Radar

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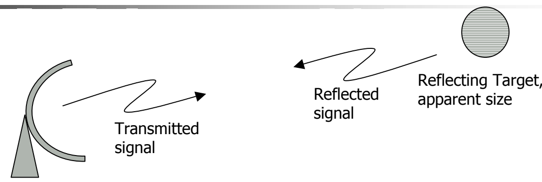
Radar

- Acronym for RAdio Detection And Ranging
- Radar can be thought of as a pair of one-way communication links, with the return link being the radar reflection.
- Consider the radar problem, where in general the transmitter and receiver are co-located and the received signal is a reflection
- The expression for power density at a distance *d* is,

$$W = \frac{P_T \cdot G_T}{4\pi\, d^2} \text{ watts/m}^2$$

Typical Radar Geometry



- A typical radar system consists of a co-located pulsed transmitter and a receiver, usually sharing an antenna
- A pulse is transmitted and then the receiver listens for the return, similar to sonar
- The strength of the return signal depends upon the distance to the target and its (electrical) size
- The radar determines the distance to the target from the time delay before receiving the reflected pulse

Free Space Propagation

- The power density at a distance, *d*, is

$$W = \frac{EIRP}{4\pi\, d^2} \text{ watts/m}^2$$

- The power available at the output of a receive antenna would be the product of the power density at that point times the antenna's effective area

$$P_R = \frac{P_T \cdot G_T}{4\pi\, d^2} \cdot A_e$$

- Substituting the expression for antenna gain yields the Friis free space loss equation

$$P_R = \frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2}{(4\pi)^2\, d^2} \text{ watts} \quad \text{or} \qquad L = \frac{P_R}{P_T} = \frac{G_T \cdot G_R \cdot \lambda^2}{(4\pi\, d)^2}$$

Radar Cross-Section

- Instead of a receive antenna effective area, in radar, the signal is determined by the RCS
- The radar cross-section (RCS) is a measure of the electrical or reflective area of a target
- It may or may not correlate with the physical size of the object
- It is usually expressed in m^2, or dBsm
- The symbol for RCS is σ_t

The Radar Equation

- So, the reflected signal can be determined from the power density at the target times the RCS

$$P_{refl} = \frac{P_T \cdot G_T}{4\pi\, d^2} \cdot \sigma_t$$

- The power density at the receiver from the reflected signal is

$$W_R = \frac{P_T \cdot G_T \cdot \sigma_t}{4\pi\, d^2} \cdot \frac{1}{4\pi\, d^2}$$

- When multiplied by the effective area of the radar antenna, this becomes

$$P_R = \frac{P_T \cdot G_T \cdot \sigma_t \cdot A_e}{(4\pi)^2\, d^4} = \frac{P_T \cdot G_T \cdot G_R \cdot \sigma_t \cdot \lambda^2}{(4\pi)^3\, d^4}$$

The Radar Range Equation

- For a required received signal level, we can solve the radar equation for *d* and find the maximum distance at which detection is possible

$$d_{max} = \sqrt[4]{\frac{P_T \cdot G_T \cdot G_R \cdot \sigma_t \cdot \lambda^2}{P_{R\min}(4\pi)^3}}$$

- In radar, it is customary to use *R* for range instead of *d* for distance

Radar Example

- Consider a radar system with the following parameters:

f = 2 GHz	σ_t = 1 m^2
P_T = 1 w = 0 dBw	$G_T = G_R$ = 18 dB
R = 2 km	B = 50 kHz
F = 5 dB	λ = 0.15 m

- What is the SNR at the receiver?

