Professional Development Short Course On:

Radar Systems Analysis & Design using MATLAB

Instructor:

Dr. Andy Harrison

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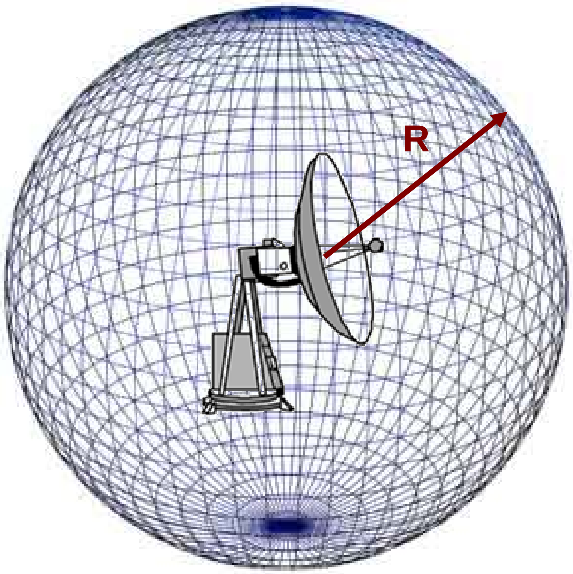
The Radar Equation

- Consider a radar with an omni directional antenna. The peak power density (power per unit area) at any point in space is



$$P_D = \frac{\text{Transmitted Power}}{\text{Area of a Sphere}} \quad \left(\frac{watts}{m^2}\right)$$

- The power density at a given range away from the radar (assuming a lossless propagation medium) is

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

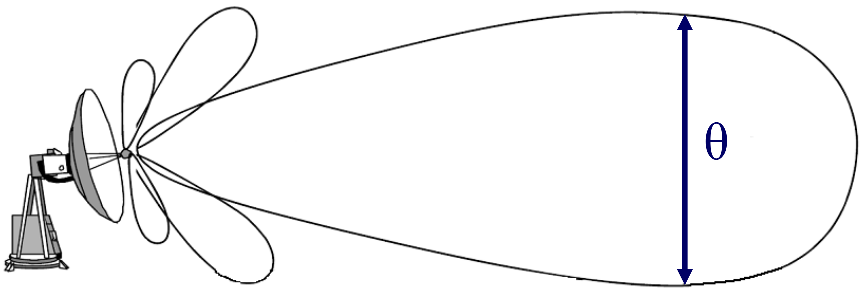
$$P_t = \text{Peak Transmitted Power}$$

$$4\pi R^2 = \text{Area of a Sphere of Radius}(R)$$

The Radar Equation

- **Radar systems utilize directional antennas in order to increase the power density in a certain direction.**

- **Directional antennas are usually characterized by the antenna gain and the antenna effective aperture, which are related by**



$$G = \frac{4\pi A_e}{\lambda^2}$$

G = Antenna Gain

A_e = Effective Aperture (m^2)

λ = Wavelength (m)

The Radar Equation

- **The antenna gain is also related to the azimuth and elevation beam widths by**

$$G = k\frac{4\pi}{\theta_e \theta_a} \qquad k \le 1$$

$$\theta_a = \text{Azimuth Beamwidth (radians)}$$
$$\theta_e = \text{Elevation Beamwidth (radians)}$$

