Combat Systems Engineering - Radar Systems

Class 2 – Radar Range Equation

Chapter #2 Lecture

Instructor – Ingar Blosfelds

Class Logistics

- Schedule:
  - Wednesday, 6:30 – 9:00 pm, Rowan Hall Extension 319
  - 15 class periods, 1 final exam period
- Required Textbook:
  - "Principles of Modern Radar, Basic Principles"
  - www.amazon.com
- Class notes (pdf e-mailed prior to each class):
- Grading:
  - 50% final
  - 20% midterm (take-home)
  - 30% homework (none this week) (only Top 10 count, zero for late)
- Communications (e-mail preferred)
  - Ingar.T.Blosfelds@LMCO.com
  - 856 722-6161 work number

Class Schedule

Class		Subject	Date
1	**Overview**	Introduction	9/5/2018
2		Radar Equation	9/12/2018
3		Detection / Probability	9/19/2018
4	**External Factors**	Propagation Effects	9/26/2018
5		Clutter Characteristics	10/3/2018
6		Target Reflectivity / Fluctuation Models	10/10/2018
7	-Midterm distributed-	Doppler Phenomenology / Fourier Transform	10/17/2018
8	**Subsystems**	Antennas	10/24/2018
9	- Midterm due -	Transmitters / Solid State Antennas	10/31/2018
10		Receivers / Exciters	11/7/2018
11	**Signal/Data Processing**	Signal Processing	11/14/2018
12	- Thanksgiving -	Pulse Compression Waveforms	11/21/2018
13		Doppler Waveforms	11/28/2018
14	- Final distributed -	CFAR	12/5/2018
15		Radar Tracking	12/12/2018
	FINAL EXAM	Final Exam Due at 9 pm	12/19/2018

Class Overview

- Radar Equation
- Receiver Thermal Noise
- Multiple Pulses
- Summary of Losses
- Decibel Tutorial
- Different Forms of the Radar Equation
- Radar Equation - One-way

Radar Equation – Defined

- The radar equation defines, for a given amount of transmitter power and a given processing technique, how large of a target can be detected at a particular range

Radar Equation – Power Density

- Transmitted RF energy radiates isotropically or omni-directionally
- Power density decreases as the sphere of RF energy propagates and spreads

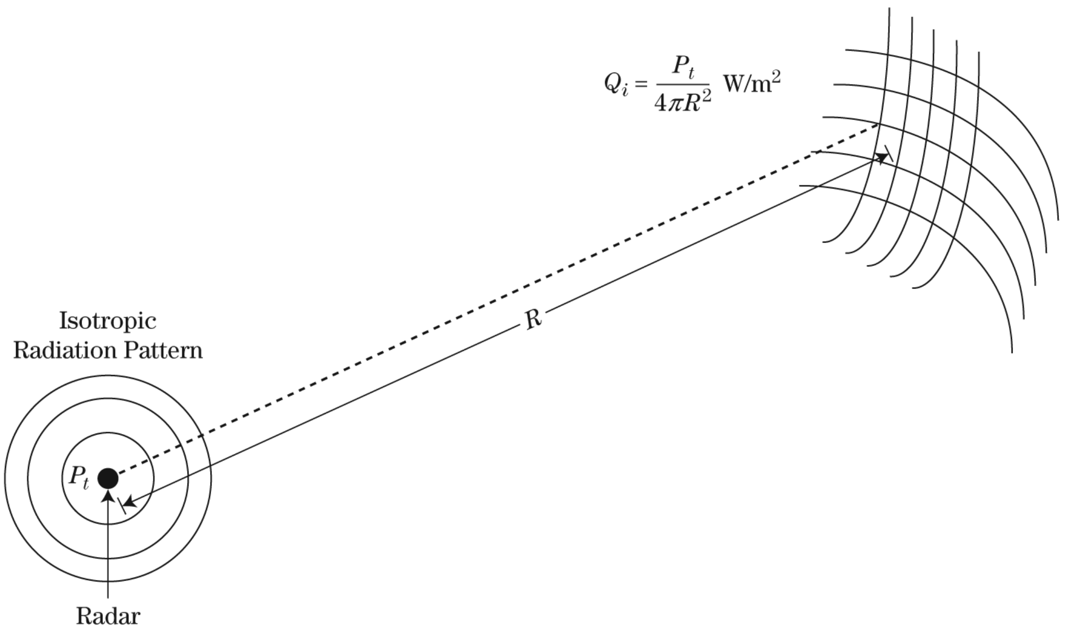

FIGURE 2-1 ■ Power density at range R from the radar transmitter, for an isotropic (omnidirectional) antenna.

"Used with Permission from Richards et al Principles of Modern Radar, Basic Principles (www.scitechpub.com)"

Radar Equation – Free-space Path Loss

- Free-space path loss is a line of sight reduction in sensitivity. A doubling in range equals a quadrupling in surface area (S_A).
- There is no refraction or diffraction factored into the radar equation.

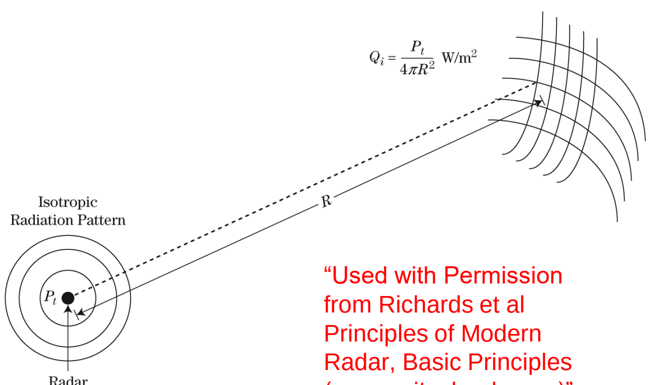

FIGURE 2-1 ■ Power density at range R from the radar transmitter, for an isotropic (omnidirectional) antenna.

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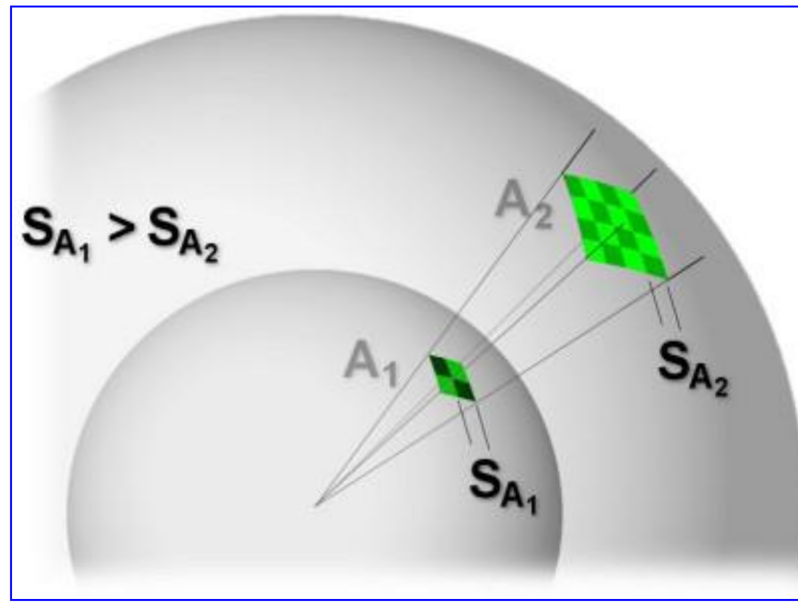

Radar Equation – Antenna Directivity

- Transmitted RF energy can be focused through the antenna as represented by the antenna gain, G_t

FIGURE 2-2 ■ Power density at range R given transmit antenna gain G_t.

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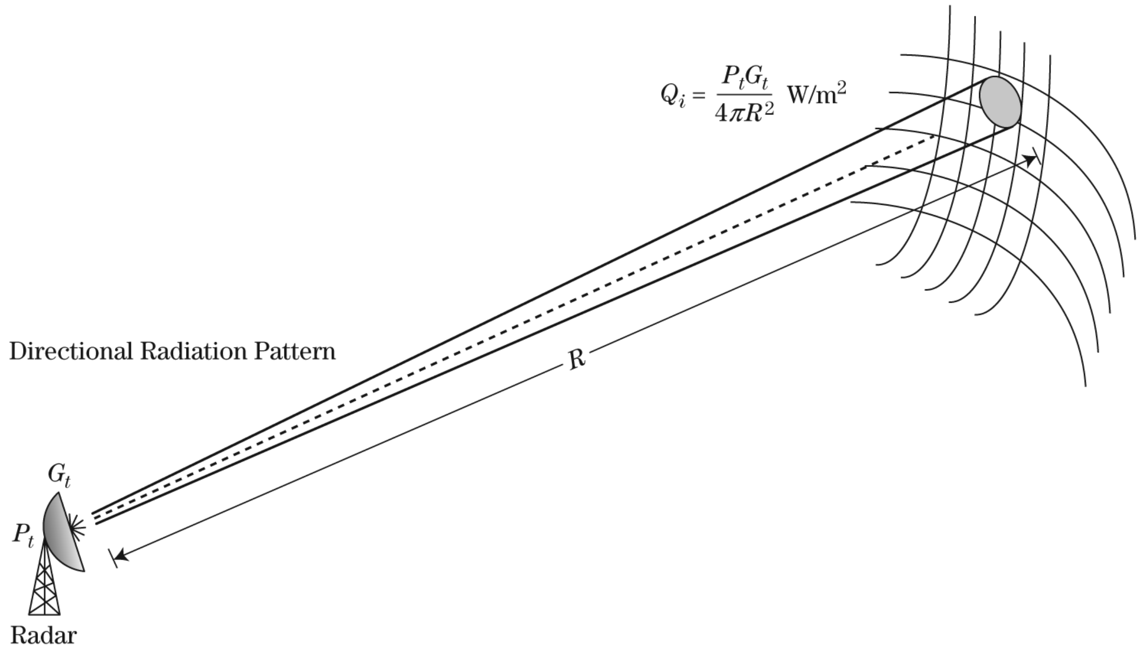

Received Power from a Target

- RF energy reflecting back to the antenna is a function of shape, size, and material

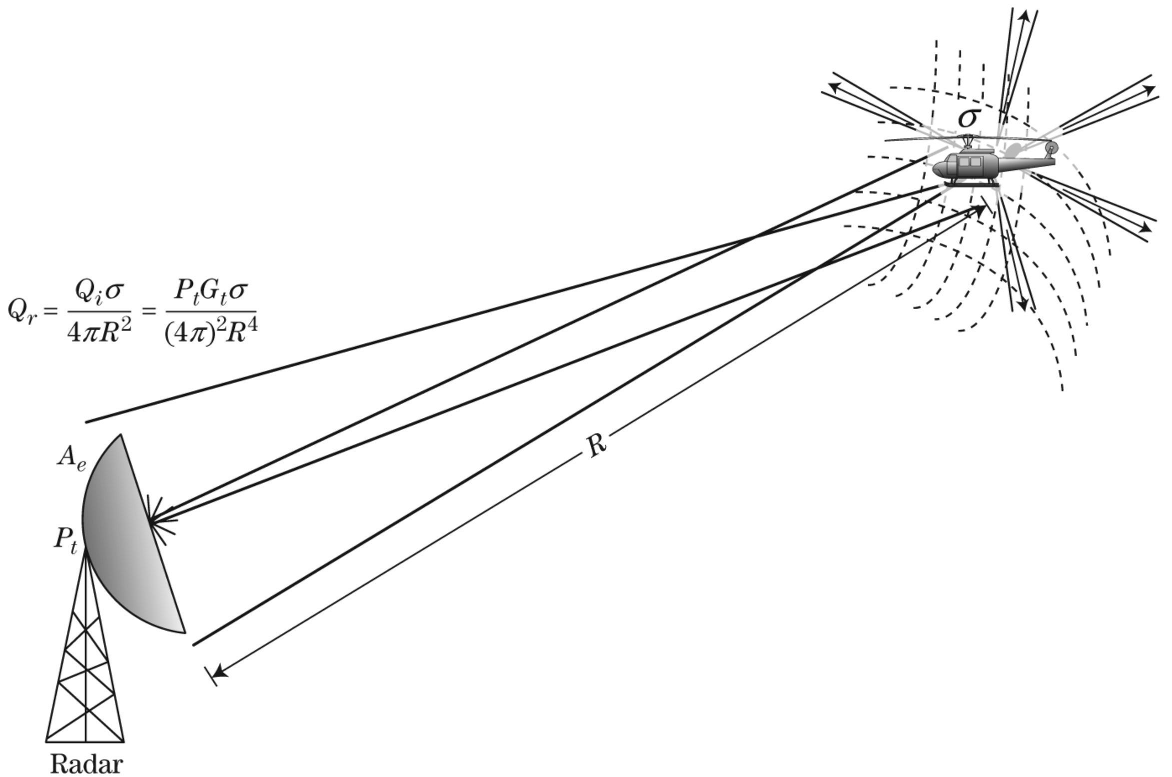

FIGURE 2-3 ■ Power density, Q_r, back at the radar receive antenna.