Radar Example

- The received signal level is

$$P_R = \frac{P_T \cdot G_T \cdot G_R \cdot \sigma_t \cdot \lambda^2}{(4\pi)^3 \, d^4}$$

- This can be computed in dBW as

P_R = 0 dBW + 18 dB + 18 dB + 0 dBsm + 20log(0.15) dBsm – 30 log(4π) - 40log(2000)dBm^4

(-16.5 dBsm) (- 33 dB) (–132 dBm^4)

P_R = -145.5 dBW or –115.5 dBm

Radar Example

- The receiver noise power is

$$N = kT_oBF$$

or,

N_{dBm} = -174 dBm/Hz + 10log(50,000)dB-Hz + 5 dB

(47 dB-Hz)

$$N_{dBm} = -122 \text{ dBm}$$

- And the SNR is

P_R – NdBm = -115.5 dBm – (-122 dBm) = 6.5 dB

Comments

- Note that the received power is inversely proportional to R^4, so doubling the distance reduces the signal level by 12 dB
- The round-trip path loss is **NOT** equal to 3 (or 6 dB) more than the one-way path loss.
- It is **double** the one-way loss in dB (i.e. loss is squared)

Pulse Radar

- Conventional pulse radar works by transmitting a short RF pulse and measuring the time delay of the return
- The bandwidth of the matched filter receiver is ~ $1/\tau$ where τ is the pulse width (this is used as the NEB in noise calculations)
- τ also determines the range resolution of the radar

$$\Delta r = \frac{c\tau}{2}$$

Pulse Radar

- Shorter pulses require larger receive bandwidths (more noise), provide less average power (less signal) but provide better range resolution
- The matched filter has an impulse response that matches the transmitted pulse
- The range to the target is

$$R = \frac{c \cdot \Delta t}{2}$$

- Where Δt is the elapsed time between transmission and reception of the pulse

Pulse Radar

- The pulses are usually transmitted periodically. This period is called the PRI or the PRT
- The pulse repetition frequency is

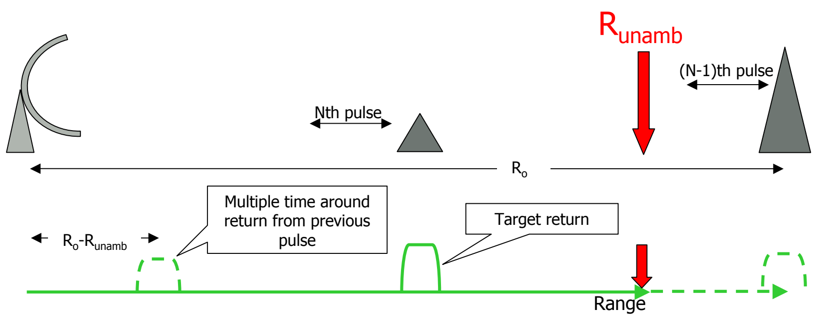
$$\mathrm{PRF} \equiv \frac{1}{\mathrm{PRI}}$$

- The PRI defines the maximum unambiguous range of the system

$$R_{unamb} = \frac{c \cdot PRI}{2}$$

Pulse Radar

- A large target beyond the unambiguous range may be interpreted as a close target

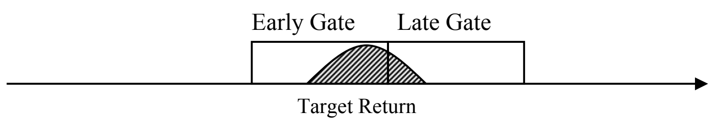


Pulse Radar

- For multiple time around returns to be an issue, the RCS of the distant reflector must usually be large
- Ideally, we would like R_{unamb} to be well beyond the maximum detection range of the radar
- In practice there are ways to mitigate the effect of these returns.

Range Measurement

- Target range can be estimated with an accuracy better than the pulse width by using a split-gate tracker
- By comparing the energy in the early and late gates, an estimate of the target position is obtained



Radar Clutter

- Clutter is defined as any unwanted radar echo
- Ground target returns will include ground clutter (*area clutter*)
- Airborne target returns may include *volume clutter* from precipitation in the propagation path

Area Clutter

- Area clutter is characterized by the average clutter cross-section per unit area, σ^{o} (sigma-zero)
- This is called the backscatter coefficient
- The units are m^2/m^2
- The amount of clutter received depends upon how much ground area is illuminated

