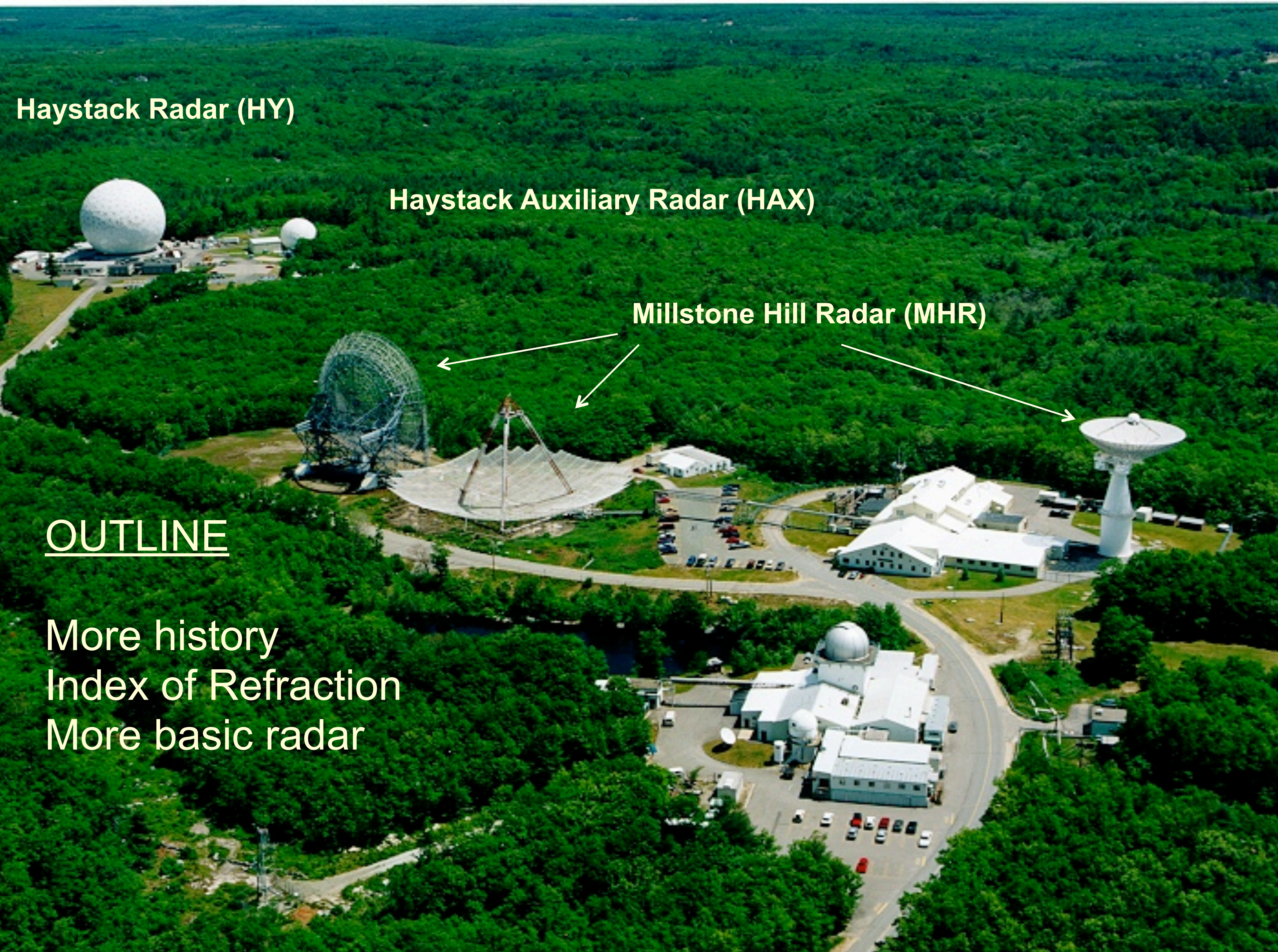


OUTLINE

More history
Index of Refraction
More basic radar

It is frequently said that, although the atomic bomb ended World War II, it was radar that won the war.

MIT Radiation Laboratory

E. G. Bowen (center), member of the British scientific mission that brought the first cavity magnetron to the United States in 1940, is shown an American-made copy by Radiation Laboratory director L. A. DuBridge (left) and associate director I. I. Rabi, a Nobel Prize winner (right). Photograph courtesy of the MIT Museum; from the Radiation Laboratory Negative Collection.

- The primary technical barrier to developing UHF systems was the lack of a usable source for generating high-power microwaves.
- In February 1940, John Randall and Harry Boot at Birmingham University in the UK built a resonant cavity magnetron.
- Bombing of London Sept 1940 – May 1941 (The Blitz)
- Britain was interested in developing practical applications for airborne microwave radar, but did not have the large-scale manufacturing ability to mass produce magnetrons.
- In1940, Britain partnered with the US National Defense Research Committee (NDRC)
-

MIT Radiation Laboratory

Over the course of five years, MIT researchers designed 50 percent of the radar used in World War II and invented over 100 different radar systems.

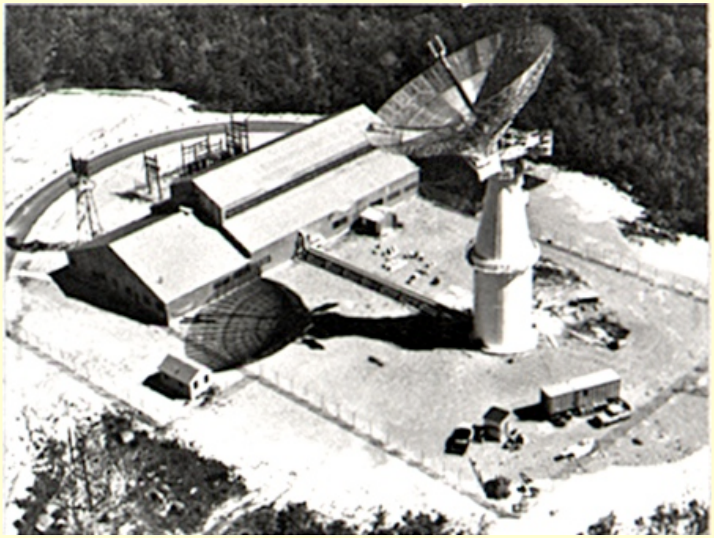
Building 20 on the MIT campus, home of the Rad Lab from 1943 to 1945.

Including:

- **Airborne bombing radars**
- **Shipboard search radars**
- **Harbor and coastal defense radars**
- **Interrogate-friend-or-foe beacon systems**
- **Long-range navigation (LORAN) system**
- **Critical contributions of the Radiation Laboratory were:**
  - **the microwave early-warning (MEW) radars, which effectively nullified the V-1 threat to London, and**
  - **air-to-surface vessel (ASV) radars, which turned the tide on the U-boat threat to Allied shipping.**