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Radar Cross Section (RCS) of Targets

- Radar cross section (RCS) is a measure of the amount of electromagnetic energy a radar target intercepts and scatters back towards the target

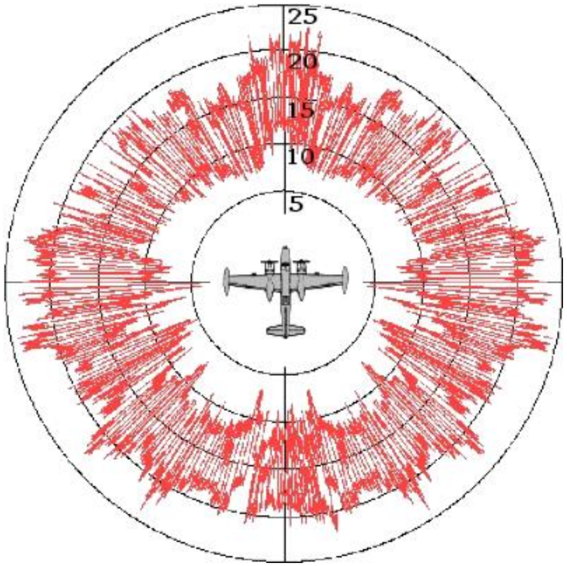
- RCS is represented by the Greek letter σ, and is the product of three factors:

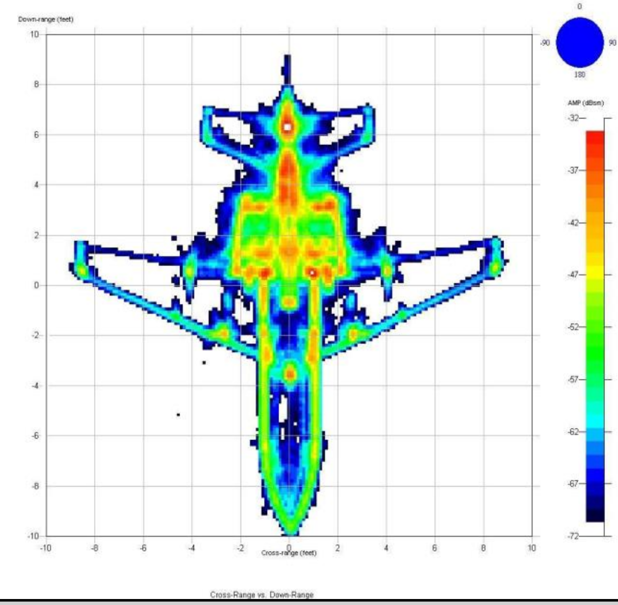
  - σ = (Geometric Cross Section) x (Reflectivity) x (Directivity)

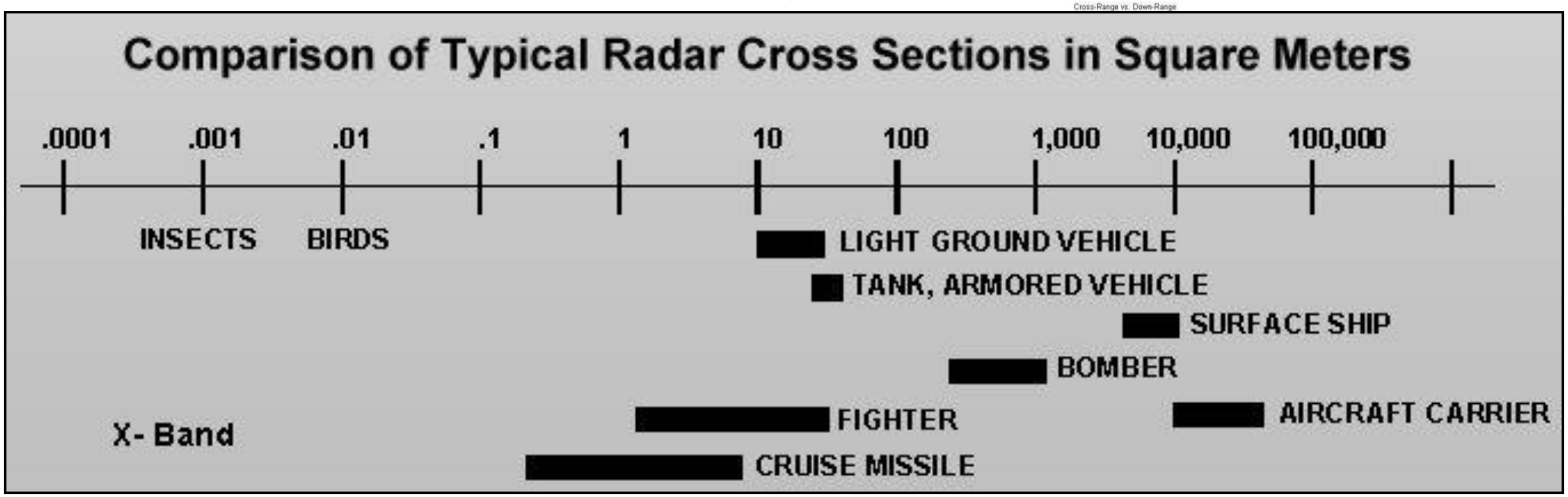
$$\left.\frac{P_T\,G_T}{4\pi R^2} \quad \mathrm{x} \quad \sigma \;\right\}\; \text{Power reflected from target } (\sigma = \text{target reflecting area})$$

Stealthy targets (low RCS) may use special materials to reduce reflectivity and streamline its structure to reduce directivity

Radar Cross Section, Examples







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Received Power Calculation

$$\frac{P_T}{4\pi R^2}$$ Power per unit area at Range R from isotropic antenna

$$\frac{P_T G_T}{4\pi R^2}$$ G_T term (transmit gain) focuses energy in direction in which gain applies

$$\frac{P_T G_T}{4\pi R^2} \times \sigma$$ Power reflected from target (σ = target reflecting area)

$$\frac{P_T G_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \quad \left(\frac{\sigma}{4\pi R^2}\right)$$ Term represents energy reflected from target per unit area at receiver

$$\frac{P_T G_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_R$$ Power collected by receive antenna A_R is effective area of receive antenna

$$\frac{P_T G_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times \frac{G_R \lambda^2}{4\pi}$$ $A_R = \frac{G_R \lambda^2}{4\pi}$ G_R = Receive Gain

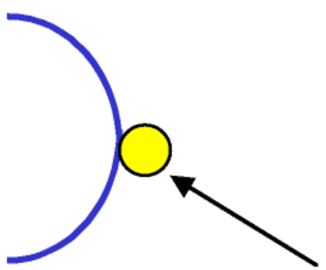
$$\frac{P_T G_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times \frac{G_R \lambda^2}{4\pi} \times \frac{I}{L}$$ Received Power

I = Integration Gain
L = System Losses
λ = Wavelength

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

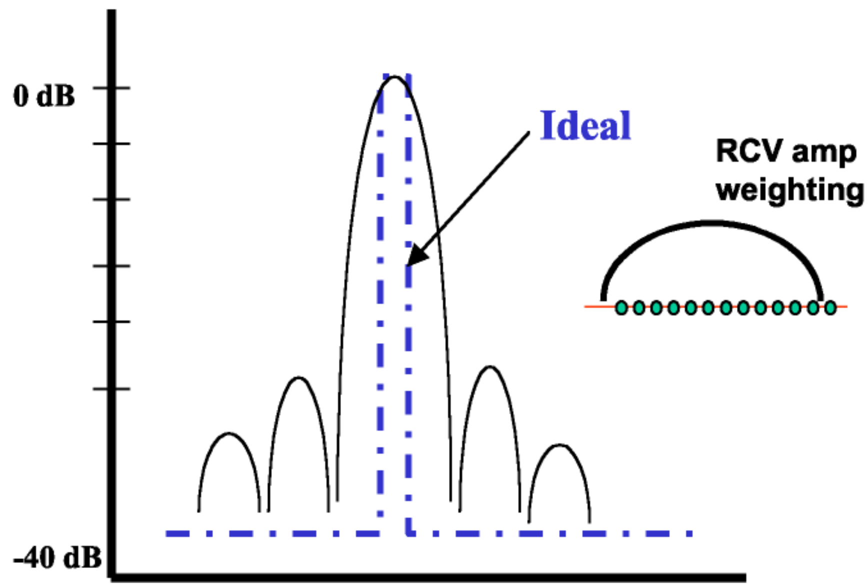
Radar Equation - Receiving

$$\frac{P_T G_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \Big\} \left(\frac{\sigma}{4\pi R^2} \right)$$ Term represents energy reflected from target per unit area at receiver



$$\frac{P_T G_T}{4\pi R^2} \left(\frac{\sigma}{4\pi R^2} \right) A_R$$

$$\boxed{P_R = \frac{P_T G_T}{(4\pi)^2} \frac{\sigma}{R^4} \left[A_R \right]}$$



RRE – Problem 4

- Ignoring losses, determine the single-pulse received power level (in dBm) for a 1 square meter target at a range of 36 km

2-4.

Using equation 2.8 on page 64, $P_r = \dfrac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$, the received power for the four systems are summarized in the table below.

System	Peak Power (w)	Antenna Gain	Frequency	Pr (dBm)
a)	25,000	36 dB	9.4 GHz	
b)	250,000	31 dB	9.4 GHz	
c)	250,000	31 dB	2.8 GHz	
d)	250,000	36 dB	9.4 GHz	

Question 4	P	Range(m)	Gain	Freq	Lambda	Pr	Pr (dB)
	25000	36000	3981.072	9.4E+09	0.031915		
	250000	36000	1258.925	9.4E+09	0.031915		
	250000	36000	1258.925	2.8E+09	0.107143		
	250000	36000	3981.072	9.4E+09	0.031915		

$$S = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$$

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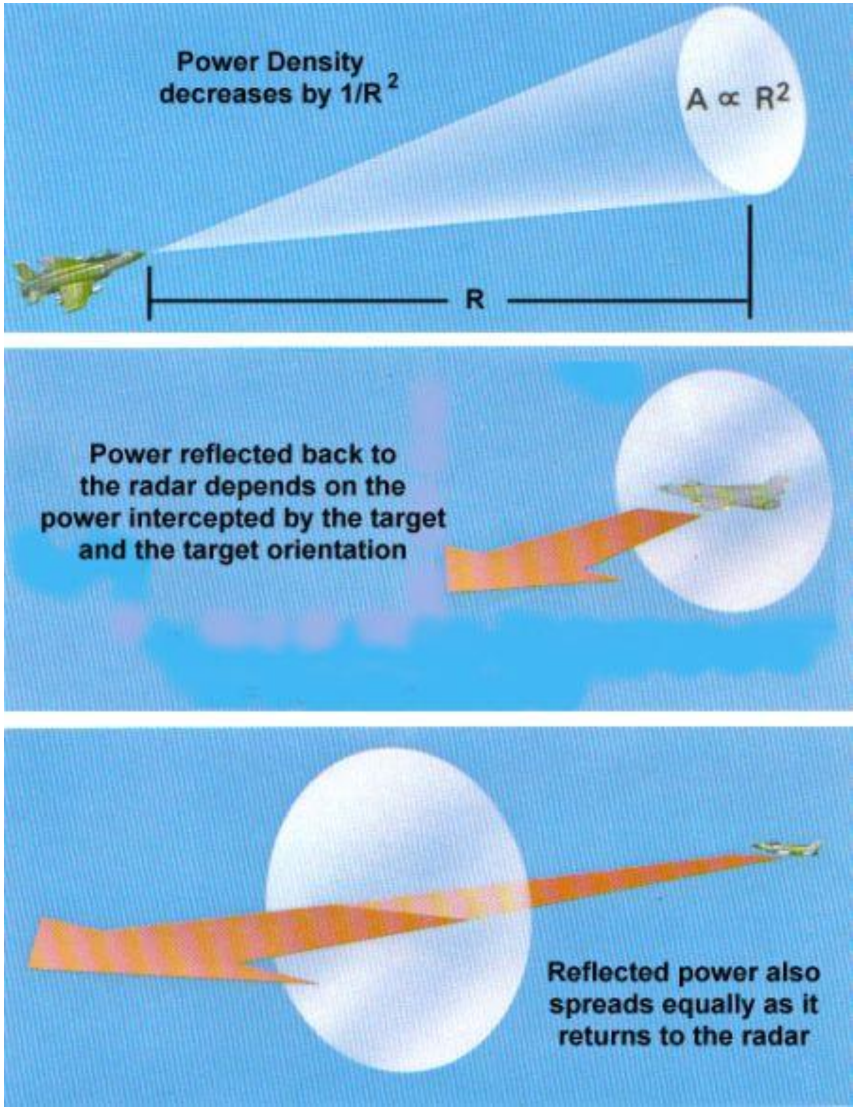
Signal to Noise Ratio

