ECE 678

Radar Engineering
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RAdio Detection And Ranging

RADAR

It has become so commonplace that the acronym RADAR has evolved into a common noun: radar.

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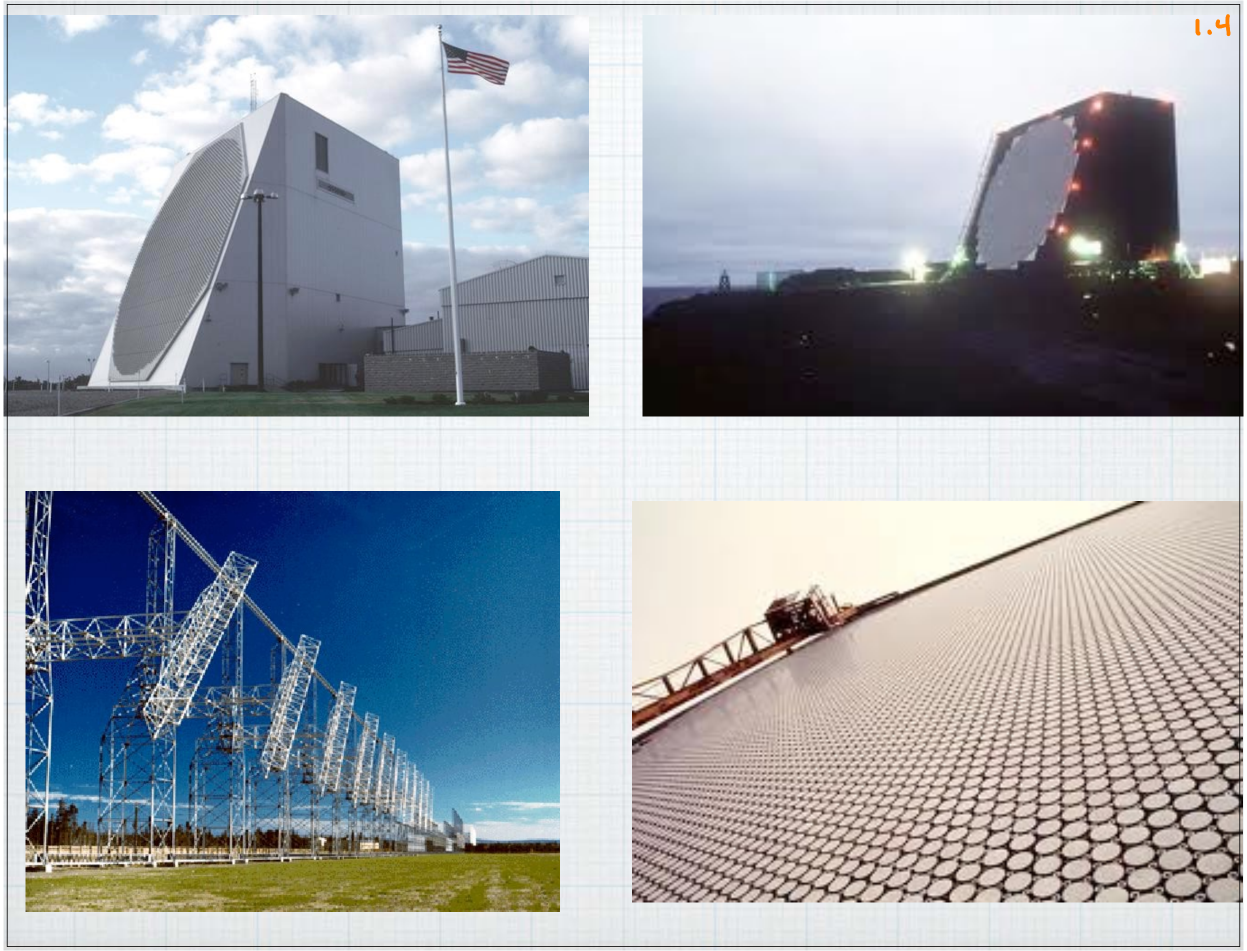


A Little History...