Area Clutter

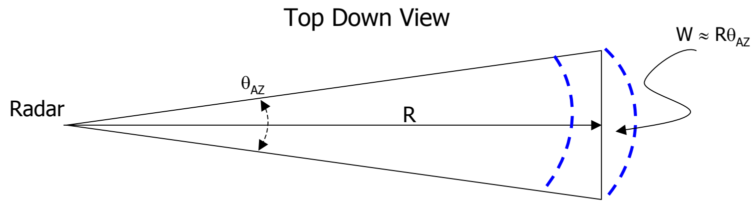
- The width of the clutter patch is defined by the antenna azimuth beamwidth and the range or distance to the clutter patch
- The length of the clutter patch is determined by either
  - the range gate size (shallow grazing angle)
  - or the elevation beamwidth for steeper grazing angles such as an airborne radar illuminating a ground target

Area Clutter

- The width of the clutter cell is

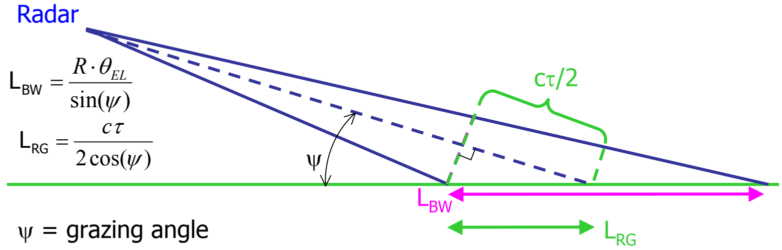
$$W \cong R\theta_{AZ}$$

- Where R is the range to the center of the clutter cell and θ_{AZ} is the antenna azimuth beamwidth in radians



Area Clutter

- The depth or length of the clutter cell is determined by the smaller of the
  - Range gate projected onto the ground
  - The elevation beamwidth times the total range projected onto the ground



$$L_{BW} = \frac{R \cdot \theta_{EL}}{\sin(\psi)}$$

$$L_{RG} = \frac{c\tau}{2\cos(\psi)}$$

ψ = grazing angle

Area Clutter

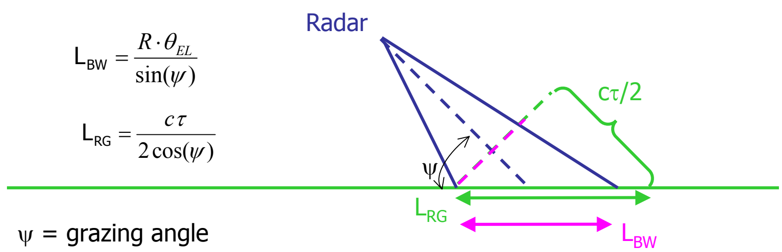
- Thus the length of the clutter cell can be expressed as

$$l \approx \min(\frac{c\tau}{2}\sec(\psi), R\theta_{EL}\csc(\psi))$$

$$L_{BW} = \frac{R \cdot \theta_{EL}}{\sin(\psi)}$$

$$L_{RG} = \frac{c\tau}{2\cos(\psi)}$$

ψ = grazing angle



Area Clutter

- As seen from the preceding development, these values are approximate
- In addition, we know that the antenna beam has a roll-off, it does not drop off to zero gain at the edge of the 3 dB beamwidth

