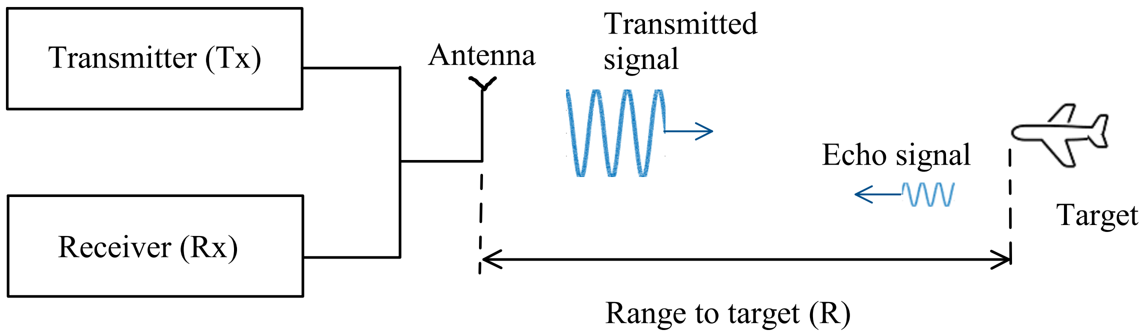
EE 585 - RADAR SYSTEMS

1. Radar principle, range measurements
2. Radar waveform (PRF, PRI)
3. Basic radar parameters
4. Simple Radar range Equation
5. Radar Applications and Examples

1. Radar principle:

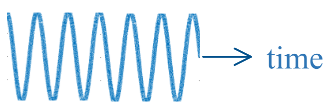
Radar: Radio Detection And Ranging



Radar original purpose: Detection and range measurement.

Classification of Radar:

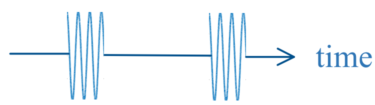
Continous wave (CW) Radar:



A cosine wave

- Modulated: Linear frequency modulated (LFM)
- Un-modulated

Pulse Radar:



Pulse modulated wave

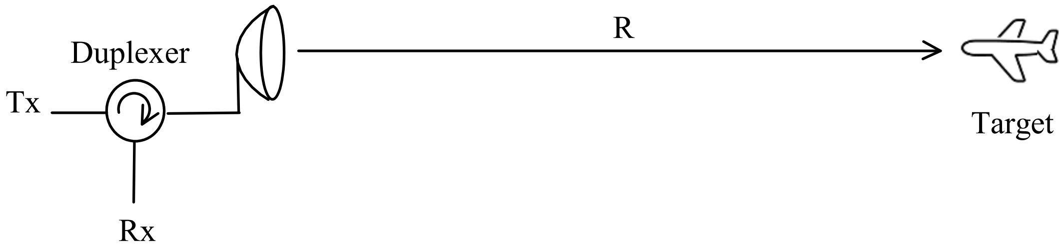
- Moving Target Indicator (MTI)
- Doppler

P2

Wednesday, October 2, 2024 1:40 PM

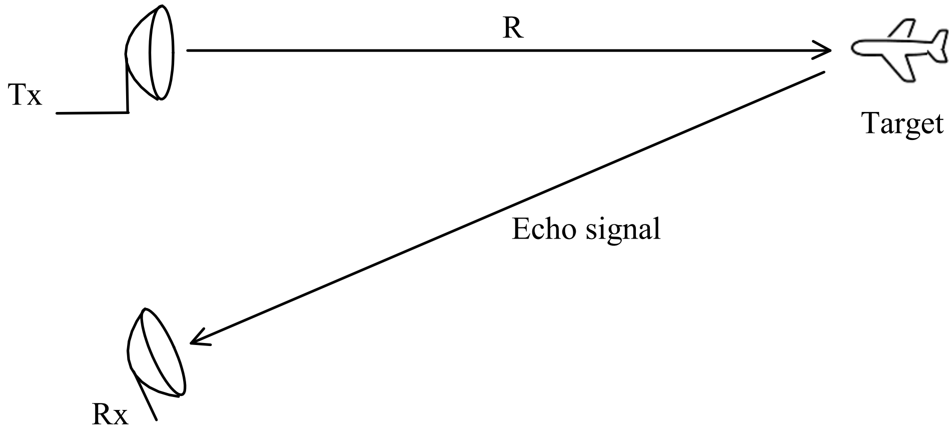
Radar Operations:

Monostatic system:



- High isolation between Tx and Rx is necessary.

