# Radar Systems Analysis and Design
# ECE 5635 Fall 2012

Week #2

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# Radar: Basic Considerations (1/2)

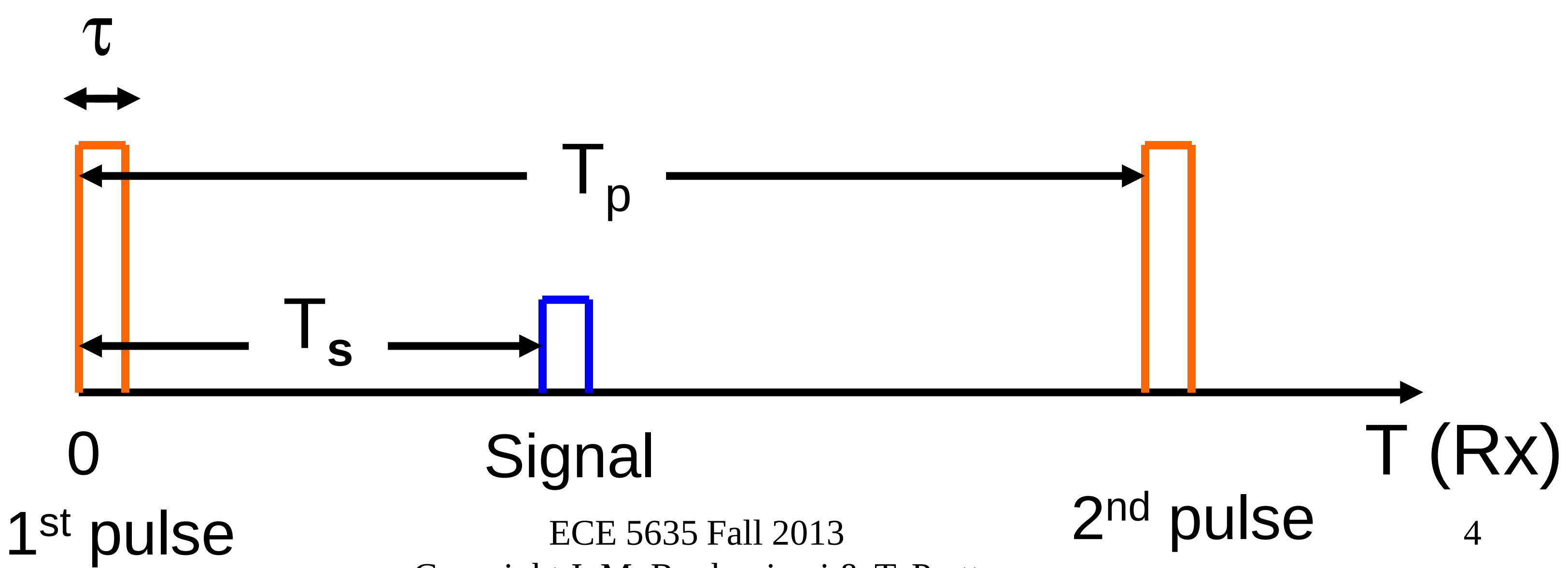
- Frequency / wavelength
- Monostatic or bistatic
- Pulse or CW
- Coherent or incoherent
- Tx/Rx/Sw/antenna configuration
- PRI, IPP, PRF = 1 / $T_p$
- Pulse width, $\tau$
- Pulse power, duty cycle, average power

# Radar: Basic Considerations (2/2)

- Range ambiguity (high prf)
- Doppler shift $f_d = 2\, v_r / \lambda$
- Velocity ambiguity (low prf)
- PRF regimes

# Summary of Radar R = cT/2 relations

- Fundamental relation between range and time:
  $R = cT/2$
- Range to target $R_s = c\,T_s / 2$
- Unambiguous range $R_{ua} = c\,T_p / 2$
- Range resolution $\Delta R = c\,\tau / 2$



# Radar Equation (review)

- The radar equation provides a way to calculate the power received from a target at a given range
- Or the maximum range at which a target of known radar reflectivity can be detected
- The basic radar equation assumes no losses and ideal propagation of radio waves

# Radar Equation (review)

- Radar parameters

| | | |
|---|---|---|
| Pulse power | $P_{\mathbf{t}}$ | watts |
| Freq / wavelength | $f / \lambda$ | Hz / meters |
| Tx antenna gain | $G_t$ | a ratio |
| Range to target | $R$ | meters |
| Target echo area | $\sigma$ | square meters |
| Rx antenna area | $A_e$ | meters (effective) |
| Received power | $P_{\mathbf{r}}$ | watts |

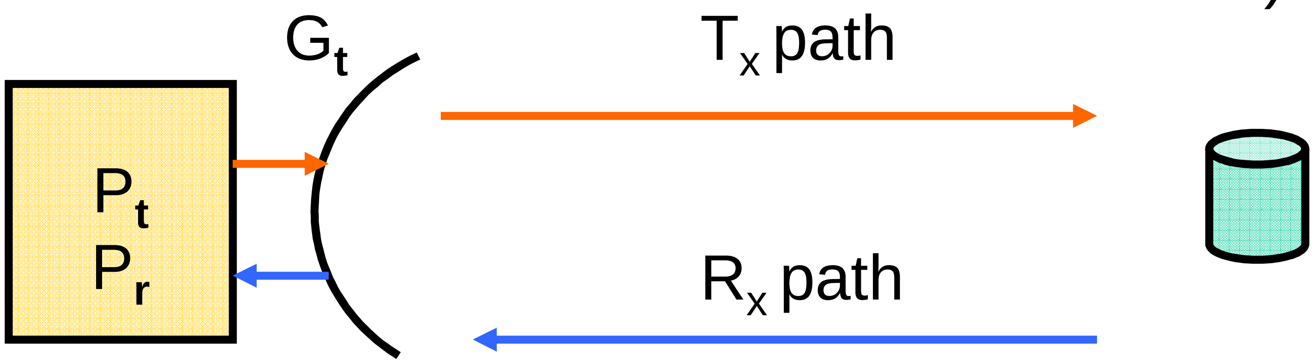
# Development of the Radar Range Equation (RE)

6) $P_r = Q_r A_e$
$= P_t\, G_t\, \sigma\, A_e / (4\pi R^2)$ W

2) $Q_i = P_t\, G_t / (4\pi R^2)$ W/m²

3) Target RCS
= $\sigma$ m²

1) $P_t$




5) $Q_r = P_{ref} / (4\pi R^2)$
$= P_t\, G_t\, \sigma / (4\pi R^2)^2$ W/m²

4) $P_{ref} = Q_i\, \sigma$
$= P_t\, G_t\, \sigma / (4\pi R^2)$ W

Note: $P_{ref}$ is the power of an equivalent isotropic radiator

# Radar Equation (review)

- Antenna gain and effective area are related by

$$G = 4 \pi A_e / \lambda^2$$

- Substituting in Equation (2.6) and assuming a monostatic radar with $G_r = G_t = G$

$$P_r = P_t G_t G_r \lambda^2 \sigma / (4 \pi)^3 R^4 \quad \text{W}$$
$$= P_t G^2 \lambda^2 \sigma / (4 \pi)^3 R^4 \quad \text{W}$$

- This is one form of the radar equation

# Review of Waves and Phase

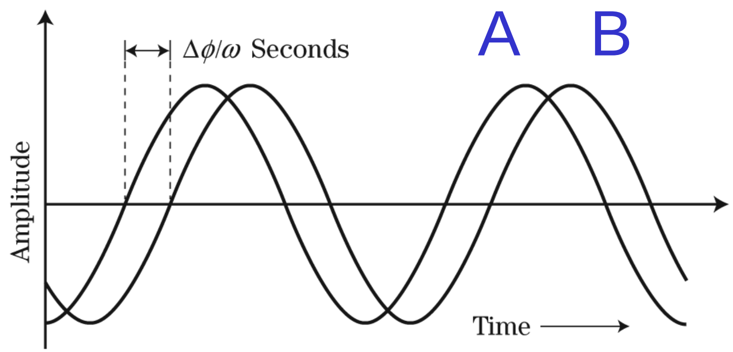



**FIGURE 1-6** ■ Two sinusoidal waves with the same frequency but a phase difference $\Delta\phi$.

Period = T = 1/f (sec)

- Wave A leads wave B in time by $\Delta t$ sec

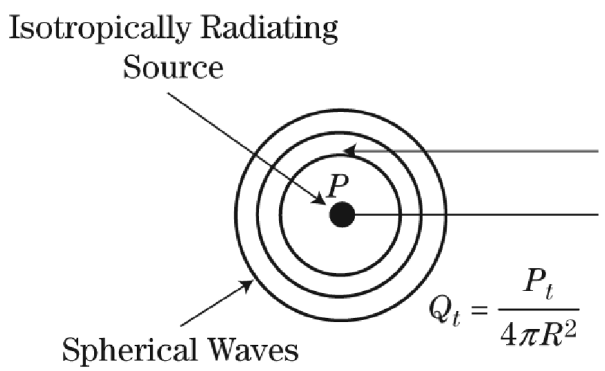
  in phase by $\Delta\varphi = 360^\circ \times \Delta t/T$ deg