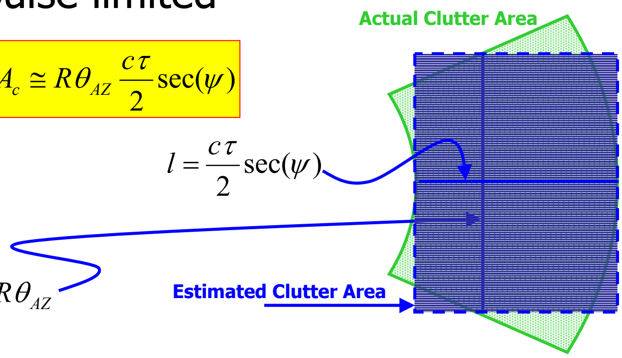
Area Clutter

- So at shallow grazing angles, when pulse limited

$$A_c \cong R\theta_{AZ}\frac{c\tau}{2}\sec(\psi)$$

$$l = \frac{c\tau}{2}\sec(\psi)$$

$$W = R\theta_{AZ}$$



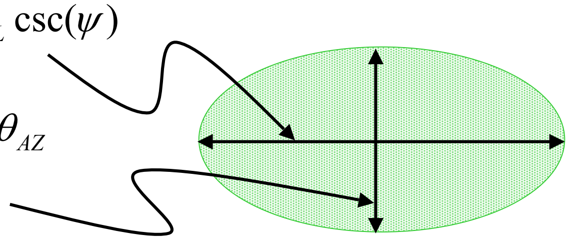
Area Clutter

- At steeper angles, when beam limited the clutter area is simply the area of the elliptical footprint

$$A_c = \frac{\pi}{4}R^2\theta_{EL}\theta_{AZ}\csc(\psi)$$

$$R\ \theta_{EL}\csc(\psi)$$

$$R\ \theta_{AZ}$$



Clutter Cross-Section

- The actual radar cross-section of the clutter is the clutter patch area multiplied by the backscatter coefficient

$$\sigma_c = \sigma^0 \cdot A_c$$

- We will only consider the pulse-limited, low grazing angle case where:

$$A_c = R\theta_{AZ} \frac{c\tau}{2} \sec(\psi)$$

Return Clutter Power

- The clutter reflection power seen at the radar is

$$P_c = \frac{P_T G^2 \lambda^2 \sigma_c}{(4\pi)^3 R^4}$$

$$P_c = \frac{P_T G^2 \lambda^2 \sigma^0 R\theta_{AZ} \frac{c\tau}{2} \sec(\psi)}{(4\pi)^3 R^4}$$

$$P_c = \frac{P_T G^2 \lambda^2 \sigma^0 \theta_{AZ} \frac{c\tau}{2} \sec(\psi)}{(4\pi)^3 R^3}$$

!

Return Clutter Power

- Thus as R increases, the clutter power drops by $1/R^3$, whereas the target power drops as $1/R^4$
- This is due to the beam spreading with distance increasing the amount of clutter that is seen
- For the <u>beam-limited case</u>, the clutter area is a function of R^2 so the return clutter power is proportional to $1/R^2$, versus $1/R^4$ for the target power

Ways to Mitigate Clutter

- Narrow antenna beams
- Short pulses
- Averaging multiple "looks" when the clutter has a short correlation time such as vegetation
- Make use of Doppler
  - If the target is moving, it is possible to take multiple looks and then filter the sequence (FFT) to extract the moving target
  - If the radar is stationary, the clutter will be centered at the zero Doppler bin

Ways to Mitigate Clutter

- If the radar is airborne, the ground clutter will have a non-zero Doppler shift, but it can be identified and ignored as long as the target has motion relative to the ground
- Doppler resolution is determined by the number of range samples used
- There can be Doppler ambiguities if the the Doppler is sufficiently large
- This is aliasing and is controlled by decreasing the time between samples, PRI, at the expense of the unambiguous range

Radar Clutter Example

- Suppose we have a radar system with
  - P_T = 1,000,000 w
  - G_{ANT} = 28 dB
  - τ = 100 μs
  - T_{eff} = 200 K
  - f = 10 GHz
- What is the SNR of the return from a 1 m^2 target at 20 km?
- Wavelength $\lambda = c/f = 0.03$ m
- Bandwidth $B \approx 1/\tau = 10$ kHz

Radar Clutter Example

- Noise floor
  - $F = 10\log(1+T_{eff}/T_0) = 2.3$ dB
  - $N = -204$ dBW/Hz + 10log(10 kHz) + F
  - $N = -161.7$ dBW
- Return signal

$$S = \frac{P_T G_T G_R \sigma \lambda^2}{(4\pi)^3 R^4}$$

  - P = 60 dBW + 28 + 28 + 0 – 30.5 – 30log(4π) – 40 log(20,000)
  - P = 60 +56 – 30.5 – 33 – 172 = -119.5 dBW
- Signal-to-Noise ratio
  - SNR = -119.5 dBW + 161.7 dBW = 42.2 dB

