Radar Systems Engineering
Lecture 4
The Radar Equation

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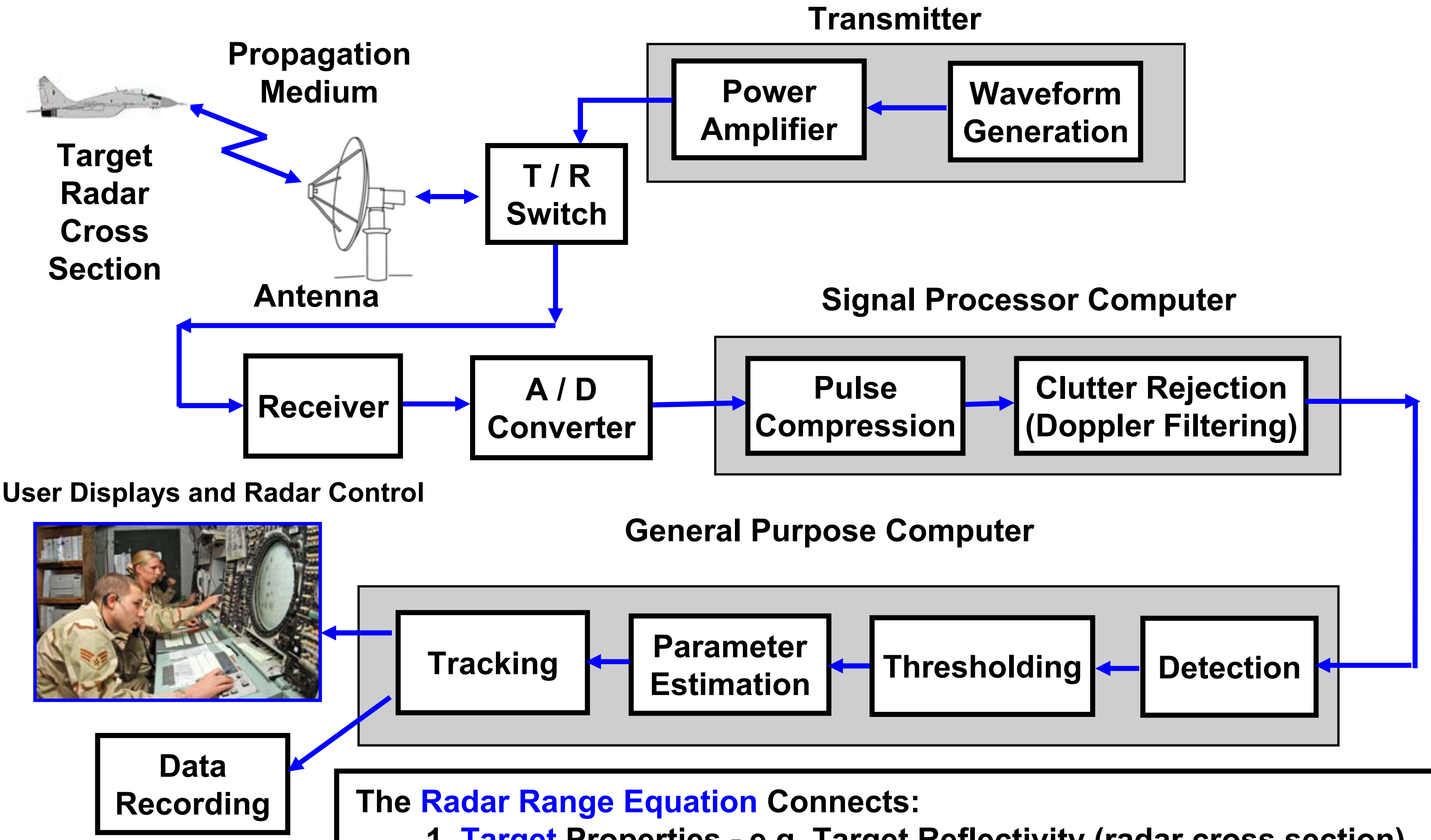
Guest Lecturer

Block Diagram of Radar System



Transmitter

Power Amplifier

Waveform Generation

Propagation Medium

Target Radar Cross Section

Antenna

T / R Switch

Signal Processor Computer

Receiver

A / D Converter

Pulse Compression

Clutter Rejection (Doppler Filtering)

User Displays and Radar Control

General Purpose Computer

Tracking

Parameter Estimation

Thresholding

Detection

Data Recording

The **Radar Range Equation** Connects:

1. **Target** Properties - e.g. Target Reflectivity (radar cross section)
2. **Radar** Characteristics - e.g. Transmitter Power, Antenna Aperture
3. Distance between **Target** and **Radar** - e.g. Range
4. Properties of the **Medium** - e.g. Atmospheric Attenuation.

Photo Image
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Outline

- Introduction
- ➡ Introduction to Radar Equation
- Surveillance Form of Radar Equation
- Radar Equation for Rain Clutter
- Radar Losses
- Examples
- Summary

Key Radar Functions

- Detection
  - Illuminate selected area with enough energy to detect targets of interest
- Measure target observables
  - Measure range, Doppler and angular position of detected targets
- Track
  - Correlate successive target detections as coming from same object and refine state vector of target
- Identification
  - Determine what target is - Is it a threat ?
- Handover
  - Pass the target on to;
    - Missile interceptor
    - Data Collection function
    - Air Traffic Controller / Operator

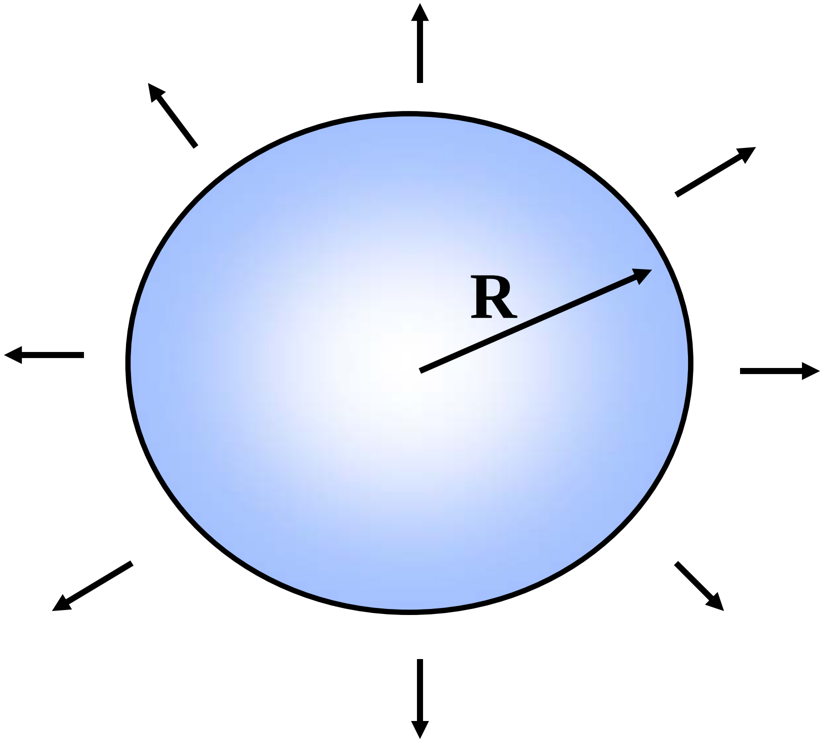
Radar Range Equation

Power density from uniformly radiating antenna transmitting spherical wave

$$\frac{P_t}{4\pi R^2}$$

P_t = peak transmitter power

R = distance from radar



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Radar Range Equation (continued)

Power density from isotropic antenna

$$\frac{P_t}{4\pi R^2}$$

Power density from directive antenna

$$\frac{P_t G_t}{4\pi R^2}$$

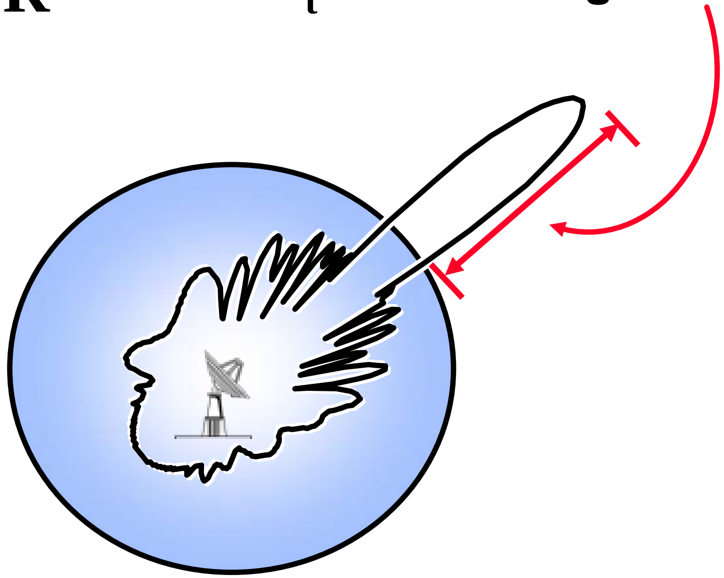
P_t = peak transmitter power

R = distance from radar

G_t = transmit gain

Gain is the radiation intensity of the antenna in a given direction over that of an isotropic (uniformly radiating) source

$$G_t = \frac{4\pi A}{\lambda^2}$$



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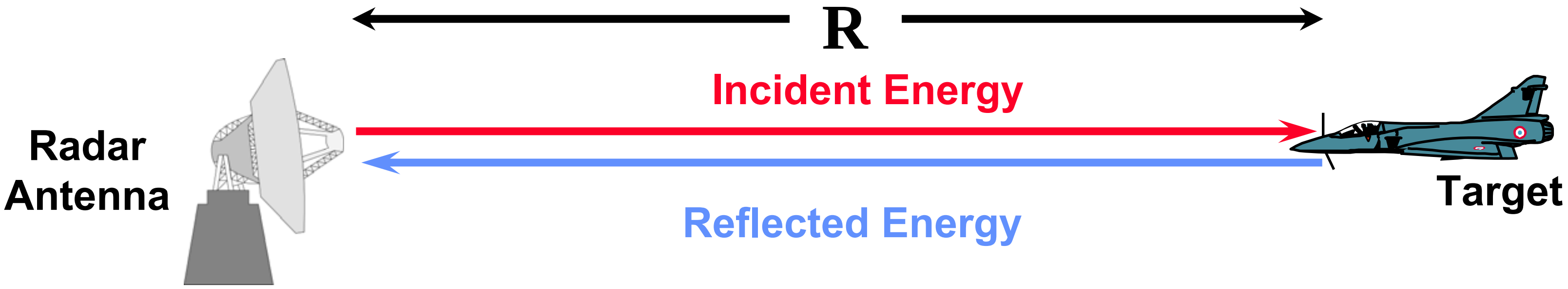
Definition of Radar Cross Section (RCS or s)