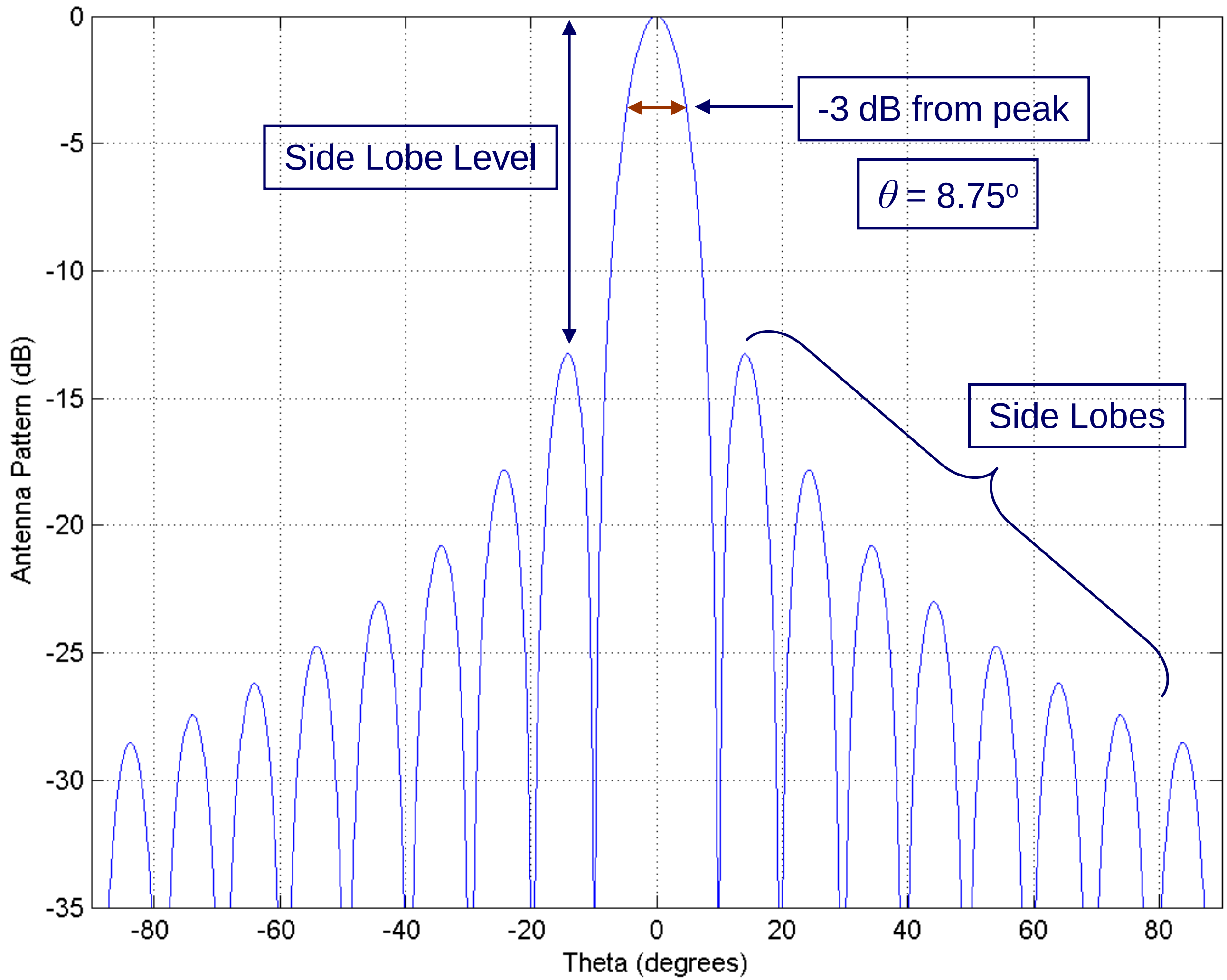
- **An accurate approximation for antenna gain is**

$$G = \frac{26000}{\theta_e \theta_a} \quad \rightarrow \quad \theta_e \theta_a \text{ (degrees)}$$

- **The power density at a given range from the radar using a directive antenna is then given by**