  $\Delta\varphi = 2\pi\ \Delta t/T$ rad

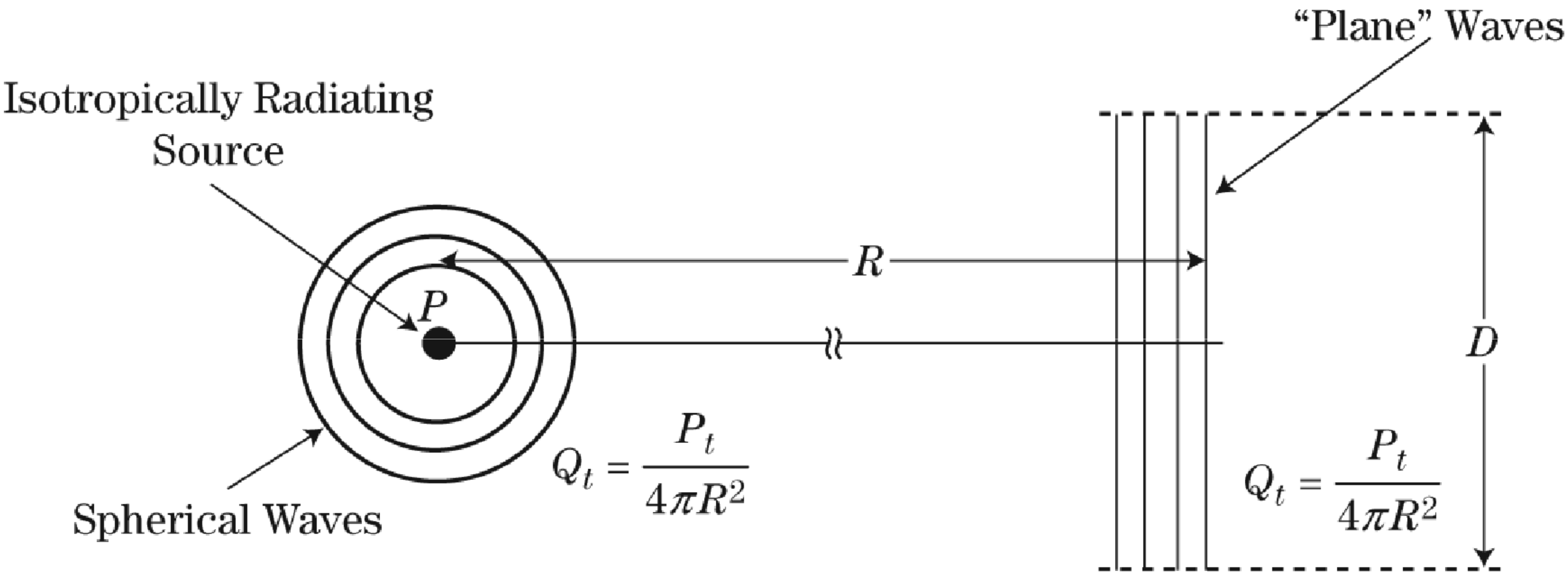
- Phase is measured relative to a reference
- Adding two waves with a shift of $0^\circ$ ($180^\circ$) results in *constructive (destructive)* interference

# Validity of Plane Wave Assumption (1/3)

- For a *plane wave*, intensity and phase are constant across planar surfaces that are oriented perpendicular to the direction of propagation
- Easiest to analyze
- An isotropic point source obviously generates *spherical waves*



# Validity of Plane Wave Assumption (2/3)




*D* represents the width of an aperture such as a receiving antenna

# Validity of Plane Wave Assumption (3/3)

- At great enough distances from the source, the spherical wavefronts will appear planar across an aperture of fixed dimension *D*
- Agreed that a phase variation across *D* of less than 1/16 cycle (22.5°) is small enough to treat the waves as planar
- The plane wave assumption is valid in the *far-field region*, which is

$$R > 2D^2 / \lambda \quad \text{meters}$$

# Antennas

- Every radar needs an antenna
- An antenna is a transducer that converts waves in a waveguide to waves in free space
- Most radars need a directional antenna
- Directional antennas transmit and receive EM waves over a small angular region
- Antennas are characterized by Gain  and Beamwidth

# Antennas

- Definition of Antenna Gain:

  "The increase in power density at a given point in space when the test antenna is used in place of an isotropic antenna"

- Power density at distance R with isotropic antenna is $Q_i$

$$Q_i = P_t / 4 \pi R^2 \qquad \text{W/m}^2$$

# Antennas

- Power density at distance R with test antenna with transmitting gain $G_t$ is $Q_t$

$$Q_t = P_t G_t / 4 \pi R^2 \qquad\qquad W / m^2$$

- Hence $G = Q_t / Q_i$

# Antennas

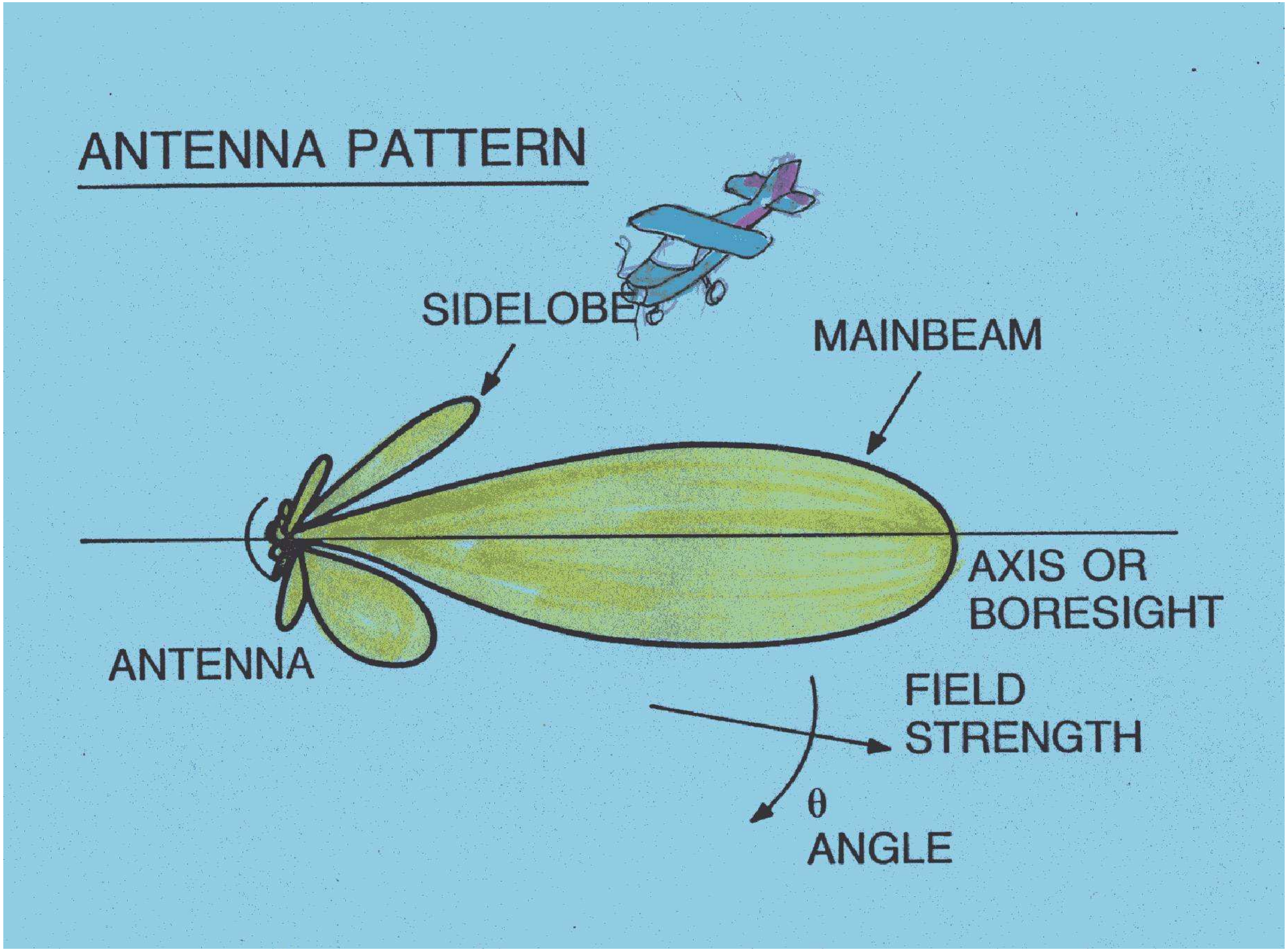
- Antenna gain is a ratio,  without dimensions
- Antenna gain is usually quoted in decibels