R

Radar Antenna

Incident Energy

Reflected Energy

Target

Radar Cross Section (RCS or σ) is a measure of the energy that a radar target intercepts and scatters back toward the radar

Power of reflected signal at target

$$\frac{P_t G_t \sigma}{4\pi R^2}$$

σ = radar cross section units (meters)^2

Power density of reflected signal at the radar

$$\frac{P_t G_t}{4\pi R^2} \frac{\sigma}{4\pi R^2}$$

Power density of reflected signal falls off as (1/R^2)

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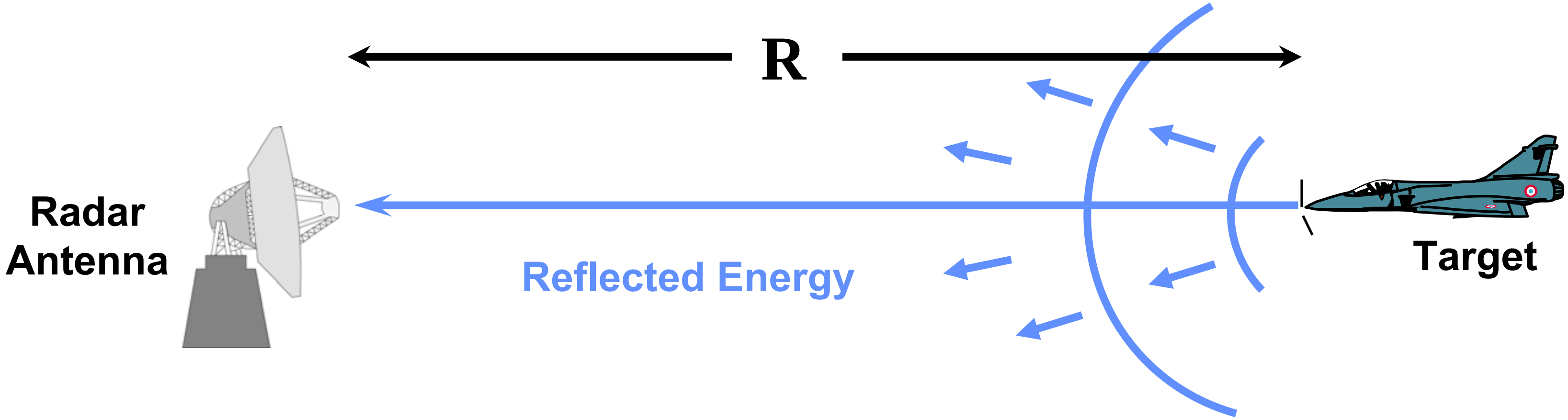
Radar Range Equation (continued)

Power density of reflected signal at radar

$$\frac{P_t G_t}{4 \pi R^2} \frac{\sigma}{4 \pi R^2}$$



The received power = the power density at the radar times the area of the receiving antenna

Power of reflected signal from target and received by radar

$$P_r = \frac{P_t G_t}{4 \pi R^2} \frac{\sigma A_e}{4 \pi R^2}$$

P_r = power received

A_e = effective area of receiving antenna

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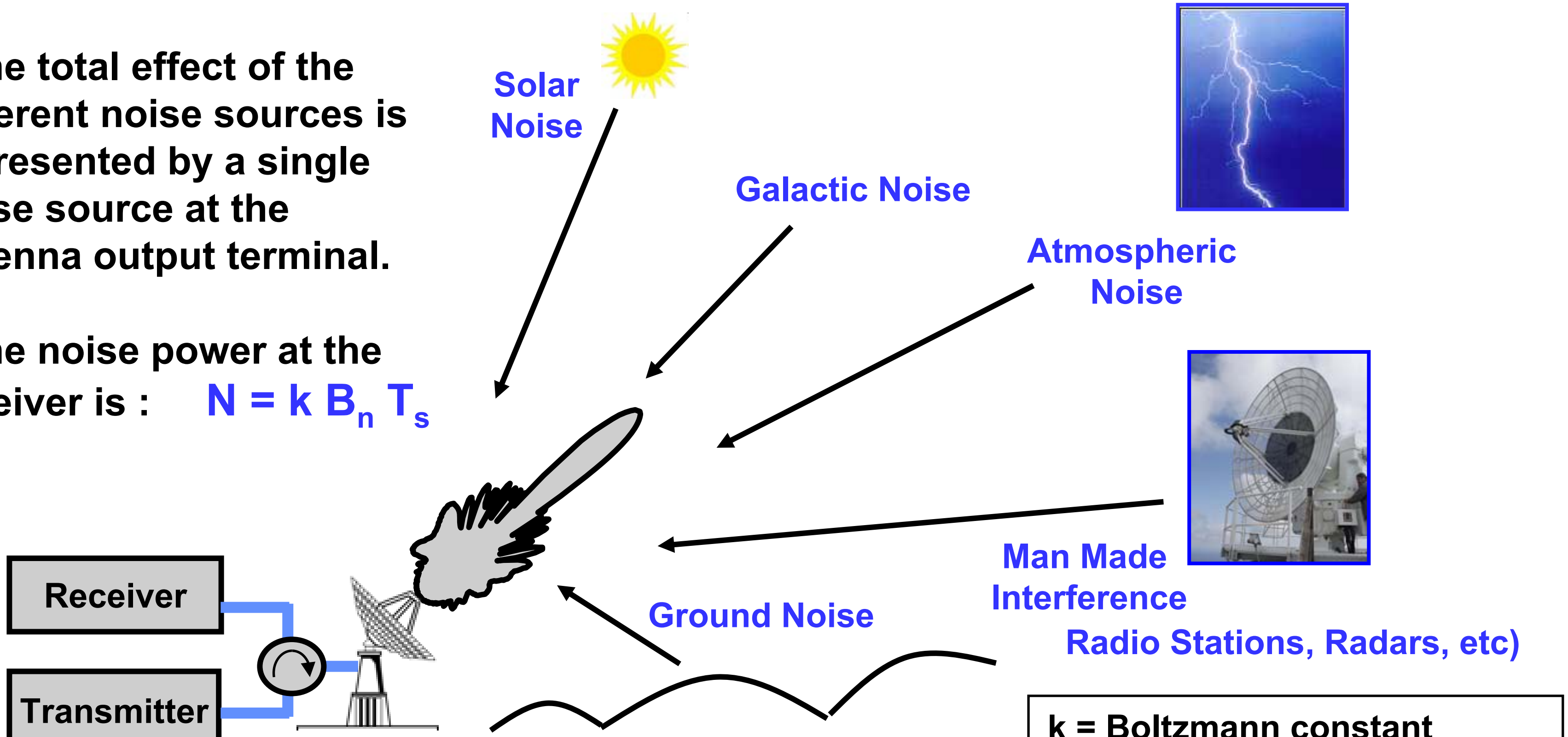
Sources of Noise Received by Radar

- The total effect of the different noise sources is represented by a single noise source at the antenna output terminal.
- The noise power at the receiver is : $N = k B_n T_s$



(Receiver, waveguide, and duplexer noise)

Noise from Many Sources Competes with the Target Echo

k = Boltzmann constant
= 1.38 x 10^{-23} joules / deg ^{o}K
T_s= System Noise Temperature
B_n = Noise bandwidth of receiver

Radar Range Equation (continued)

Signal Power reflected from target and received by radar

$$P_r = \frac{P_t G_t}{4\pi R^2} \frac{\sigma A_e}{4\pi R^2}$$

Average Noise Power

$$N = k B_n T_s$$

Signal to Noise Ratio

$$\frac{S}{N} = \frac{P_r}{N}$$

Assumptions :

$G = G_r = G_t$

L = Total System Losses

T_o= 290° K

$$\boxed{\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}}$$

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Signal to Noise Ratio (S/N or SNR) is the standard measure of a radar's ability to detect a given target at a given range from the radar

" S/N = 13 dB on a 1 m^2 target at a range of 1000 km"

radar cross section of target

System Noise Temperature

The System Noise Temperature, T_s ,is divided into 3 components :

Where:

$$T_s = T_a + T_r + L_r T_e$$

T_a is the contribution from the antenna

T_r is the contribution from the RF components between the antenna and the receiver

L_r *is loss of the input RF components (natural units)*

T_e is temperature of the receiver

The 3 temperature components can be broken down further :

$$T_a = (0.88 T_{sky} - 254)/(L_a + 290)$$

Where:

$$T_r = T_{tr}\,(L_r - 1) \quad \text{and} \quad T_e = T_o (F_n - 1)$$

T_{sky} *is the apparent temperature of the sky (from graph)*

L_a *is the dissipative loss within the antenna (natural units)*

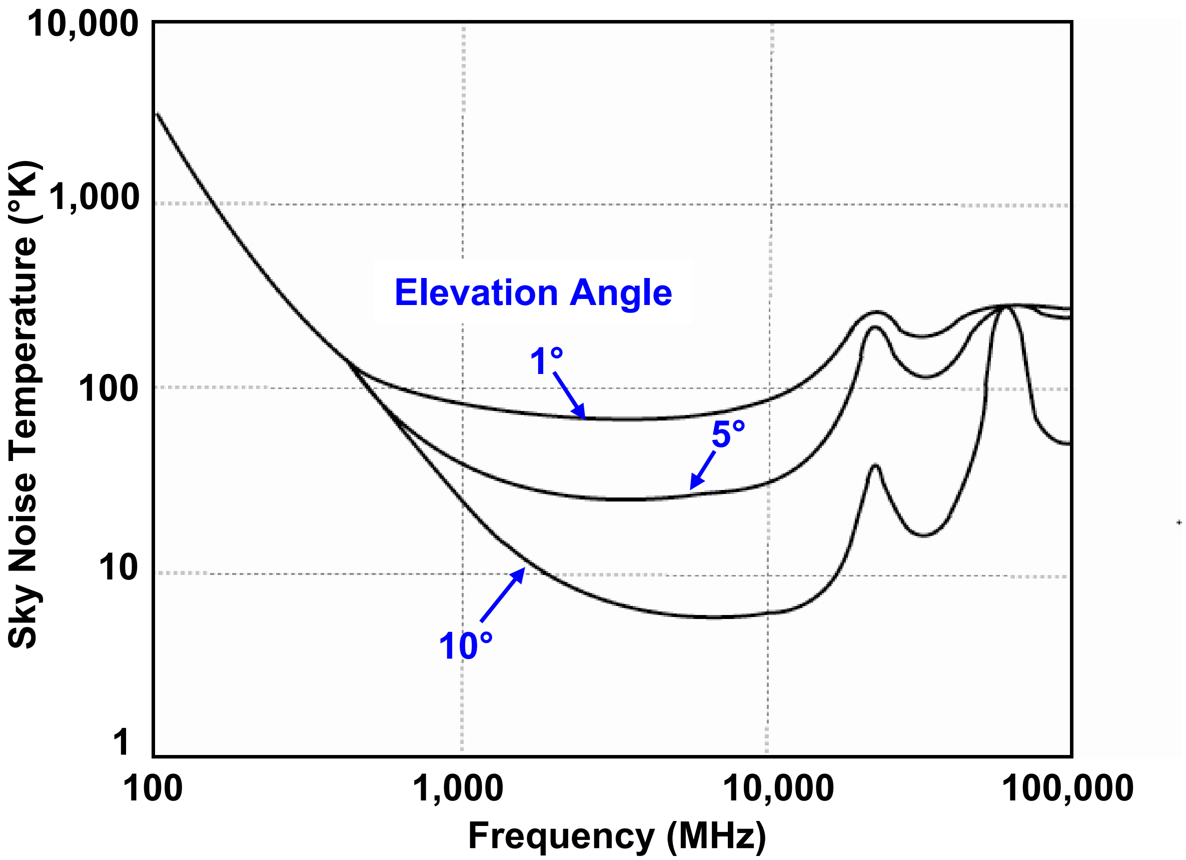
T_{tr} *is physical temperature of the RF components*