Bi-static system:



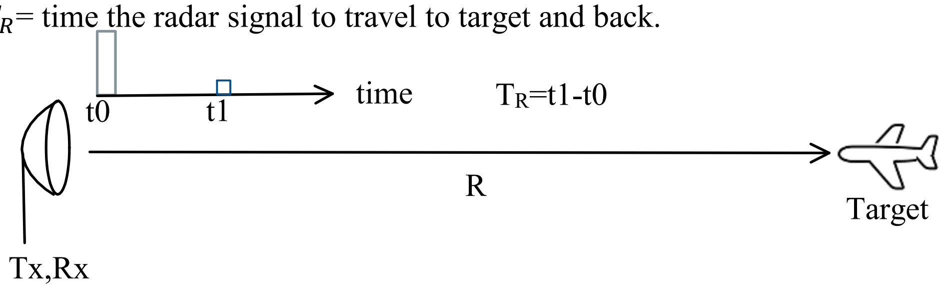
- Multi-static systems also exist with multiple Tx and Rx blocks.

Pulse Radar:

1. Range measurement:

c = wave velocity in air = 3×10^8 $\left(\frac{m}{s}\right)$.

T_R= time the radar signal to travel to target and back.



$$\Rightarrow 2R = c\,T_R = \left(3 \times 10^8\right) T_R$$

Thus,

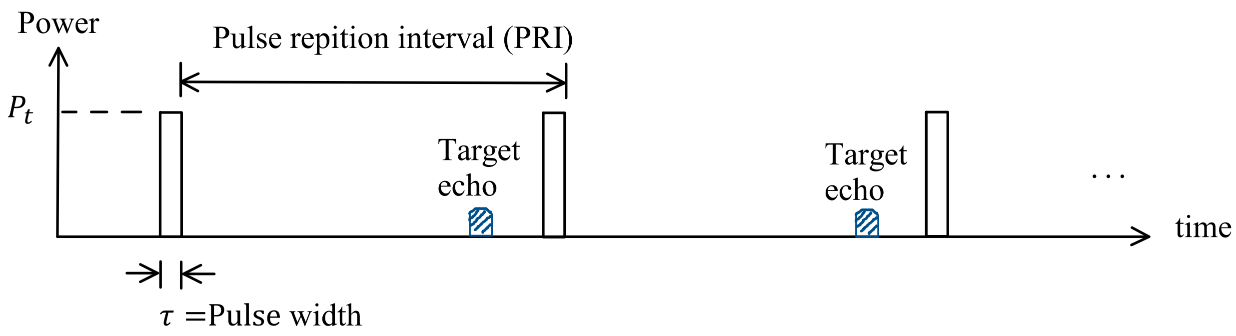
$$R = \frac{cT_R}{2}\ (m)$$

P3

Tuesday, October 1, 2024 12:32 PM

2. Radar waveform (pulse train)

Radar signal is a pulse train as shown below:



where

T_P = Pulse repition interval (PRI)

$f_P = 1/T_P$=Pulse repition frequency (PRF)

τ/T_P = Duty cycle

P_{av} = Average power $= \frac{1}{T_P}\int_0^{T_P} P(t)dt = \frac{1}{T_P}\tau P_t = P_t \tau f_P \ (W)$

E_P = Pulse energy $= P_t \tau$ (J)

Example:

An airborne pulsed radar has a peak power of 10kW, and uses two PRFs, $f_{P1} = 10\text{kHz}, f_{P2} = 30\text{kHz}$. What are the required pulse widths for each PRF so that the average transmitted power is constant and equal to 1500 watts. Compute the pulse energy in each case.

Answer:

$P_t = 10\text{kW}$,

$$P_{av} = 1500 = f_{P1}\tau_1 P_t \Rightarrow \tau_1 = \frac{1500}{f_{P1}P_t} = \frac{1500}{(10000)(10000)} = 15\ \mu s.$$

Similarly,

$$P_{av} = 1500 = f_{P2}\tau_2 P_t \Rightarrow \tau_2 = \frac{1500}{f_{P2}P_t} = \frac{1500}{(30000)(10000)} = 5\ \mu s.$$