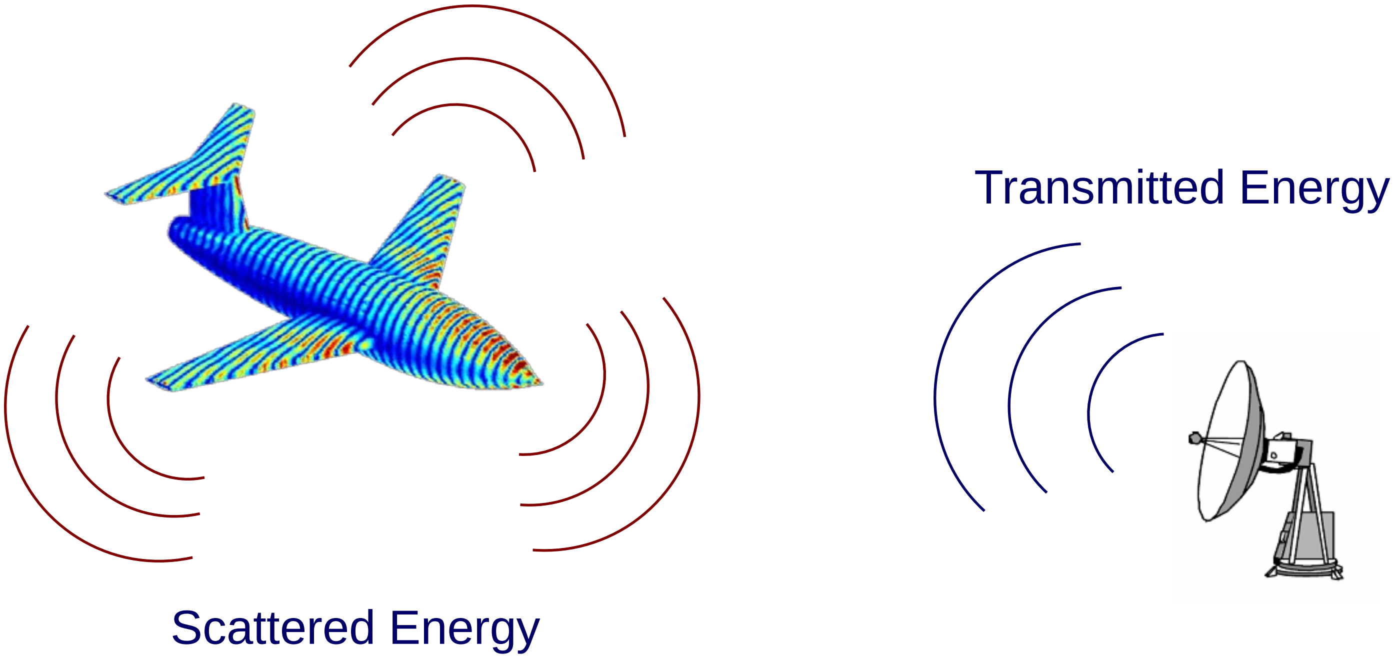
$$P_D = \frac{P_t G}{4\pi R^2}$$

Antenna Beamwidth



The Radar Equation

- When the radiated energy from a radar impinges on a target, the induced surface currents on that target re-radiate or scatter electromagnetic energy in all directions.



The Radar Equation

- The amount of the scattered energy is proportional to the target size, orientation, physical shape, and material, which are all lumped together in one target-specific parameter called the Radar Cross Section (RCS) and is denoted by σ.

- The radar cross section is defined as the ratio of the power reflected back to the radar to the power density incident on the target.