F_n *is the noise factor of the receiver (natural units)*

T_o *is the reference temperature of 290^o K*

Note that all temperature quantities are in units of °K

Noise Temperature vs. Frequency



- **The data on this graph takes into account the following effects:**
  - **Galactic noise, cosmic blackbody radiation, solar noise, and atmospheric noise due to the troposphere**

(Adapted from Blake, Reference 5, p 170)

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- Introduction
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- ➡ Surveillance Form of Radar Equation
- Radar Equation for Rain Clutter
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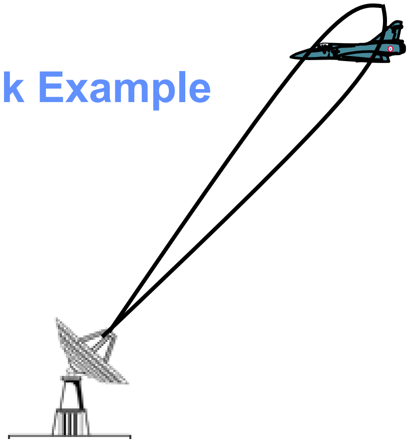
Track Radar Equation

Track Radar Equation

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$

- When the location of a target is known and the antenna is pointed toward the target.

Track Example



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Development of Search Radar Equation

Track Radar Equation

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$

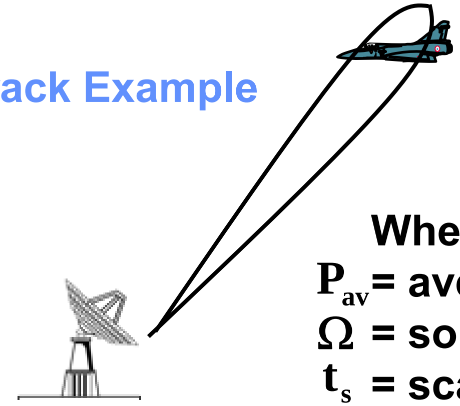
- When the location of a target is known and the antenna is pointed toward the target.

Search Radar Equation

$$\boxed{\frac{S}{N} = \frac{P_{av} A_e t_s \sigma}{4\pi \Omega R^4 k T_s L}}$$

- When the target’s location is unknown, and the radar has to search a large angular region to find it.

Track Example



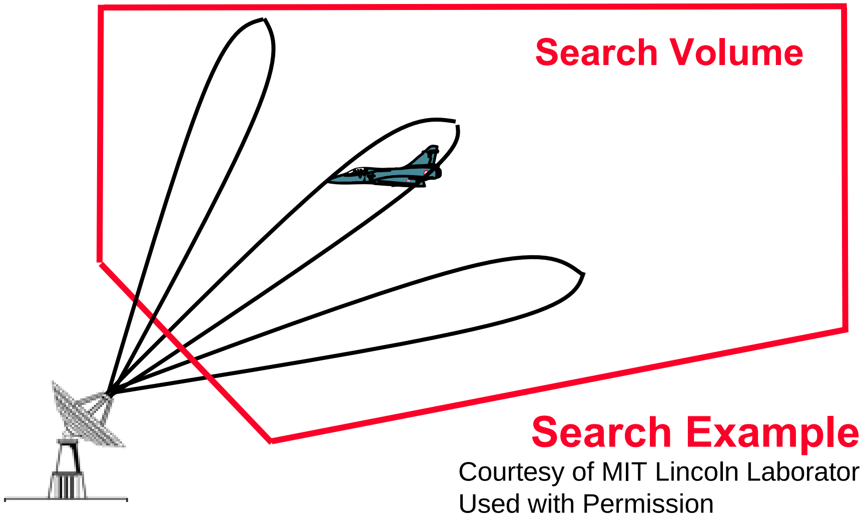
Where:

P_{av} = average power

Ω = solid angle searched

t_s = scan time for Ω

A_e = antenna area



Search Example

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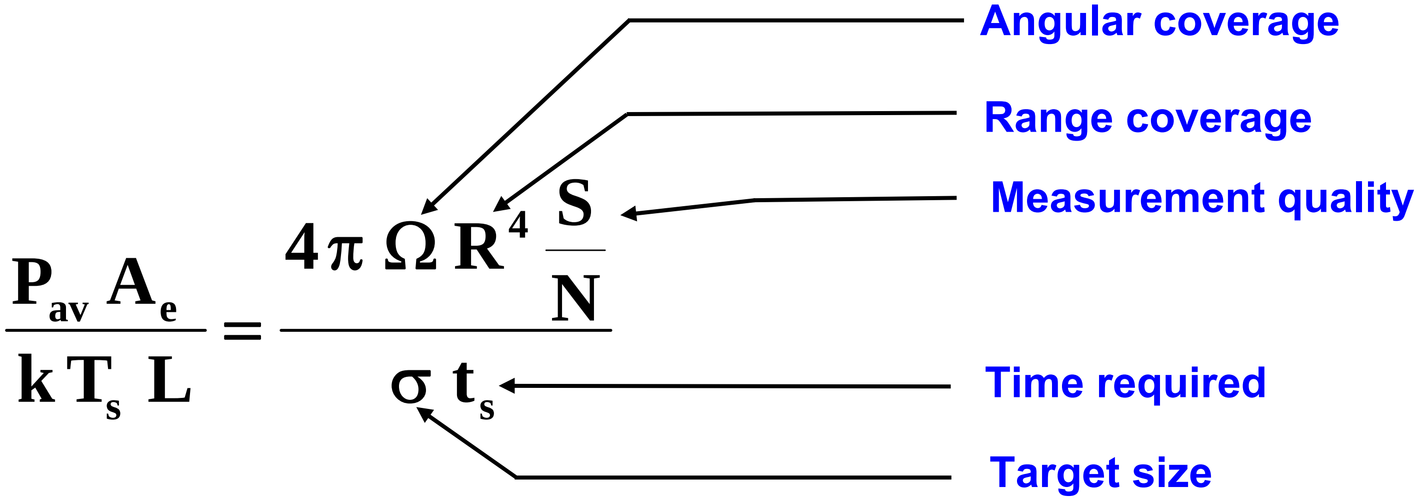
Search Radar Range Equation

$$\boxed{\frac{S}{N} = \frac{P_{av}\, A_e\, t_s\, \sigma}{4\pi\, \Omega\, R^4\, k\, T_s\, L}}$$

Re-write as:

f (design parameters) = g (performance parameters)



$$\frac{P_{av}\, A_e}{k\, T_s\, L} = \frac{4\pi\, \Omega\, R^4\, \frac{S}{N}}{\sigma\, t_s}$$

Angular coverage

Range coverage

Measurement quality

Time required

Target size

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Scaling of Radar Equation

$$\frac{S}{N} = \frac{P_{av}\, A_e\, t_s\, \sigma}{4\pi\, \Omega\, R^4\, k\, T_s\, L} \Longrightarrow P_{av} = \frac{4\pi\; R^4\, \Omega\, k\, T_s\, L\, (S/N)}{A_e\, t_s\, \sigma}$$

- Power required is:
  - Independent of wavelength
  - A very strong function of R
  - A linear function of everything else

Example Radar Can Perform Search at 1000 km Range
How Might It Be Modified to Work at 2000 km ?

Solutions Increasing R by 3 dB (x 2) Can Be Achieved by:

1. Increasing P_{av} by 12 dB (x 16)

or 2. Increasing Diameter by 6 dB (A_e by 12 dB)