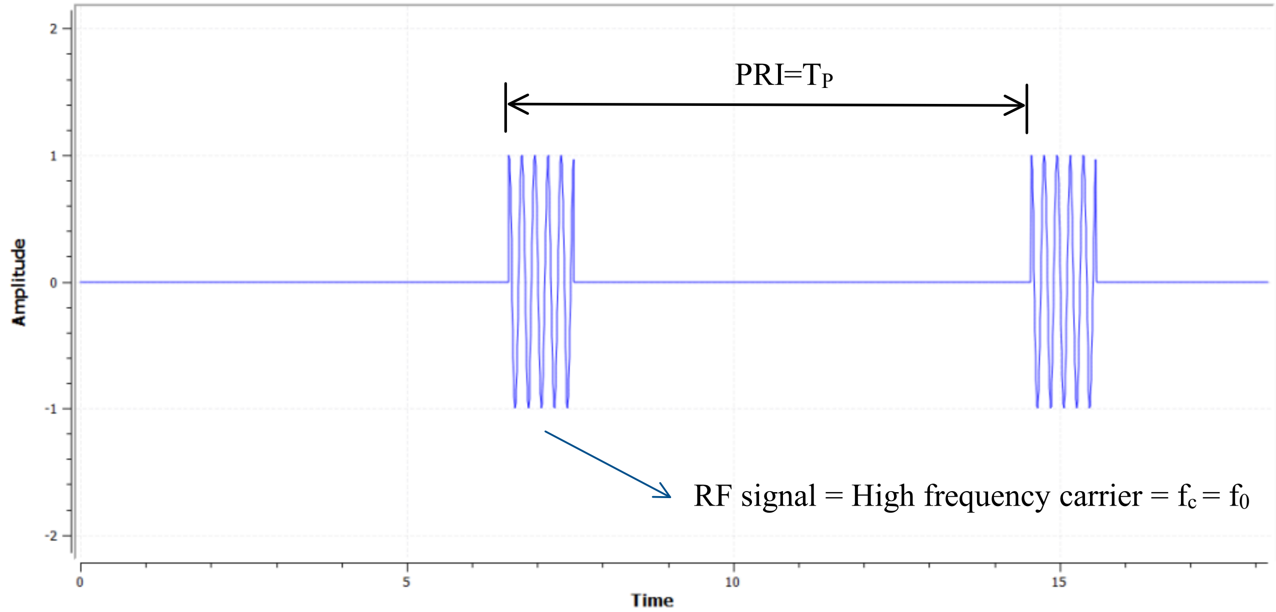
$E_{P1} = P_t\tau_1 = (10000)(15\mu s) = 0.15$ (J), $\quad E_{P2} = P_t\tau_2 = (10000)(5\mu s) = 0.05$ (J)

P4

Tuesday, October 1, 2024 1:20 PM

Radar Waveform Temporal (modulated pulse-train)

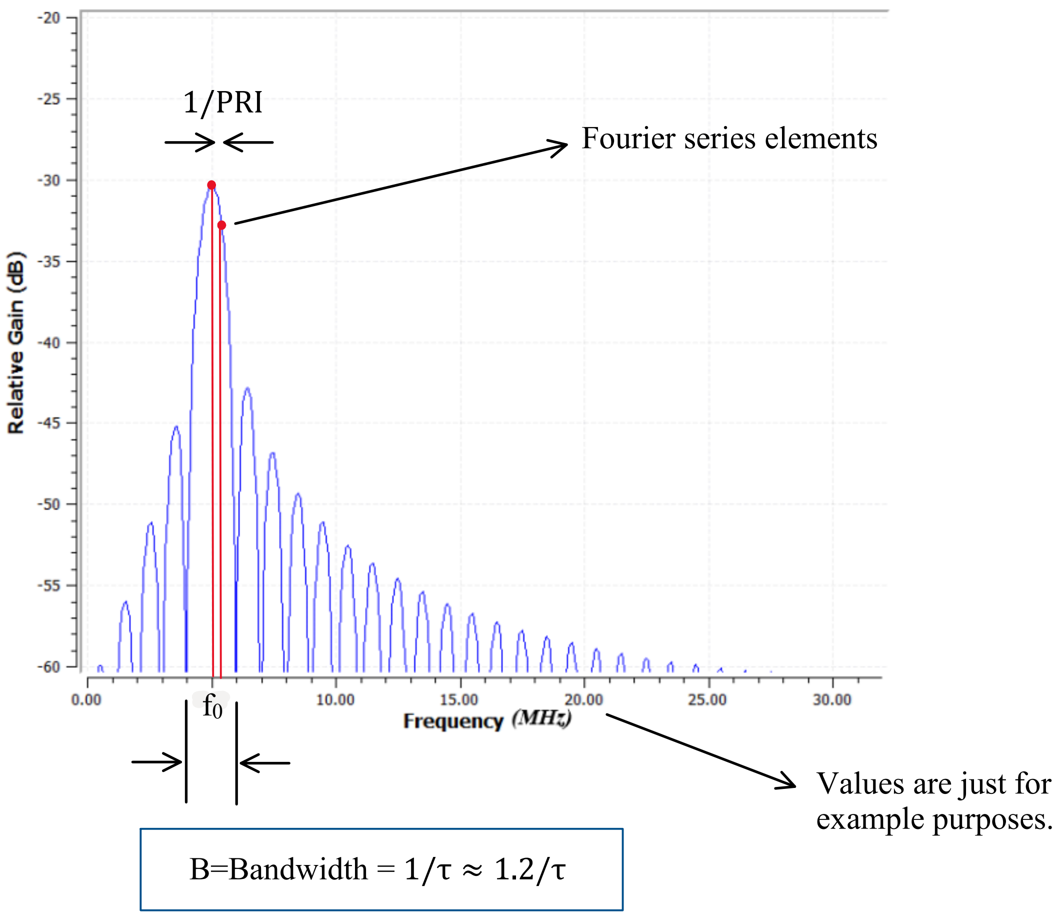
Radar signal is a modulated pulse train as shown below:



Note that $f_{RF} \gg f_P$.

Radar Waveform Spectral (sinc function)

Radar signal is a "sinc" function in frequency spectrum (using Fourier series):



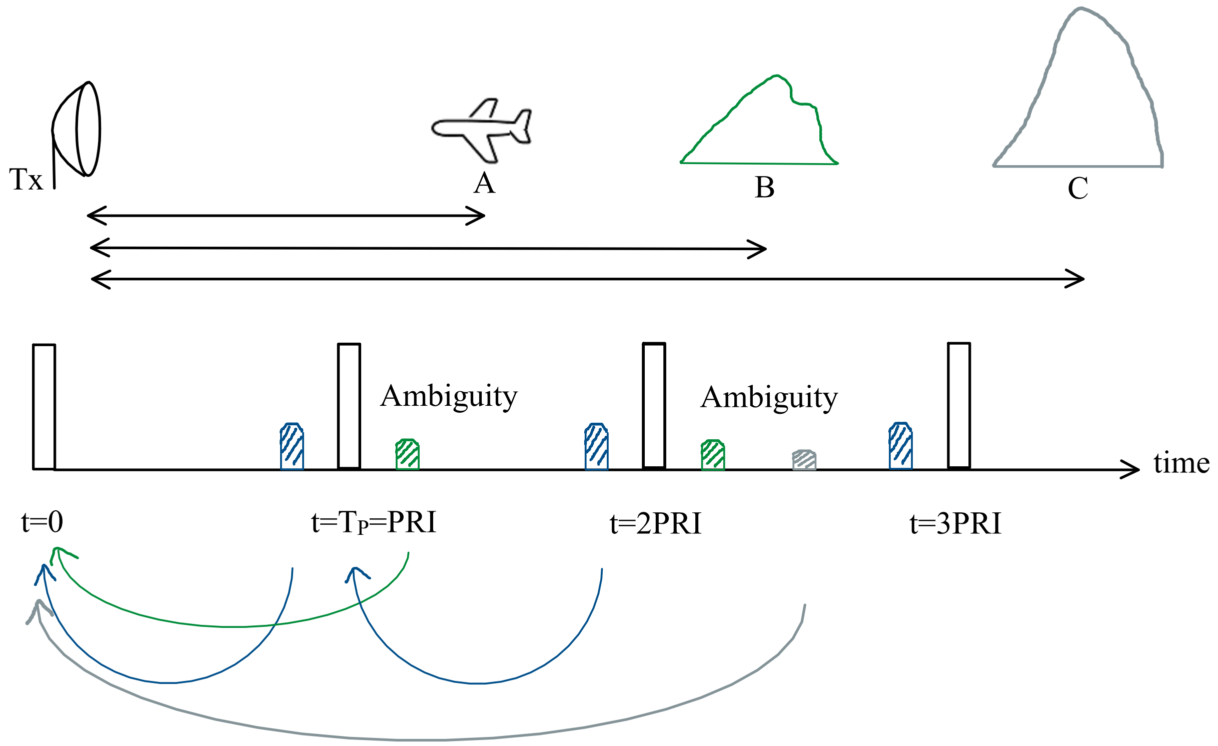
P5

Tuesday, October 1, 2024 2:13 PM

1. Basic Radar Parameters:

   (Maximum) Unambiguous Range:

- Time between the pulses is too short, then an echo signal from a long range target might arrive after the transmission of the next pulse, introducing an incorrect or ambiguous range measurement.