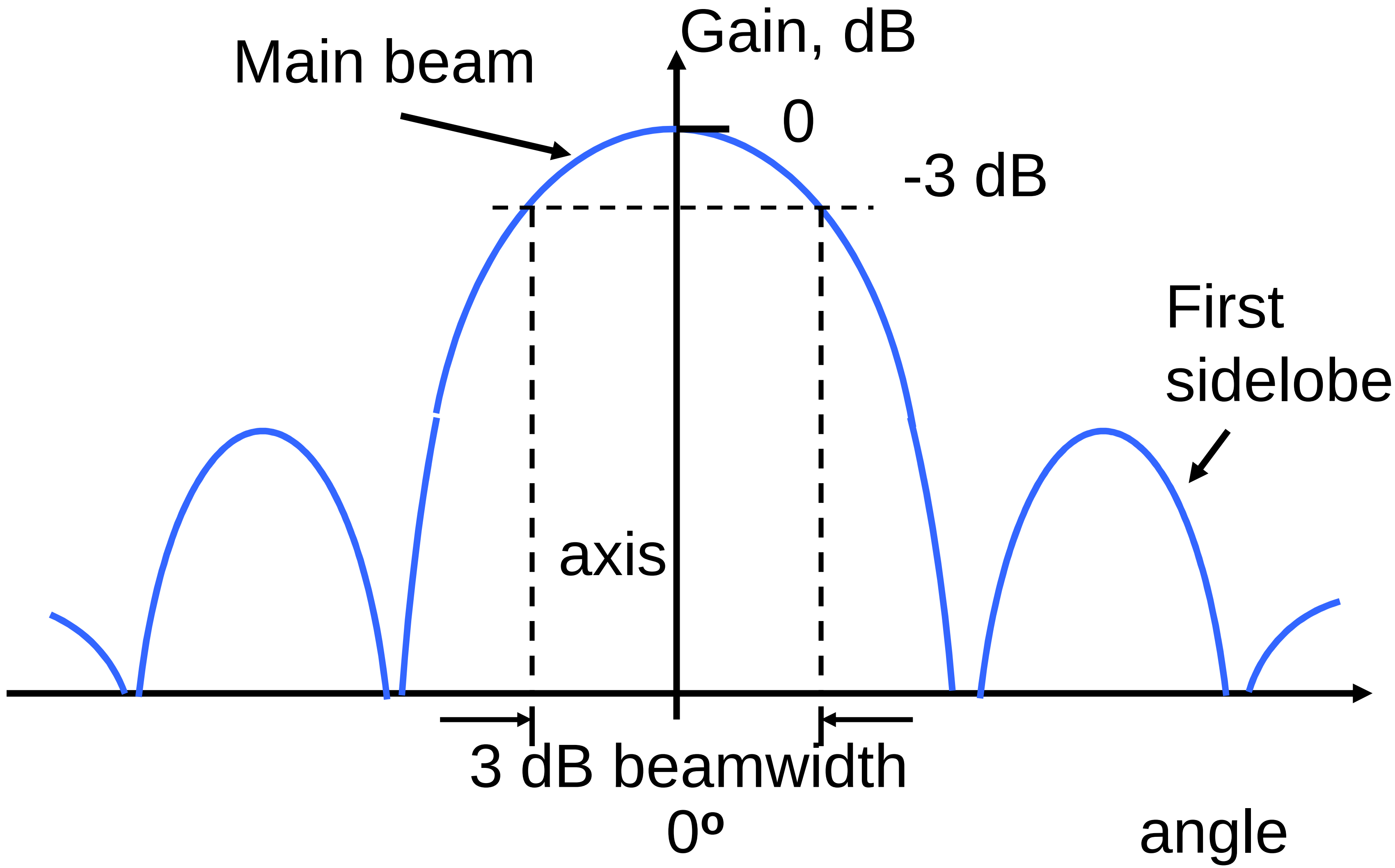
$$G\ (\text{dB}) = 10 \log_{10} G$$

- Note:  G (dB) is NOT  20 $\log_{10}$ G  because G appears in a power relationship and the definition of the decibel is as a power ratio

# Antennas

- Antenna gain varies with angle
- If quoted as just “gain”, the maximum (on axis, boresight) value is inferred.
- The variation of antenna gain with angle is known as the Antenna Pattern
- Antenna patterns have a main lobe and sidelobes
- Usually presented as gain vs angle in a plane


ANTENNA PATTERN
SIDELOBE
MAINBEAM
AXIS OR
BORESIGHT
ANTENNA
FIELD
STRENGTH
θ
ANGLE




Antenna patterns

# Antenna Beamwidth

- Beamwidth is defined as the angular extent between the 3 dB points of the main beam
- Note that this is not the angle between the antenna axis (direction of maximum gain) and one 3 dB (half power) point
- Gain and beamwidth are related
- Approximate formula – not in dB

$$G = 33{,}000 / (\text{beamwidth in degrees})^2$$

# Beamwidth

- Typical radar and communications antennas have beamwidths given by

$$\theta_{\mathbf{3\,dB}} \sim 75\,\lambda / D \qquad \text{degrees}$$

  where D is the antenna dimension in the plane of interest

- Another form of the relationship is

$$\theta_{\mathbf{3\,dB}} \sim 1.3\,\lambda / D \qquad \text{radians}$$

# Beamwidth

- These relationships are approximate but very useful for radar analysis
- Example: What are the beamwidth and gain of a circular antenna that has $D = 5$ m and $f = 3$ GHz?

# Beamwidth

- These relationships are approximate but very useful for radar analysis
- Example: What are the beamwidth and gain of a circular antenna that has D = 5 m and f = 3 GHz?

$\lambda$ [cm] f [GHz] = 30 $\rightarrow$ $\lambda$ = 10 cm (S band)

$\theta_{\mathbf{3\ dB}} \sim 75\,\lambda / D = 75\,(.1 / 5) = 1.5$ deg

$G = 33{,}000 / (\theta_{\mathbf{3\ dB}})^{2} = 14700 \sim 41$ dB

# Sidelobes

- All directional antennas have sidelobes in their patterns that are defined by *nulls* (directions in which no energy is radiated)
- Nulls are due to destructive interference of transmissions from across the antenna aperture
- The forward direction produces a *main beam* because of constructive interference
- Application of Huygen's principle

# Sidelobes

- Radar targets can appear in the sidelobes of the antenna – gives an erroneous direction
- Jammers can radiate noise and false signals into antenna sidelobes
- Sidelobes can be reduced but not eliminated
- We will often sketch just the main beam of the antenna in our drawings but remember that sidelobes are still there

# Homework

- News will be posted to Scholar in announcements (that can be revised)
- Let me know of particular difficulties with making deadlines
- HW#2 will be issued at the conclusion of this class
- Submitting to Scholar? Provide a PDF as an Attachment in the Assignments area or as a file to DropBox

# Homework

- Expectation in design work is that you <u>explain</u> your solution (use words, not too many)
- Where possible start off with a sketch
- Conclude with a statement about what you have determined
- Can be hand-written (neatly) or typed
- Do not submit first draft, rough work
- Make it a good read!

# Course Project: A word or two

- Will take place in the second half of the course
- Will involve design work, possibly carried out in stages
- Teams of 1 or 2 students
- Final report will need to be submission quality
- May have presentations, depending on the technology

# Next week

- I expect to be away on travel
- Prof. Tim Pratt will give the lecture
- Prof. Pratt has a long and distinguished record in radar and communications
- ECE5635 is his creation
- He may be available for help with the homework

# Radar Targets

- Radar targets scatter EM waves with patterns that are similar to antenna patterns
- Pattern depends on size and shape of target
- RCS varies with the pattern and so depends on direction

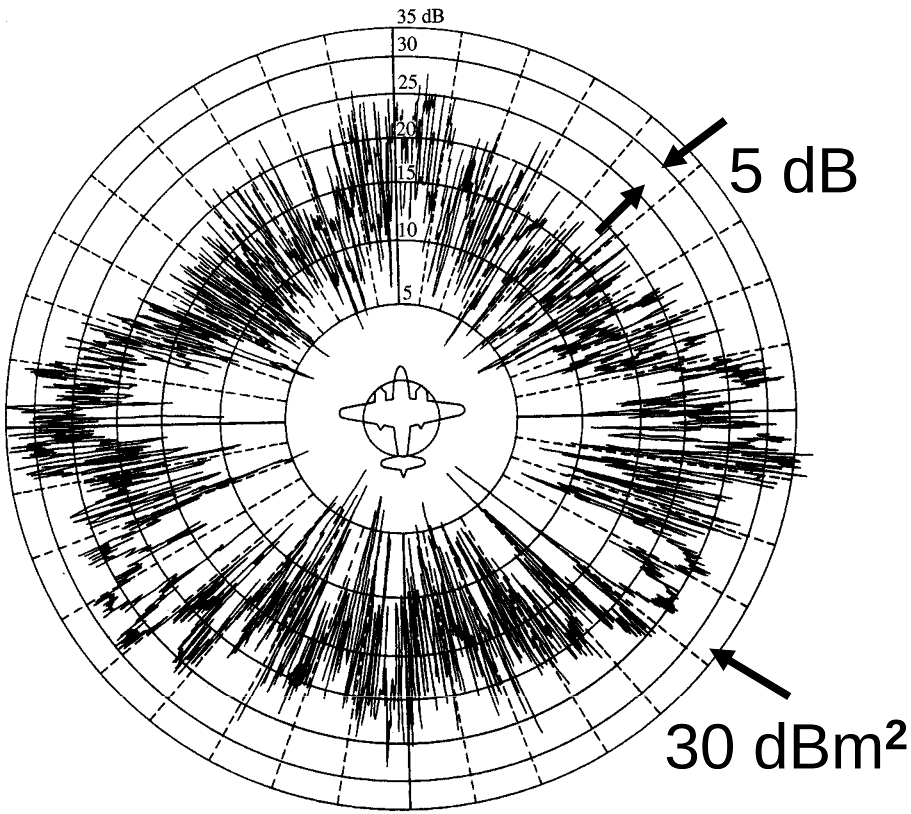



**Figure 2.15** Backscatter from a full-scale B-26 two-engine (propeller driven) medium-bomber aircraft at 10-cm wavelength as a function of azimuth angle. This figure has appeared in many books on radar and radar scattering since it is one of the few examples readily available in the literature of the measurement of backscatter from a full-size aircraft without averaging over a range of angles.
(From Ridenour,[28] courtesy McGraw-Hill Book Company, Inc.)