- Establish the Signal-to-Noise ratio, S/N
  - Calculate signal level reflected from target and received by radar at the detector
  - Calculate receiver noise level: this is the background noise level against which the received signal must be detected
  - The ratio of these is the Signal-to-Noise ratio, S/N
- If jamming power is greater than noise power, then jamming power replaces noise power, S/J

$$\frac{S}{N+J} \approx \frac{S}{J}, \text{ if } \mathrm{J} >> \mathrm{N}$$

- If clutter power is dominant, then clutter power replaces noise power, S/C

$$\frac{S}{N+C} \approx \frac{S}{C}, \text{ if } \mathrm{C} >> \mathrm{N}$$



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Noise Interference

- Noise is the unwanted EM energy that interferes with the ability of the radar receiver to detect the wanted signal. It may originate within the receiver or may enter via the receiving antenna along with the desired signal

- Noise power measured relative to input
  - N = noise power of the receiver
  - k = Boltzmann's constant
  - B_N = Receiver Noise Bandwidth
  - F = Noise Figure or Factor (sometimes listed as NF)
  - T_O = Reference Temp ~ 290°

- $N = k\,T_O\,B_N\,NF$ = equivalent noise power of the receiver

Noise Figure & System Temperature

- $NF = N / (k\,T_O\,B_N)$
  - The noise figure is the ratio of the noise out of a practical receiver to the noise out of an ideal receiver at standard temperature, T_0 = 290°K = 17°C
- The receiver noise can also be expressed as a function of equivalent noise temperature or system temperature where
  - $N = k\,T_S\,B_N$ = equivalent noise power of the receiver
  - Noise power measured relative to input
    - N = noise power of the receiver
    - k = Boltzmann's constant
    - T_S = System Temperature
    - B_N = Receiver Noise Bandwidth
- It is important to know where in the receive chain the noise figure or temperature is defined. The output of the circulator is a typical reference point.

Radar Equation – Signal to Noise

- The ratio of the received signal power versus the noise power represents the SNR (signal-to-noise ratio)

$$S/N = \frac{P_T G^2}{(4\pi)^3} \left[\frac{\sigma}{R^4} \right] \left[\frac{\lambda^2}{K\, T_o\, B_n\, F_n} \right]$$

- Add in the system losses and your radar equation is

$$\widehat{S/N} = \frac{P_T G^2}{(4\pi)^3} \left[\frac{\sigma}{R^4} \right] \left[\frac{\lambda^2 \quad G_{SP}}{K\, T_o\, B_n\, F_n} \right] \left[\frac{1}{L} \right]$$

Radar Range Equation (Noise Limited) Case

$$S/N = \frac{P_T G_T}{(4\pi) R^2_T} \times \frac{\sigma}{(4\pi) R^2_T} \times A_R \times \frac{I}{k T_o B \overline{NF_o}} \times \frac{1}{L}$$

Where:

- P_T = Transmit power
- G_T = Transmit gain
- σ = Target Radar Cross-Section area
- L = System Losses
- R_T = Target Range
- A_R = Receiver antenna area

$$A_R = \frac{G_R \lambda^2}{4\pi}$$

Where:

- G_R = Receiver Gain
- λ = Wavelength

Receiver Noise:

- k = Boltzmann's constant
- T_o = Reference noise temperature, o_k
- B = Receive bandwidth
- $\overline{NF_o}$ = Operating noise figure
- I = Integration gain

Then:

$$S/N = \frac{P_T G_T G_R \lambda^2 I \sigma}{(4\pi)^3 R_T^4 L \times k T B \overline{NF_o}}$$

RRE – Problem 5

- **Same inputs as problem 4 as well as a bandwidth of 10 MHz. The noise figure is 3.2 dB for the 9.4 MHz radar and 2.7 dB for the 2.8 GHz radar. Use eq 2.11 and calculate SNR (dB) for the four radars.**

Question 5

$$SNR = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 k T_0 B F R^4}$$

k	T	B	NF	Pr	SNR	SNR (dB)
1.38E-23	290	1.00E+07	2.089296	1.2108E-13		
1.38E-23	290	1.00E+07	2.089296	1.2108E-13		
1.38E-23	290	1.00E+07	1.862087	1.3647E-12		
1.38E-23	290	1.00E+07	2.089296	1.2108E-12		

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Multiple Pulse Benefits

- Coherent integration of multiple pulses improves the SNR of the received return

$$SNR_c(n_p) = n_p \cdot SNR$$

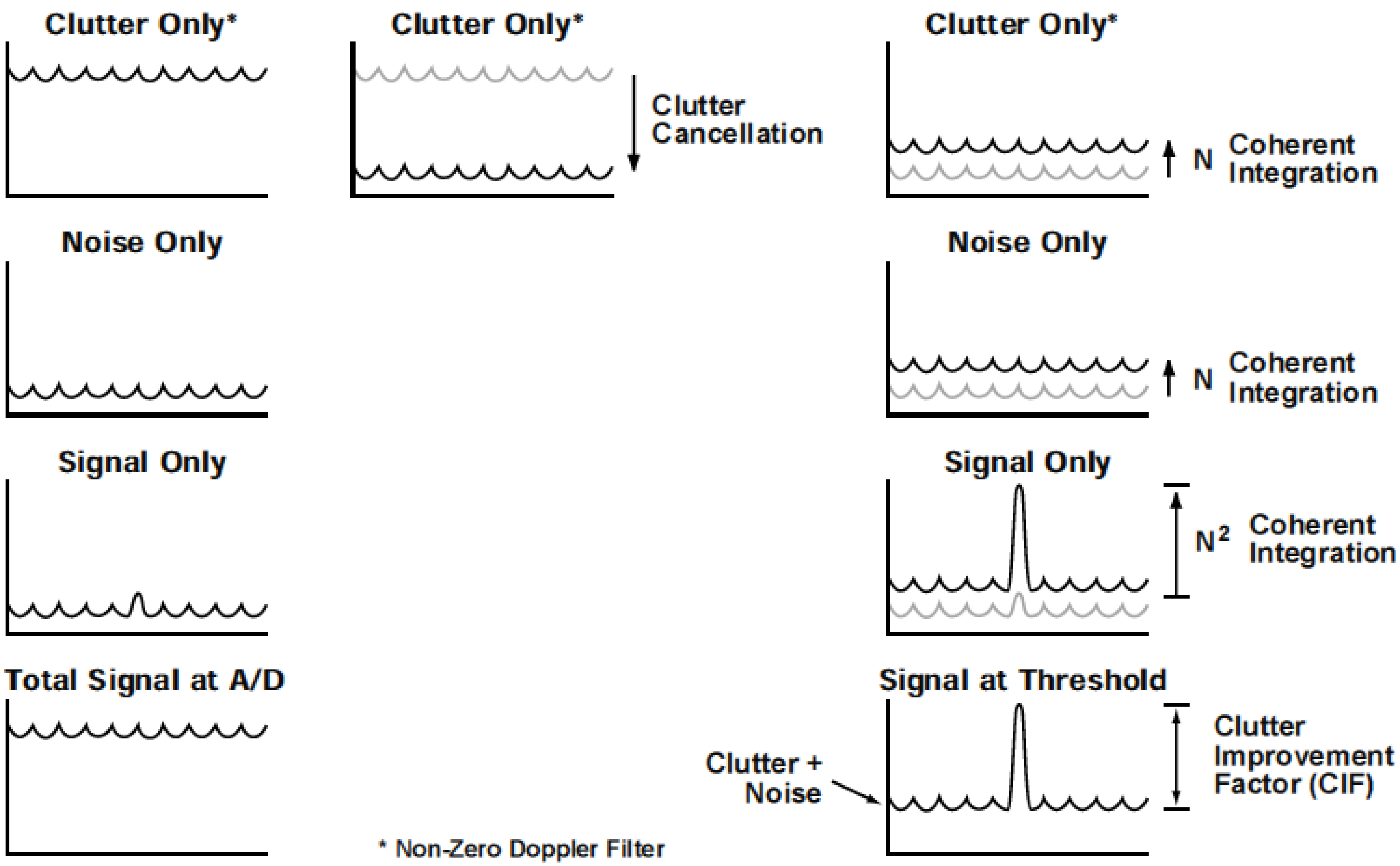
- Non-coherent integration does not utilize phase so its gain is represented by

$$SNR_{nc}(n_p) = \sqrt{n_p} \cdot SNR$$

or

$$SNR_{nc}(n_p) = n_p^{\,0.7} \cdot SNR$$

Pulse Doppler Processing
Clutter Cancellation & CIF - Illustration



Clutter Cancellation Drives Hardware Requirements
CIF is Signal to Interference Improvement After Coherent Processing

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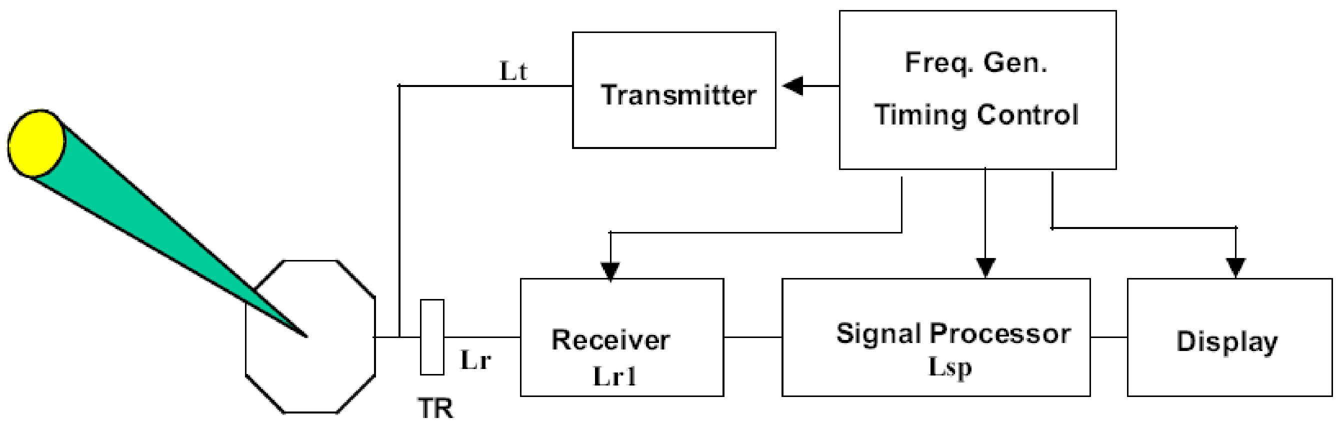
System Losses, I