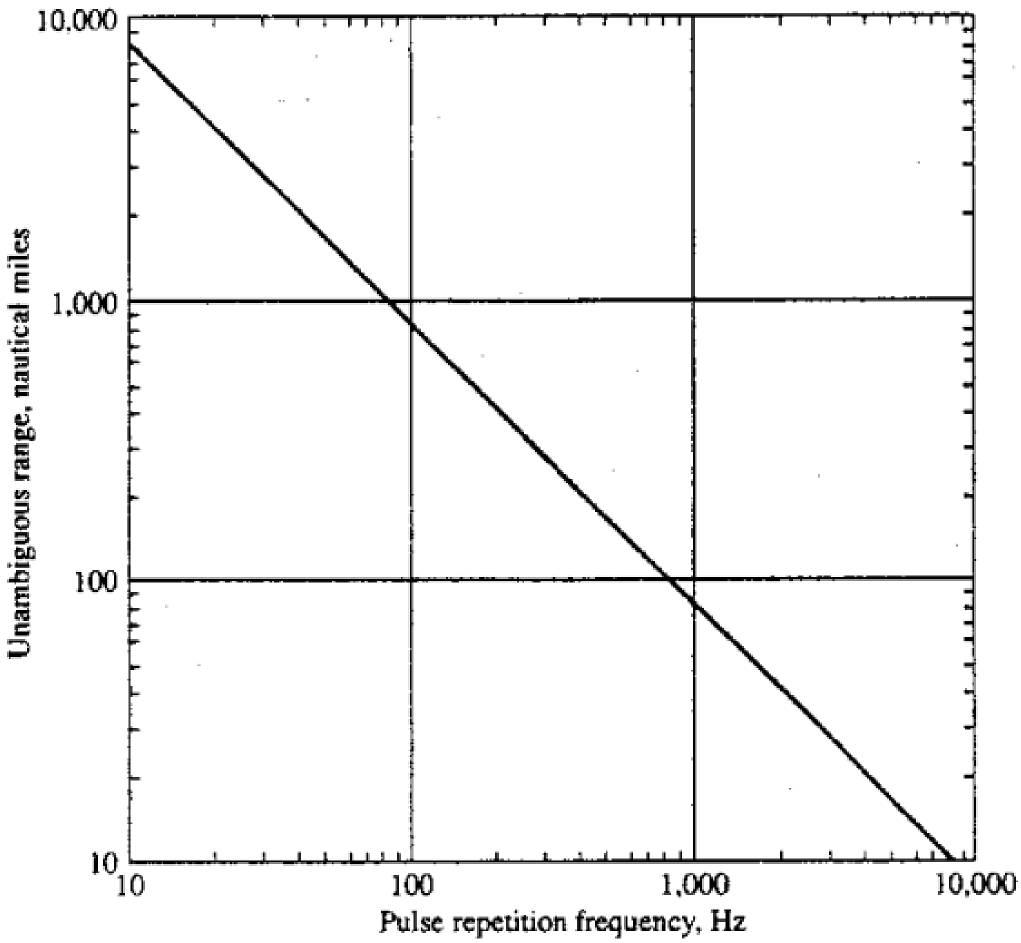


- Echos arriving after the transmission of the next pulse:
  - Second time around echos.
  - Multiple time around echos.
- The maximum unambiguous range is the range beyond which targets appear as second time around echos.

$$R_{un} = \frac{cT_P}{2} = \frac{c}{2f_P}$$

- R_{un} is defined before the use of the radar.

Unambiguous range α PRI:



(Skolnik, Introduction to Radar Systems)

Nautical miles = nm

1 nm = 1.85 km

1 mil = 1.6 km.

Example:

Find the unambugious range for a pulsed radar with 1 kHz PRF.

Answer:

From the graph, R_{un}=80 nm, $\Rightarrow R_{un} = (80)(1.85\text{km}) \approx 150$ km.

Example: Airborne Fire control radar (F16C/D)

Many variants in X-band=8-12.5 GHz. Low, medium and high PRF for air and surface targets.