or 3. Increasing t_s by 12 dB

or 4. Decreasing Ω by 12 dB

or 5. Increasing σ by 12 dB

or 6. An Appropriate Combination of the Above

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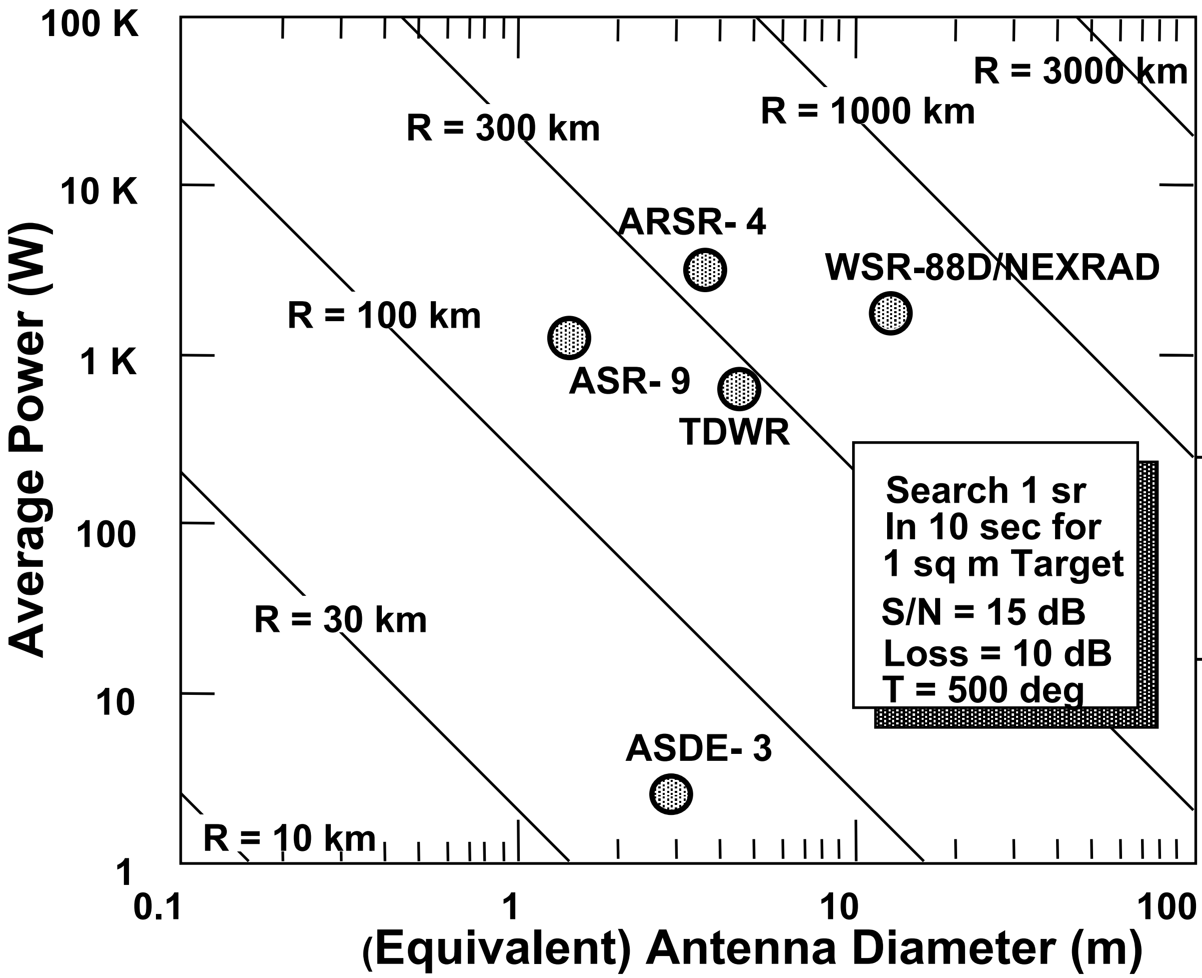
Search Radar Performance



ASR- 9
Airport Surveillance Radar

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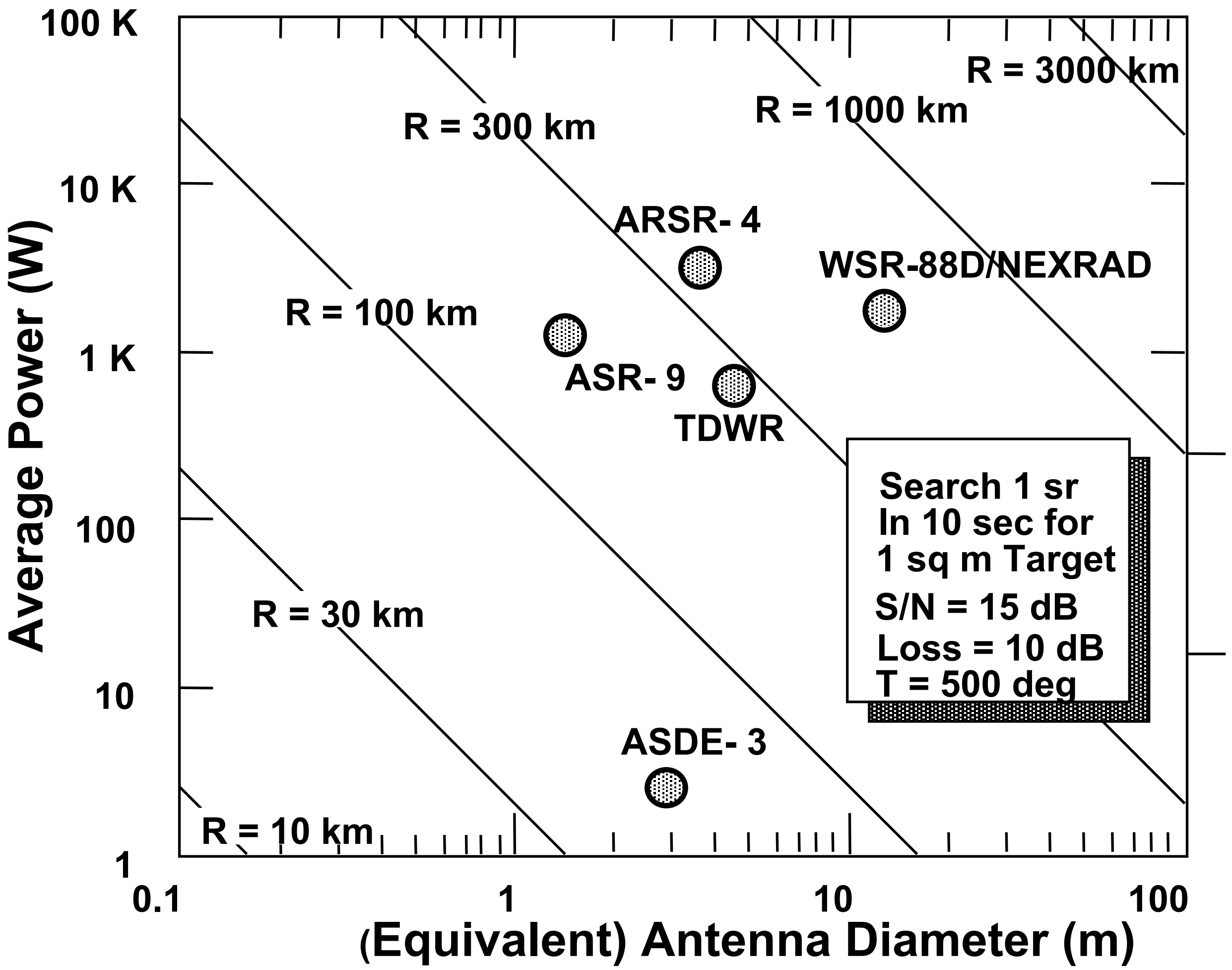
Search Radar Performance



Search 1 sr
In 10 sec for
1 sq m Target
S/N = 15 dB
Loss = 10 dB
T = 500 deg

ASDE- 3
Airport Surface Detection Equipment

Courtesy Target Corporation

Courtesy of MIT Lincoln Laboratory
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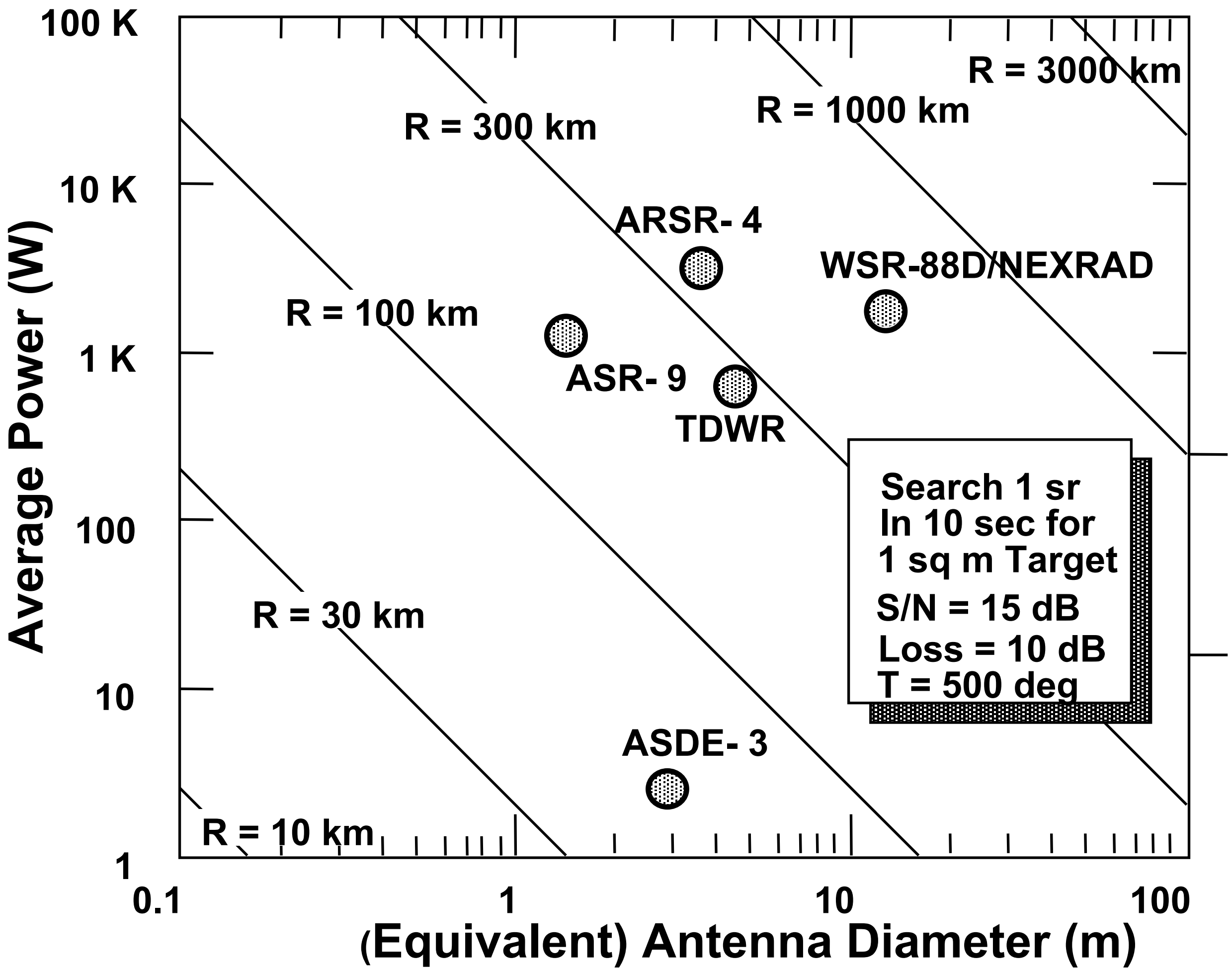
Search Radar Performance



Courtesy of MIT Lincoln Laboratory
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ARSR- 4
Air Route Surveillance Radar

ARSR- 4 Antenna
(without Radome)