From Skolnik
WW II aircraft RCS in horizontal plane at 10 cm

# Radar Targets

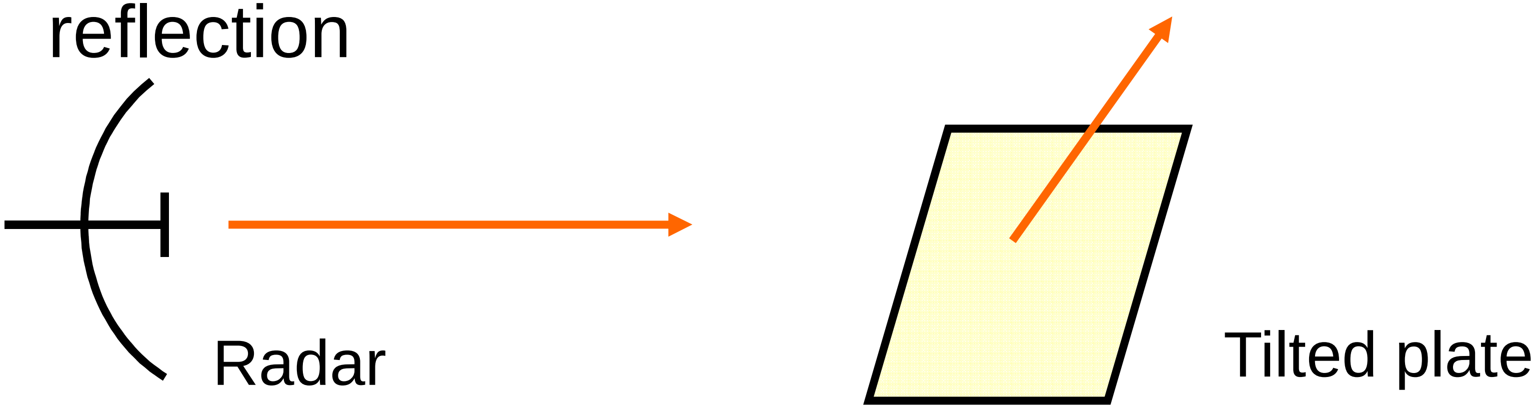
- If target has circumference << $\lambda$
  target scatters in all directions (i.e., is more isotropic)
- Called a *Rayleigh* scatterer
- Example:
- Raindrop with d = 6 mm seen by 10 cm radar

# Radar Targets

- If target has circumference >> $\lambda$
  target scatters in preferred directions (i.e, is more directive), unless it is a sphere
- Called an *optical* scatterer
- Example:
- Automobile seen with $\lambda = 3$ cm (X-band radar)

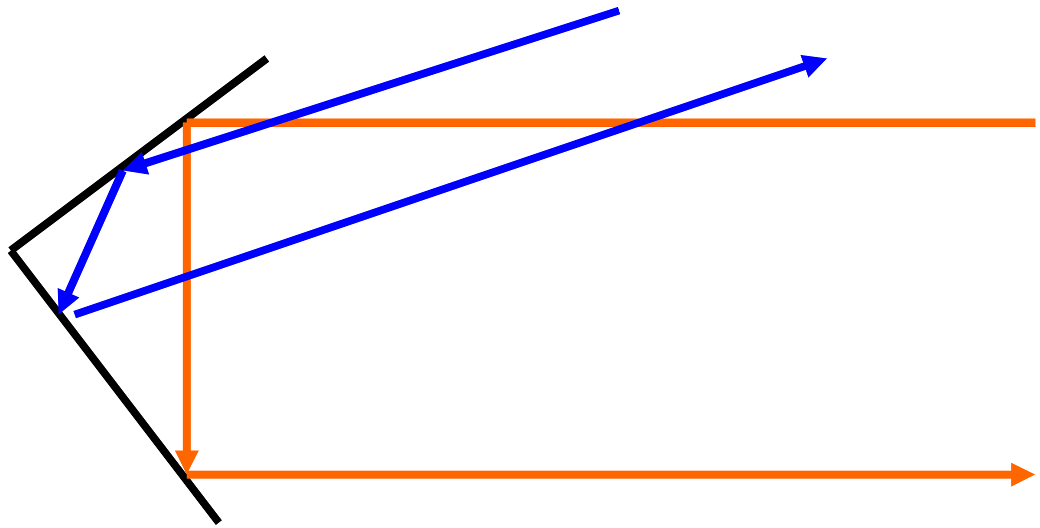
# Radar Targets

- Larger targets have specific scatter patterns
- Example:  Flat plate a, b >> $\lambda$
- Behaves like an antenna with aperture a, b,
- Energy is reflected in direction of ray reflection