$$\sigma = \frac{P_r}{P_D} \quad (m^2)$$

$$P_r = \text{Reflected Power}$$

$$P_D = \text{Incident Power Density}$$

Signature Modeling Techniques

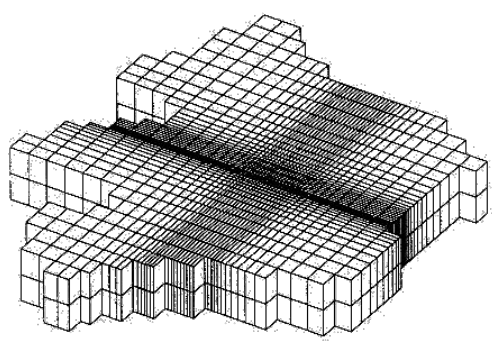
- There are different ways to solve the EM scattering problem. The method used depends on variables such as
  - Desired accuracy and appropriateness of the method
  - Number of CPUs and amount of RAM available
  - Amount of wall time available
- The different methods are often grouped together into what are called "low" and "high" frequency computational techniques.
- "Low frequency" methods solve the scattering problem in an "exact" sense, incorporating all electromagnetic effects. They are often limited by problem size or computer power.
- "High Frequency" methods approximate the scattering problem. They are generally less accurate, though often much faster and less demanding on CPU resources than a low frequency method.

Finite Difference Time Domain (FDTD)

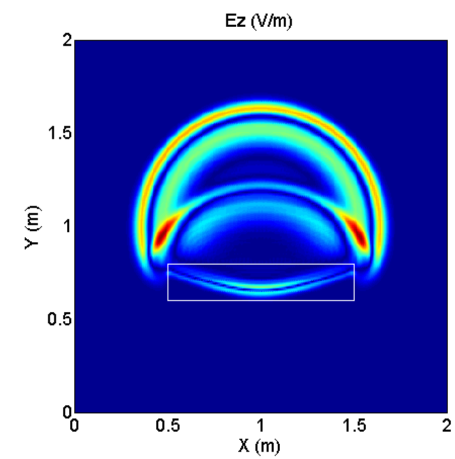
- **FDTD solves the time-domain version of Maxwell’s Equations. FDTD is considered to be a “full wave” or “exact” method.**
- **For scattering problems, the target and some adjoining space must be discretized on a rectangular grid to support the electromagnetic fields.**
- **FDTD has high memory and CPU demands, and is not typically used for targets that are electrically large.**

$$\mu\frac{\partial H_x}{\partial t} = \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}$$
$$\mu\frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}$$
$$\mu\frac{\partial H_z}{\partial t} = \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}$$
$$\epsilon\frac{\partial E_x}{\partial t} = \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \vec{J}_x$$
$$\epsilon\frac{\partial E_y}{\partial t} = \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \vec{J}_y$$
$$\epsilon\frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \vec{J}_z$$

3D Maxwell Equations



FDTD Grid



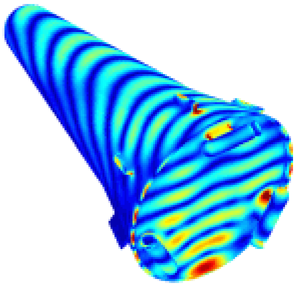
Time-Domain Field

Method of Moments (MoM)

- The MoM is used in the scattering problem in the frequency-domain by solving the integral Maxwell's Equations. It is considered to be a "full wave" or "exact" method.
- The MoM solves for the induced surface current on an object by discretizing the target surface into a number of subdomain "basis functions". The number of basis functions (N) needed is proportional to the radar wavelength.
- The MoM creates a matrix equation of order N^2. This ultimately limits its application to problems of small electrical size.

$$\vec{E}_s = -jw\vec{A} - \frac{j}{\epsilon\mu\omega}\nabla\nabla\cdot\vec{A}$$

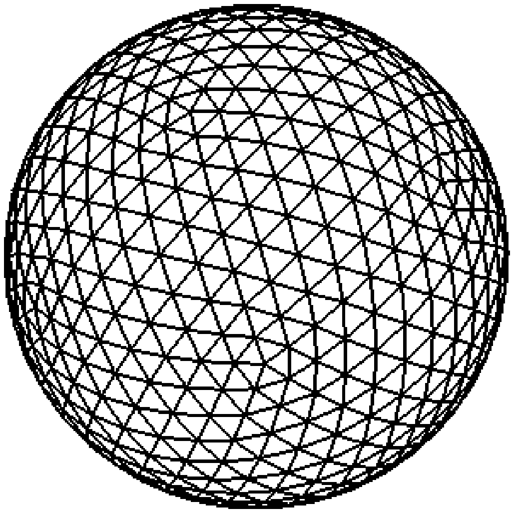
$$4\pi\ \hat{n}\times\vec{H}^i = 2\pi\vec{J} + \hat{n}\times\iint_S \vec{J}\times\nabla\frac{e^{jkR}}{R}\ dS$$