- Transmit, L_t
  - Plumbing losses as the RF signal travels from the output of the transmitter to the antenna (includes waveguide losses)
- Receive, L_r
  - Plumbing losses as the RF signal is received and sent to the signal processor
- Signal Processing, L_{sp}

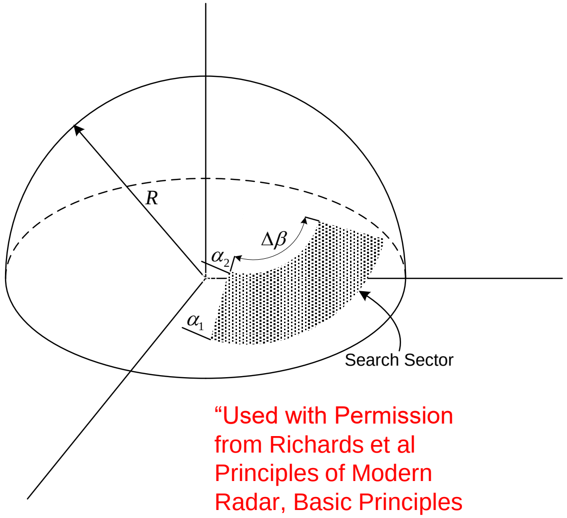


System Losses, II

- Search lattices
  - Number of beams required to search a designated sector:

$$\eta = K_{pack}\Omega_{search\_area} / \Omega_{beam}$$

    - K_{pack} = beam packing factor
    - Ω = search area in steradians



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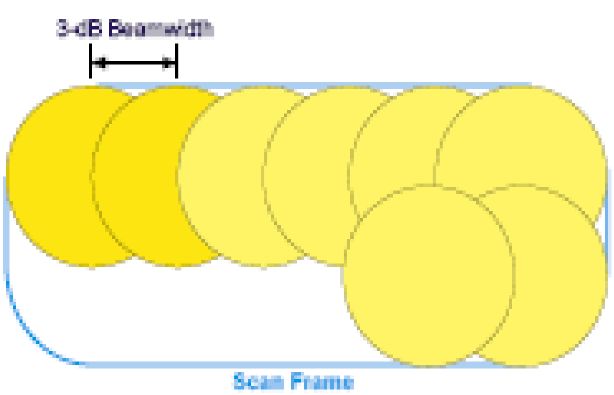
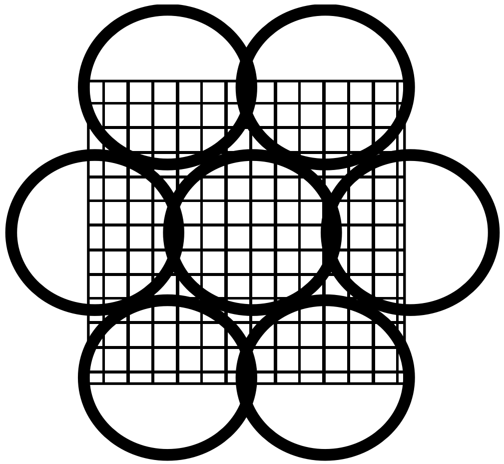
- Beamshape Loss
  - Function of how tightly packed the antenna beams are spaced in a search lattice (grid on the bottom right is used to model beamshape loss).





System Losses, Beam Scan

- Search Losses
  - As a rotating radar scans, it antenna pattern relative to the target position varies as does its antenna gain relative to the target

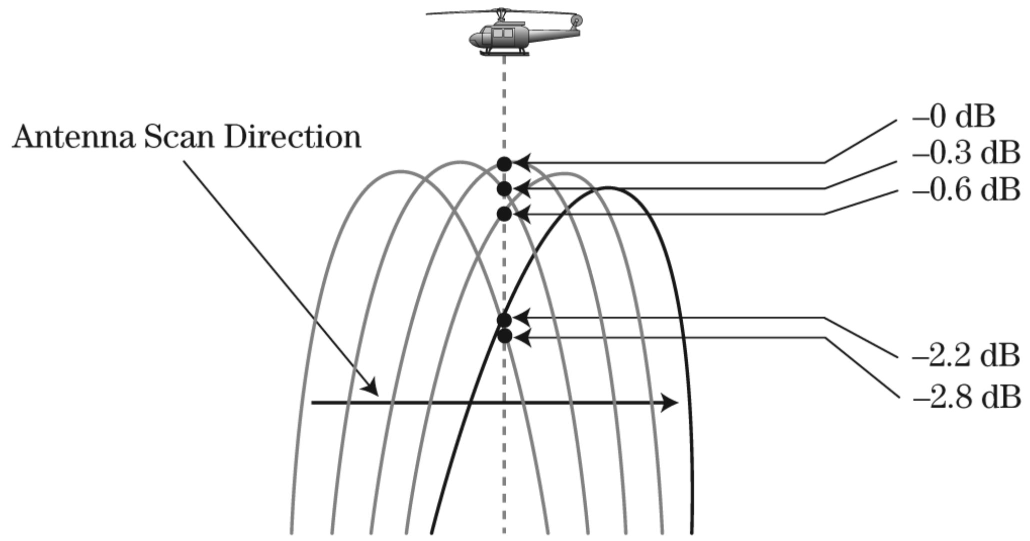


FIGURE 2-4 ■ Target signal loss due to beam scan.

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System Losses, Doppler Straddling

- Pulse Doppler waveforms operate by transforming the signal return from the time domain to the frequency domain via the FFT
- Each filter has a given width, receiving a band of Doppler frequencies, effectively separating different target velocities into different filter bins
- The filter gains vary as a function of frequency such that targets that “straddle” two filters will have an associated loss

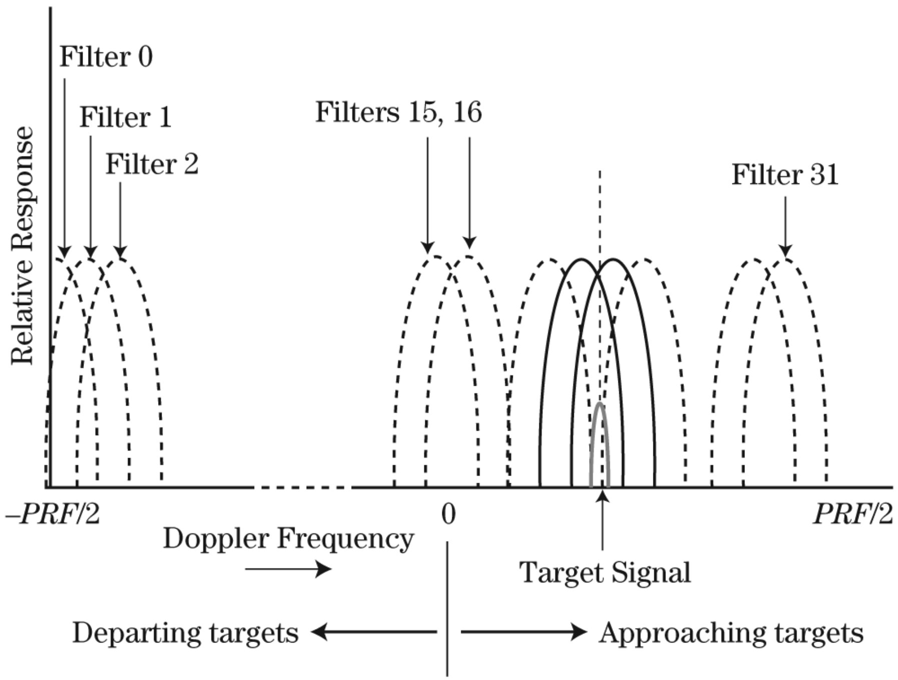

FIGURE 2-5 ■ Doppler filter bank, showing a target straddling two filters.

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Loss Budgets

Receive Losses

L_{R1} = Loss between antenna and low noise amplifiers

$\approx$ 2 to 4 dB

L_{R2} = Receive beam shape loss

$\approx$ 1 to 2 dB for search
$\approx$ 0 to 0.5 dB for track

L_{R3} = Receive beam scan loss, function of off-array-normal steering angle

$\approx$ 0 to 2 dB

For Phased Arrays

L_{R4} = Signal processing losses

- Loss compared to ideal matched filter
- Doppler mismatch loss
- Range mismatch loss
- Various processing losses — limiting, quantization, etc.

$\approx$ 2 to 5 dB

$$L_R = L_{R1} + L_{R2} + L_{R3} + L_{R4}$$

Transmit Losses

L_{T1} = Loss between high power amplifier outputs and antenna

$\approx$ 2 to 4 dB

L_{t2} = Transmit beam shape loss

$\approx$ 1 to 2 dB for search
$\approx$ 0 to 0.5 dB for track

L_{T3} = Transmit beam scan loss, function of off-array-normal steering angle

$\approx$ 0 to 2 dB

External Factors

L_A = Atmospheric loss

L_p = Propagation loss (multi-path)

$$L_T = L_{T1} + L_{T2} + L_{T3}$$

$$\text{System Losses, } L = L_R + L_T$$

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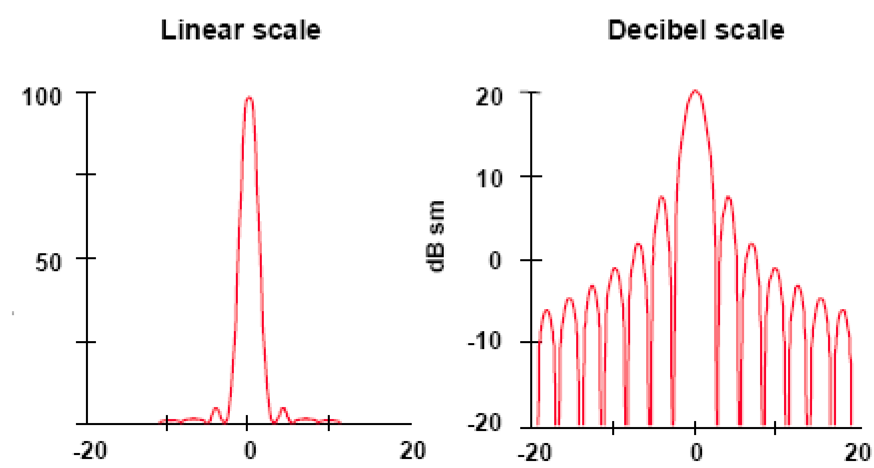
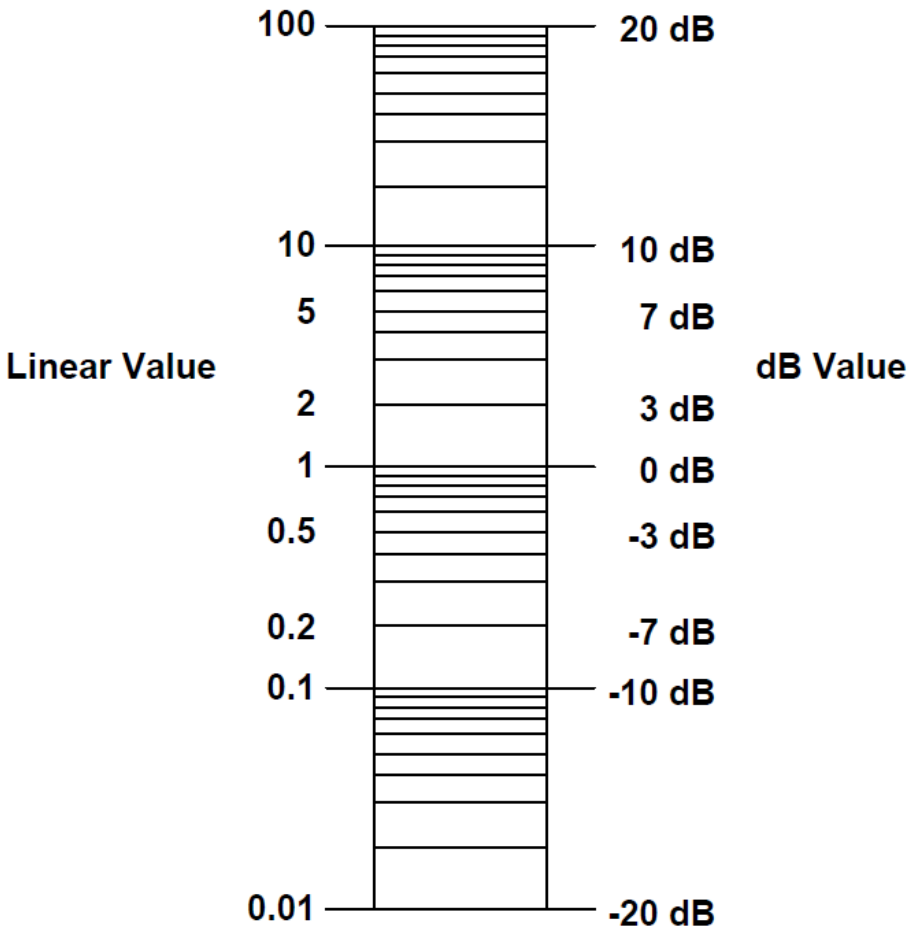
The (deci)Bel