Millstone

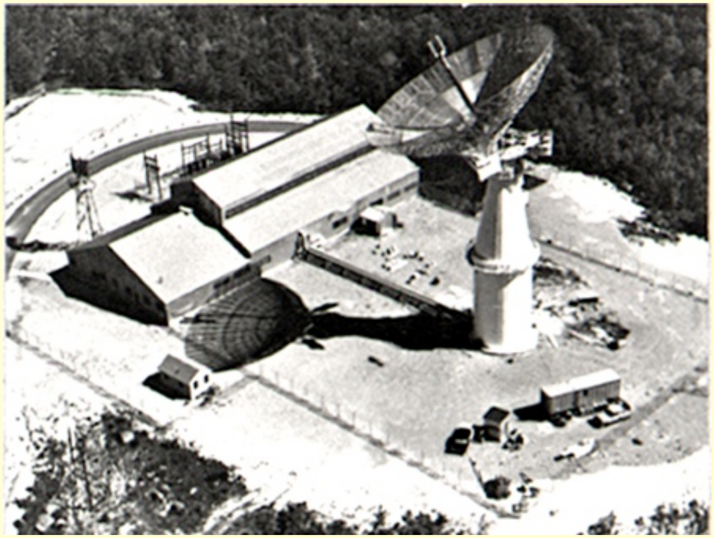
The BMEWS Prototype



Millstone Radar
1957

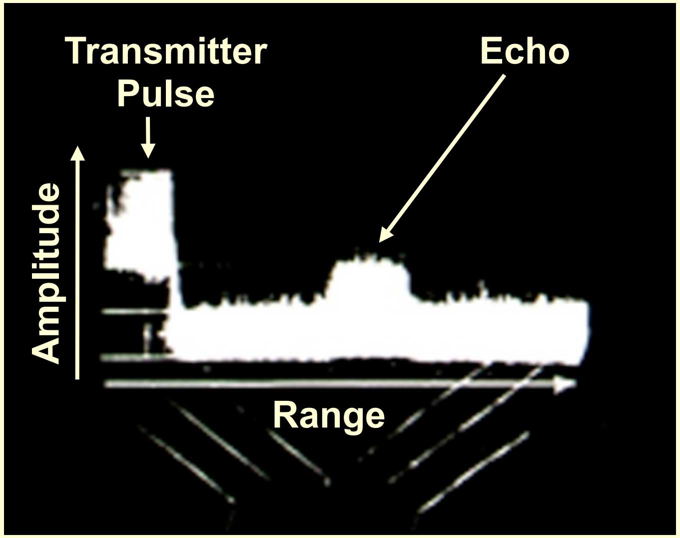
Millstone

The BMEWS Prototype



Millstone Radar
1957

First in Space Surveillance



Sputnik
A-Scope Trace

Outline

- More History
- Index of Refraction
- More Basic Radar

Appleton - Hartree

but also …

Outline

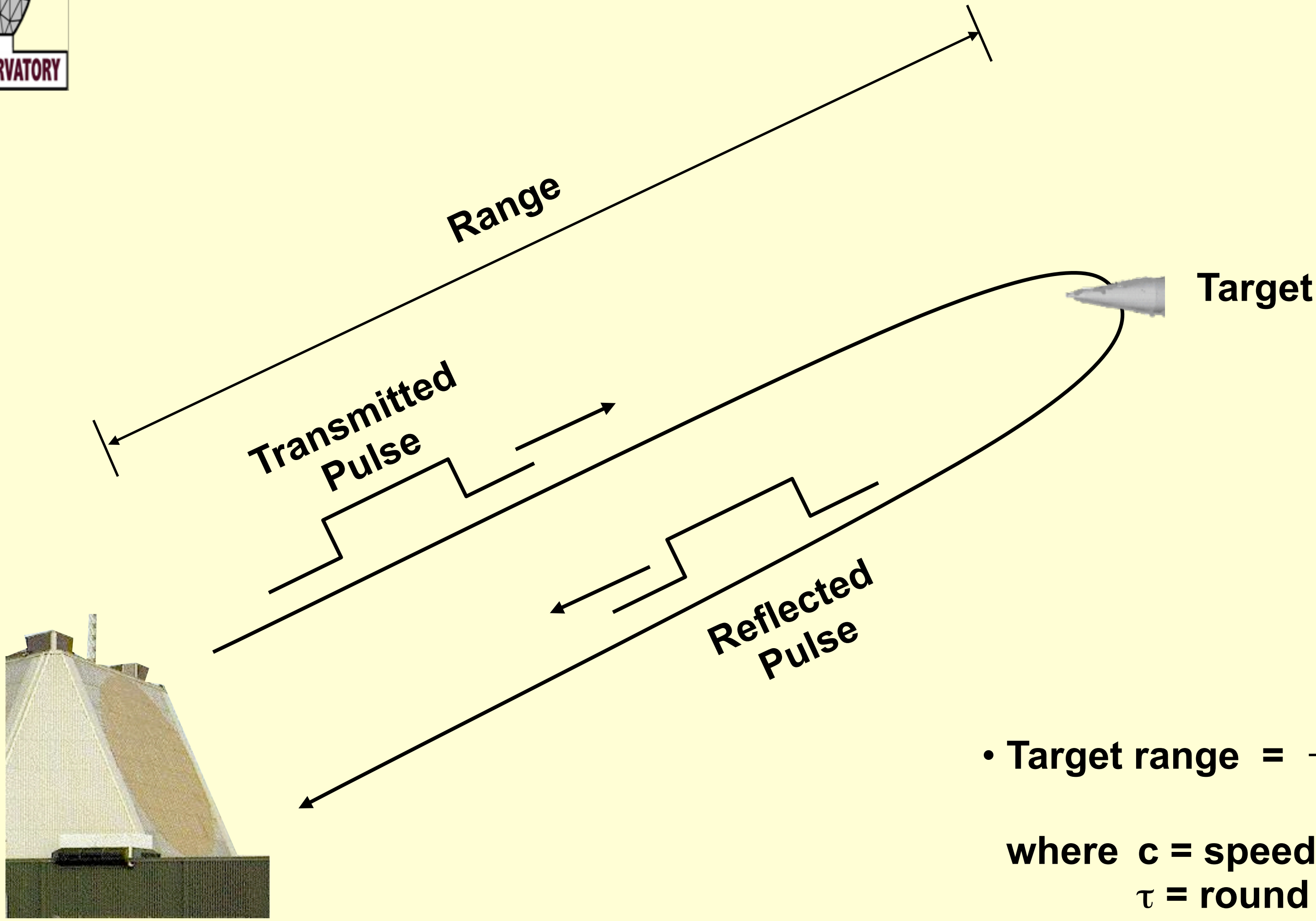
- More History
- Index of Refraction
- More Basic Radar

Appleton - Hartree

but also …

Until 1976, it was almost unknown that Appleton had collaborated with the Austrian physicist Wilhelm Altar on magneto-ionic theory in 1925-26. Altar wrote a paper which contains the magneto-ionic equations in so-called "dielectric tensor" form, and in general terms contains what would today be called the dispersion relation in cold plasma theory.

Radar Range Measurement



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

  where c = speed of light
  τ = round trip time

Phase Velocity, Group Velocity, Index of

$$v_p = \frac{\omega}{k}$$

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

$$n = \frac{c}{v_p}.$$

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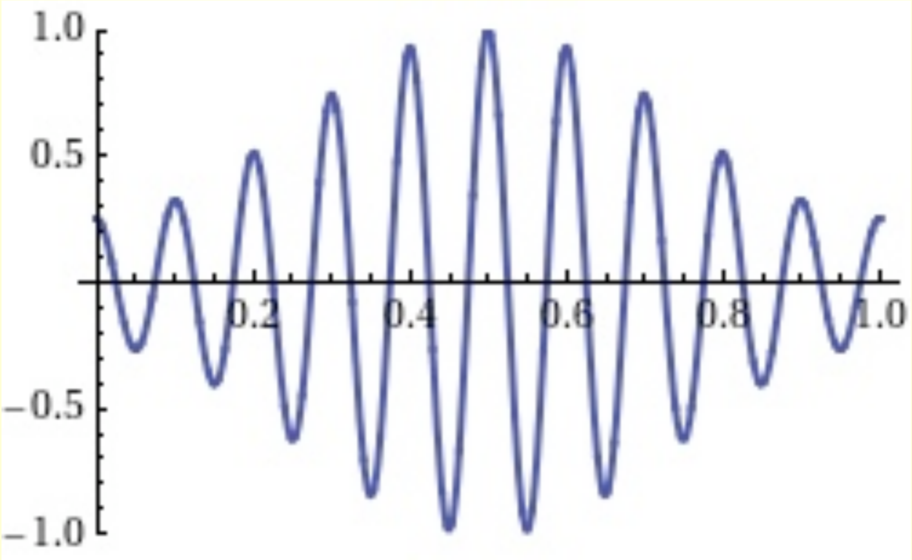
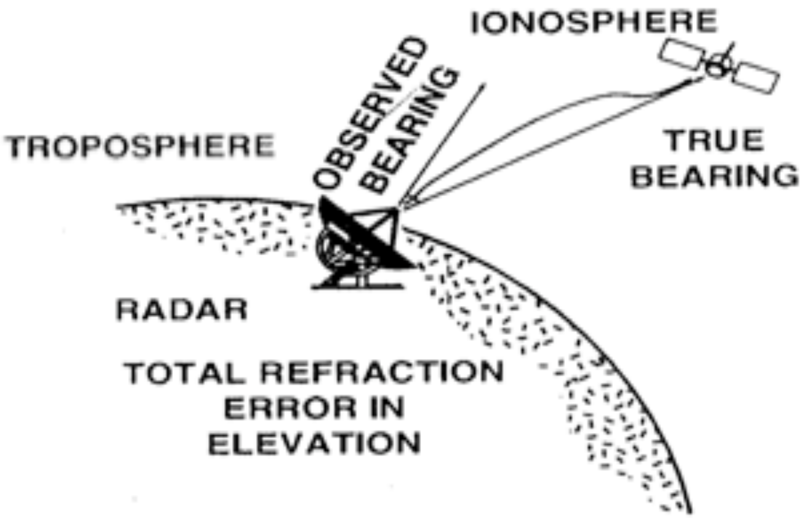
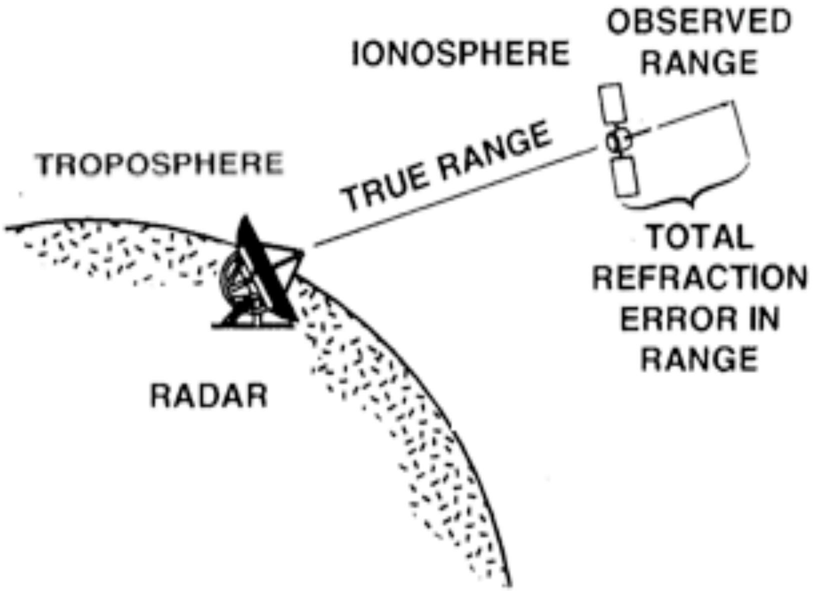