- Bats, dolphins, whales, and some birds have been doing this for a long time.
- Allied Submarine Detection Investigation Committee—World War I (Lord Rutherford)
- In 1922, Marconi suggested radar for ship detection.
- "Radio Fence" experiments at Naval Research Labs in 1930s.

Robert Buderi, *The Invention that Changed the World*.

Radar development intensified with outbreak of WW II (1939)

- Royal Radar and Signals Establishment (UK)
- MIT Radiation Laboratory (MIT Lincoln Labs)(MIT Radiation Lab Series—28 volumes documenting WWII radar development.)
- Other US Laboratories (Bell Labs, Stanford)
- Germany also had a radar development program.

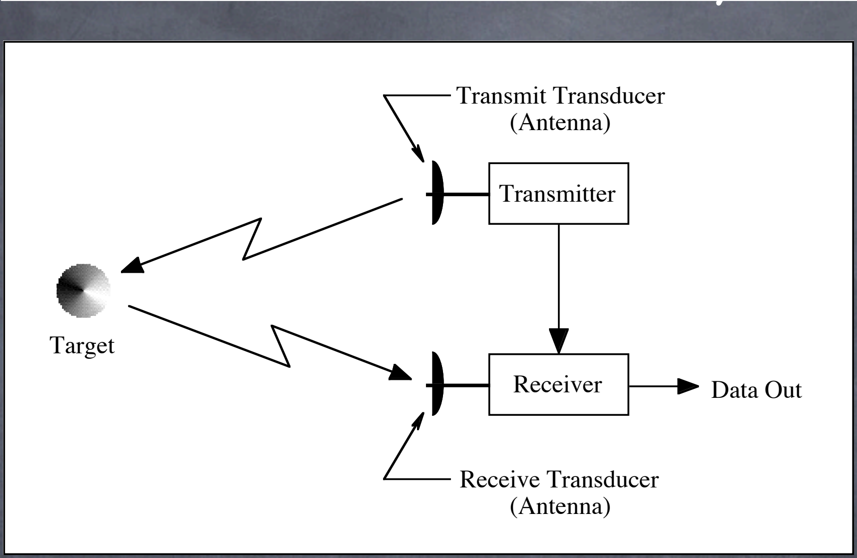
The Pearl Harbor SCR-270 Radar Set

- The Japanese aircraft that attacked Pearl Harbor were detected and tracked by radar while over 100 miles (50 minutes) away.
- Unlikeliness of attack resulted in radar detection not being acted on.

- After WWII, during 1950s–1980s, radar development continued at an intense rate, driven by the Cold War with the Soviet Union.
- In the last 20 years, there has been a renaissance in radar research fueled by new technological (computational) capabilities:
    - Adaptive signal processing
    - Adaptive waveform design
    - MIMO Radar

How Does a Radar Work?

Pulse-Echo Measurement System



A pulse-echo measurement system is any system that uses the scattering of radiated waves (electromagnetic or acoustic) from an object to obtain information about that object.

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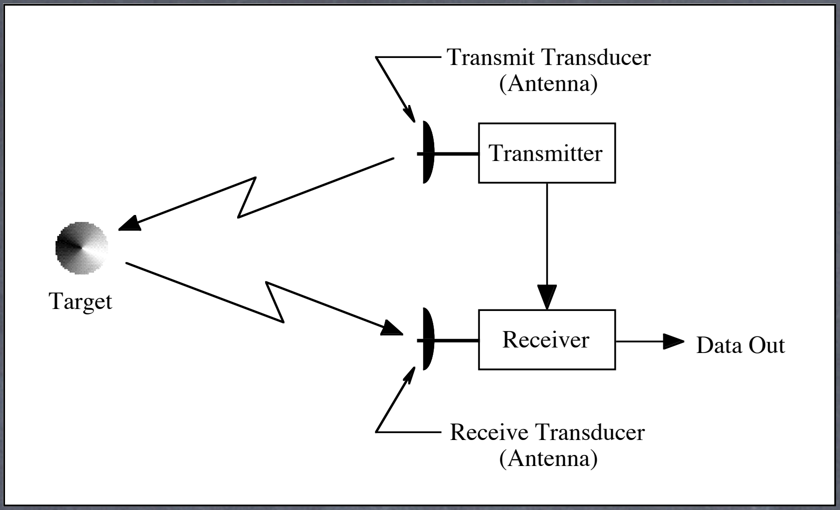

- It consists of

1. Transmitter
2. Transmit Transducer (Antenna)
3. Receive Transducer (Antenna)
4. Receiver

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- Transmitter: Generates the signal to be generated.