- Developed or defined at Bell Laboratories to define transmissions levels for early telephony
- A Bel is the $\log_{10} (P/ P_{ref})$
  - The Bel did not have enough granularity
    - A decibel is $10 \log_{10}(P/ P_{ref})$
- Allows us to represent high dynamic range signals with more clarity



- Often the reference level is a fixed value
  - E.g., a ratio referenced to 1 mW is described dBmW or X dBm

The Decibel Scale



- The Decibel Scale represents linear values that vary significantly in magnitude.
- For example, values from 0.01 to 100 are represented with -20 dB and +20 dB

Decibel Equations

$$D = 10\log_{10} L \qquad L = 10^{\frac{D}{10}}$$

- D – value in decibels
- L – linear value

Common Decibel Equivalents

Decibel	Linear
-1000	1×10^{-100}
-100	1×10^{-10}
-10	0.1
0	1
1	≈1.25
3	≈2
10	10
100	1×10^{10}
1000	1×10^{100}

Quick Arithmetic Rules

- Linear Arithmetic
  - Multiplication: x * y
  - Division: x / y
  - Power: y^a
- Decibel Arithmetic
  - Multiplication: x + y
  - Division: x – y
  - Power: a * y

Arithmetic Examples

- What is 11 dB?
  - In Decibels:

    3 dB + 3 dB + 3 dB + 1 dB + 1 dB
  - In Linear:

    2 * 2 * 2 * 1.25 * 1.25 ≈ 12.5
- OR…
  - In Decibels:

    20 dB – 3 dB – 3dB – 3 dB
  - In Linear:

    100 ÷ 2 ÷ 2 ÷ 2 ≈ 12.5

20 log (x) or 10 log (x)

- In electrical systems power = $voltage^2/R$
  - electrical ratio in dB = 10 log10($voltage^2/voltage_{ref}^2$)
- Similarly in sound systems power = $pressure^2$
  - Sound gain in dB = 10 log10($pressure^2/pressure_{ref}^2$)
- So if we are measuring voltage the exponent rule is used
  - Log x^m = m log (x)
- Thus when measuring voltage and obtaining a power ratio we use the formulation 20 log (v/ v_{ref})

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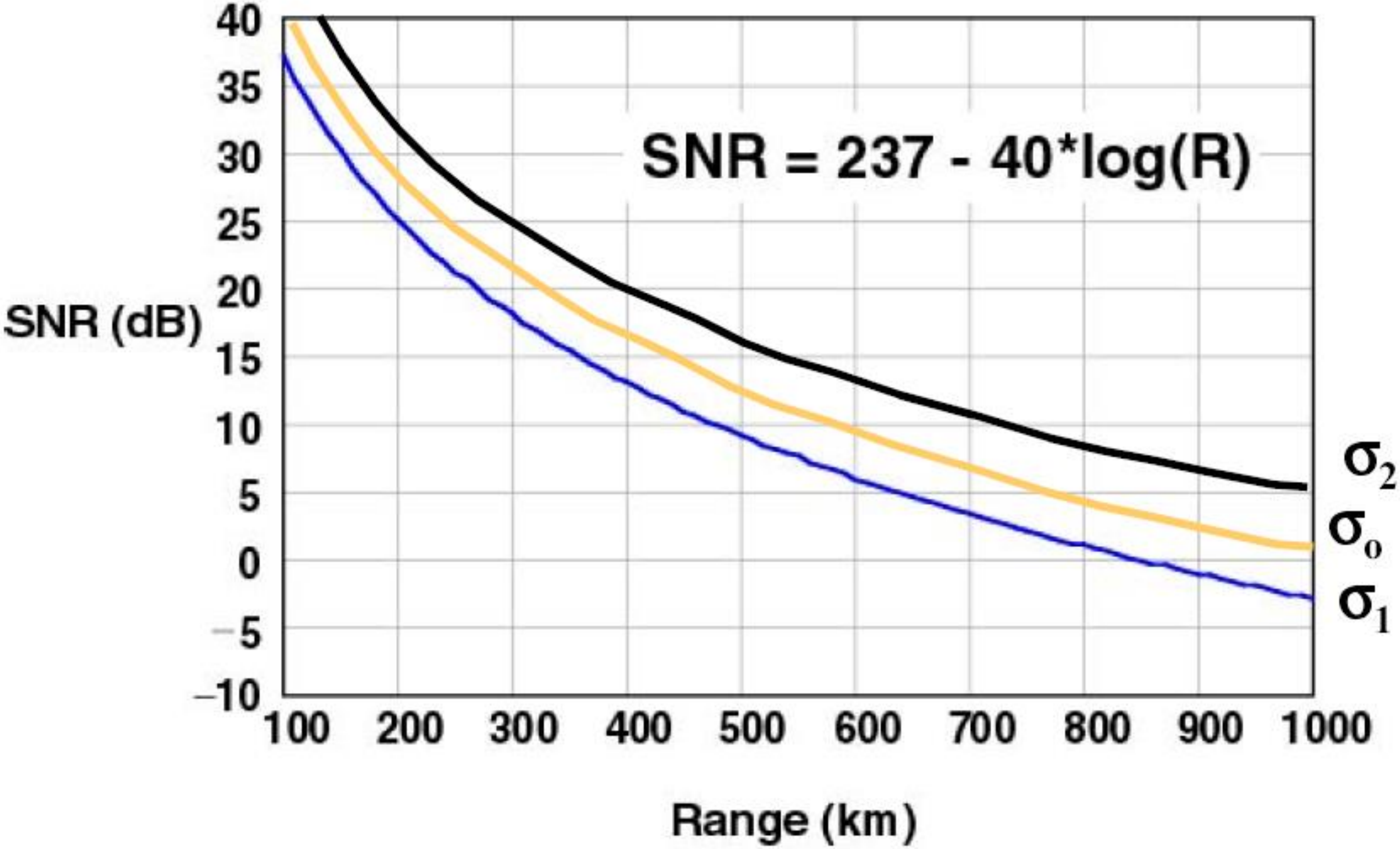
Sample Radar Range Calculation

Variable	Num (linear)	Num (dB)	Den (linear)	Den (dB)
Pt (Watt)	1,000,000	60.0		
Gt (XMT Gain)	10,000	40		
Gr (Rcv Gain)	10,000	40		
Sigma (sqm)	1.00	0		
Frequency (GHz)	3.00			
(Lamda)**2		-20		
Integration gain	100	20		
_ radar cross section	0 m^2	0		
[4*π]**3				33.0
R**4				40*log(R)
k (Boltzman's Constant)			1.38E–23	-228.6
T			290	24.6
Bandwidth			1.00E+06	60.0
NF (Noise Figure)				4.0
Losses, Total			10	10

Sub Total 140.0 -97.0

Total SNR (dB) = 237.0 - 40*log(R)

Sample Radar Calculation Plot



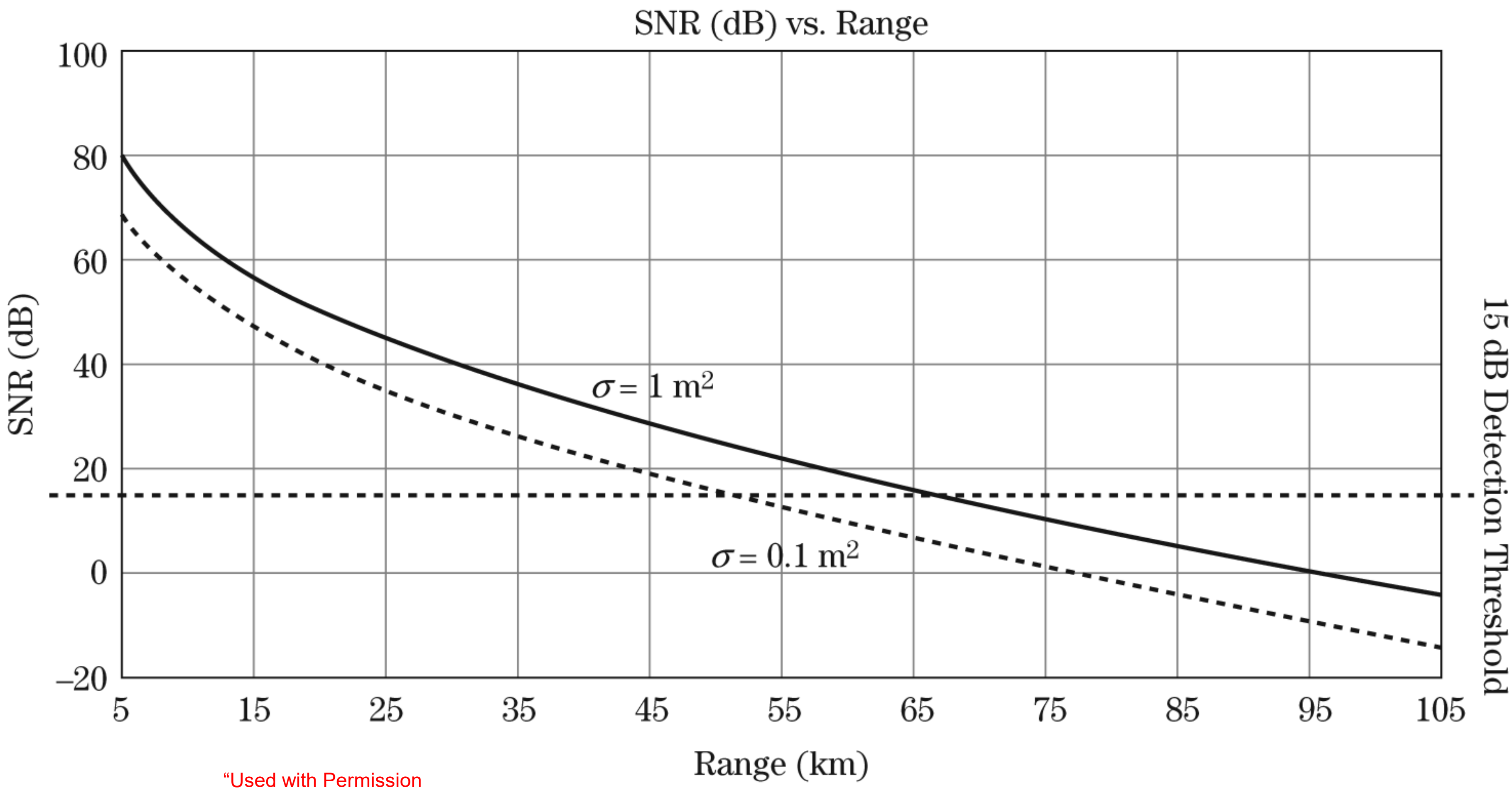
Another Radar Range Calculation

Transmitter	150 kW peak power
Frequency	9.4 GHz
Pulsewidth	1.2 us
PRF	2 kilohertz
Antenna	2.4 meter diameter (0.6 efficiency)
Processing dwell time	18.3 ms
Receiver noise figure	2.5 dB
Transmit losses	3.1 dB
Receive losses	2.4 dB
Signal processing losses	3.2 dB
Atmospheric losses	0.16 dB/km one-way
Target RCS	0 dBsm, -10 dBsm
Target range	5 to 105 km