Illustration of Atmospheric Effects





Appleton-Hartree Equation

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{1}{2}Y^2\sin^2\theta}{1-X-iZ} \pm \frac{1}{1-X-iZ}\left(\frac{1}{4}Y^4\sin^4\theta + Y^2\cos^2\theta\,(1-X-iZ)^2\right)^{1/2}}$$

or, alternatively[4]:

$$n^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2\sin^2\theta \pm \left(\left(\frac{1}{2}Y^2\sin^2\theta\right)^2 + (1-X)^2\,Y^2\cos^2\theta\right)^{1/2}}$$

n = complex refractive index

$i = \sqrt{-1}$

$X = \frac{\omega_0^2}{\omega^2}$

$Y = \frac{\omega_H}{\omega}$

$Z = \frac{\nu}{\omega}$

ε_0 = permittivity of free space

μ_0 = permeability of free space

B_0 = ambient magnetic field strength

e = electron charge

m = electron mass

θ = angle between the ambient magnetic field vector and the wave vector

ν = electron collision frequency

$\omega = 2\pi f$ (radial frequency)

f = wave frequency (cycles per second, or Hertz)

$\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\epsilon_0 m}}$ = electron plasma frequency

$\omega_H = 2\pi f_H = \frac{B_0|e|}{m}$ = electron gyro frequency

Index of Refraction in the Ionosphere

$$n^2 = 1 - \frac{X(1-X)}{(1-X) - \frac{1}{2}Y_T^2 \pm \left(\frac{1}{4}Y_T^4 + (1-X)^2 Y_L^2\right)^{1/2}}$$

$$X = \frac{\omega_N^2}{\omega^2} \qquad Y = \frac{\omega_H}{\omega} \qquad \omega_N = \left(\frac{Ne^2}{\varepsilon_0 m_e}\right)^{1/2} \qquad \omega_H = \frac{e|B|}{m_e}$$

ω = the angular frequency of the radar wave,

$Y_L = Y\cos\theta$, $Y_T = Y\sin\theta$,

θ = angle between the wave vector $\bar{k}$ and $\bar{B}$,

$\bar{k}$ = wave vector of propagating radiation,

$\bar{B}$ = geomagnetic field, N = electron density

e = electronic charge, m_e = electron mass,

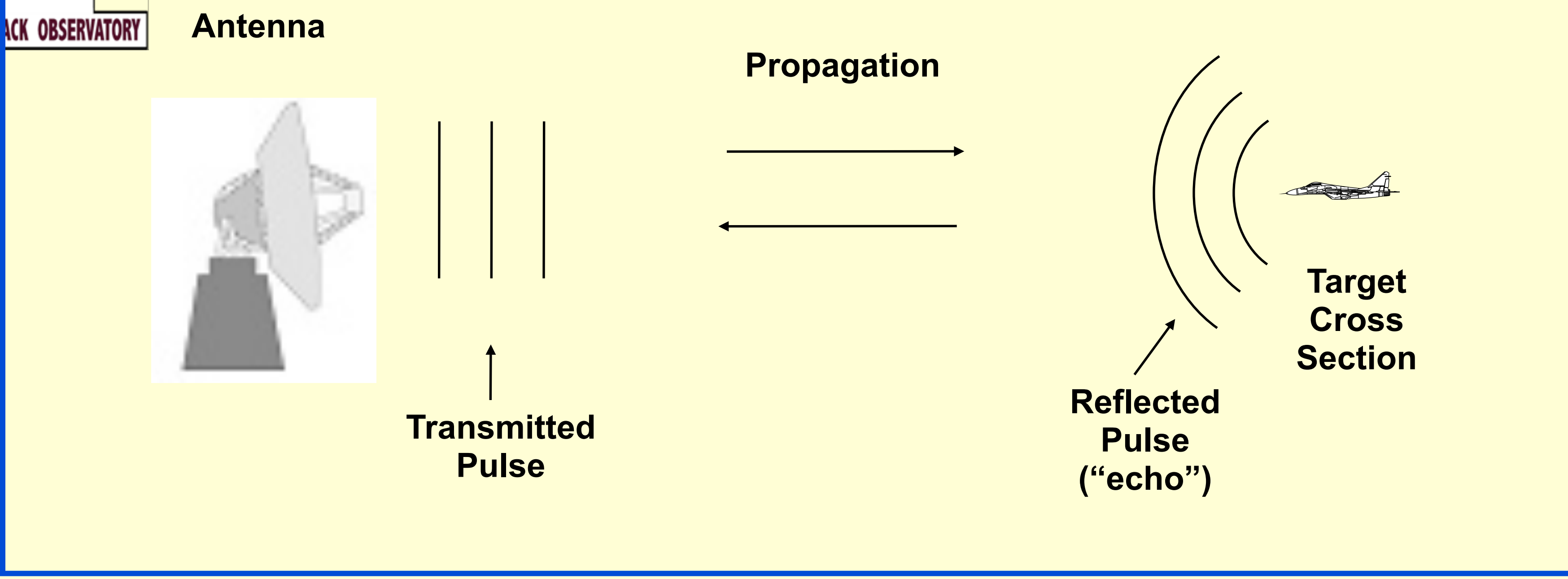
and ε_o = permittivity constant.