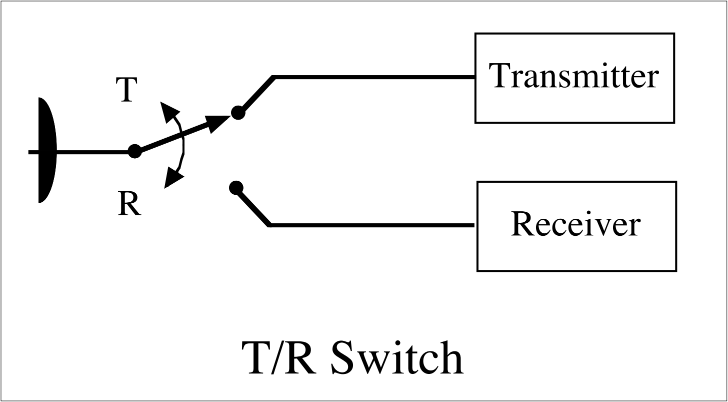
- Transmit Transducer: Couples the energy in the transmitted signal to the propagating medium.

- Receive Transducer: Couples a portion of the scattered energy in the propagating medium to the receiver.

- Receiver: Processes the signal collected by the receive transducer and extracts desired information about scattering objects.

- Form of transducer depends on radiation:
- RF and Microwaves ---> Antennas
- Optical Radiation ---> Lens, "telescopes"
- Sonar ---> Electromechanical Devices
- Ultrasound---> Piezo-electric transducers
- Geophysical ---> explosives, "thumpers"

The transmit and receive antenna may or may not be the same physical antenna:



T/R Switch

Radars that use the same antenna for transmit and receive—or have the two antennas co-located— are called monostatic radars.

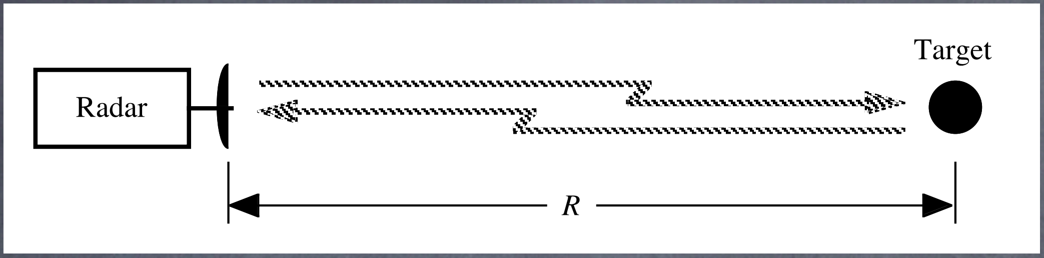
- The “Transmitter” includes:
  - Signal Generators
  - Modulators
  - Power Amplifiers

- The “Receiver” includes:
  - RF Amplifiers
  - Mixers
  - IF Amplifiers
  - Detectors
  - Filters

and...

  - Doppler Filters, Range Gating Circuits, CFAR Processors, SAR Processors, etc.

Delay and Range in Radar



An electromagnetic pulse transmitted through space travels at a velocity of $c = 2.998 \times 10^8$ m/sec, while covering a distance of 2R.

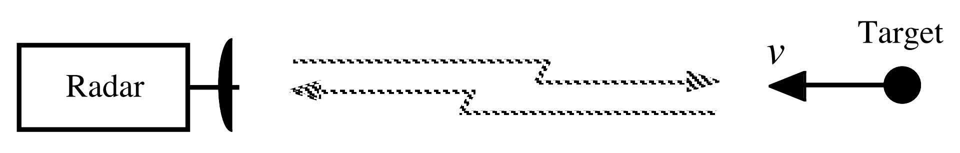
Rate x Time = Distance $\Longrightarrow$ $c\tau = 2R$

$$\Longrightarrow \quad \boxed{\tau = \frac{2R}{c}} \quad \text{or} \quad \boxed{R = \frac{c\tau}{2}}$$

$$\boxed{\tau = \frac{2R}{c} \quad \text{or} \quad R = \frac{c\tau}{2}}$$

- Thus we can determine the range to the target by measuring the delay until the echo is heard.
- For EM waves in free space, $c = 2.998 \times 10^8$ m/sec.
- For an acoustic wave in air at Standard Temperature and Pressure (STP), c =341 m/sec.
- Do determine R, you must accurately measure (estimate) delay. This can be difficult in noise.