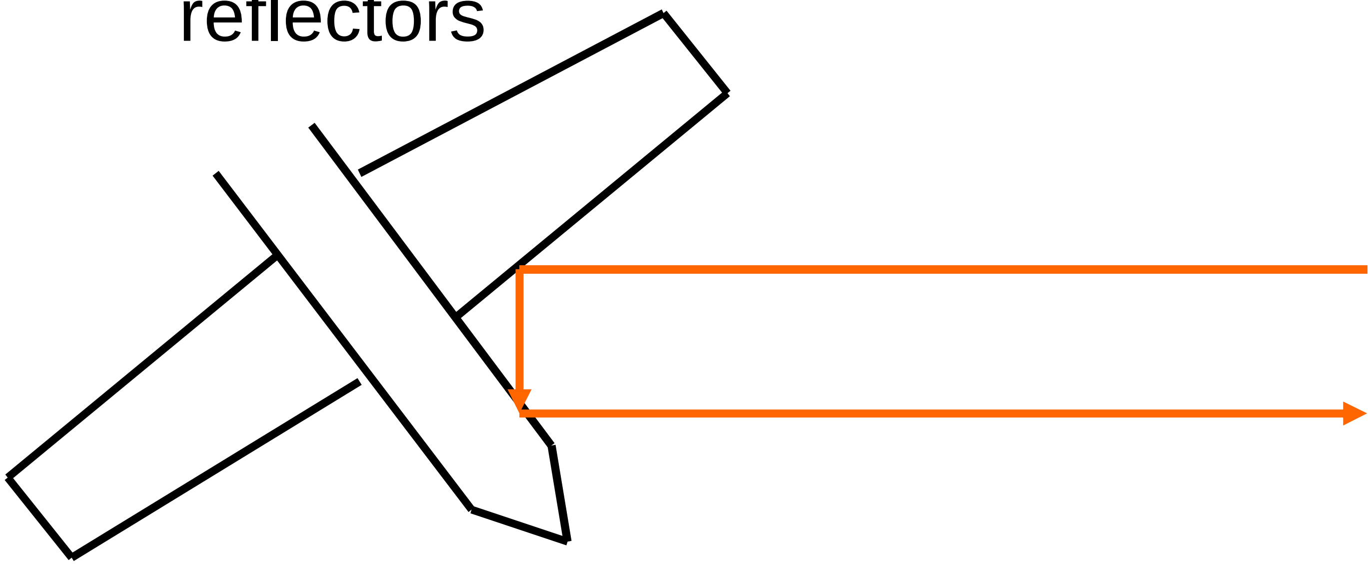
# Corner reflector

- The corner reflector has a large backscatter RCS over a wide angular range



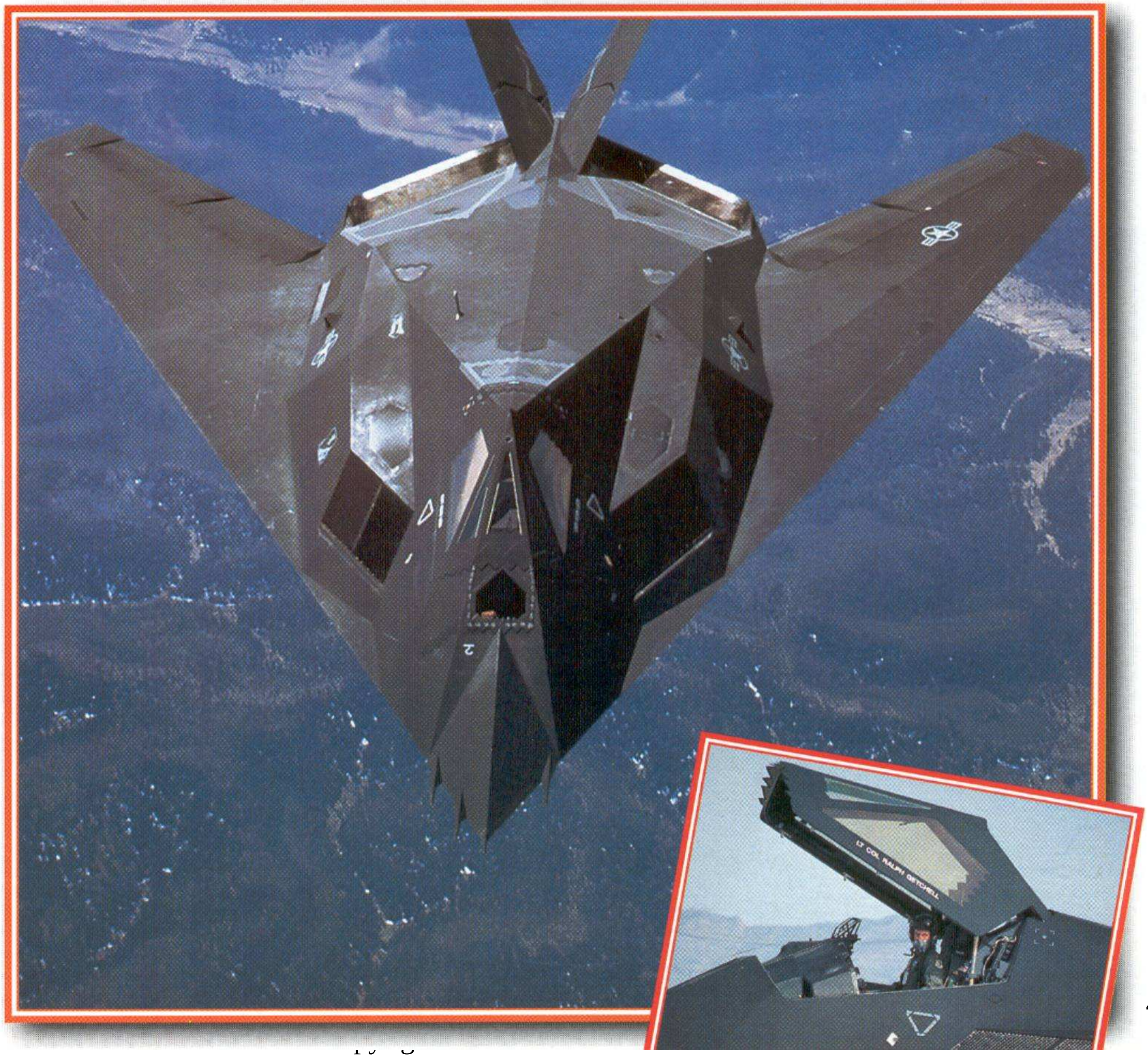
# Corner reflector

- Most aircraft are seen as several corner reflectors



# Stealth technology

- Targets such as aircraft can be designed to have low RCS in certain directions
- The SR-71 Blackbird is an early example
- Key elements:
  - Avoid corner reflectors
  - Use rounded surfaces
  - Use flat plates to direct energy away
- The F117A Nighthawk has low backscatter RCS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# What is a Radar Cross Section?

- RCS is based on an equivalence to the reflection of radio signals by a metal sphere
- If diameter of sphere is D and D > $\lambda$ then RCS, $\sigma$, is

  $\sigma = \pi D^2 / 4 \ \ m^2$

- This is the cross sectional area of the sphere
- Therefore a radar target with RCS = $\sigma$ looks to the radar like a sphere with $D = \sqrt{(4\sigma/\pi)}$ m

# Radar Equation

- Monostatic form of the Equation:

$$P_r \quad = \; P_t \, G^2 \, \lambda^2 \, \sigma_{mono} \, / \, ( 4 \, \pi )^3 \, R^4 \qquad\qquad W$$

- Bistatic form of the Equation:

$$P_r \quad = \; P_t \, G_t \, G_r \, \lambda^2 \, \sigma_{bistat} \, / \, ( 4 \, \pi )^3 \, R_t^2 \, R_r^2 \quad W$$

# Radar Equation

- If a monostatic radar can just detect received power of $S_{\mathbf{min}}$ watts

- Then

$$R_{\mathbf{max}} = [\, P_{\mathbf{t}}\, G^{\mathbf{2}}\, \lambda^{\mathbf{2}}\, \sigma / (\, 4\, \pi\,)^{\mathbf{3}}\, S_{\mathbf{min}}\,]^{\mathbf{1/4}} \quad \text{meters}$$

# Radar Equation

- Worked Range Example for monostatic S-band radar
- $P_t = 1 \text{ MW} = 10^6 \text{ W}$
- $G = 40 \text{ dB} = 10^4$
- $f = 3 \text{ GHz} \rightarrow \lambda = 10 \text{ cm} = 0.1 \text{ m}$
- $\sigma = 10 \text{ m}^2$
- $S_{min} = 0.1 \text{ nW} = 10^{-10} \text{ W}$

# Radar Equation Example

- Apply the radar equation to find maximum range

$$R_{\mathbf{max}} = [\, P_{\mathbf{t}}\, G^{\mathbf{2}}\, \lambda^{\mathbf{2}}\, \sigma / (\, 4\,\pi\,)^{\mathbf{3}}\, S_{\mathbf{min}}\,]^{\mathbf{1/4}} \text{ meters}$$

$$= \left( \frac{[\;10^{\mathbf{6}} \times 10^{\mathbf{8}} \times 10^{\mathbf{-2}} \times 10]}{[(\,4\,\pi\,)^{\mathbf{3}} \times 10^{\mathbf{-10}}]} \right)^{\mathbf{1/4}} \text{ m}$$

$$= [\,10^{\mathbf{23}} / 1984\,]^{\mathbf{1/4}} = 84.3 \text{ km}$$

- The target could be an aircraft flying many thousands of feet above earth

# Radar Equation

- If the target in the previous example had a radar cross section (RCS) of 2 $m^2$ instead of 10 $m^2$, what would the maximum detectable range be?

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

- Observe that $\sigma$ has changed by a factor of 5, and that $R_{max}$ varies as $\sigma^{1/4}$
- So, the adjustment factor to $R_{max}$ is $5^{1/4} \approx 1.5$

# Radar Equation

- Obviously, $R_{\mathbf{max}}$ must decrease since the RCS is smaller.
- So, New $R_{\mathbf{max}}$ is Old $R_{\mathbf{max}}$ / 1.5 = 84 / 1.5 = 56 km
- Observe that we did not work through the range equation again

# Using Decibels

- Radar engineers invariably use decibels to make performance calculations
- Many parameters have decibel values
- ALL dB values in radar work are of the form

$$Y \text{ dB} = 10 \log ( X )$$

- NEVER 20 log ( X )
- The dB is a power ratio defined by

$$Y = 10 \log ( P_2 / P_1 )$$

# Example of Using Decibel Units

- Calculate the power in the receiver when a circular antenna of effective radius, $r_{\mathbf{eff}}$ , intersects a wave of power density, $Q_{\mathbf{r}}$ :

  $P_r = Q_{\mathbf{r}} \times A_{\mathbf{eff}} = Q_{\mathbf{r}} \times \pi r_{\mathbf{eff}}^{\mathbf{2}}$ watts

- Take $Q_{\mathbf{r}} = 10^{\mathbf{-9}}$ W/m $^{\mathbf{2}}$ and $r_{\mathbf{eff}} = 2$ m

- Determine dB equivalents and calculate P, first in dBW and then convert to Watts

  $P_r = Q_{\mathbf{r}}$ [dBW/m $^{\mathbf{2}}$] + π [dB]

  + 2 $r_{\mathbf{eff}}$ [dBmeters] dBW

# Example of Using Decibel Units

- $Q_{\mathbf{r}}$ = -90 dBW/m $^{\mathbf{2}}$
- $\pi$ = 5 dB (dimensionless)
- $r_{\mathbf{eff}}$ = 3 dBmeters

- Then in dB units

$$P_r = Q_{\mathbf{r}} + \pi + 2 \times r_{\mathbf{eff}}$$

$$P_r = -90 + 5 + (2 \times 3) = -79 \text{ dBW}$$

$$= 1.3\ 10^{-8} \text{ watts}$$

# Example of Using Decibel Units

- Reduce the transmitter power by a factor of 10. What would $r_{\mathbf{eff}}$ have to be to compensate so we generate the same Rx power?
- The new dB equation is

$$P_r \quad = \; (-90 - \mathbf{10}) \; + \; 5 \; + \; 2 \times \mathbf{New\_r_{eff}} \; = \; -79 \text{ dBW}$$