Radar Clutter Example

- If
  - the azimuth beamwidth is $\theta_{AZ} = 0.3°$
  - the grazing angle is $\psi = 5°$
  - and $\sigma^0 = 0.01$,
- What is the Signal-to-Clutter ratio (SCR)
- What is the Clutter-to-Noise ratio (CNR)

Radar Clutter Example

- First we must compute the clutter return
  - Clutter Area

$$A_c = R\theta_{AZ}\frac{c\tau}{2}\sec(\psi)$$

    - Ac = 20,000 (m)·0.00523 (rad)·1.5·10^8 (m/s)·10^{-4} (s)·sec(5°) = 1,575000 m^2
    - Which can be expressed as 62 dB-m^2 or 62 dBsm

Radar Clutter Example

- Next we compute the power received from clutter reflection

$$P_c = \frac{P_T G^2 \lambda^2 \sigma^0 A_c}{(4\pi)^3 R^4}$$

- P_c = 60 dBW + 56 – 30.5 dBm² + 10log(0.01) + 62 dB-m² – 33 –172
- So the clutter return is Pc = -77.5 dBW

Radar Clutter Example

- The signal-to-clutter ratio
  - SCR = -119.5 + 77.5 = -42 dB
- The clutter-to-noise ratio
  - CNR = -77.5 + 161.7 = 84.2 dB
- So for this system clutter is the limiting factor (80 dB over the noise) and the signal is buried in clutter.
- It would require a significant amount of processing to extract a meaningful signal from 42 dB below the clutter

Volume Clutter

- When considering volume clutter, the overall volume of clutter that is illuminated depends upon
  - Range gate length
  - Range to the range gate of interest
  - Azimuth and elevation beamwidth of the antenna
- The volume of the clutter cell will be approximately

$$V = (\pi/4) \cdot (c\tau/2) \cdot R \cdot \theta_{EL} \cdot R \cdot \theta_{AZ} \ \ m^3$$

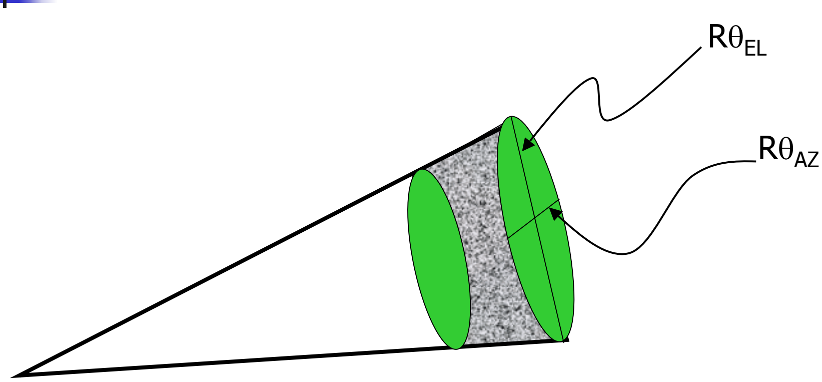
Volume Clutter

- Volume clutter is characterized by the backscatter cross-section per unit volume, η, which is in units of m^2/m^3
- The total clutter cross section then becomes

$$\sigma = \eta \cdot \frac{\pi}{4} \cdot \frac{c\tau}{2} \cdot R^2 \theta_{AZ}\ \theta_{EL}\ \ \mathrm{m}^2$$

- So when the radar range equation is applied, we find that the clutter return only decreases as R^2 because of the dependence of the clutter volume on R^2

Volume Clutter Cell



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Conclusions

- Radar systems suffer path loss that is proportional to R^4 rather than the R^2 for the one-way propagation of a communication system
- The radar range equation provides a power means of predicting return signal strength
- Clutter can be either area (ground) or volume (weather)
- Since the clutter area or volume grows with R or R^2, the clutter does not decrease with distance as quickly as the signal strength does
- The return signal strength is proportional to a parameter called the radar cross section which may be applied to clutter or to targets