Outline

- More History
- Index of Refraction
- More Basic Radar

RADAR

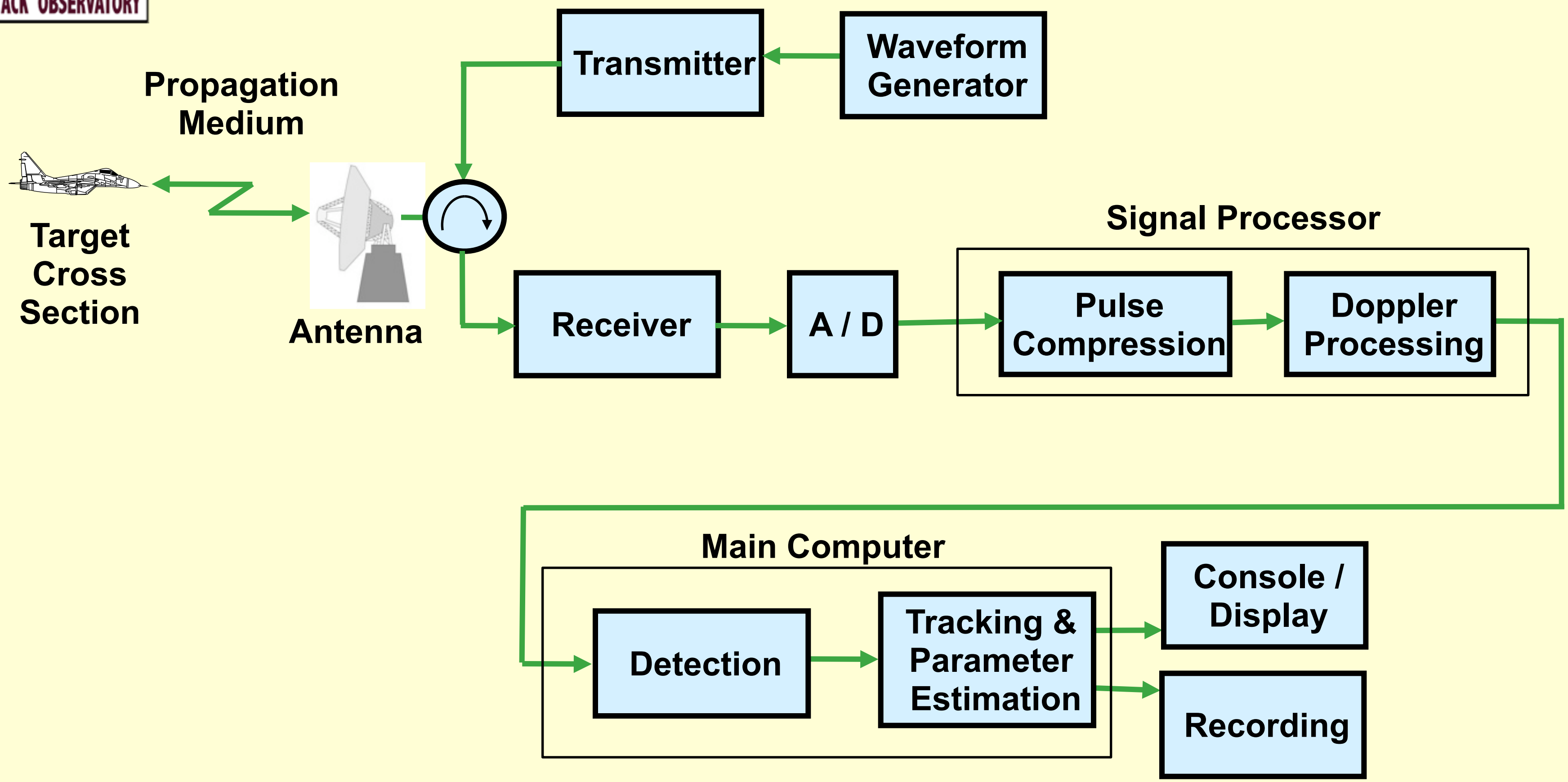
RAdio Detection And Ranging



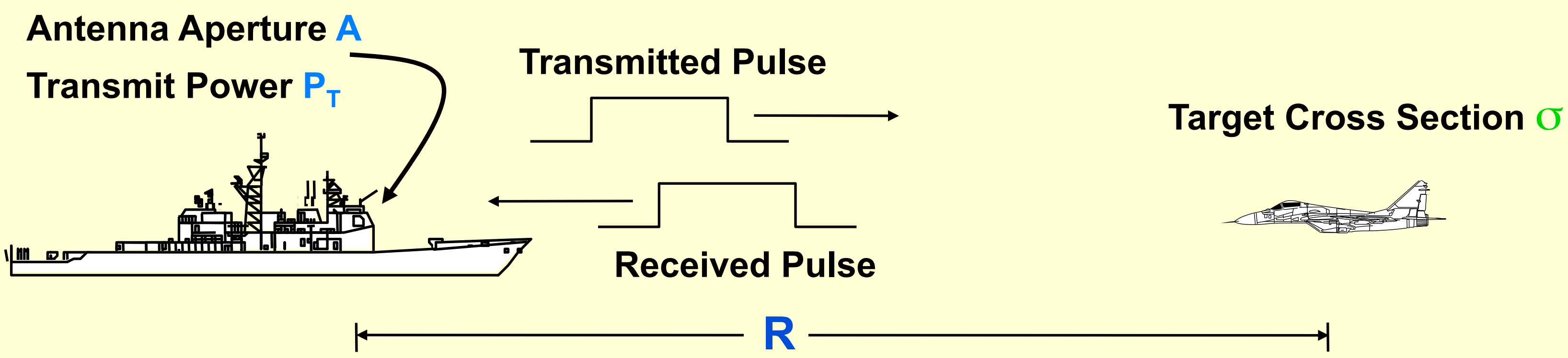
Radar observables:

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

Radar Block Diagram



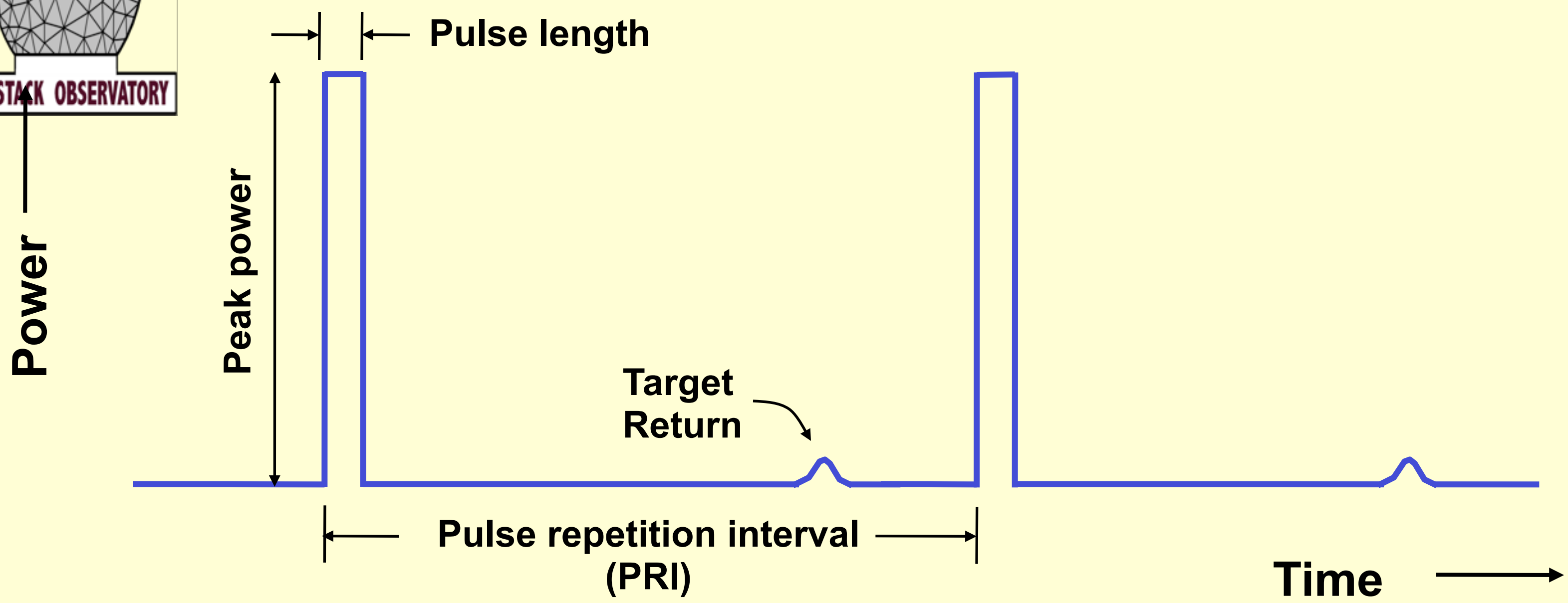
Radar Range Equation



Transmit Power	Transmit Gain	Spread Factor	Losses	Target RCS	Spread Factor	Receive Aperture	Dwell Time

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

Pulsed Radar
Terminology and Concepts



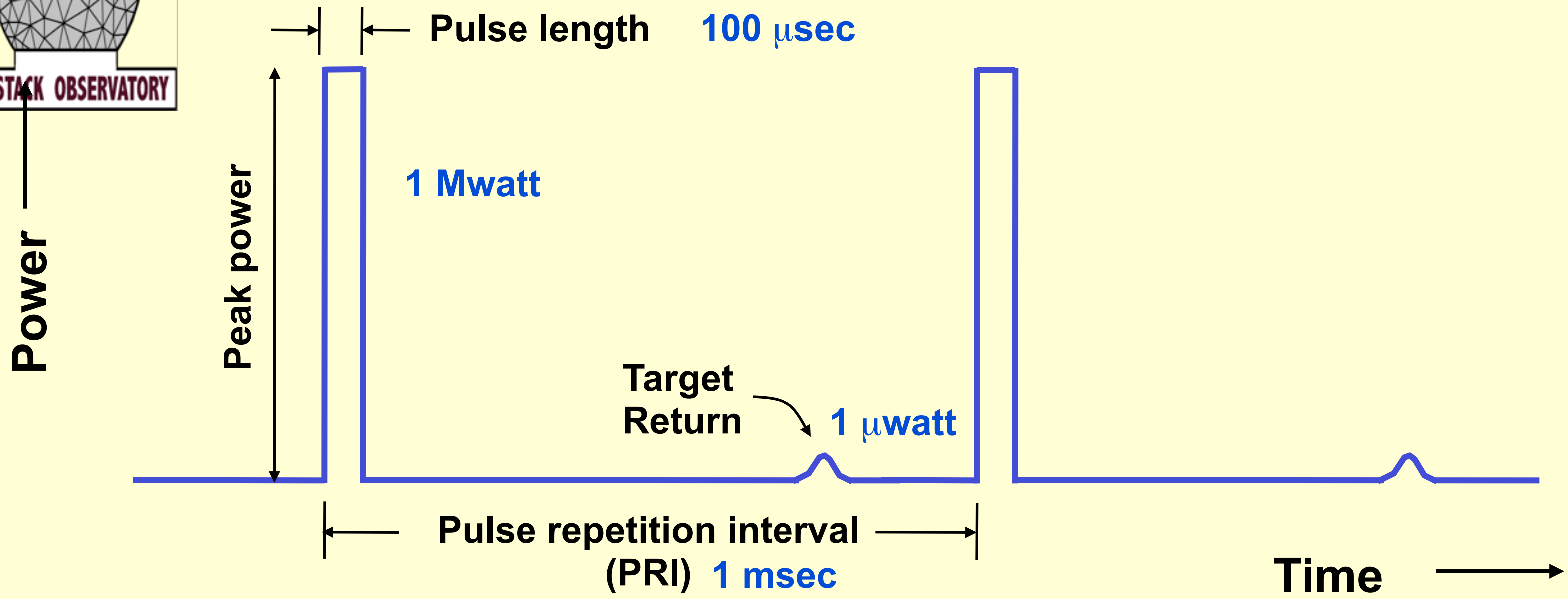
Duty cycle = $\frac{\text{Pulse length}}{\text{Pulse repetition interval}}$