- New_$r_{\mathbf{eff}}$ needs to be larger by 5 dB :

New_$r_{\mathbf{eff}}$ = 3 + 5 = 8 dB meters

- New linear $r_{\mathbf{eff}}$ is 6.3 m (compare with 2 m)

# Original Radar Range Example in dB

- $P_t$ = 1 MW = 60 dB W
- G = 40 dB
- f = 3 GHz

  $\rightarrow$ $\lambda$ = 0.1 m = - 10 dB meters
- $\sigma$ = 10 dB meters squared
- $S_{min}$ = -100 dBW

# Radar Range Example in dB

- $4\ R_{max} = (\ P_t + 2G + 2\lambda + \sigma\ - 33 -\ S_{min}\ )$ dB mtr
- Maximum range is

$R_{max} = 0.25 \times (\ 60 + 80 - 20 + 10\ - 33 + 100\ )$

$= 0.25 \times 197 = 49.3$ dB mtr

$= 85.1$ km (versus 84.3 km)

- Difference between answers is rounding error

# Radar Range Example in dB

- Radar calculations are to nearest 0.1 dB
- It is not possible to achieve high accuracy
- Do NOT quote decibel results to more than ± 0.1 dB resolution (regardless of your calculator readout)
- Example:

0.25 x 197 = 49.3 dB meters

NOT 49.250 dB meters

# dB versus Linear units

- In this course you will be required to work out problems in dB units
- This is closer to the practice of working radar designers and engineers
- It gives deeper insight into the trade-offs involved with radar design
- Also helps reduce orders-of-magnitude type errors

# Radar Equation

- The power received at a monostatic radar from a target with Radar Cross Section (RCS) $\sigma$ square meters is

$$P_r = P_t G^2 \lambda^2 \sigma / (4\pi)^3 R^4 \quad \text{W}$$

- The minimum detectable power $S_{min}$ is set by a threshold level in the radar receiver
- When $P_r > S_{min}$ a target is detected

# Radar Equation: S/N ratio

- Radar analysis usually works in terms of signal-to-noise ratio, S/N. A minimum detectable S/N can be defined as

$$S_{\mathbf{min}} = N \times (S / N)_{\mathbf{min}} \text{ in watts}$$

where N is the noise power in the receiver

- Or using dB arithmetic

$$S_{\mathbf{min}} = N + (S / N)_{\mathbf{min}} \quad \text{(in dBW)}$$

- $(S / N)_{\mathbf{min}}$ is typically 15 dB, a ratio of 31.6

# Receiver Noise

- The noise power in the receiver, referred to its input, which is where $P_r$ is measured, is

$$N = k\, T_s\, B_n \qquad \text{watts}$$

- $T_s$ is the system noise temperature of the receiver in Kelvins (note: <u>not</u> degrees Kelvin)
- $B_n$ is the receiver noise bandwidth in Hz
- k is Boltzmann's constant = $1.38 \times 10^{-23}$ J/K

# Receiver Noise

- The Rx noise is thermal in origin and is assumed to be spread evenly in frequency (constant power spectral density)
- Also called *white noise*
- The dependence of noise power on $B_n$ creates an incentive to make the receiver bandwidth small

# Receiver Noise

- Another expression for noise power in the receiver is

  $$N = k\, T_0\, F\, B_n \qquad\qquad \text{watts}$$

  where F is the noise figure (linear, dimensionless)

  and $T_0$ = 290 K is a standard temperature

# Radar Equation

- Usual receiver designs take $B_n \sim 1 / \tau$
  where $\tau$ is the radar pulse duration
- Substituting in the noise formula

$$N = k\, T_s\, B_n \qquad = k\, T_s / \tau \ \text{watts}$$

- If we use the 15 dB requirement on $(S / N)_{min}$
  then $S_{min} = N \times 31.6 \qquad W$

$$S_{min} = 31.6\ k\, T_s / \tau \ W$$

# Radar Equation: Pulse energy form

- Now equate $S_{min}$ to received power from a radar target using the RE:

$$S_{min} = 31.6\ k\, T_s / \tau$$
$$= P_t\, G^2 \lambda^2 \sigma / (4\pi)^3 R_{max}^4 \quad \text{watts}$$

- Hence

$$R_{max} = [P_t\, \tau\, G^2 \lambda^2 \sigma / (4\pi)^3\, 31.6\ k\, T_s]^{1/4}$$
$$R_{max} \propto [P_t\, \tau]^{1/4} \quad \text{m}$$

- Hence maximum range $\propto$ energy in the pulse

# Radar Sensitivity

- Being able to detect a target at greater range amounts to greater sensitivity
- Hence, the sensitivity of a typical radar increases with the energy in a pulse
- The reason for taking $B_n \sim 1 / \tau$ for a typical radar is a bit mysterious at this point

# Radar Frequencies (review)

- Early radars operated in the bands:

  HF 3-30 MHz

  VHF 30-300

  UHF 300-1000 MHz

- Most radars today operate at microwave frequencies - 1000 to 100,000 MHz

  = 1 GHz to 100 GHz

- Radars may be identified by wavelength or by a letter denoting an frequency band

# Radar Frequencies

| Frequency | Band | Approx. Wavelength |
|---|---|---|
| 3 – 1000 MHz | HF,VHF,UHF | ~1 m |
| 1 – 2 GHz | L | 30 cm |
| 2 – 4 GHz | S | 10 cm |
| 4 – 8 GHz | C | 5 cm |
| 8 – 12 GHz | X | 3 cm |
| 12 – 18 GHz | $K_u$ | 2 cm |
| 18 – 27 GHz | K | 1.5 cm |
| 27 – 40 GHz | $K_a$ | 1 cm |

# Useful relations between frequency and wavelength for radar systems

- MHz radar systems:

$$\lambda\ [\text{m}]\ f\ [\text{MHz}] = 300$$

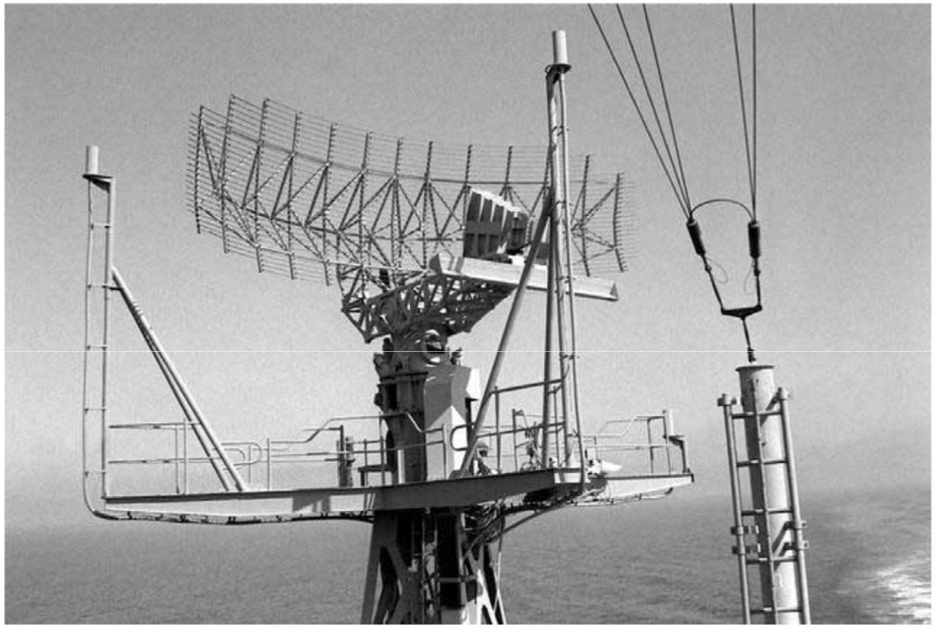
e.g., 30 MHz signal corresponds to $\lambda = 10$ m

- GHz radar systems:

$$\lambda\ [\text{cm}]\ f\ [\text{GHz}] = 30$$

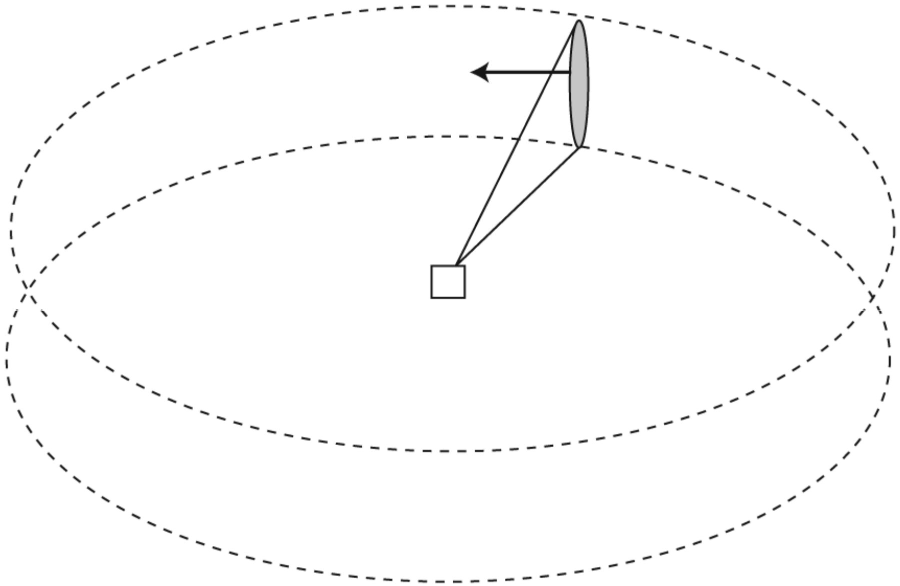
e.g., 2 GHz signal corresponds to $\lambda = 15$ cm