Excel Spreadsheet Range Calculation

	VALUE	GAIN	LOSS			
Power (W)	150000.00	51.76				
Transmit Gain	45.25	45.25		Eq. 2.7		
Receive Gain	45.25	45.25				
Duty Factor (pw * PRF)	0.24%		26.20			
Processing Time, ms	18.30		17.38			
PRF	2000.00					
RCS m2	1.00	0.00				
Freq (MHz) for λ^2	9400.00		29.92		LOSSES:	
$(4\ \pi)^3$			32.98		- Xmit	3.10
k - Boltzman		228.60			- Rec	2.40
T_0 (deg K)	290.00		24.62		- SigProc	3.20
Noise figure			2.50		- Atmos	1.60
Σ LOSSES			10.30			
Range (km)	5.00		147.96			
TOTALS		370.86	291.85			
SNR at 5 km =		79.01				

Sample Radar Calculation Plot



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Average Power Radar Equation

$$P_{avg} = P_t f_r \tau \quad or \quad P_t = \frac{P_{avg}}{f_r \tau}$$

$$n = f_r T_d$$

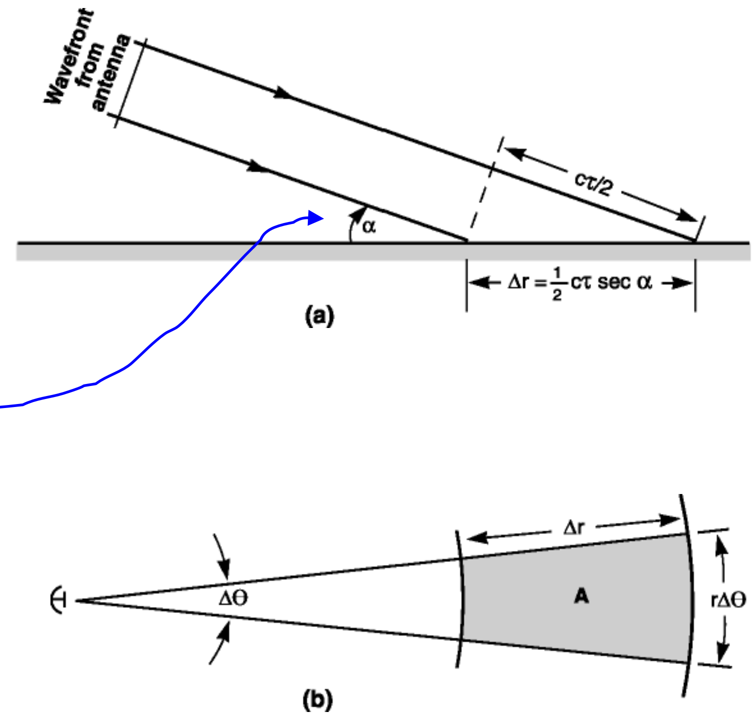
$$\tau = \frac{1}{B} \quad for\ a\ "matched-filter"\ receiver$$

$$\frac{P_t n}{B} = \left(\frac{P_{avg}}{f_r \tau}\right)(f_r T_d)(\tau) = P_{avg} T_d$$

$$\left(\frac{S}{N}\right)_i = \frac{P_t G^2 \lambda^2 \sigma n}{(4\pi)^3 k T_0 B F L_s R^4} = \frac{P_{avg} G^2 \lambda^2 \sigma T_d}{(4\pi)^3 k T_0 F L_s R^4}$$

Clutter as the Target

- Clutter is unwanted interference scattering back to the antenna
- Reflectivity is a factor that quantifies how much energy is reflected back and how much continues forward
- The grazing angle or the angle at which the radar energy bounces off the clutter is a key factor in the reflectivity (like skipping stones, shallow angles skip forward and do not scatter back)
- Clutter area is a function of beamwidth, pulse width, reflectivity, and the gain of the antenna towards the clutter patch



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$$\sigma_0 = \text{AREA} \times \text{REFLECTIVITY} \times \text{DIRECTIVITY}$$

Volume and Area Clutter Illustrations

FIGURE 2-8 ■ Volumetric (atmospheric) clutter.

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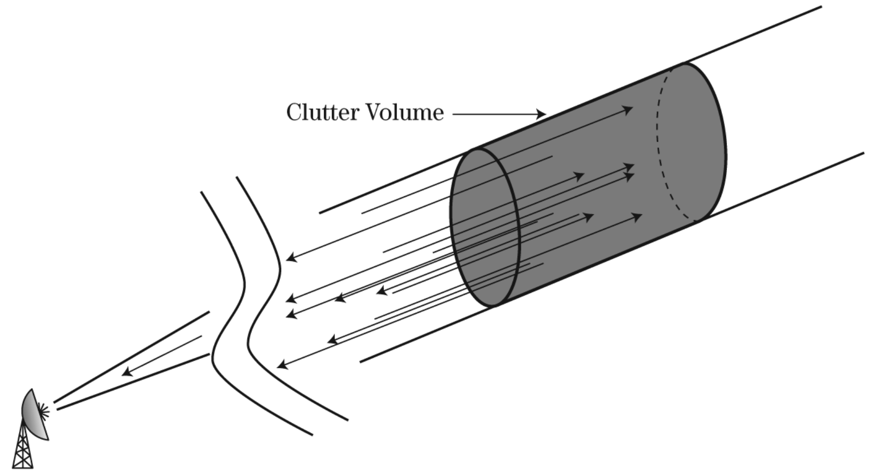

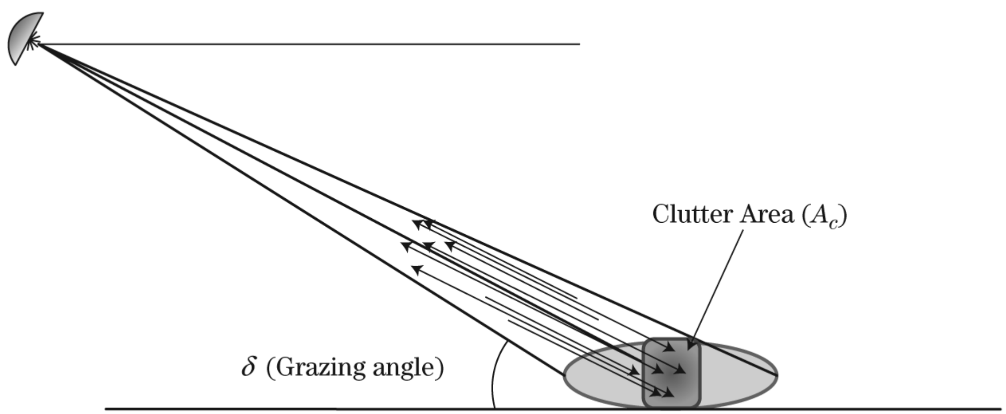

FIGURE 2-7 ■ Area (surface) clutter.

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Typical Mean Reflectivity (m^2/m^2)

	S-Band 3.3 GHz	C-Band 5.6 GHz	X-Band 10.0 GHz
Sea Clutter, Sea State 3 Graz Angle = 0.1°	-90	-78	-67
Rain Clutter (4 mm/hr) (m^2/m^3)	-83	-72	-62
Lowlands	-30	-30	-30
Highlands	-20	-20	-20
Urban	-10	-10	-10

Excel Spreadsheet CNR Calculation

Beamwidth (Eq 1.9) (deg)	1.00					
Beamwidth, radians	0.01745					
Width of clutter cell, m	87.27					
Range of clutter cell, m	180.00					
Area of clutter cell, m2	15707.96					
Mean reflectivity (dBm2/m2)	-67.00					
Effective clutter area, m2	0.00313					
	VALUE	GAIN	LOSS			
Power (W)	150000.00	51.76				
Transmit Gain	45.25	45.25		Eq. 2.7		
Receive Gain	45.25	45.25				
Duty Factor (pw * PRF)	0.24%		26.20			
Processing Time, ms (1-pulse)	0.50		33.01			
PRF	2000.00					
Clutter RCS m2	0.00	-25.04				
Freq (MHz) for λ^2	9400.00		29.92		LOSSES:	
$(4\pi)^3$			32.98		- Xmit	3.10
k - Boltzman		228.60			- Rec	2.40
T_0 (deg K)	290.00		24.62		- SigProc	3.20
Noise figure			2.50		- Atmos	1.60
Σ LOSSES			10.30			
Range (km)	5.00		147.96			
TOTALS		345.82	307.49			
CNR at 5 km =		38.33				

Signal to Clutter + Noise

- In determining clutter to noise, use the same methodology for SNR calculations and substitute the target RCS with the apparent clutter RCS (clutter area x reflectivity x directivity).

- If C/N levels can be kept below -6 dB (0.25) or so, then the ability to detect targets should not be impacted significantly by clutter.

- In designing radar systems, anticipated clutter levels may necessitate the use of clutter processing that can attenuate the clutter to acceptable levels.

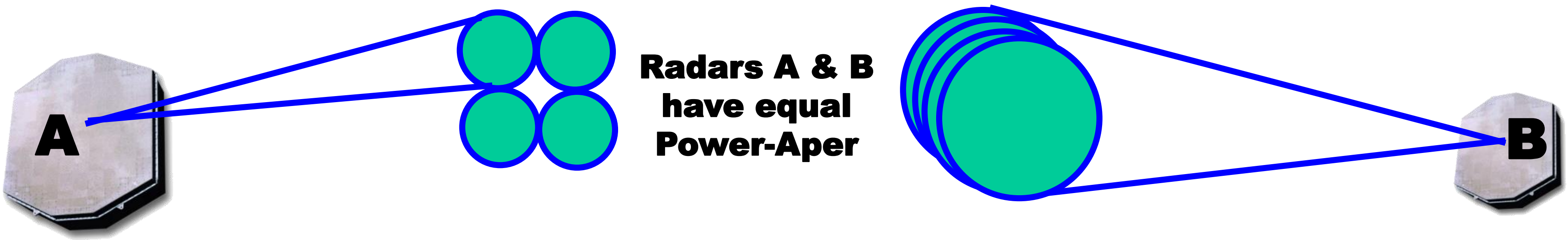
$$\frac{S}{C+N} = \frac{\frac{S}{N}}{\frac{C}{N}+1} = \frac{\frac{S}{N}}{\frac{C}{N}+\frac{N}{N}} = \frac{\frac{S}{N}}{\frac{C+N}{N}} = \frac{S}{C+N}$$

Power Aperture Comparisons - Volume Search

- The power aperture product is the fundamental gauge of search performance
  - Systems with equivalent power aperture will transmit the same amount of energy into the same search volumes
  - Detection ranges may differ because that energy may be combined coherently or non-coherently

Lower module power, larger array searches volume with higher antenna gain (coherent) and smaller beamwidths

Higher module power, smaller array searches each position with multiple beams (non-coherent) to compensate for less antenna gain



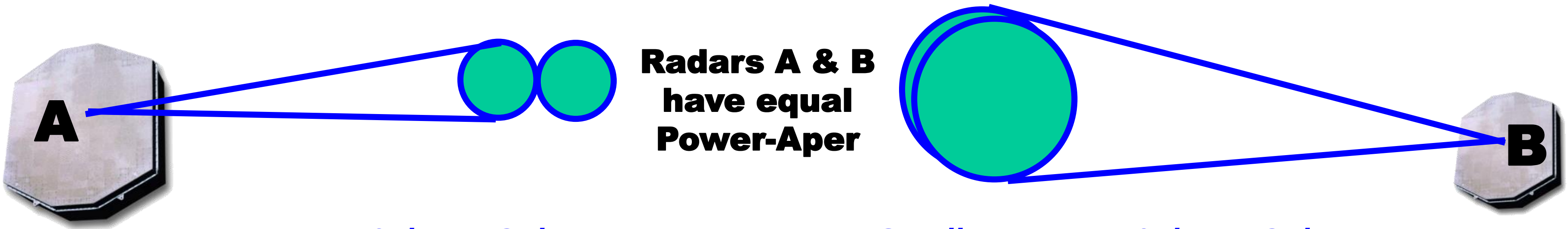
Larger array: +6 dB Tx Gain
+6 dB Rx Gain
+0 dB Peak Power
+0 dB Beam integration