Courtesy of Northrop Grumman.
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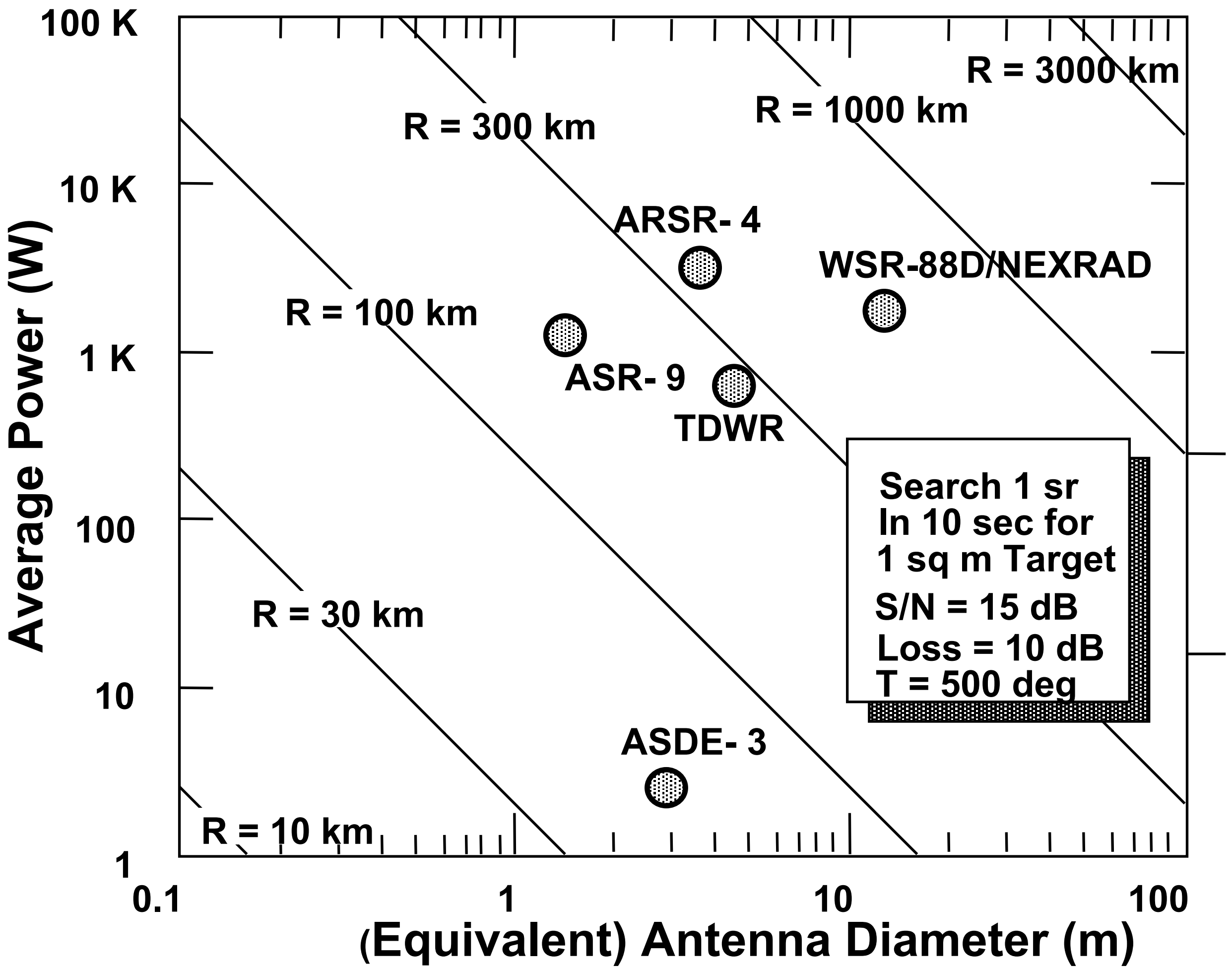
Search Radar Performance



WSR-88D / NEXRAD

Courtesy of NOAA.

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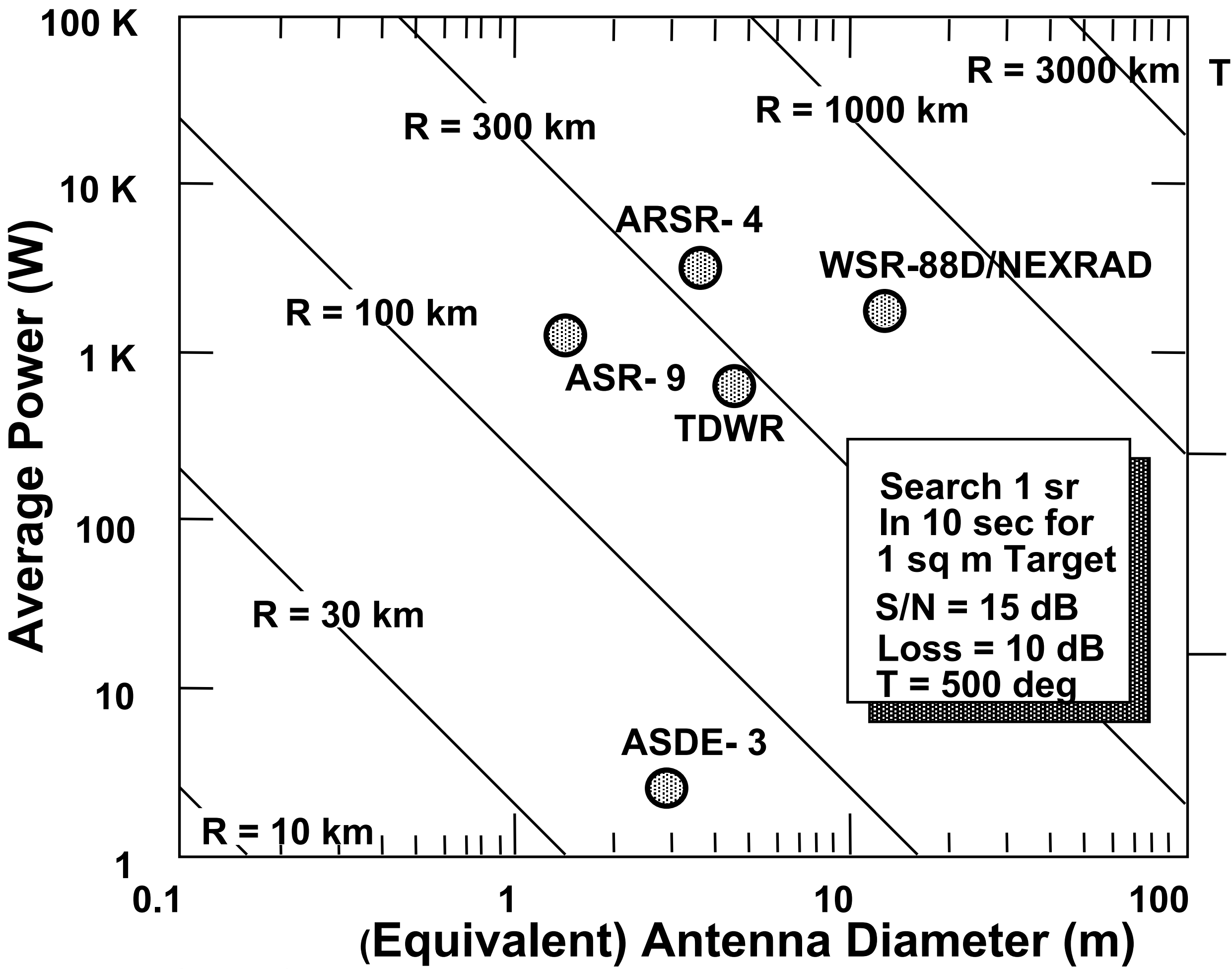
Search Radar Performance



Search 1 sr
In 10 sec for
1 sq m Target
S/N = 15 dB
Loss = 10 dB
T = 500 deg

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TDWR
Terminal Doppler Weather Radar

Courtesy of Raytheon.

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Radar Equation for Rain Clutter (and other Volume Distributed Targets)

- Standard radar equation ⟹ $\dfrac{S}{N} = \dfrac{P_t\, G^2 \lambda^2\, \sigma}{(4\pi)^3 R^4\, k\, T_s\, B_n\, L}$
- If the target is a diffuse scatterer (e.g. rain), which completely fills the range-azimuth-elevation cell of the radar, then the radar cross section of the target takes the form:

$$\sigma = \eta V \quad \text{and} \quad V = \frac{\pi}{4}\left(R\,\theta_B\right)\left(R\,\phi_B\right)\left(\frac{c\,\tau}{2}\right)\frac{1}{2\ln_e 2}$$

- And the radar equation becomes:

$$\frac{S}{N} = \frac{P_t\, G\, \lambda^2 c\, \tau\, \eta}{1024\,(\ln_e 2) R^2\, k\, T_s\, B_n\, L}$$

Note, for Gaussian antenna pattern $G \approx \dfrac{\pi^2}{\theta_B\, \phi_B}$

- Note, that volume distributed backscatter is a function of $1/R^2$ rather than the usual $1/R^4$

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System Loss Terms in the Radar Equation

Transmit Losses

Radome
Circulator
Waveguide Feed
Waveguide
Antenna Efficiency
Beam Shape
Low Pass Filters
Rotary Joints
Scanning
Atmospheric
Quantization
Field Degradation