**FIGURE 1-34** ■ AN/SPS-49 2-D search radar antenna. (Courtesy of U.S. Navy.)



# Two-dimensional (2-D) Search System

**FIGURE 1-33** ■
Fan beam searching a volume providing 2-D target position.



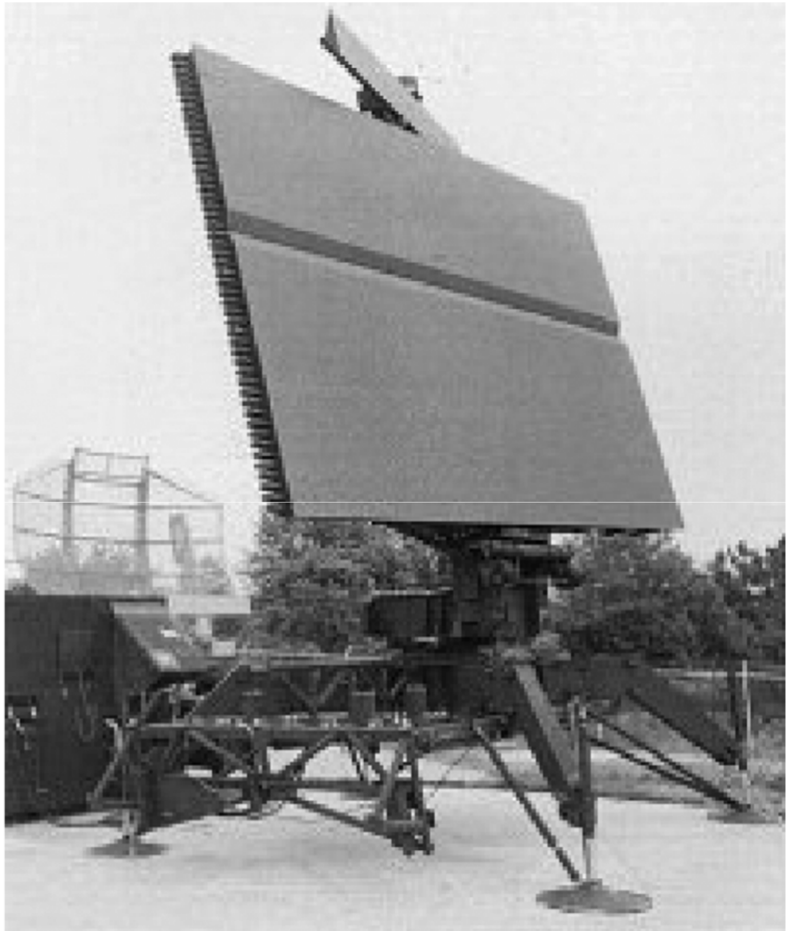
# AN Nomenclature for US Systems

- Developed by US military in WWII
- Designations follow the pattern AN/xxx-nn
- The x–letters designate: (AN/SPS-49)
  - Type of Installation (S: Ship)
  - Type of Equipment (P: Radar)
  - Purpose (S: Search)
- The n's are a numerical sequence
- Read POMR 1.9 and see inside of back cover

**FIGURE 1-37** ■ AN/TPS-75 air defense radar. (Courtesy of U.S. Air Force.)

T – Ground, transportable

Note the smaller rectangular antenna on top for the Identification, Friend, or Foe (IFF) system



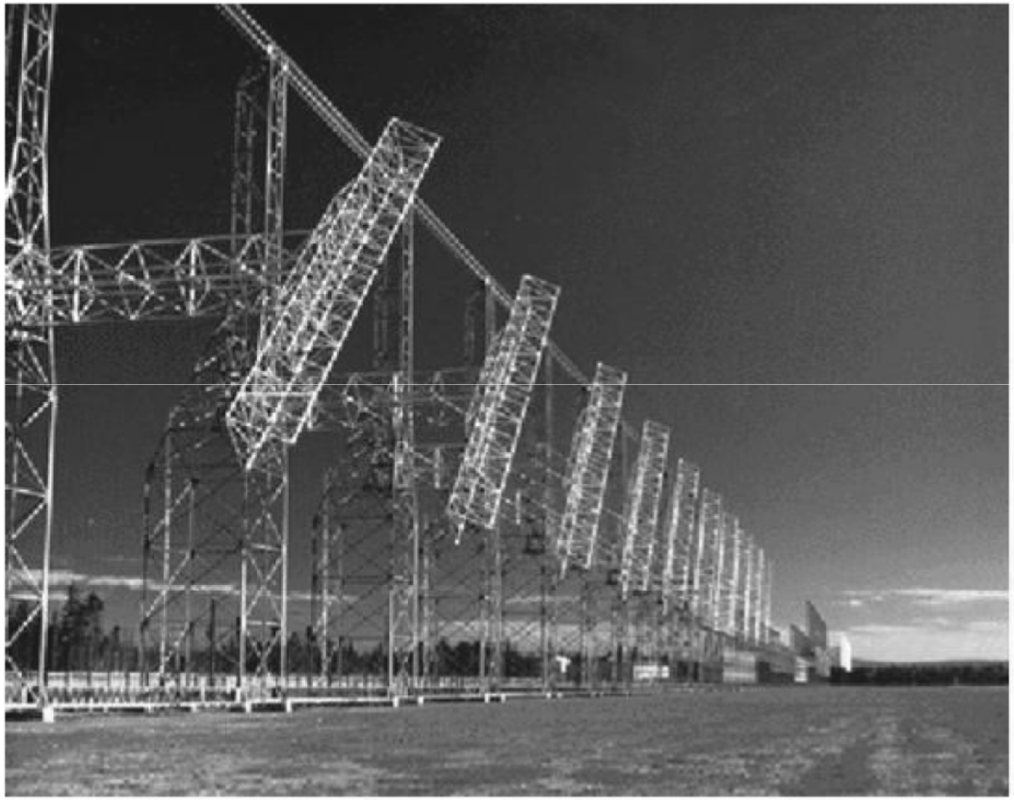


**FIGURE 1-39** ■ Over-the-horizon radar system—Transmit array. (Courtesy of U.S. Air Force.)

Utilizes ionospheric refraction (bending) on HF frequencies (3-30 MHz) to see out to enormous ranges (thousands of kilometers)

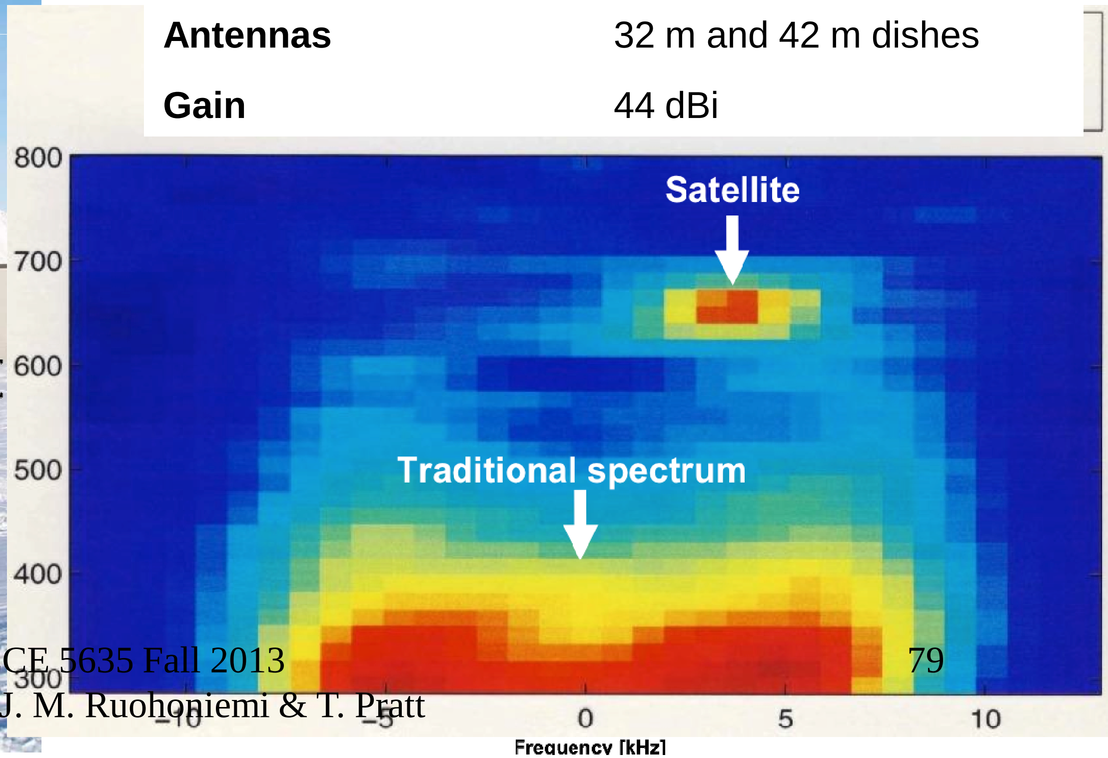
**FIGURE 1-41** ■ Pave Paws (AN/FPS-115) ballistic missile defense radar. (Courtesy of Missile Defense Agency.)