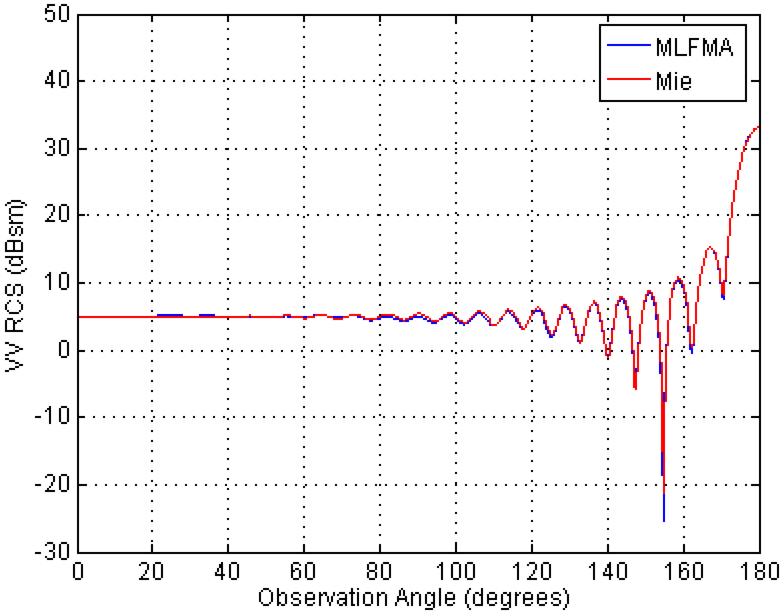
Surface Currents

Method of Moments (MoM)

- **The Fast Multipole Method (FMM/MLFMA) can be used to reduce the complexity of the MoM matrix system and allow the MoM to be used in problems previously unsolvable.**
- **Reliable, industrial-strength FMM software is slowly becoming commercially available. These codes still require supercomputer-class hardware to solve very large MoM problems.**



8 Wavelength Sphere



81920 unknowns

Regular MoM:

50 GB RAM

FMM:

1.2 GB RAM

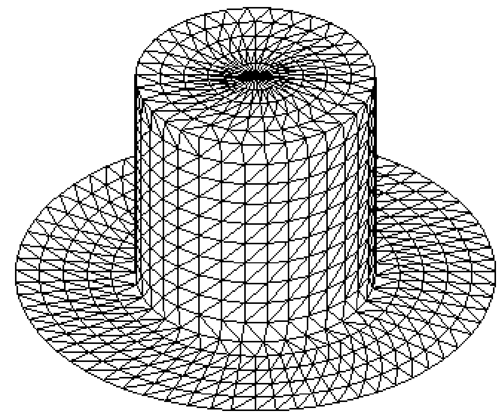
A factor of 40/1 !