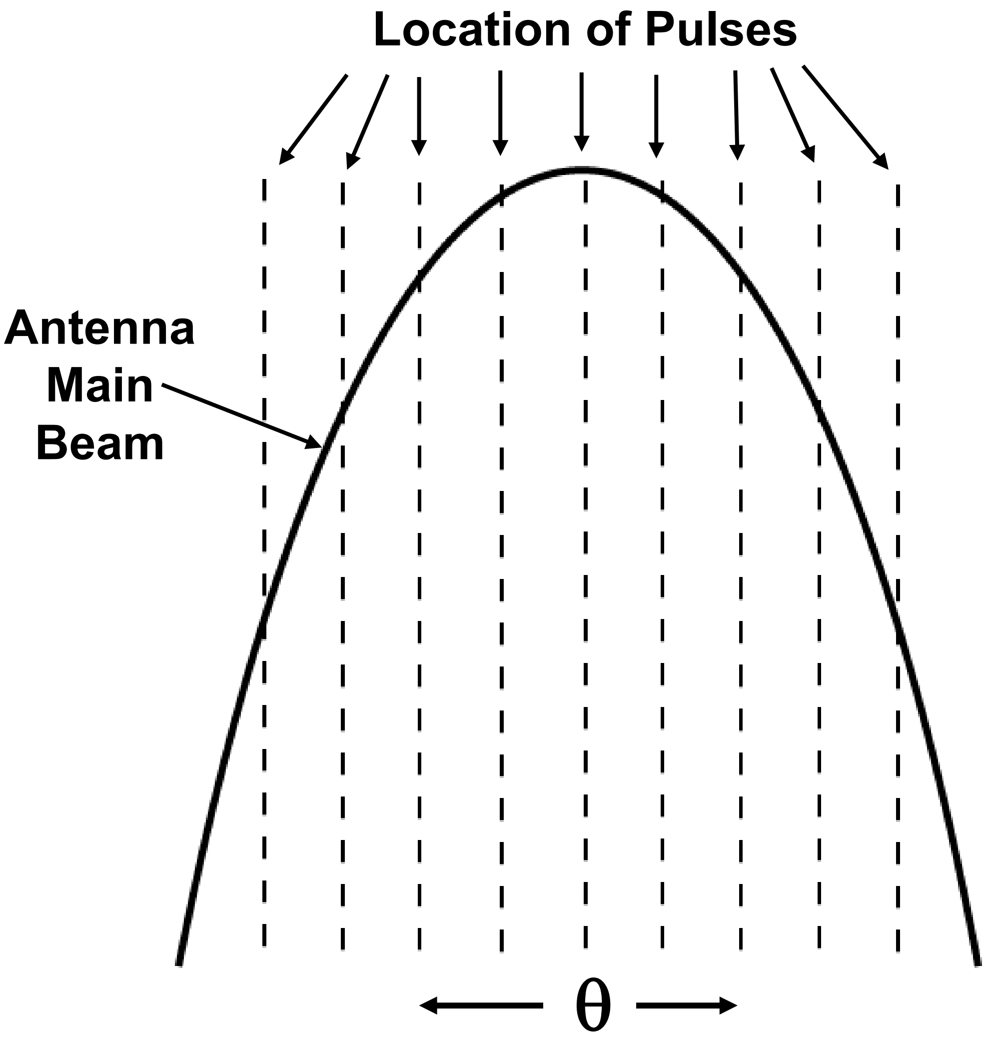
Receive Losses

Radome
Circulator
Waveguide Feed
Waveguide
Combiner
Receiver Protector
Rotary Joints
Transmit / Receive Switch
Antenna Efficiency
Beam Shape
Scanning
Doppler Straddling
Range Straddling
Weighting
Non-Ideal Filter
CFAR
Quantization
Atmospheric
Field Degradation

Major Loss Terms in Radar Equation

- **Beam Shape Loss**
  - Radar return from target with scanning radar is modulated by shape of antenna beam as it scans across target. Can be 2 to 4 dB
- **Scanning Antenna Loss**
  - For phased array antenna, gain of beam less than that on boresite
- **Inputs to System Noise Temperature**
  - Noise received by antenna
    - Local RF noise
    - Galactic noise
  - Receiver noise factor
  - Receive waveguide losses
  - Antenna ohmic losses

Nature of Beam Shape Loss



Radar Equation assumes n pulses are integrated, all with gain G.

Except for the pulse at the center of the beam, the actual pulses illuminate the target with a gain less than the maximum.

(Adapted from Skolnik, Reference 1, p 82)

Major Loss Terms in Radar Equation

- **Waveguide and Microwave Losses**
  - Transmit waveguide losses (including feed, etc)
  - Rotary joints, circulator, duplexer
- **Signal Processing Loss**
  - Range and Doppler Weighting
  - A /D Quantization Losses
  - Adaptive thresholding (CFAR) Loss
  - Range straddling Loss
- **Lens Effect Loss**
  - Refraction in atmosphere causes spreading of beam and thus degradation in S/N
- **Atmospheric Attenuation Loss**
  - Attenuation as radar beam travels through atmosphere (2 way loss)

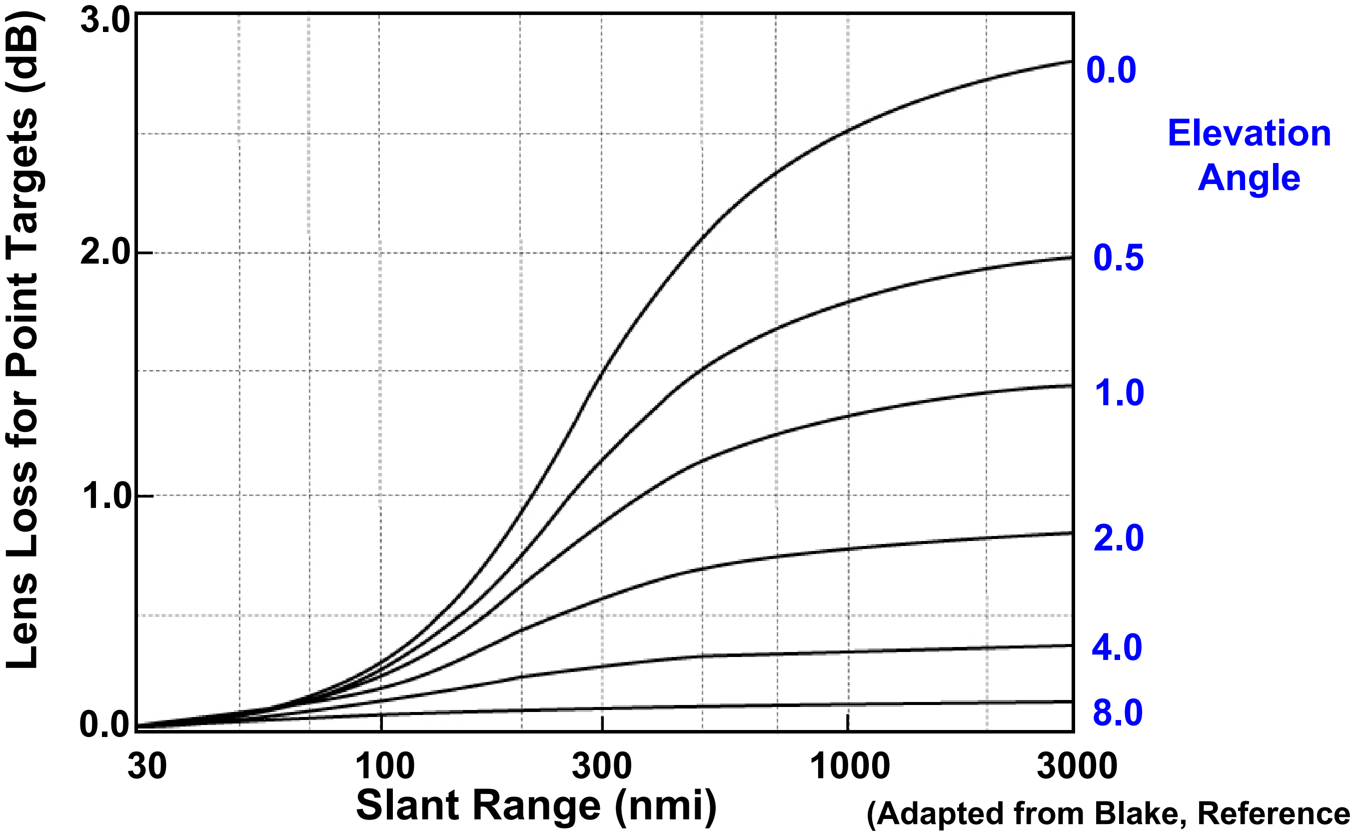
Rectangular Waveguide Attenuation

Frequency Band		Frequency Range of Dominant TE_{10} Mode (GHz)	Attenuation- Lowest to Highest Frequency (dB/100 ft)
UHF	Aluminum	0.35 - 0.53	0.054 - 0.034
L Band		0.96 - 1.44	0.20 - 0.135
S Band	Brass	2.6 - 3.95	1.10 - 0.75
C Band		3.95 - 5.85	2.07 - 1.44
X Band		8.2 - 12.40	6.42 - 4.45
K_u Band		12.4 - 18.0	9.58 - 8.04
K_a Band	Silver Clad Copper	26.5 - 40.0	21.9 - 15.0

(Adapted from Volakis, Reference 7, pp 51-40 to 51- 41)