Average power = Peak power * Duty cycle

Pulse repetition frequency (PRF) = 1/(PRI)

Continuous wave (CW) radar: Duty cycle = 100% (always on)

Pulsed Radar
Terminology and Concepts



$$\text{Duty cycle} = \frac{\text{Pulse length}}{\text{Pulse repetition interval}} \qquad 10\%$$

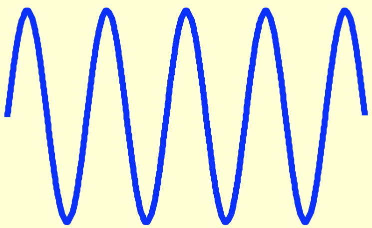
Average power = Peak power * Duty cycle   100 kWatt

Pulse repetition frequency (PRF) = 1/(PRI)   1 kHz

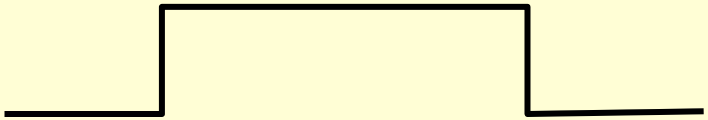
Continuous wave (CW) radar: Duty cycle = 100% (always on)

Radar Waveforms

What do radars transmit?



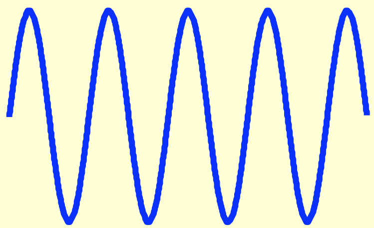
Waves?



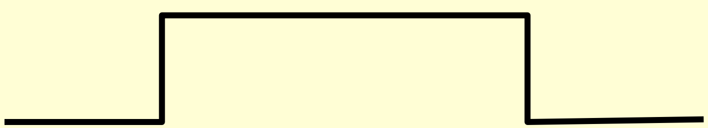
or Pulses?

Radar Waveforms

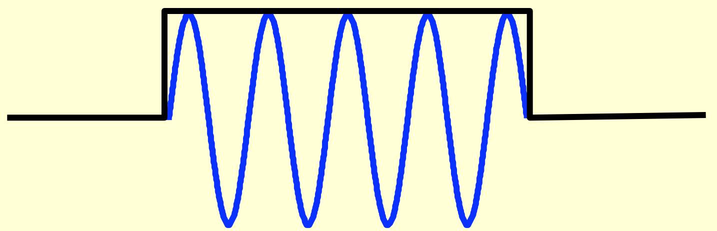
What do radars transmit?



Waves?



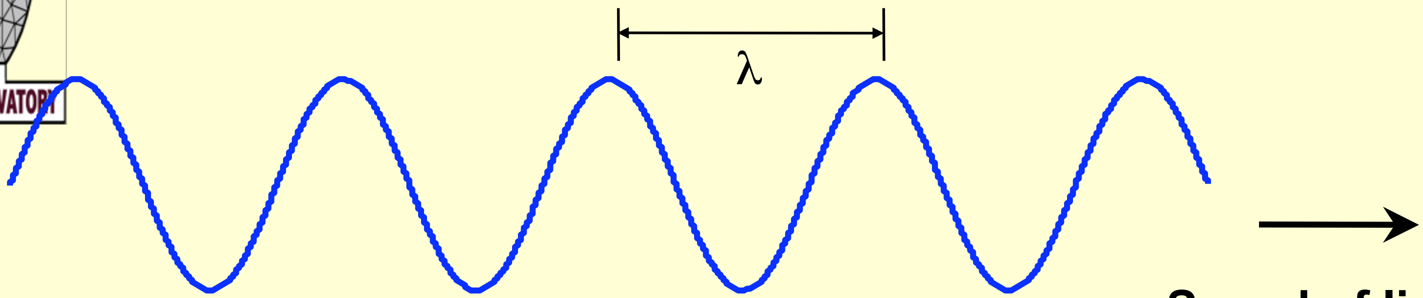
or Pulses?



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

Properties of Waves

Relationship Between Frequency and Wavelength



Speed of light, c

$c = 3 \times 10^8$ m/sec

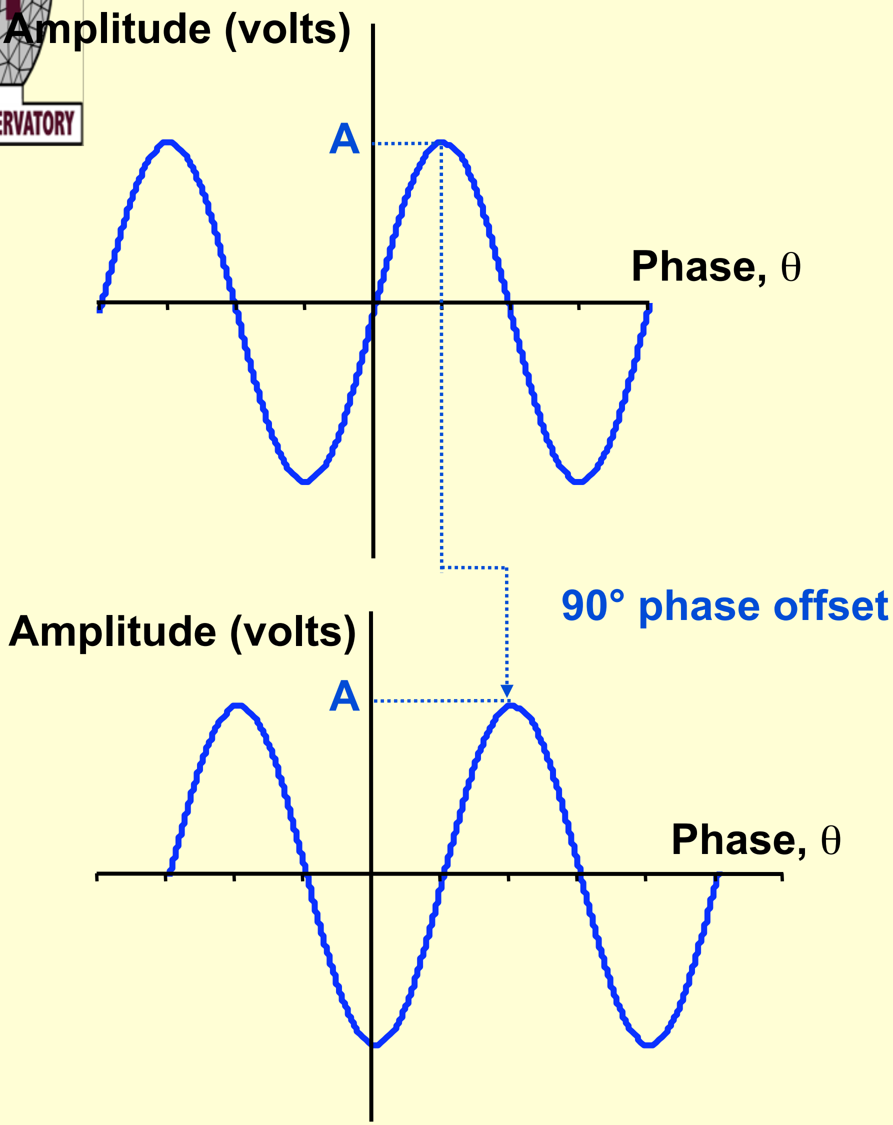
$= 300,000,000$ m/sec

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

Examples:

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

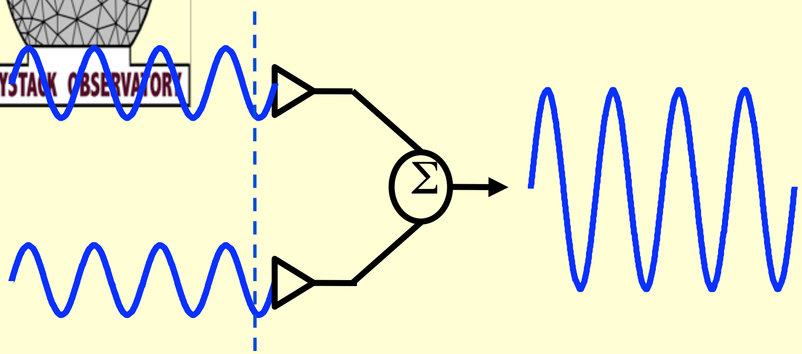
Properties of Waves
Phase and Amplitude



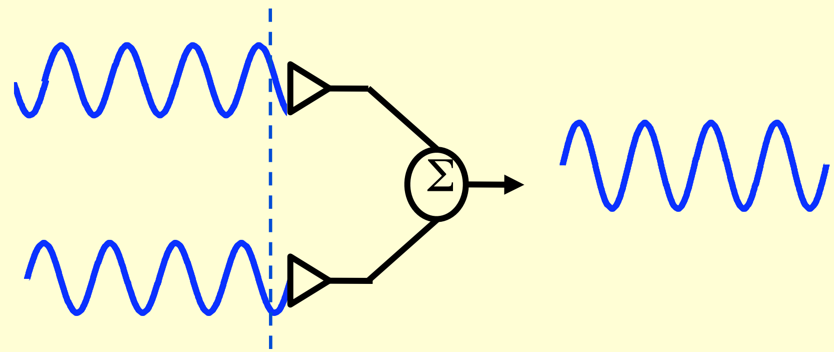
$A \sin(\theta)$

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

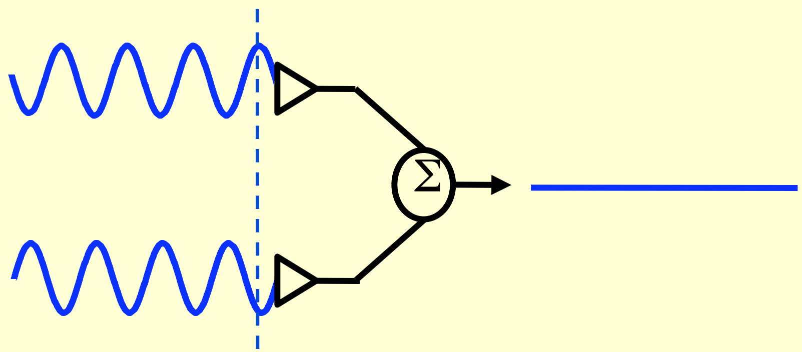
Properties of Waves
Constructive vs. Destructive Addition