Approximate (High-Frequency) Methods

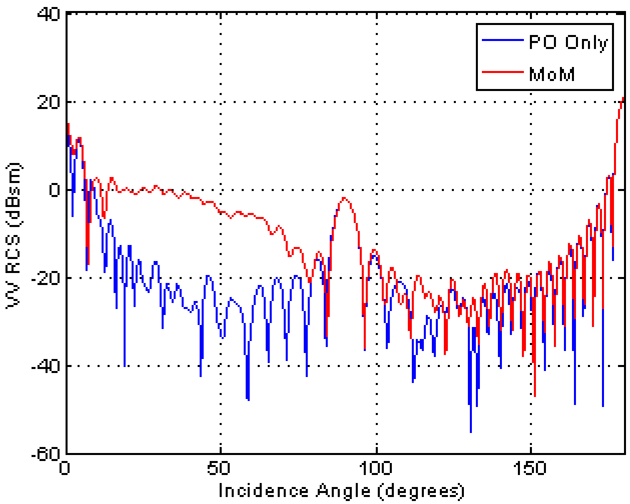
- "High Frequency" methods approach the scattering problem by assuming the target is very large compared to the radar wavelength.
- Approximations can then be made to simplify and expedite signature prediction by considering different scattering mechanisms separately.
- Physical Optics (PO) is a commonly used method that approximates the surface currents by assuming the surface is locally flat. This method does well at speculars but is fair to poor at off-specular angles.
- The Physical Theory of Diffraction (PTD) supplements PO by accounting for single diffractions from edges.
- Shooting and Bouncing Rays (SBR) supplements PO and PTD by using ray-optics to model multiple-bounce scattering.
- Other scattering mechanisms (traveling and creeping waves) can be considered, but are difficult to formulate analytically for general targets.

Comparison of MoM and Approximate Methods

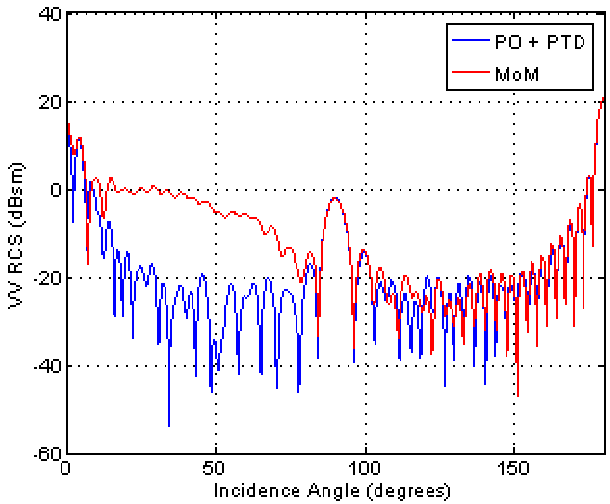
- **Target: 16 x 8 inch “Top Hat”**
- **Monostatic RCS Calculated at 7 GHz**
- **Target approximately 10 x 5 wavelengths in electrical size.**



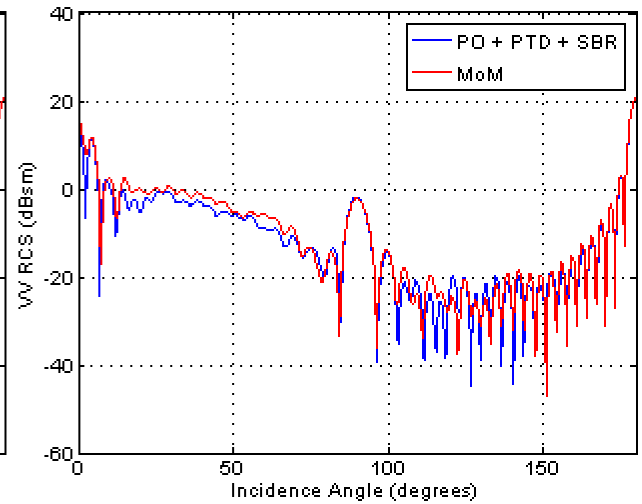
“Top Hat”



PO Only



PO + PTD



PO + PTD + SBR

Signature Modeling Software

- **Finite Difference Time Domain (FDTD)**
  - **Remcom *xfdtd* (packaging, machines)**
  - **EMS+ *EZ-FDTD* (packaging, machines)**

- **Finite Element Method (FEM)**
  - **Ansys, Inc. *ANSYS* (packaging, machines)**

- **Method of Moments (MoM)**
  - **EM Software and Systems *FEKO* (wire and planar antennas)**
  - **Tripoint Industries *Serenity* (Scattering by MoM/MLFMA)**
  - **Tripoint Industries *Galaxy* (Scattering by MoM-BoR)**

- **Physical Optics / PTD / SBR**
  - **Tripoint Industries *lucernhammer MT* (High-frequency scattering)**
  - **SAIC *xPatch* (High-frequency scattering)**

The Radar Equation

- Typical RCS values of various objects at X-Band.