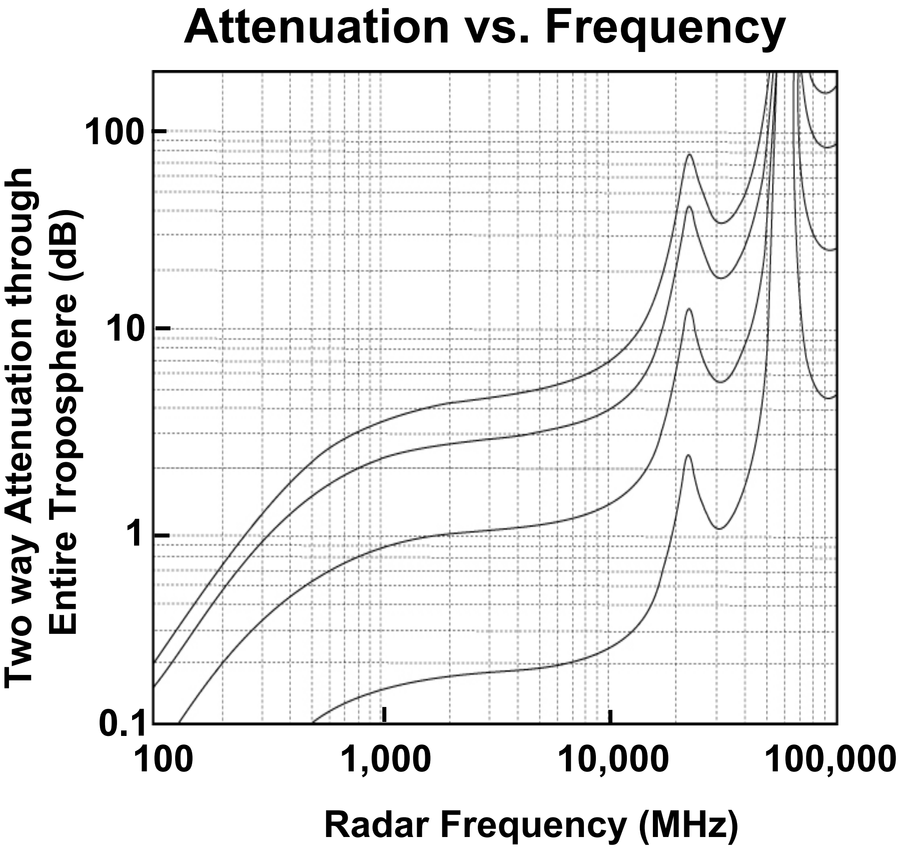
Lens Loss vs. Range

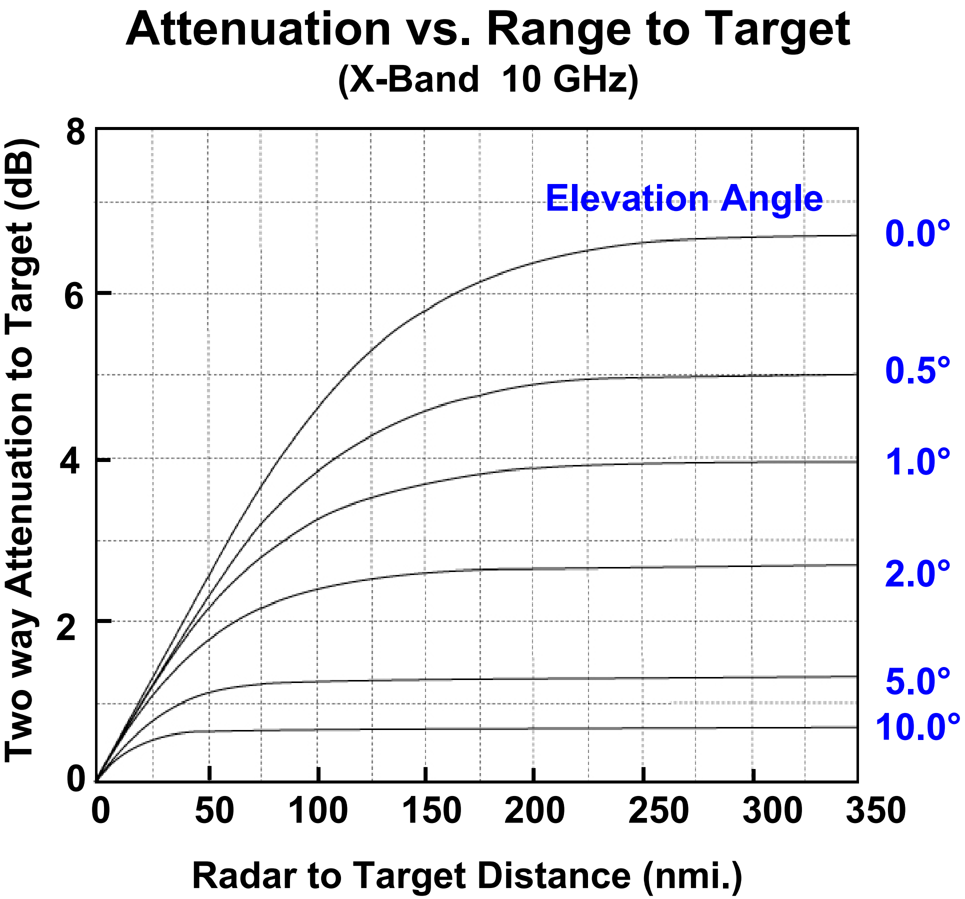
- The gradient of atmospheric refraction at lower elevation angles, causes a spreading of the radar beam, and thus a small diminishment radar power
- This lens loss is frequency independent
- It is significant only for targets that are at long range.



(Adapted from Blake, Reference 5, p 192)

Loss Due to Atmospheric Attenuation





0,1,5,30 deg

(Adapted from Blake, see Reference 5, p 192)

Major Loss Terms in Radar Equation

- Bandwidth Correction Factor
  - Receiver not exact matched filter for transmitted pulse
- Integration Loss
  - Non coherent integration of pulses not as efficient as coherent integration
- Fluctuation Loss
  - Target return fluctuates as aspect angle changes relative to radar
- Margin (Field Degradation) Loss
  - Characteristics of radar deteriorates over time (~3 dB not unreasonable to expect over time)
    - Water in transmission lines
    - Weak or poorly tuned transmitter tubes
    - Deterioration in receiver noise figure

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Radar Equation - Examples

- Airport Surveillance Radar
  - 0 th order
  - Back of the envelope

- Range Instrumentation Radar
  - A more detailed calculation

Example - Airport Surveillance Radar

- **Problem : Show that a radar with the parameters listed below, will get a reasonable S / N on an small aircraft at 60 nmi.**

Radar Parameters

Range	60 nmi
Aircraft cross section	1 m^2
Peak Power	1.4 Megawatts
Duty Cycle	0.000525
Pulsewidth	.6 microseconds
Bandwidth	1.67 MHz
Frequency	2800 MHz
Antenna Rotation Rare	12.7 RPM
Pulse Repetition Rate	1200 Hz
Antenna Size	4.9 m wide by 2.7 m high
Azimuth Beamwidth	1.35 °
System Noise Temp.	950 ° K

$$\lambda = c / f \quad = .103 \text{ m}$$

$$G = \frac{4 \pi A}{\lambda^2} \quad = 15670$$

= 42 dB, (actually 33 dB with beam shaping losses)

Number of pulses per beamwidth = 21

Assume Losses = 8dB

Courtesy of MIT Lincoln Laboratory
Used with Permission

Example - Airport Surveillance Radar

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$

P_t = 1.4 Megawatts
G = 33 dB = 2000
λ = .1 m
σ = 1 m^2
k = 1.38×10^{-23} w / Hz ° K

R = 111, 000 m
T_s = 950 ° K
B_n = 1.67 MHz
L = 8dB = 6.3
$(4\pi)^3$ = 1984

$$\frac{(1.4 \times 10^{6}\ \text{w})(2000)(2000)(.1\text{m})(.1\text{m})(1\text{m}^2)}{(1984)\ (1.11\ \text{X}\ 10^{5}\ \text{m})^4\ (1.38 \times 10^{-23}\ \text{w / Hz °K})\ (950\ \text{°K})\ (6.3)\ (1.67 \times 10^{6}\ \text{Hz})}$$

$$\frac{5.6 \times 10^{+6+3+3-1-1}}{415 \times 10^{+3+20-23+2+6}} = \frac{5.6 \times 10^{+10}}{4.15 \times 10^{+2+3+20-23+2+6}} = \frac{5.6 \times 10^{+10}}{4.15 \times 10^{+10}} = 1.35 = 1.3\ \text{dB}$$

S / N = 1.3 dB per pulse (21 pulses integrated) => S / N per dwell = 14.5 dB
+ 13.2 dB

Courtesy of MIT Lincoln Laboratory
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Example - Airport Surveillance Radar

dB Method

		(+)	(-)
Peak Power	1.4 MW	61.5	
(Gain) ^{2}	33 db	66	
(Wavelength) ^{2}	.1 m		20
Cross section	1 m^2	0	
$(4\pi)^3$	1984		33
(Range)^4	111 km		201.8
k	1.38 x 10 $^{-23}$ w / Hz ^{o} K	228.6	
System Temp	950		29.8
Losses	8 dB		8
Bandwidth	1.67 MHz		62.2
		+ 356.1	- 354.8

+ 1.3 dB

S / N = 1.3 dB per pulse (21 pulses integrated) => S / N per dwell = 14.5 dB
(+ 13.2 dB)

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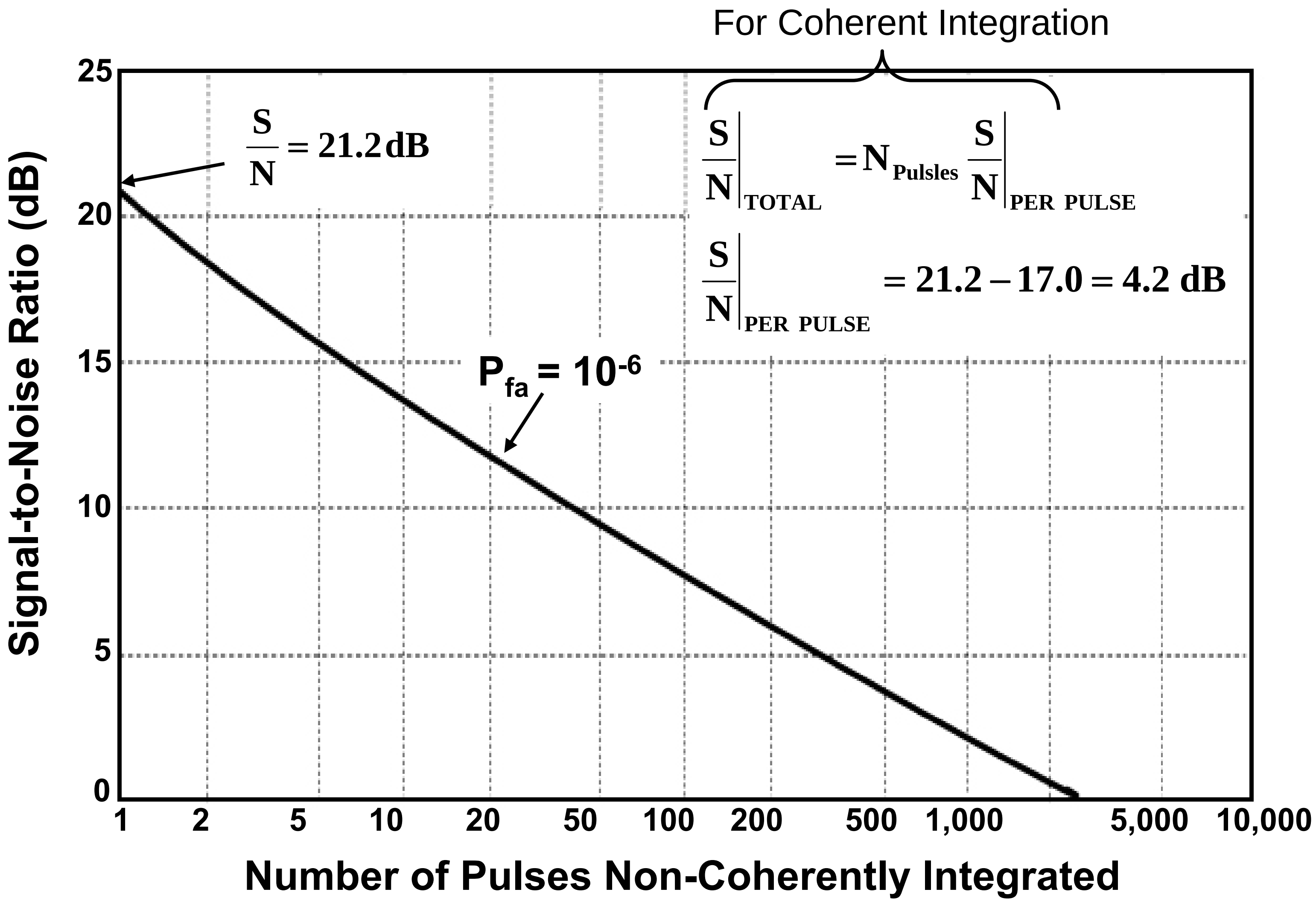
Example # 2 – Range Instrumentation Radar

- Problem : For a C-band pulsed radar with a 6.5 m dish antenna and 1,000 kW of peak power (0.1% duty cycle), what is the maximum detection range on a target with 0 dBsm cross section, a Pd of .9, and Pfa of 10^{-6} (Assume a Swerling Case 1 target fluctuations and a 1 μsec pulse) ?