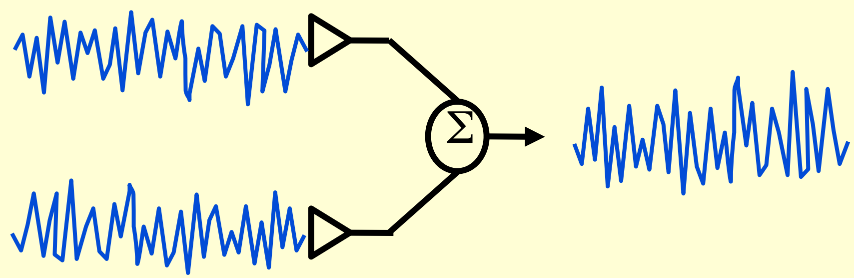
**Constructive
(in phase)**



**Partially Constructive
(somewhat out of phase)**



**Destructive
(180° out of phase)**

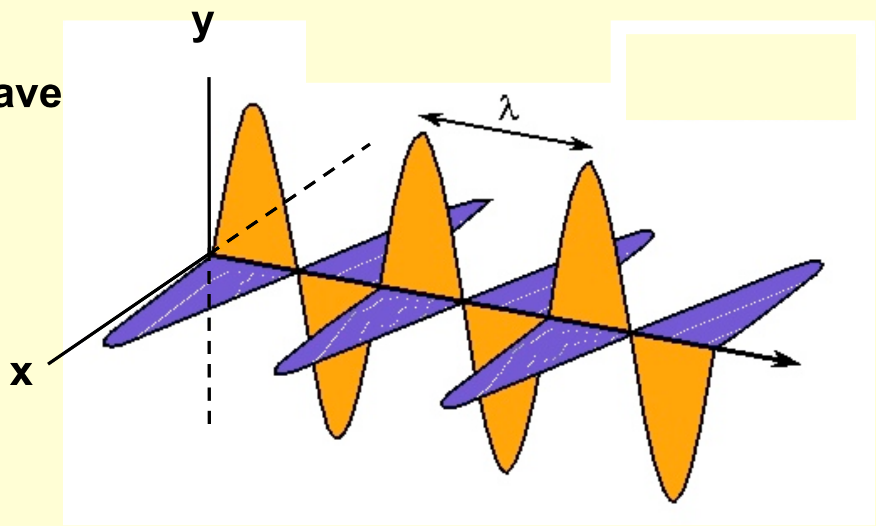


**Non-coherent signals
(noise)**

Haystack 2003-
AJC 08/01/11

Polarization

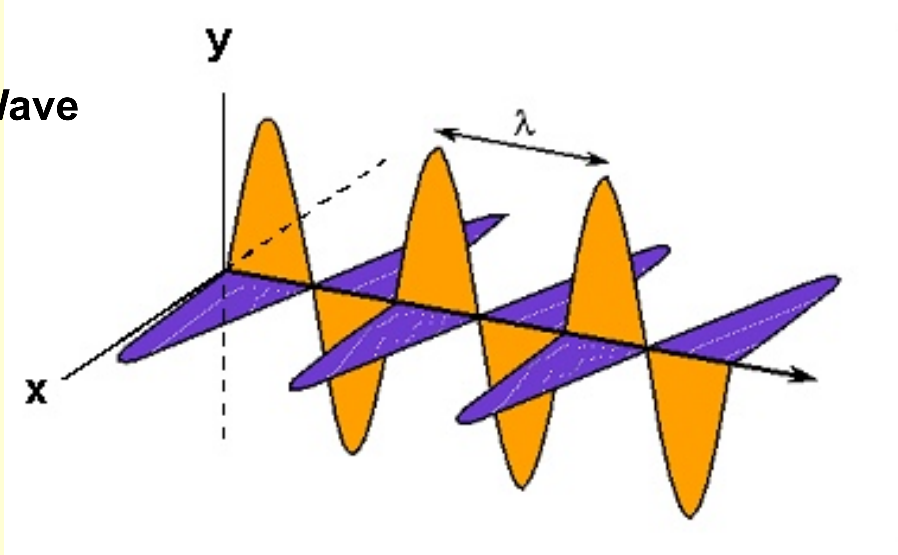
Electromagnetic Wave

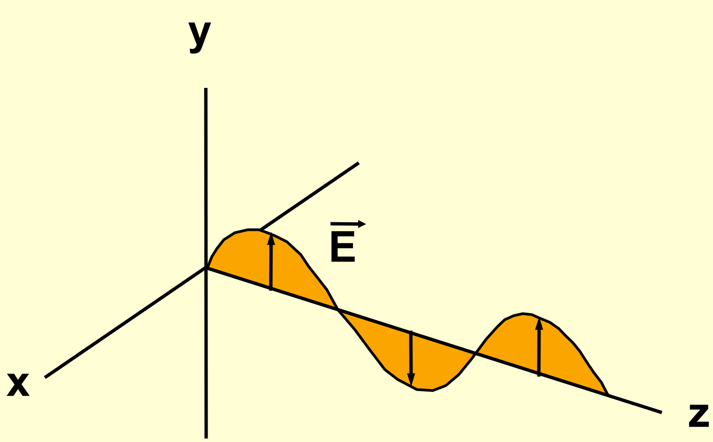


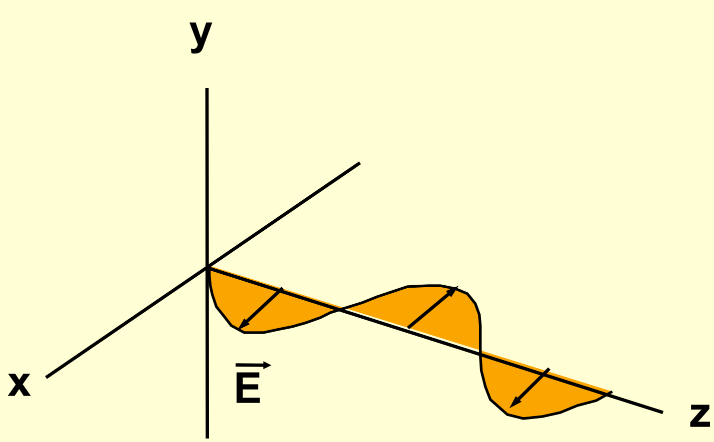
Electric Field

Magnetic Field

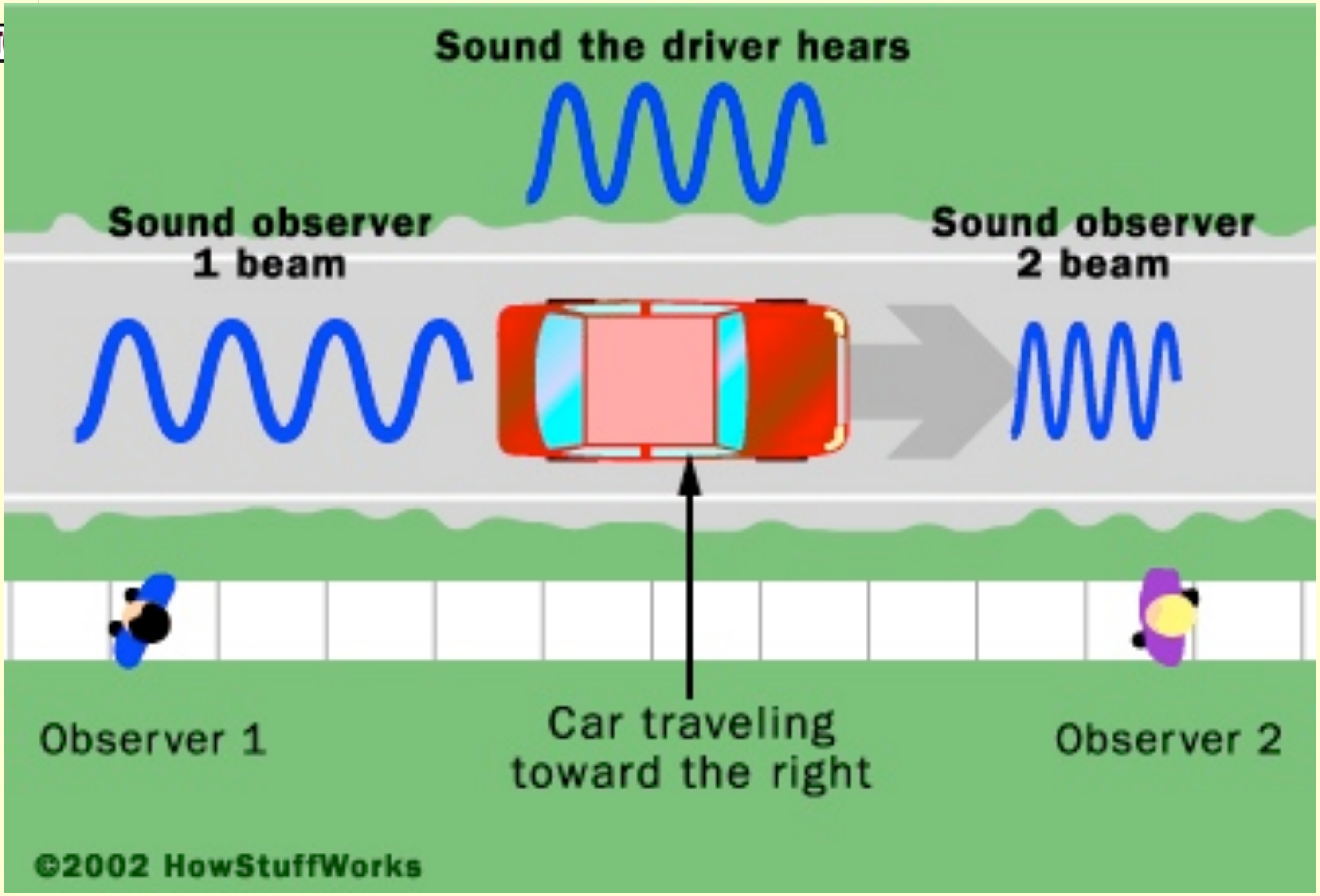
Polarization



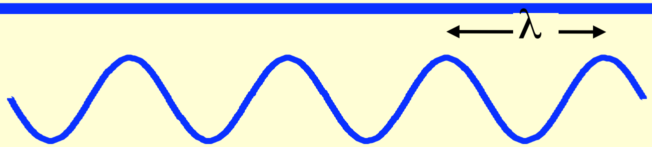