Multimode radar system

- Low PRF (high PRI) mode: air to surface engagements (500 Hz)
- High PRF velocity search mode:increased detection range for air interceptions (15 kHz)
- Medium PRF search mode: increases range and angle information [0.5,15] kHz.
- More enhancements.

P8

Wednesday, October 2, 2024 11:49 AM

Example: Early warning radar (Tall King)

Properties:

- A-band=(150-170 MHz sub-band)
- Low PRF (100-200 Hz)
- Range=500-600 km (max. 1200 km)
- Power rate = 900 kW.
- First introduced in 1950's.
- Early warning against high altitude aircrafts.

Example:

For the last Tall King radar system with given properties, why is the antenna so big? Any advantages of this selection?

Answer:

1. Low carrier frequencies can use the atmosphere as a waveguide and do not escape to space; thus, the wave can travel further distances.
2. A_e = Receiving antenna effective capture area $= \frac{\lambda^2}{4\pi}$, thus for the same size antenna,

lower frequencies yield more energy reception, decreasing the free space path loss.

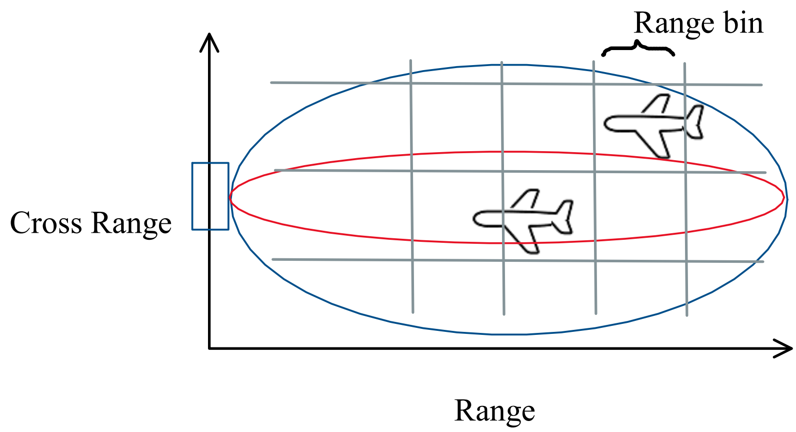
$(FSLP^{-1} = \left(\frac{\lambda}{4\pi R}\right)^2 = \frac{A_e}{4\pi R^2})$.

P9

Wednesday, October 2, 2024 2:10 PM

Range Resolution and Cross Range:

Divide the range into small intervals, called "bins".



The range bin is defines as

$$\Delta R = \frac{R_{max} - R_{min}}{N}$$

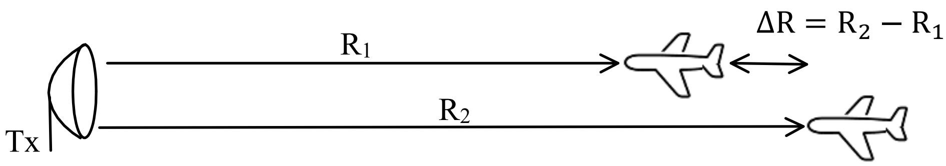
where N=Total number of bins in range.

Resolving targets in cross range requires signal processing techniques.

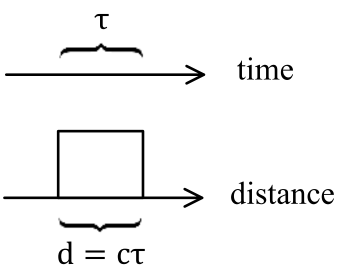
(limited by antenna beamwidth in azimuth)

Range resolution:

Consider two targets at distances R_1 and R_2.



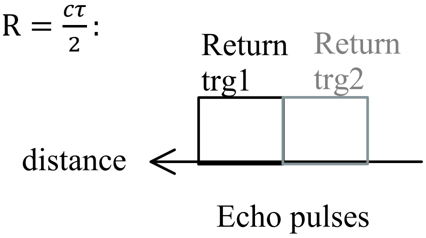
Pulse in time and distance:



$$\Rightarrow \Delta R = \frac{c\tau}{2} = \frac{c}{2B}$$

(Range resolution)

If $\Delta R = \frac{c\tau}{2}$:



Thus, $\Delta R \geq \frac{c\tau}{2}$ is the necessary condition in order to resolve targets seperated by ΔR.