The Doppler Effect



- > The radar transmits waveform s(t).
- > The received waveform is of the form

$$r(t) \;=\; \sqrt{\alpha}\cdot s(\alpha t-\tau) \;=\; \sqrt{\alpha}\cdot s(\alpha(t-\tau')),$$

where

$$\alpha=\frac{1+v/c}{1-v/c}.$$

is the Doppler compression factor.

Expanding α in a Taylor series about $v/c=0$,

$$\alpha=\alpha\left(\frac{v}{c}\right)=1+2\frac{v}{c}+2\left(\frac{v}{c}\right)^2+\cdots$$

$$=1+2\sum_{k=1}^{\infty}\left(\frac{v}{c}\right)^k$$

$$=1+2\left(\frac{v}{c}\right)+\text{\o}\left(\left|\frac{v}{c}\right|\right)$$

For a radar utilizing EM radiation, where v<<c

$$\alpha\approx 1+2\left(\frac{v}{c}\right)$$

Hence it follows that the received signal is

$$r(t) = \boxed{\sqrt{1+\frac{2v}{c}}}\, s\left(\left(1+\frac{2v}{c}\right)t-\tau\right)$$

$$\approx s\left(\left(1+\frac{2v}{c}\right)t-\tau\right)$$

Now suppose that

$$s(t) = \sin\left(\omega_o t+\theta\right)$$

Then the received signal is

$$r(t) = s\left(\left(1+\frac{2v}{c}\right)t-\tau\right)$$

$$= \sin\left(\omega_o\left(\left(1+\frac{2v}{c}\right)t-\tau\right)+\theta\right)$$

$$= \sin\left(\underbrace{\omega_o\left(1+\frac{2v}{c}\right)}_{\text{Frequency Shifted}}t+(\theta-\underbrace{\omega_o\tau}_{\text{Propagation delay phase shift}})\right).$$

This is a sinusoid of radian frequency

$$\omega_R = \omega_o \left(1 + \frac{2v}{c}\right)$$

or cyclic frequency

$$f_R = f_o \left(1 + \frac{2v}{c}\right).$$

We call

$$f_D = f_R - f_o = \boxed{\frac{2vf_o}{c}}$$

the <u>Doppler shift.</u>

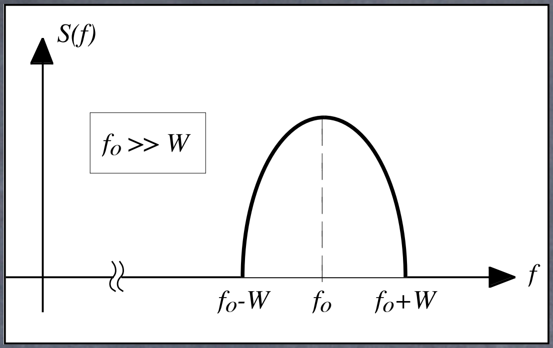
$$\boxed{f_D = \frac{2vf_o}{c} = \frac{2v}{\lambda}}$$

where

$$\lambda = \frac{c}{f_o} = \text{wavelength.}$$

- For signals of a single frequency, the Doppler effect corresponds to a shift in frequency.
- Doppler shift is proportional to carrier frequency and velocity.