Radar Parameters

Maximum Detection Range	?? km
Probability of Detection	.9
Probability of False Alarm	10^{-6}
Target Cross Section	0 dBsm (1 m^2)
Target Fluctuations	Swerling Case 1
Peak Power	1,000 Kilowatts
Duty Cycle	0.1 %
Pulsewidth	1 microsecond
Frequency	5,500 MHz
Antenna Size	6.5 m dish
Number of Pulses Integrated	50

Detection Statistics for Swerling Case 1
(Probability of Detection = 0.9)



$\frac{S}{N} = 21.2\,\text{dB}$

$P_{fa} = 10^{-6}$

For Coherent Integration

$$\left.\frac{S}{N}\right|_{TOTAL} = N_{Pulsles} \left.\frac{S}{N}\right|_{PER\ PULSE}$$

$$\left.\frac{S}{N}\right|_{PER\ PULSE} = 21.2 - 17.0 = 4.2\text{ dB}$$

(Adapted from Blake in Skolnik, see Reference 4, p 192)

Radar Equation Example #2

Radar and Target Parameters – Inputs	Natural Units	(dB)
Peak Power (kilowatts)	1,000	60.0
Pulse Duration (microseconds)	1.0	- 60.0
Noise Bandwidth (MHz)	1.0	60.0
Transmit Antenna Gain (dB)		49.6
Receive Antenna Gain (dB)		49.6
Frequency (GHz)	5.5	
Wavelength (meters)	5.45	- 25.3
Single Pulse Signal to Noise Ratio		4.2
Target Radar Cross Section (meters)^2	1.0	0.0
k - Boltzmann's Constant 1.38 x 10^{-23} (w / Hz °K)		- 228.6
$(4\pi)^3$		33.0
System Noise Temperature (°K)	598.2	27.8
Total System Losses		9.0
Range (kilometers)	519	

Antenna

Efficiency	65 %
Diameter (meters)	6
Gain (dB)	49.6

Radar Equation # 2 System Losses

System Losses	(dB)
Bandwidth Correction Factor (dB)	0.70
Transmit Loss (dB)	1.30
Scanning Antenna Pattern Loss (dB)	0.00
Signal Processing Losses (dB)	1.90
Atmospheric Attenuation Loss (dB)	1.80
Lens Effect Loss (dB)	0.25
Integration Loss (dB)	0.00
Target Fluctuation Loss (dB)	0.00
Margin / Field Degradation Loss (dB)	3.00
Total Loss Budget (dB)	8.95

Loss – Input to System Noise Temperature	
Receiver Noise Factor (dB)	4.00
Antenna Ohmic Loss (dB)	0.20
Receive Transmission Line loss (dB)	0.40
Sky Temperature (°K)	50.00
C-Band at 3°	

Transmit Losses	(dB)
Circulator (dB)	0.40
Switches (dB)	0.40
Transmission Line	0.50
	1.30

Signal Processing Losses	(dB)
Threshold Loss (dB)	0.50
A/D Quantization Loss (dB)	0.10
Range Straddling Loss	0.20
Weighting Loss	1.10
	1.90

$$T_s = T_a + T_r + L_r T_e = 598.2^\circ K$$

$$T_a = (0.88\,T_{sky} - 254)/(L_a + 290)$$

$$T_r = T_{tr}\,(L_r - 1) \quad \text{and} \quad T_e = T_o(F_n - 1)$$

Outline

- Introduction
- Introduction to Radar Equation
- Surveillance Form of Radar Equation
- Radar Equation for Rain Clutter
- Radar Losses
- Examples
- ➡ Summary

Cautions in Using the Radar Equation (1)

- The radar equation is simple enough, that just about anyone can learn to use and understand
- Unfortunately, the radar equation is complicated enough that anyone can mess it up, particularly if you are not careful
  - See next viewgraph for relevant advice

Cautions in Using the Radar Equation (2)

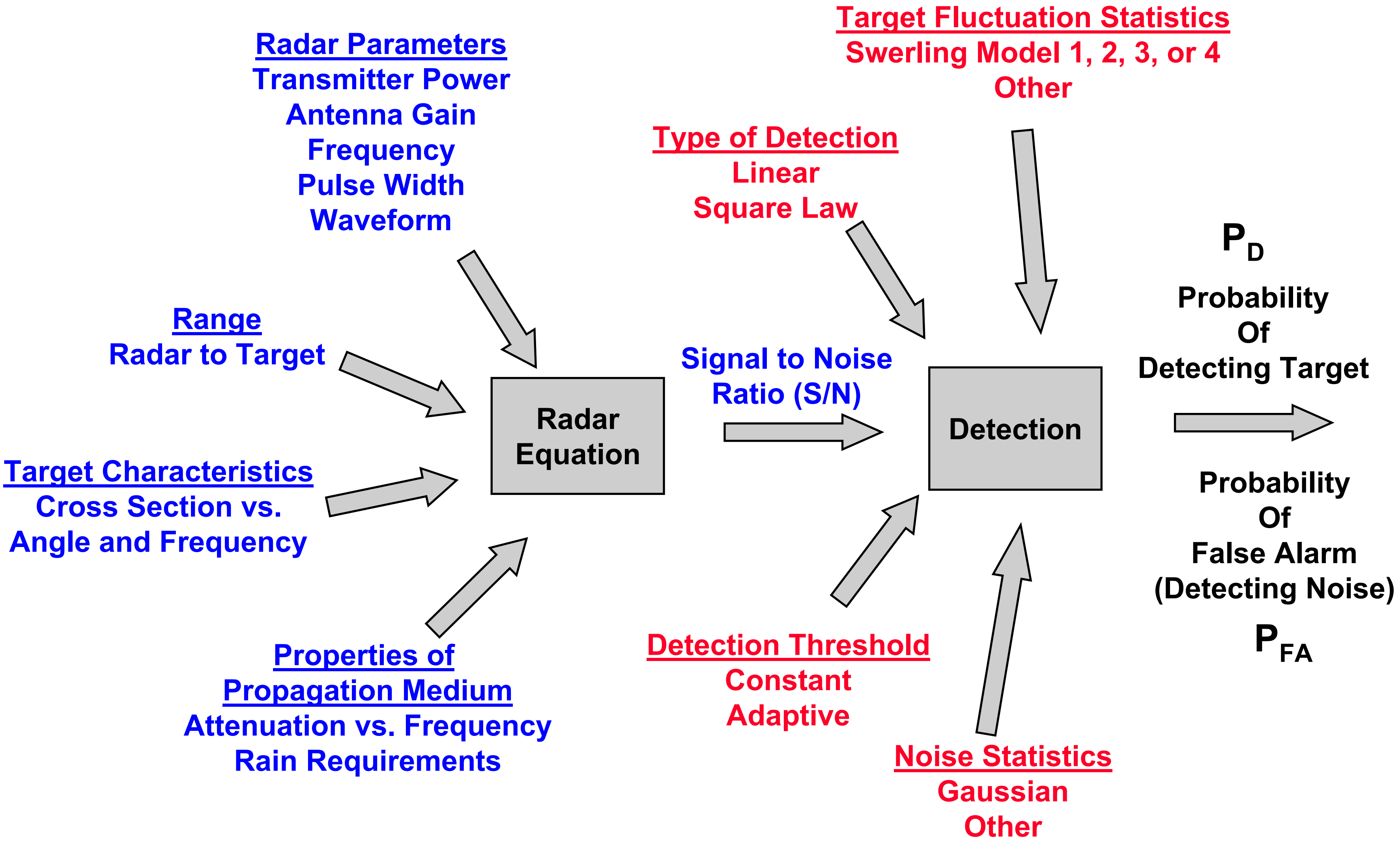
The Sanity Check

- **Take a Candidate Radar Equation**

$$\frac{S}{N} = \frac{P_t\, G^2 \lambda^2 \sigma}{(4\pi)^3 R^4\, k\, T_s\, B_n\, L}$$

- **Check it Dimensionally**
  - **R and λ are distance**
  - **σ is distance squared**
  - **P_t is energy / time**
  - **S/N, G, and L are dimensionless**
  - **kT_s is energy**
  - **B_n is (time)$^{-1}$**
- **Check if Dependencies Make Sense**
  - **Increasing Range and S/N make requirements tougher**
  - **Increasing Power and Antenna Gain make radar more capable**
  - **Decreasing Wavelength and Radar Cross Section make the radar less capable**

Radar Equation and the Detection Process



Radar Parameters
Transmitter Power
Antenna Gain
Frequency
Pulse Width
Waveform

Range
Radar to Target

Target Characteristics
Cross Section vs.
Angle and Frequency

Properties of
Propagation Medium
Attenuation vs. Frequency
Rain Requirements

Radar Equation

Signal to Noise
Ratio (S/N)

Type of Detection
Linear
Square Law

Target Fluctuation Statistics
Swerling Model 1, 2, 3, or 4
Other

Detection Threshold
Constant
Adaptive

Noise Statistics
Gaussian
Other

Detection

P_D

Probability
Of
Detecting Target

Probability
Of
False Alarm
(Detecting Noise)

P_{FA}

Summary

- The radar equation relates:
  - Radar performance parameters - Detection range, S/N, etc.

    and
  - Radar design parameters - Transmitter power, antenna size, etc.
- There are different forms of the radar equations for different radar functions
  - Search, Track
- Scaling of the radar equation allows the radar designer to understand how the radar parameters may change to accommodate changing requirements
- Be careful, if the radar equation leads to unexpected results
  - Do a sanity check !

    Look for hidden variables or constraints

    Compare parameters with those of a real radar

References

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7. Volakis, J. L., *Antenna Engineering Handbook*, McGraw-Hill, New York, 4th Ed., 2007

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Homework Problems

- From Reference 1, Skolnik, M., Introduction to Radar Systems, 3rd Edition, 2001
  - Problem 1-5
  - Problem 1-6
  - Problem 2-22
  - Problem 2-24
  - Problem 2-25