Object	RCS (m^2)	RCS (dBsm)
Pickup Truck	200	23
Automobile	100	20
Jumbo Jet	100	20
Commercial	40	16
Cabin Cruiser Boat	10	10
Large Fighter Aircraft	6	7.78
Small Fighter Aircraft	2	3
Adult Male	1	0
Conventional Winged Missile	0.5	-3
Bird	0.01	-20
Insect	1×10^{-5}	-50
Advanced Tactical Fighter	1×10^{-6}	-60

The Radar Equation

- **The power scattered by the target is then**

$$P_{\text{target}} = \frac{P_t G \sigma}{4\pi R^2} \quad (watts)$$

- **Recalling that the power density at a given range is**

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

- **Substituting the target's scattered power gives the total power density delivered back to the antenna.**

$$P_{antenna} = \frac{P_t G \sigma}{\left(4\pi R^2\right)^2}$$

The Radar Equation

- Multiplying by the effective area of the antenna gives the total power received by the radar.

$$P_{radar} = \frac{P_t G \sigma}{\left(4\pi R^2\right)^2} A_e$$

- Substituting for the effective aperture then gives

$$P_{radar} = \frac{P_t G^2 \lambda^2 \sigma}{\left(4\pi\right)^3 R^4} \quad (watts)$$

The Radar Equation

- **Denote the minimum detectable signal power by** $S_{\min}$.
- **It follows that**

$$S_{\min} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

- **Rearranging the equation gives the maximum Range to the target.**

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

The Radar Equation

- **In realistic situations, the returned signals received by the radar will be corrupted by noise.**

- **Noise is random in nature and may be described by its Power Spectral Density (PSD).**

$$PSD = kT_s$$

$$k = \text{Boltzmann's Constant} = 1.38 \times 10^{-23} \quad \left(\frac{Joules}{Kelvin} \right)$$

$$T_s = \text{System Noise Temperature} \quad (Kelvin)$$

The Radar Equation

- **The input noise power for a radar of a given operating bandwidth is then given as**

$$N_i = PSD \times B \quad = \quad kT_s \times B$$

- **It is always desirable that the minimum detectable signal power be greater than the noise power.**

- **The fidelity of a radar receiver is normally described by a figure of merit called the noise figure which is defined as**

$$F = \frac{SNR_i}{SNR_o} = \frac{S_i / N_i}{S_o / N_o}$$

$$SNR_i = \text{Input Signal to Noise Ratio}$$

$$SNR_o = \text{Output Signal to Noise Ratio}$$

The Radar Equation

- **The input signal power may be rewritten as**

$$S_i = kT_s B\, F\, SNR_o$$

- **The minimum detectable signal is then**

$$S_{\min} = kT_s B\, F \left(SNR_o\right)_{\min}$$

- **Setting the detection threshold to the minimum output SNR results in**

$$R_{\max} = \left(\frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, k\, T_s\, B\, F \left(SNR_o\right)_{\min}} \right)^{1/4}$$