Smaller Array: +0 dB Tx Gain
+0 dB Rx Gain
+6 dB Peak Power
+6 dB Integrate 4 beams

Larger arrays with higher antenna gain provide marginally better detection performance than smaller arrays with equal power-aperture

Power Aperture Comparisons - Horizon Search

- Systems sized for equivalent volume search performance do not translate to equivalent horizon search performance
  - Horizon search is a single row, not multiple rows (Array A must transmit two beams to cover the same azimuth extent as one B beam)



Larger array: +6 dB Tx Gain
+6 dB Rx Gain
+0 dB Peak Power
+0 dB Beam integration

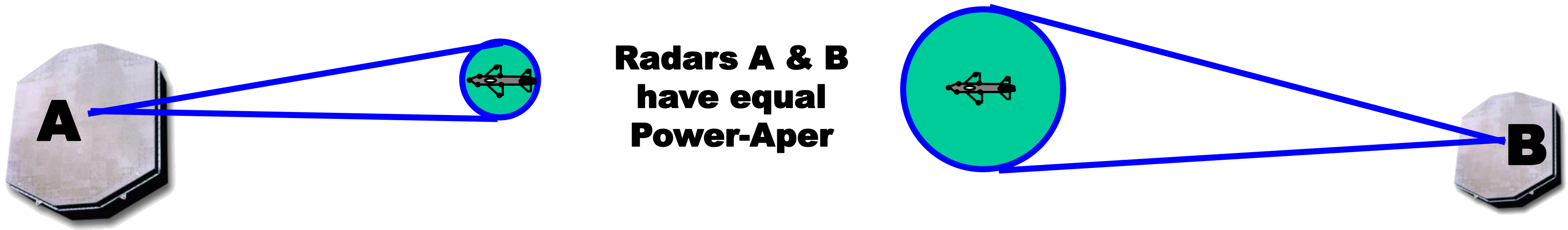
Smaller Array: +0 dB Tx Gain
+0 dB Rx Gain
+6 dB Peak Power
+3 dB Integrate 2 beams

  - Smaller array can compensate with higher antenna placements and better propagation performance

Larger arrays with higher antenna gain provide better detection performance that can only be offset with higher antenna mounts

Power Aperture Comparisons - Track

- Systems sized for equivalent volume search performance do not translate to equivalent track performance
  - Track requires a single beam, not multiple beams



Larger array: +6 dB Tx Gain
+6 dB Rx Gain
+0 dB Peak Power
+0 dB Beam integration

Smaller Array: +0 dB Tx Gain
+0 dB Rx Gain
+6 dB Peak Power
+0 dB Beam Integration

  - Smaller array may be able to compensate with higher antenna placements and better propagation performance against sea skimmers

Larger arrays with higher antenna gain provide much better track performance

RRE – Problem 18

- A search radar being designed by LM engineers has to search the following solid angle volume in the stated amount of time.
  - Azimuth angle: 90 degrees
  - Elevation angle: 3 degrees
  - Full scan time: 1.2 seconds
  - Maximum Range: 30 km
  - Target RCS: -10 dBsm

$$\frac{P_{avg} A_e}{L_s T_0 F} \geq SNR_{\min} 4\pi k \left(\frac{R^4}{\sigma} \right) \left(\frac{\Omega}{T_{fs}} \right)$$

- What is the required power aperture product of the system if the system has the following characteristics?
  - Noise figure: 2.5 dB
  - System losses: 6.7 dB
  - Required SNR: 16 dB

SNR	F	Losses	Range	Sigma	Pavg Ae
39.81072	1.778279	4.677351	30000	270	30349.71

Class Overview

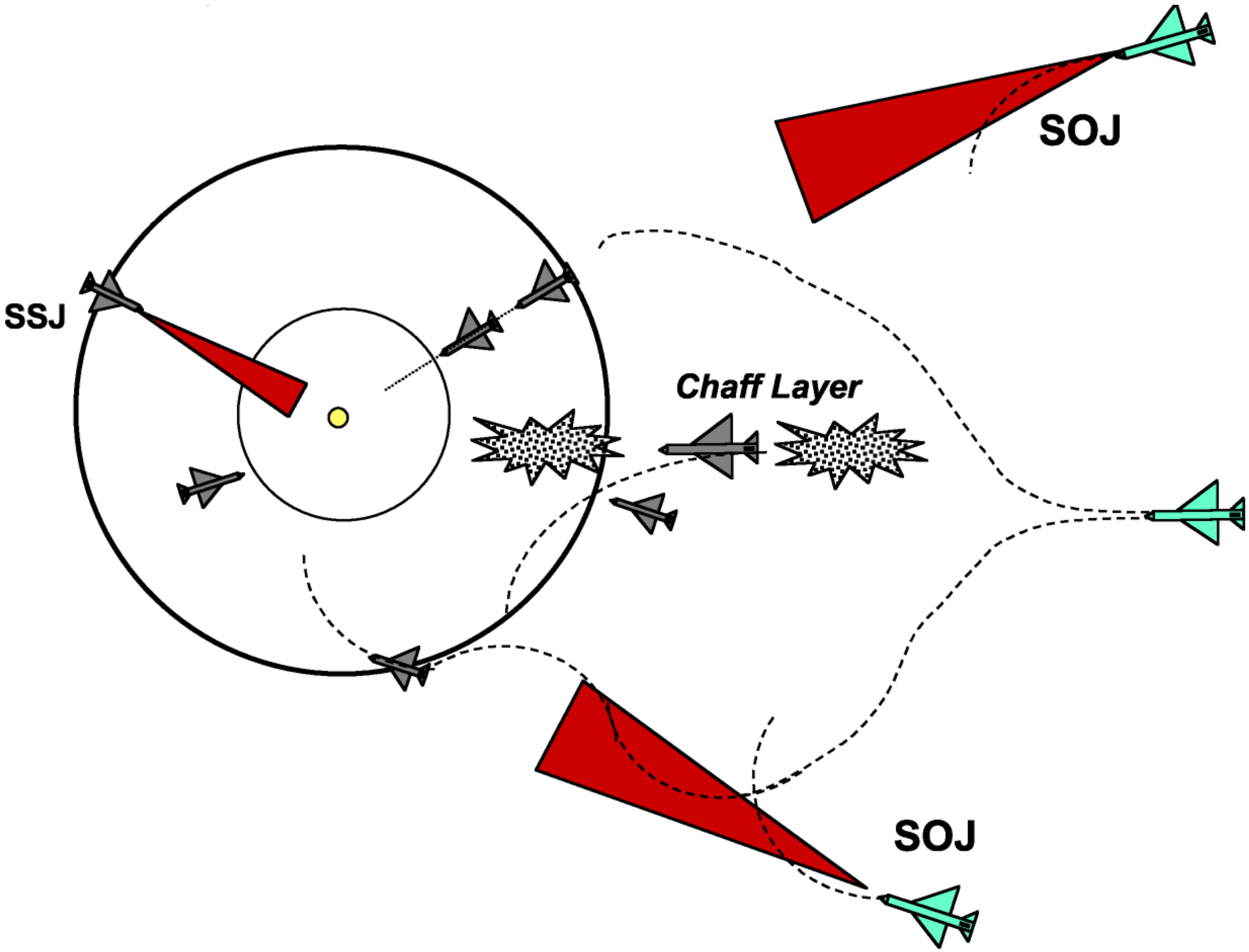
- ❑ Radar Equation
- ❑ Receiver Thermal Noise
- ❑ Multiple Pulses
- ❑ Summary of Losses
- ❑ Decibel Tutorial
- ❑ Different Forms of the Radar Equation
- ❑ Radar Equation - One-way

Man Made Interference

- ECM (Electronic Countermeasure)
  - Interfering signals (one-way) intended to suppress or create false detections

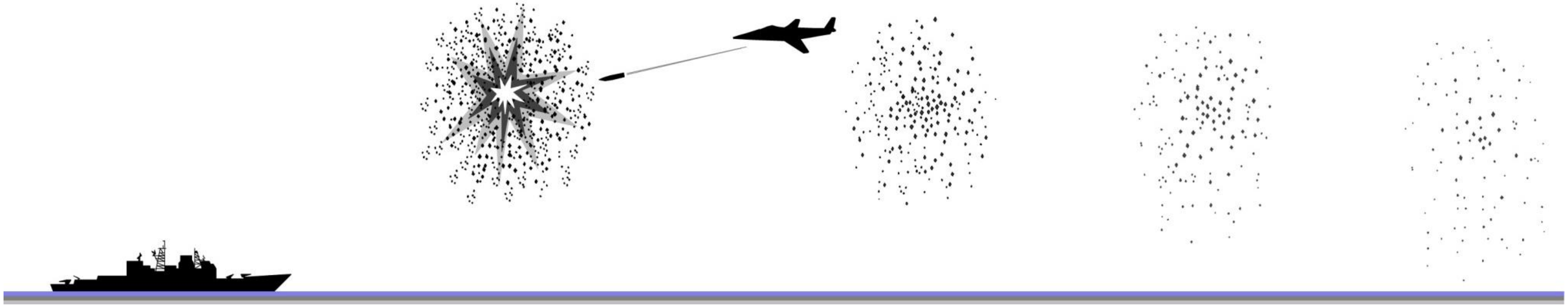
- ECCM (Electronic Counter Countermeasure)
  - Defeating the ECM measures

Jamming Environment



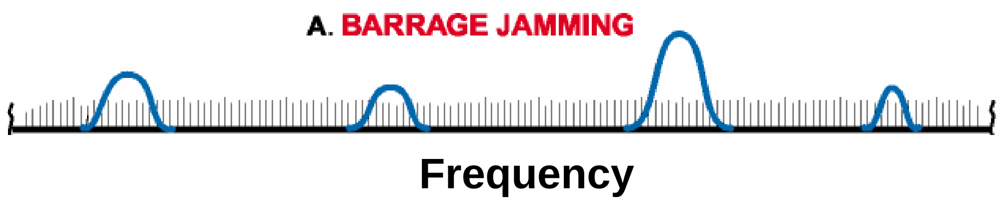
Chaff

- Simple and highly reflective (strips of metal, generally aluminum)
- Upon being dispensed, rapidly decelerates and can be processed like clutter
- Without clutter processing, it can be very effective at masking raids.



