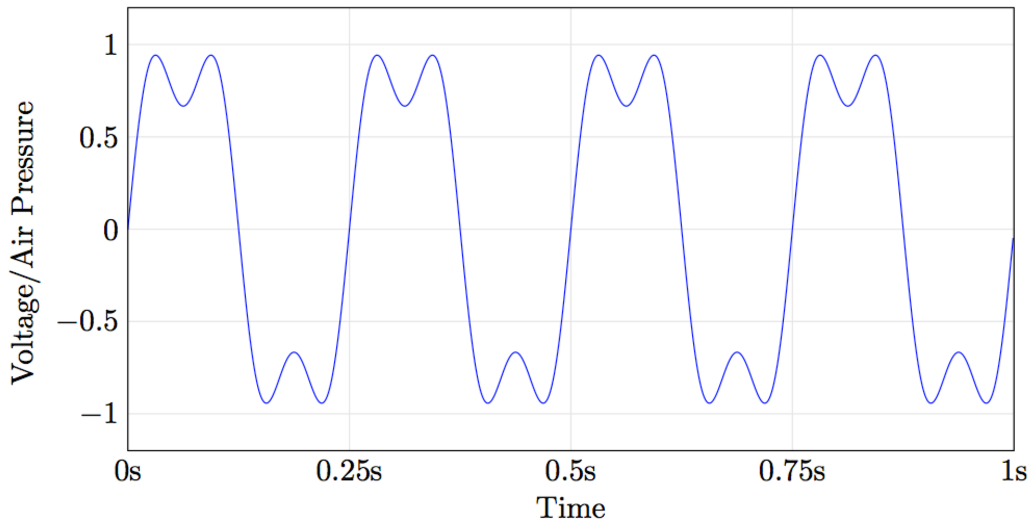


Figure 4: 4Hz + 12Hz Sin Wave.

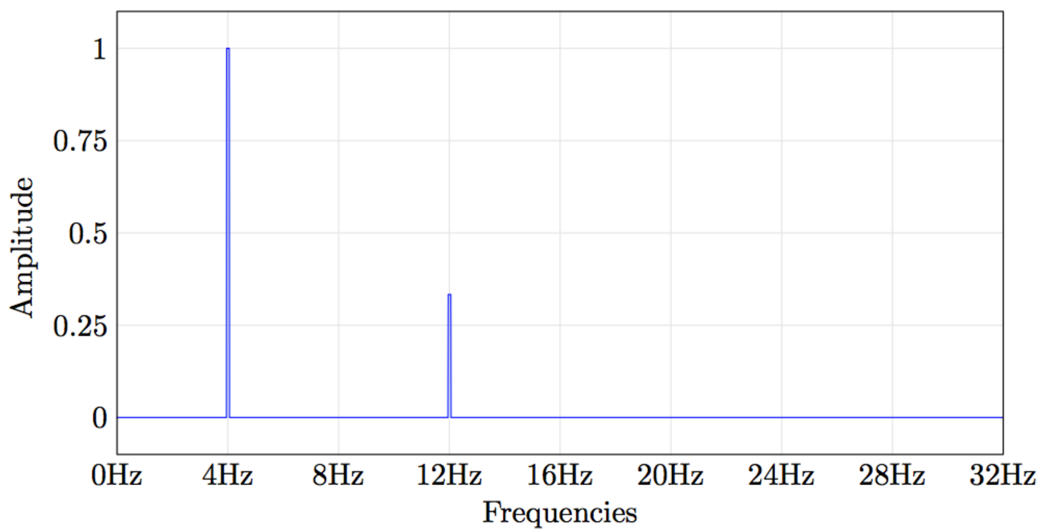
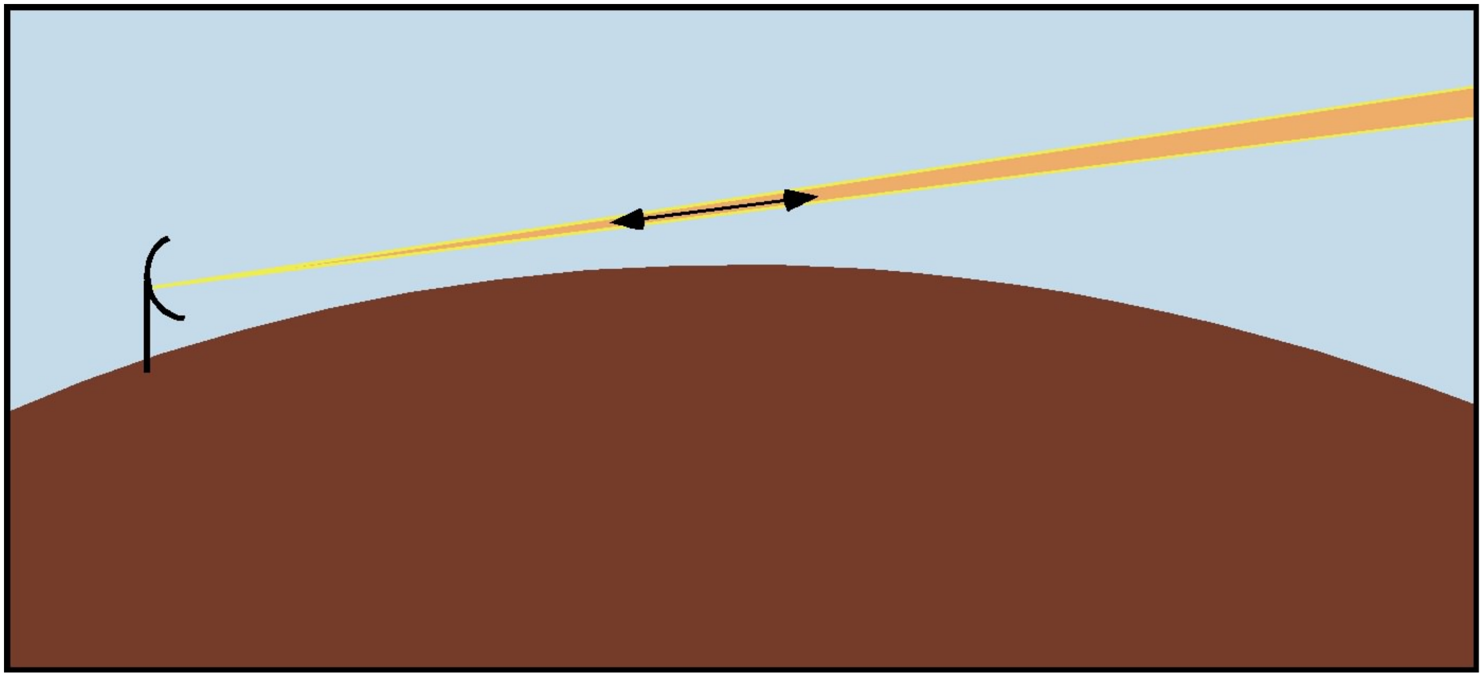