The Narrowband Approximation



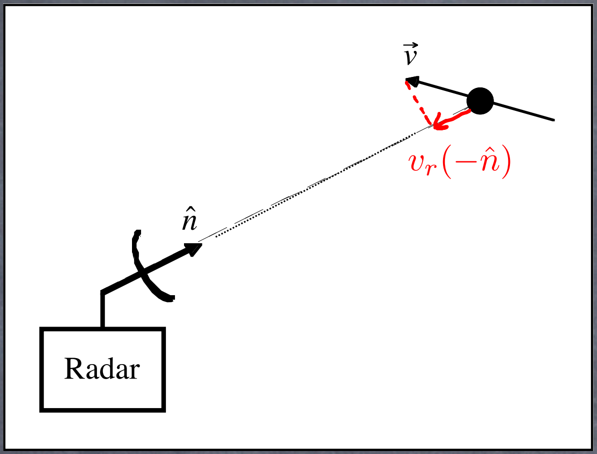
- If we have a narrowband signal (bandwidth << carrier freq.), we assume that each frequency component is shifted by the same amount
- This is an approximation—the "Narrowband Approximation"

In general, if $s(t) \overset{\mathcal{F}}{\Leftrightarrow} S(\omega)$

$$\sqrt{\alpha}s(\alpha t) \overset{\mathcal{F}}{\Leftrightarrow} \frac{1}{\sqrt{\alpha}} S\left(\frac{\omega}{\alpha}\right)$$

- This is a scaling in frequency, not a frequency shift.
- But for narrowband signals and v<<c, the narrowband approximation is good.
- In sonar, the narrowband approximation is often bad.

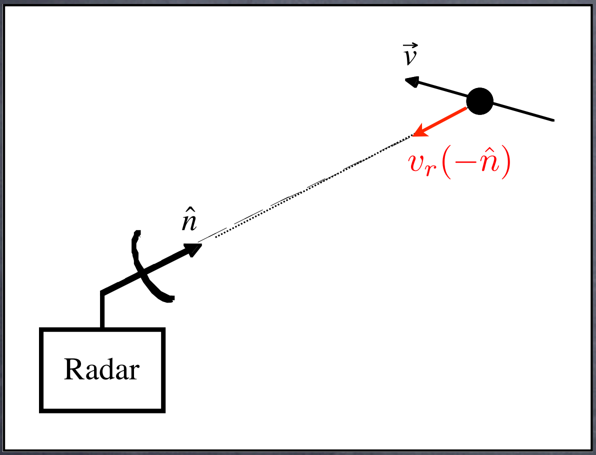
Radial Velocity and Doppler



- It is the radial component of the velocity that determines the Doppler effect.
- The radial velocity is the velocity is the velocity that matters in computing the Doppler shift.

Radial Velocity and Doppler

$$R(t) = \text{Range of the target from antenna at time } t$$



$$v_r = -\dot{R}(t) = \boxed{-}\frac{dR(t)}{dt}$$

Negative sign defines radial velocity directed at radar.

$$f_D = \frac{2 v_r f_c}{c} \quad \Longrightarrow \quad v_r = \frac{c f_D}{2 f_c}$$

Radial Velocity and Doppler

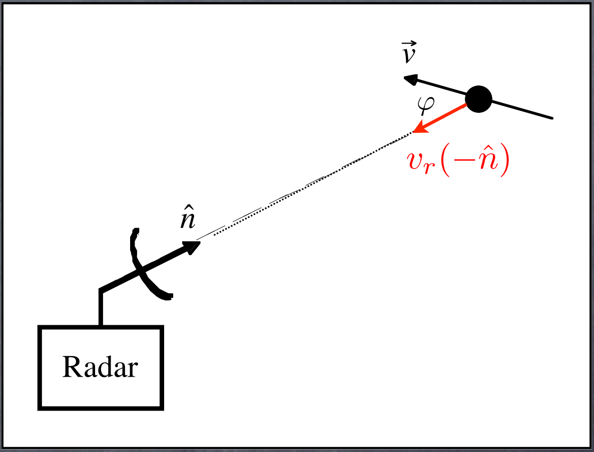
$$v_r = -\hat{n} \cdot \vec{v}$$

$$\Downarrow$$

$$f_D = \frac{-2(\hat{n} \cdot \vec{v}) f_c}{c}$$

In general

$$\vec{a} \cdot \vec{b} = |\vec{a}||\vec{b}| \cos\varphi$$



$$\Longrightarrow \; f_D = \frac{-2|\vec{v}| f_c \cos\varphi}{c}$$

“cosine effect”