P10

Example:

For a radar system with an unambiguous range of 100 km, and a bandwidth of 0.5 MHz, compute the required PRF, PRI, ΔR, and τ.

Answer:

$$\mathrm{R_{un}} = 10^5 = \frac{c}{2f_P}$$

$$\Rightarrow \mathrm{f_P} = \frac{c}{2 \times 10^5} = 1500\ m = 1.5\ km.$$

$$\Rightarrow \mathrm{T_P} = \frac{1}{f_P} = \frac{1}{1500} = 6.67 \times 10^{-4}\ sec. = 0.667\ ms.$$

Then, range resolution is

$$\Delta\mathrm{R} = \frac{c}{2B} = \frac{3 \times 10^8}{2 \times 0.5 \times 10^6} = 300\ m.$$

Also,

$$\tau = \frac{1}{B} = \frac{1}{0.5 \times 10^6} = 2\ \mu s.$$

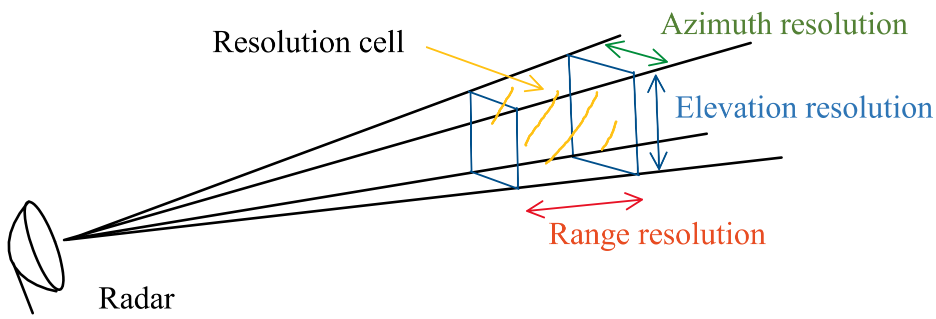
P11

Wednesday, October 9, 2024 6:39 PM

Radar Resolution Cell:

It defines the resolution in 3D as:

1. Range resolution $\propto$ pulse width.
2. Azimuth resolution $\propto$ antenna beamwidth in azimuth
3. Elevation resolution $\propto$ antenna beamwidth in elevation.



Example:

Calculate range resolutions for a target at 100 km for an early warning radar system.

f=1 GHz, PRF=300 Hz, PW=10 us,

Antenna beamwidth (azimuth) = 2^o = 0.035 rad.

Antenna beamwidth (elevation) = 5^o = 0.087 rad.

Answer:

Range resolution= $\Delta R = \frac{c\tau}{2} = \frac{(3\times10^8)(10\times10^{-6})}{2} = 1500\text{m}.$

Azimuth resolution=(Beamwidth)(range)=(100000)(0.035) = 3.5 km.

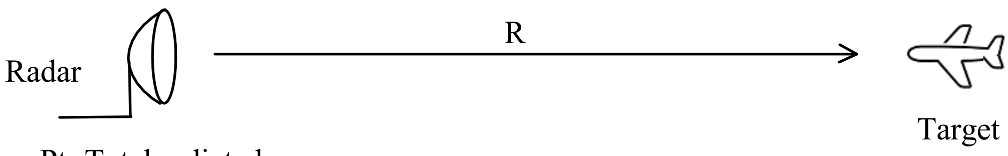
Elevation resolution=(Beamwidth)(range)=(100000)(0.087) = 8.7 km.

P12

Wednesday, October 9, 2024 8:31 PM

Radar Range Equation:

Consider the following radar radiating a total power of Pt and gain G:



Pt=Total radiated power
G=Antenna gain at broadside

Define "Effective isotropic radiated power" (EIRP) as

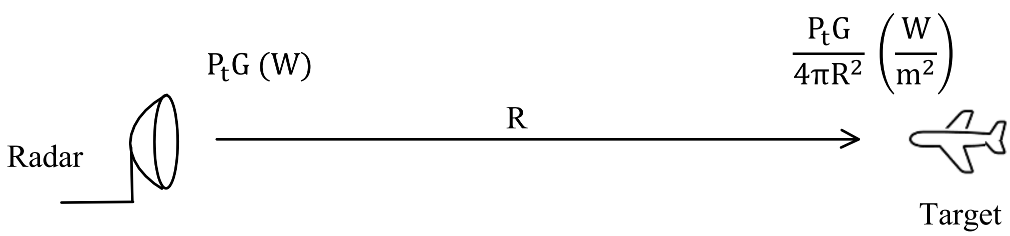
$$\boxed{EIRP = P_t G}$$

EIRP is the total power radiated by an isotropic source which yields the same power density at broadside as the radar antenna.