Figure 5: Frequency Domain of 4Hz + 12Hz Sin Waves.

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*



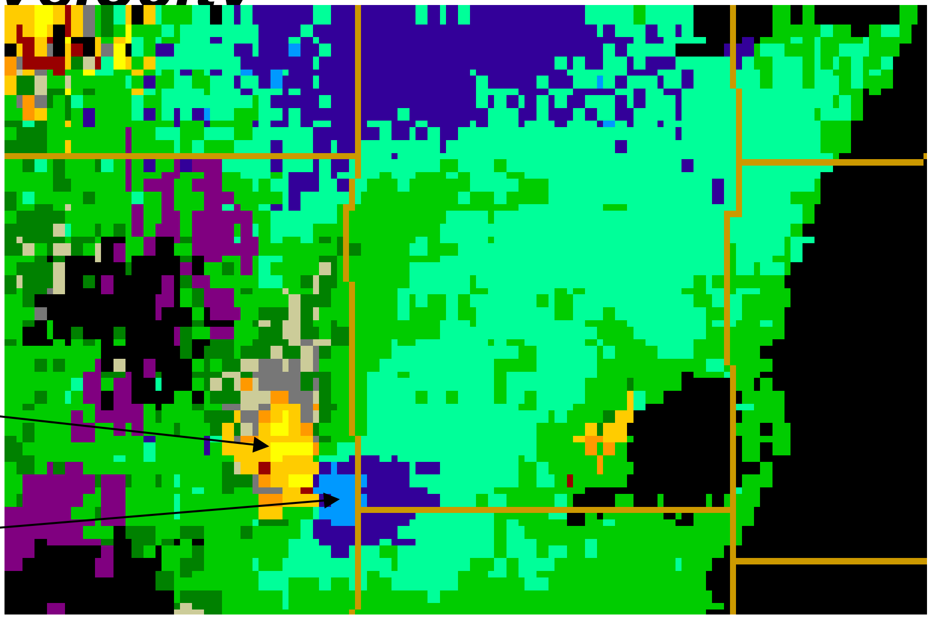
Question: how does a steerable dish like Millstone – or a phased array dish like PFISR – determine vector ion velocities?

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



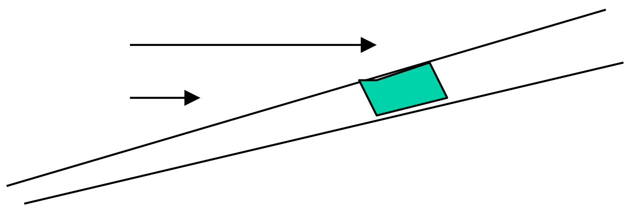
Red: Receding from radar

Blue: Toward radar

Real characteristics of a returned signal from a distributed target

Velocity of individual targets in contributing volume vary due to:

1) Wind shear (particularly in the vertical)



2) Turbulence

3) Differential fall velocity (particularly at high elevation angles)

4) Antenna rotation

5) Variation in refraction of microwave wavefronts

NET RESULT: A series of pulses will measure a spectrum of velocities (Doppler frequencies)

Power per unit velocity interval (db)