Doppler Effect

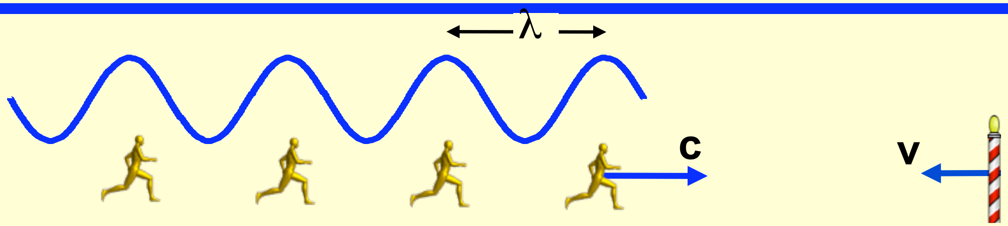


Doppler Shift Concept



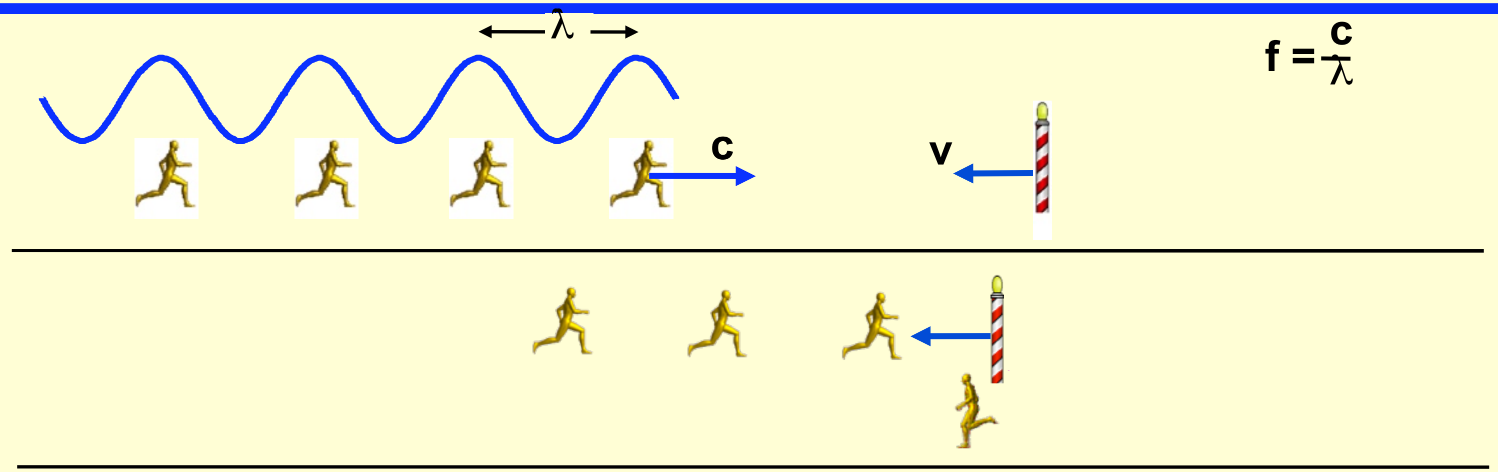
$$\lambda = \frac{c}{f}$$

Doppler Shift Concept



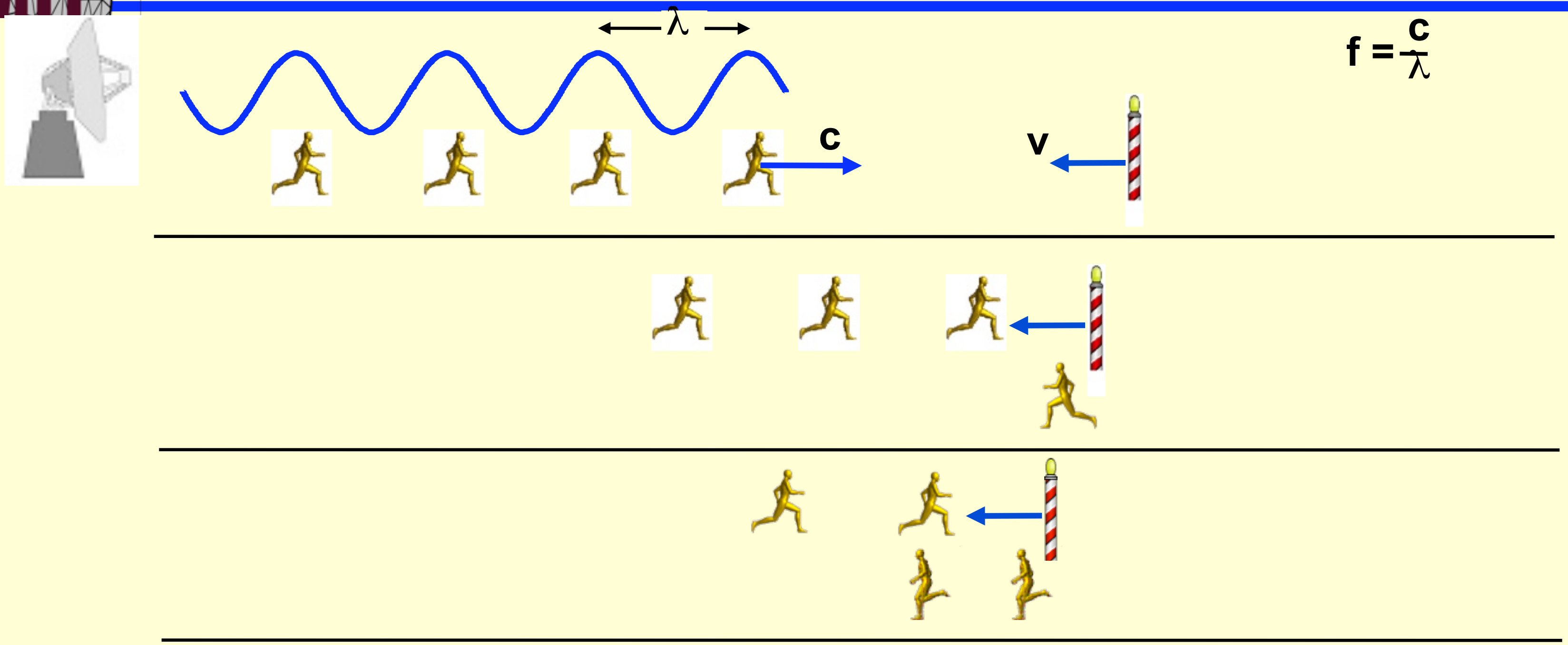
$\lambda = \frac{c}{f}$

Doppler Shift Concept

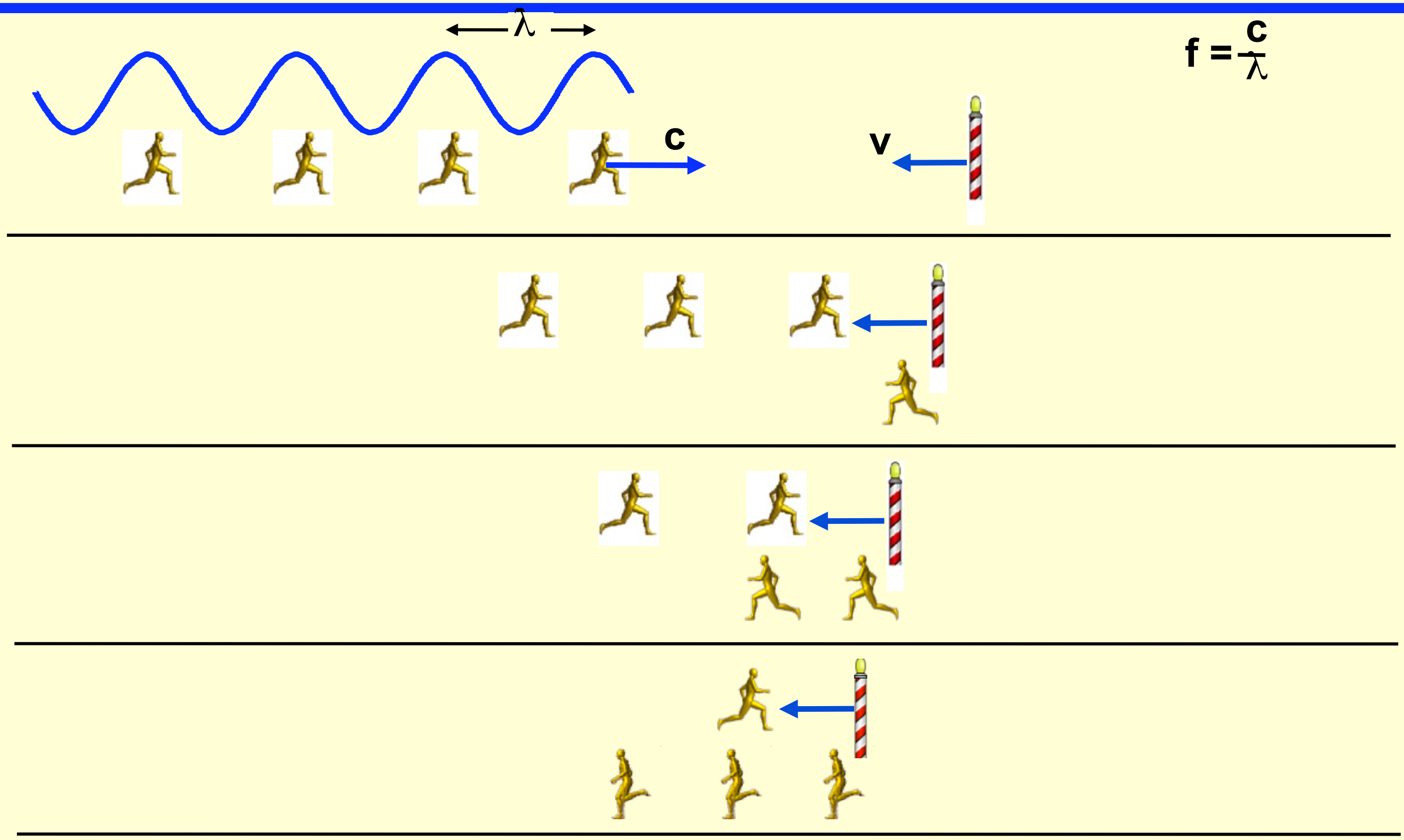


$f = \frac{c}{\lambda}$

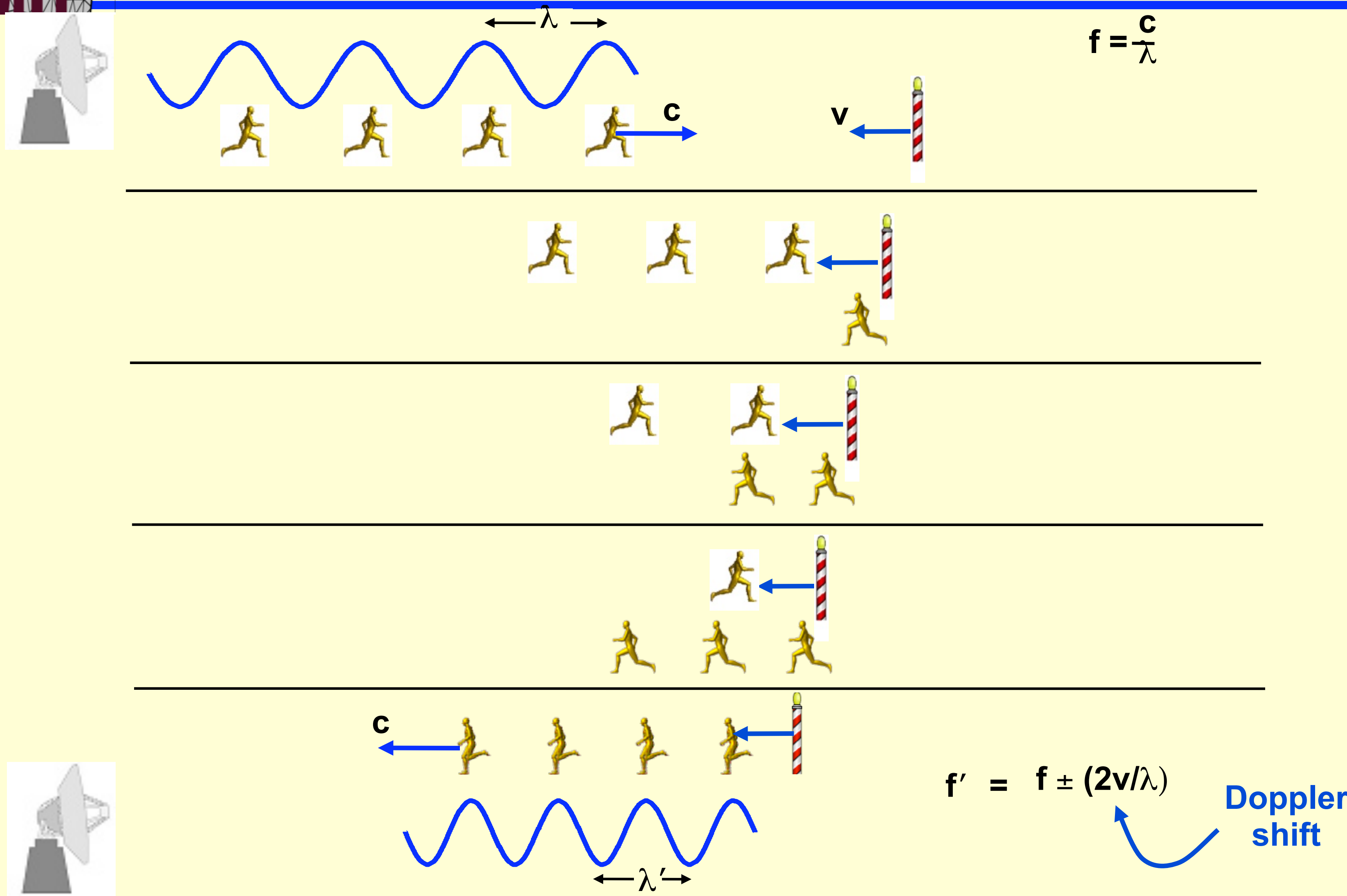
Doppler Shift Concept



Doppler Shift Concept



Doppler Shift Concept



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): $A\exp(j2\pi f_D t) = I + jQ$