Jamming

- Jamming noise is similar to thermal noise; it can raise the level of background noise, thereby raising the detection threshold and making detection of small targets difficult
- *Barrage Jamming*
  - Jamming over entire operating frequency, ensuring that the radar will be jammed but spreading dilutes power



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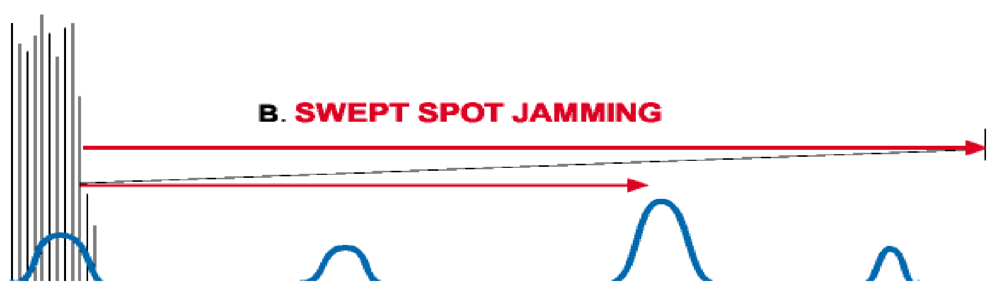
- *Spot Jamming*
  - Jam specific frequencies with maximum power thereby masking targets



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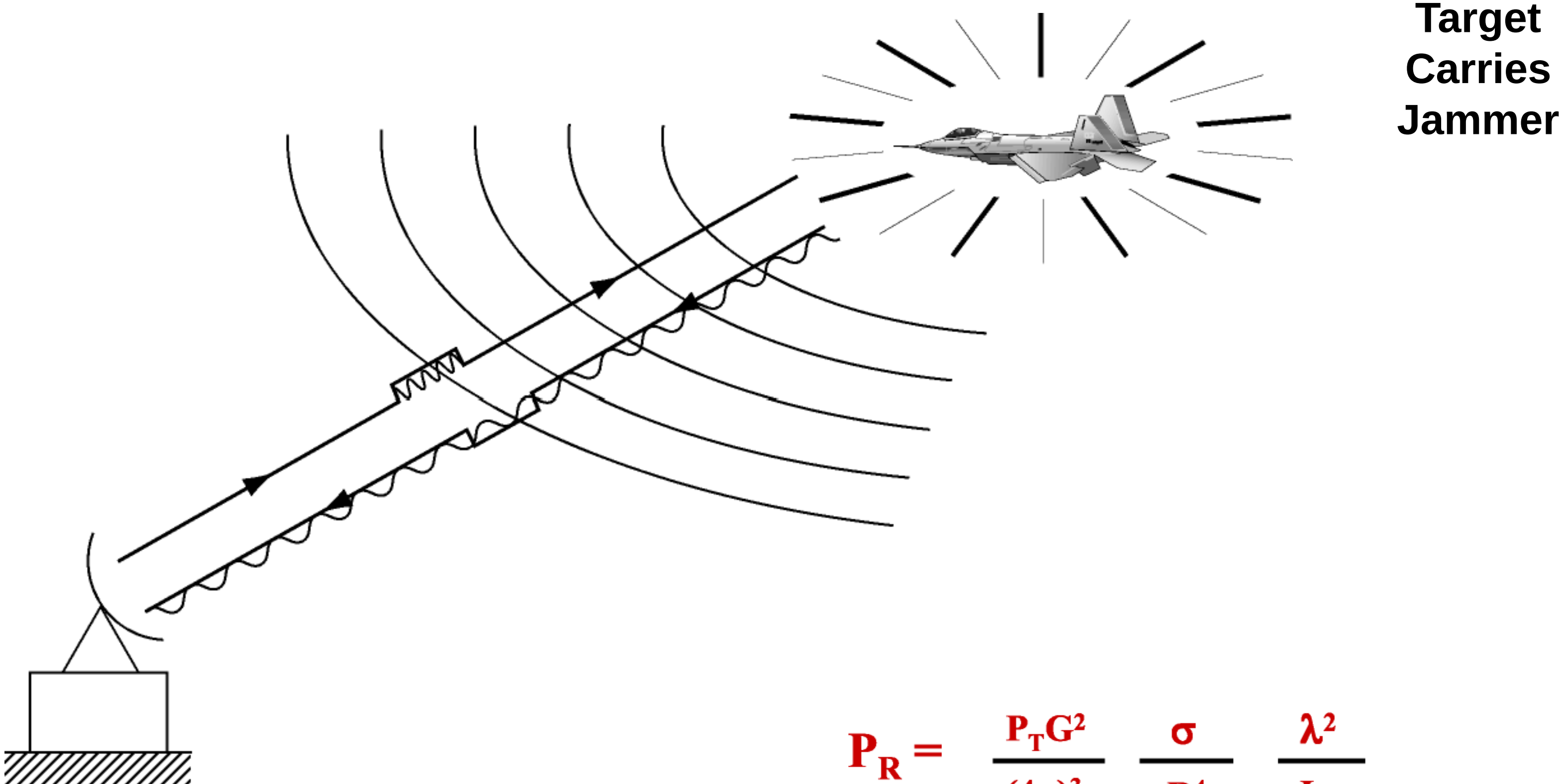
Self Screening Jammer

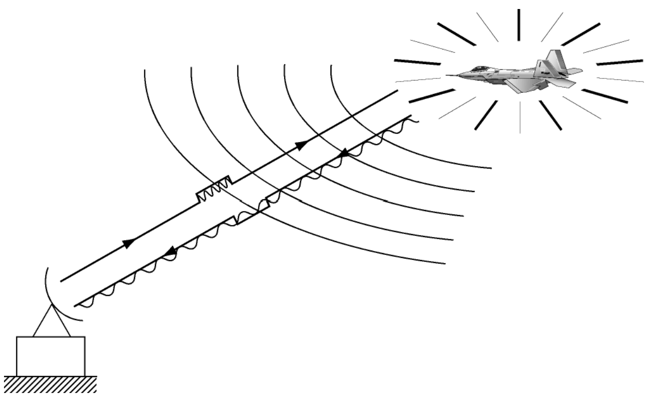


$$P_R = \frac{P_T G^2}{(4\pi)^3} \; \frac{\sigma}{R^4} \; \frac{\lambda^2}{L}$$

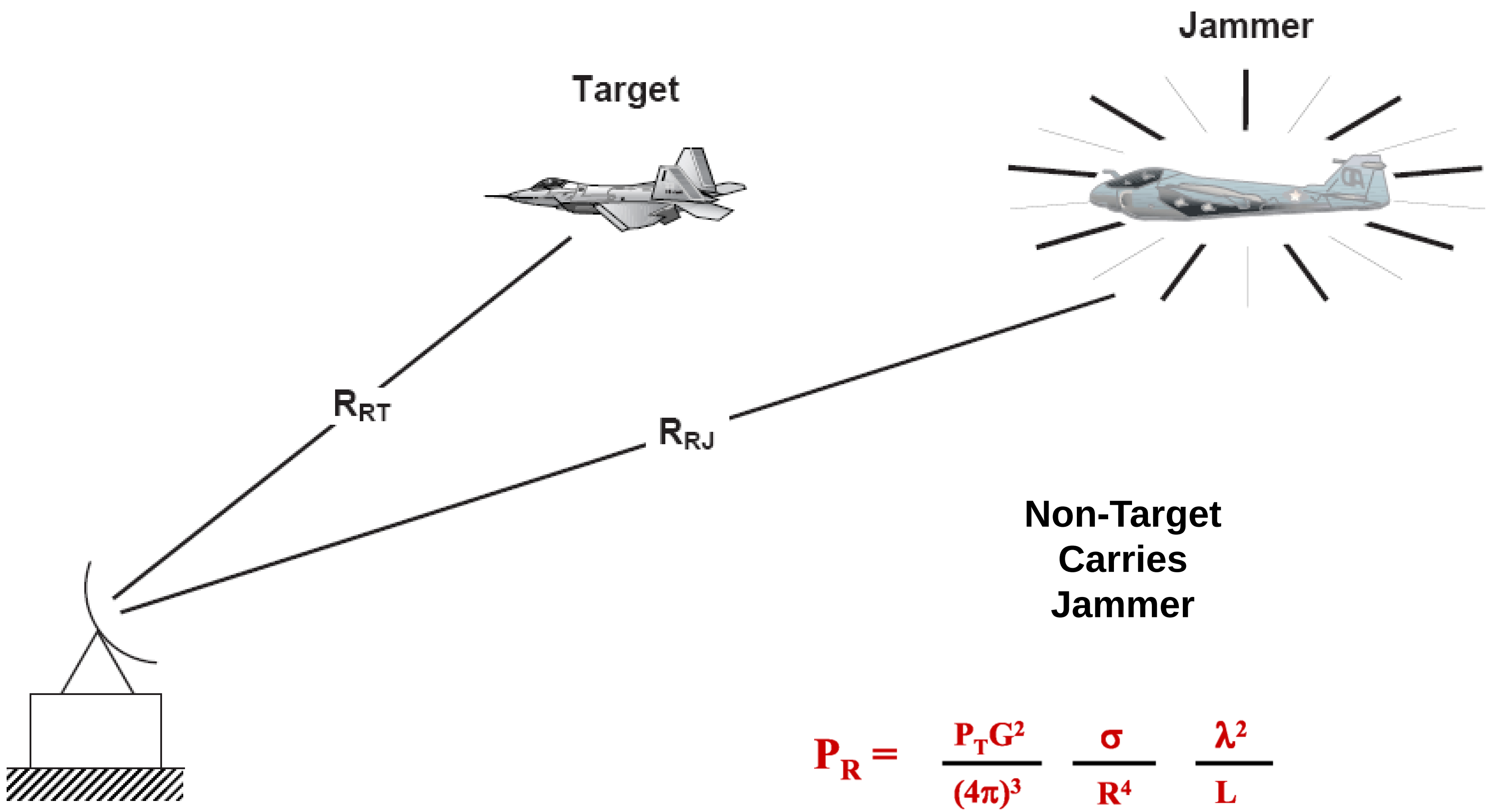
$$P_{RJ} = \left(\frac{P_J G_J}{4\pi \; R_J^2}\right)\left(\frac{\lambda^2 \; G_R}{4\pi}\right)\left(\frac{B_R}{B_J}\right)\left(\frac{1}{L^1}\right)$$

Challenges with Self Screening Jammer

- Power/gain battle between jammer and radar
- S/J ration is dependent upon R^2
- Sensitivity of the receiver not a factor
- Since the jamming signal and the radar return are from same place, antenna gain on receive not a factor
- Gain of jammer dependent upon antenna and therefore impacts aerodynamic configuration
- By jamming, SSJ always betrays his direction (bearing and elevation)



Stand-off Jammer



Non-Target Carries Jammer

$$P_R = \frac{P_T G^2}{(4\pi)^3} \frac{\sigma}{R^4} \frac{\lambda^2}{L}$$

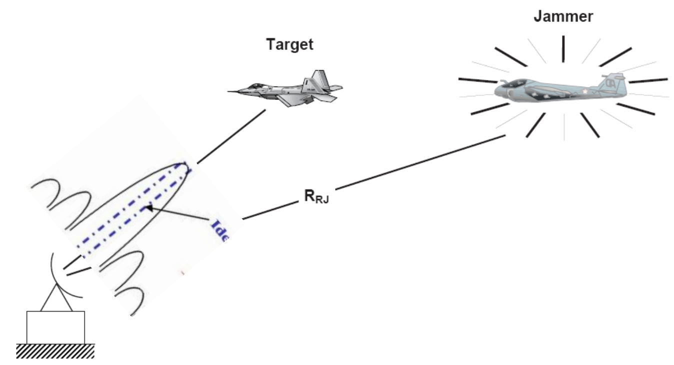
$$P_{RJ} = \left[\frac{P_J G_J}{4\pi R_J^2}\right]\left[\frac{\lambda^2 G_R}{4\pi}\right]\left[\frac{B_R}{B_J}\right]\left[\frac{1}{L^1}\right]$$

R_{RT} = Range from radar to target

R_{RJ} = Range from radar to jammer

Challenges with Stand-off Jammer

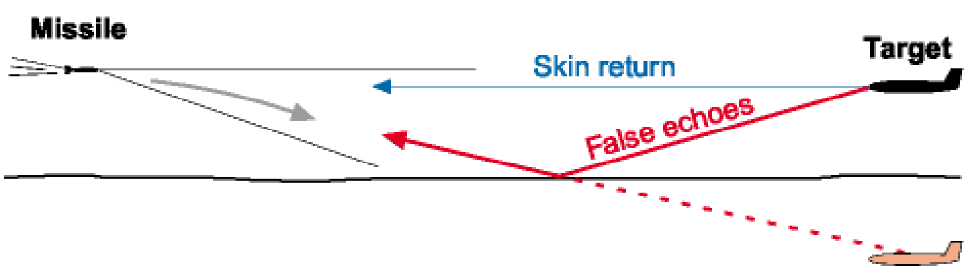
- The greater the range of the SOJ, the less the effect
- The effect of the SOJ is critically dependent upon the gain of the radar in the direction of the jammer relative to the direction of the target (sidelobe performance – see picture)
- SOJs usually carry significantly greater jamming power and can afford antennas with significant gain
- The direction (bearing and evaluation) of the SOJ does not betray the direction of the silent target



R_{RT}= Range from radar to target
R_{RJ}= Range from radar to jammer

Other Types of ECM

- Repeater
  - Repeaters have memory that records the RF signal
  - Recorded signals are transmitted back, at different delays to create false targets
- Gate Stealing
  - Transmit false target within the gate that a radar tracker places around the target. By making the false target signal larger than the real target signal, successive delays can "walk" or have the radar follow the false target and lose track on the real target.
- Terrain Bounce Jamming
  - Bounce jamming power off the surface and trick the missile seeker into locking on the false return.



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