Thus, at distance R from the radar antenna, the power density is:

$$\boxed{P = \frac{EIRP}{4\pi R^2} = \frac{P_t G}{4\pi R^2}\left(\frac{W}{m^2}\right)}$$

Thus, we can depict this power density at the target as shown below:



When this power density, P, hits the target, it generates a reflected power (W), which is

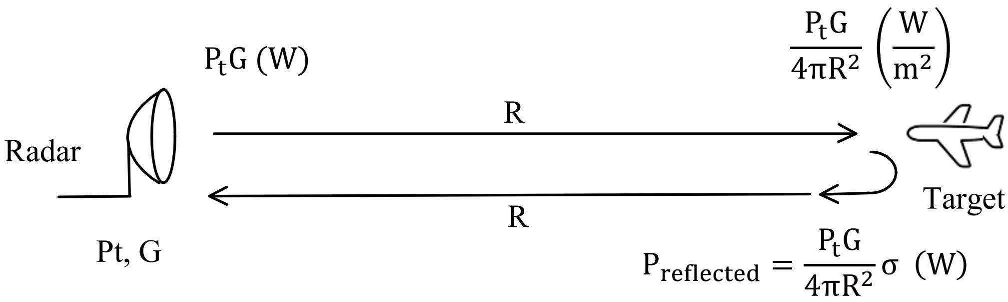
$$P_{reflected} = \frac{P_t G}{4\pi R^2}\sigma \ (W)$$

where σ = equivalent target area (m^2) that generates the amount of reflected power from the target. Note that σ is not the physical area, the physical area may be large, but the reflected power may be small giving rise to a small effective target area (σ = Radar Cross Section).

P13

Wednesday, October 9, 2024 8:57 PM

Thus, we can depict this reflected power from the target as shown below:



This reflected power also travels a distance R, back to the radar antenna. Thus, the power density of this reflected power at the radar antenna can be written as

$$P_{density} = \frac{P_tG}{4\pi R^2}\sigma\left(\frac{1}{4\pi R^2}\right) \quad (W/m^2)$$

Then, the total received power by the radar antenna is equal to this power density times the effective area (effective aperture) of the radar antenna, in other words, the received power, P_r is

$$P_r = P_{density}A_e \Rightarrow \qquad P_r = \frac{P_tG}{4\pi R^2}\sigma\left(\frac{1}{4\pi R^2}\right) A_e \quad (W)$$

or

$$\boxed{P_r = \frac{P_tGA_e\sigma}{(4\pi)^2R^4} \quad (W)} \qquad \text{(Radar Range Equation)}$$

where effective area is related to the antenna gain by

$$\boxed{A_e = \frac{\lambda^2}{4\pi}G} \qquad \text{(Effective Aperture)}$$

Note that for the same frequency, as the antenna gain increases, the effective aperture also increases, and visa versa.

If we call the minimum received power required by the radar to operate correctly as $S_{min} = P_r|_{min}$, then,

$$\boxed{S_{min} = \frac{P_tGA_e\sigma}{(4\pi)^2R_{max}^4} \quad (W)}$$

P14

Wednesday, October 9, 2024 9:14 PM

Substituting A_e from the previous equation gives

$$S_{min} = \frac{P_t G \sigma}{(4\pi)^2 R_{max}^4} \frac{\lambda^2}{4\pi} G \ \ (W)$$

Solving for R_{max} gives

$$R_{max} = \left[\frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 S_{min}}\right]^{1/4}$$

Example:

In order to double the range, how much the tranmitter power must be increased?

Answer:

$$2 = (P_t)^{1/4} \Rightarrow P_t = 2^4 = 16$$

Example:

In order to double the range, how much the wavelength must be increased?

Answer:

$$2 = (\lambda^2)^{1/4} = (\lambda)^{1/2} \Rightarrow \lambda = 2^2 = 4$$

It's important to note that reducing the carrier frequency by a factor of four can appear to be a straightforward method for increasing range. However, at lower frequencies, it becomes necessary to increase the antenna size in order to maintain a consistent gain, which may be impractical.

In the following questions, we will examine the effect of one variable while assuming that all other variables remain constant. We should keep this in mind!