The Radar Equation

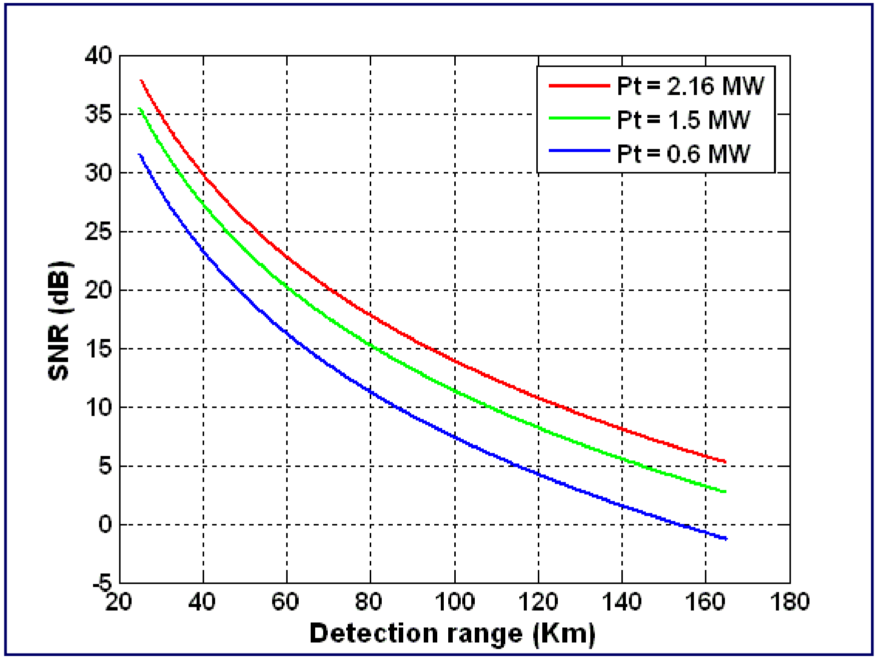
- **Rearranging gives the SNR at the output of the receiver.**

$$SNR_o = \frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, k\, T_s\, B\, F\, R^4}$$

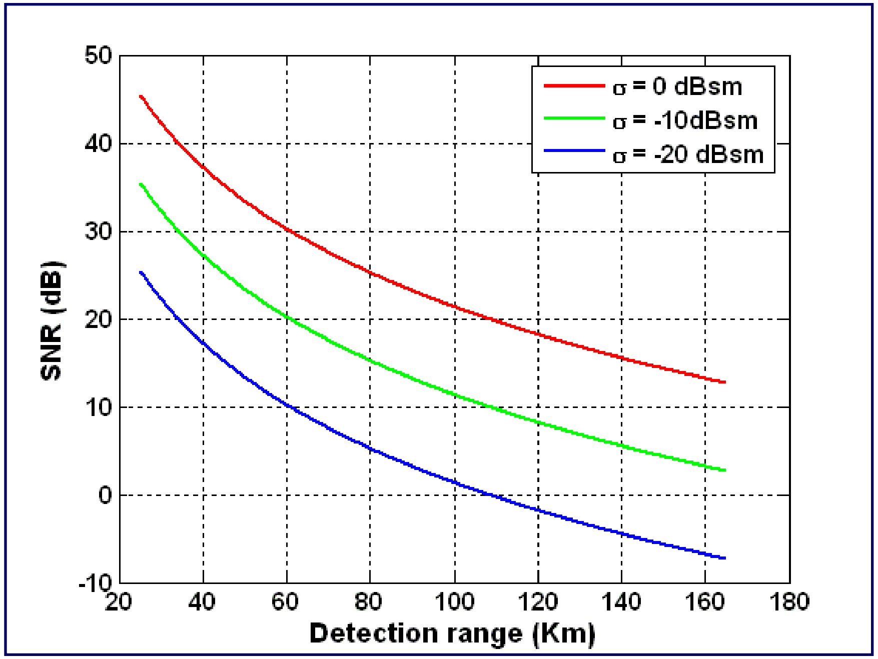
- **In general, radar losses, L, reduce the overall SNR and thus**

$$\boxed{SNR_o = \frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, k\, T_s\, B\, F\, L\, R^4}}$$

Radar Reference Range



SNR vs Detection Range for Varying Peak Power



SNR vs Detection Range for Varying Target RCS

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