F – Fixed ground

Note the planar arrays of transmit/receive antenna elements

# EISCAT Svalbard ISR Radar


| | |
|---|---|
| **Operating Frequency** | 498.0 – 502.0 MHz |
| **Peak Power** | 1 MW |
| **Antennas** | 32 m and 42 m dishes |
| **Gain** | 44 dBi |



# Radar: New Basic Considerations

- Antenna gain, G, beamwidth, $\theta_B$

  $G = 33{,}000 / (\text{beamwidth in degrees})^2$

  $\theta_{3\,dB} \sim 75\,\lambda / D$ degrees

- Receiver bandwidth, $B_n$

  $B_n \sim 1 / \tau$

- Receiver thermal noise power, N, and system noise temperature, $T_s$

  $N = k\,T_s\,B_n$

# Multiple Pulses

- Radars rarely attempt to detect a target with a single pulse
- Most attempt to illuminate the target with a series of pulses
- Integrating the returns from the multiple pulses improves the ability to detect the target
- The receiver performs the function of adding up the returned pulses

# Multiple Pulses

- Integrating pulses helps because signal tends to add up systematically while noise adds up randomly
- The integration can be *coherent*, adding in both amplitude and phase, or,
- The integration can be *noncoherent*, adding in amplitude only
- Coherent integration gives more improvement but requires more complicated hardware

# Integration Gain

- The text treats integration gain as a boost to the S/N ratio over that expected from a single pulse
- For coherent integration the boost to S/N scales just as the number of pulses, $n_p$ , i.e.,

$$S/N\ (n_p) = n_p \times S/N\ (1)$$

- We can write this in dB notation as

$$(S/N)_{n_p} = (S/N)_1 + G_{int}$$

where the *integration gain* is

$$G_{int} = 10 \log (n_p)$$

# Integration Gain

- Integration gain effectively improves the S/N in the radar receiver
- Example: If the required (S/N) to detect a target is 15 dB and $G_{int}$ = 10 dB

  then $(S/N)_1 = 5$ dB
- Receiver can detect the target with a single pulse S/N of 5 dB instead of a single pulse S/N of 15 dB

# Integration Gain trade-offs

- Now we have to wait for $n_p$ pulses to be transmitted and received before we make a decision about a possible target
- Could be a problem if time is of the essence, e.g., close-in missile defense

# Integration Gain

- Coherent integration gain is

$$G_{\mathbf{co}} = 10 \log (n_{\mathbf{p}})$$

where $n_{\mathbf{p}}$ is the number of pulses

- Noncoherent integration gain is

$$G_{\mathbf{inco}} = 10 \log (n_{\mathbf{p}}) - \text{Integration Loss}$$

- That is, noncoherent gain is always less than that obtained with coherent gain for integrating the same number of pulses
- Integration loss is often estimated with the help of Tables

# Losses

- A 'loss' is anything that detracts from ideal S/N
- Read Section 2.7 for detailed account of loss types
- The text presents an expression (Eq. 2.16) for the total system loss, $L_s$ ,

$$L_s = L_t\, L_a\, L_r\, L_{sp} \quad \text{where}$$

$L_t$ = transmit loss $\quad$ $L_a$ = atmospheric loss

$L_r$ = receiver loss $\quad$ $L_{sp}$ = signal processing loss

# Modified Radar Equation

- In dB units this takes on the simpler form

$$L_s = L_t + L_a + L_r + L_{sp} \qquad \text{dB}$$

- Now modify the RE in dB form for integration gain $G_{int}$ and system loss $L_s$:

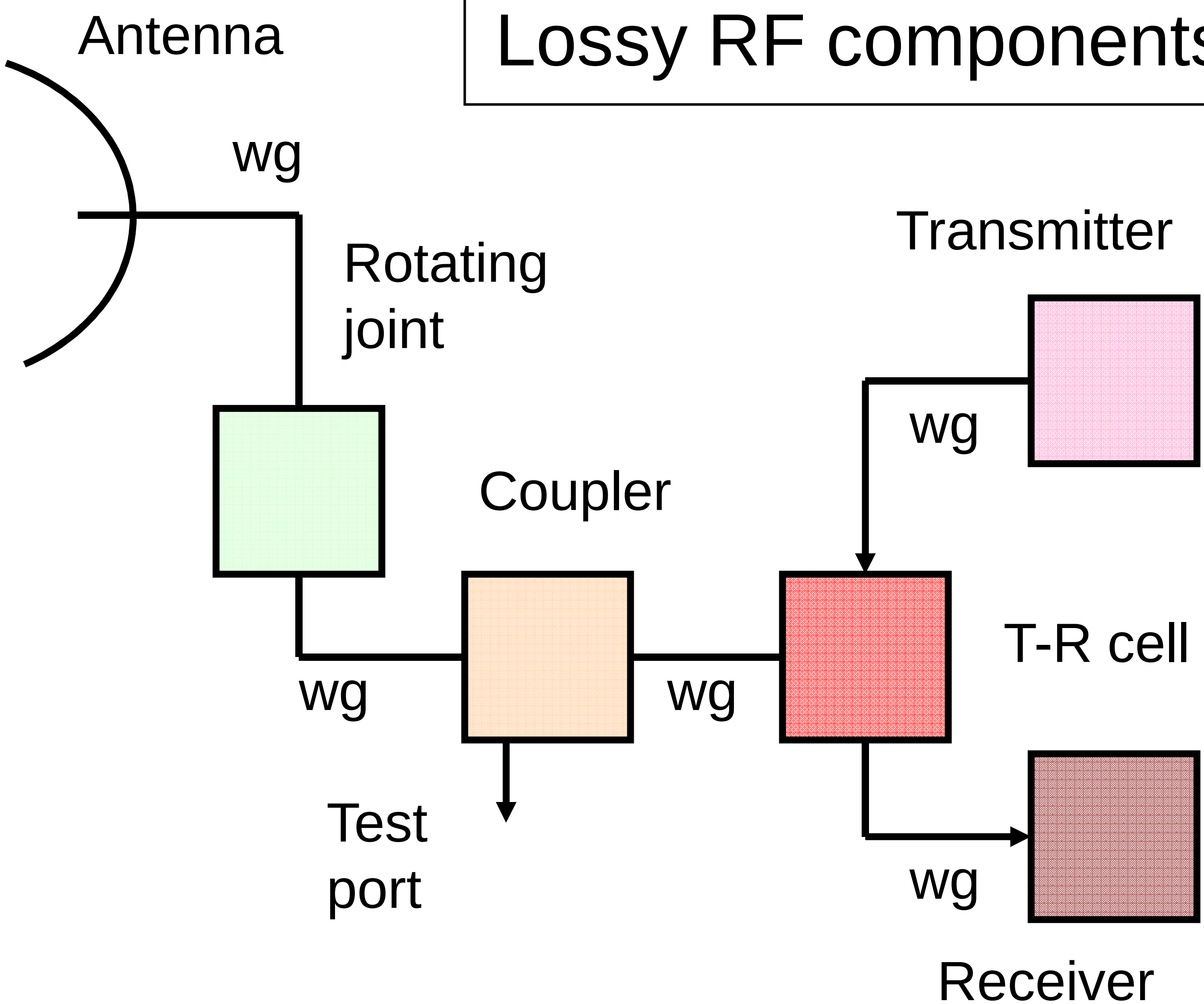
$$P_r = P_t + 2\,G + 2\,\lambda + \sigma + G_{int} - L_s - 33 - 4\,R$$

- Typically, integration gain is about 10 dB and system losses are 10 – 16 dB

# System Losses

- Microwave plumbing losses
- Between transmitter and antenna
  receiver and antenna
- Waveguide run
- Rotating joint
- T-R cell (duplexer)
- Waveguide components

# Lossy RF components



# RF Loss Example

- S band radar RF loss example
- Antenna – T-R cell waveguide run requires 100 ft RG-113/U waveguide
- Waveguide loss 1.0 dB
- T-R cell loss 2.0 dB
- Rotary joint 0.8 dB
- Coupler, bends, etc 0.7 dB
- Total one way loss 4.5 dB

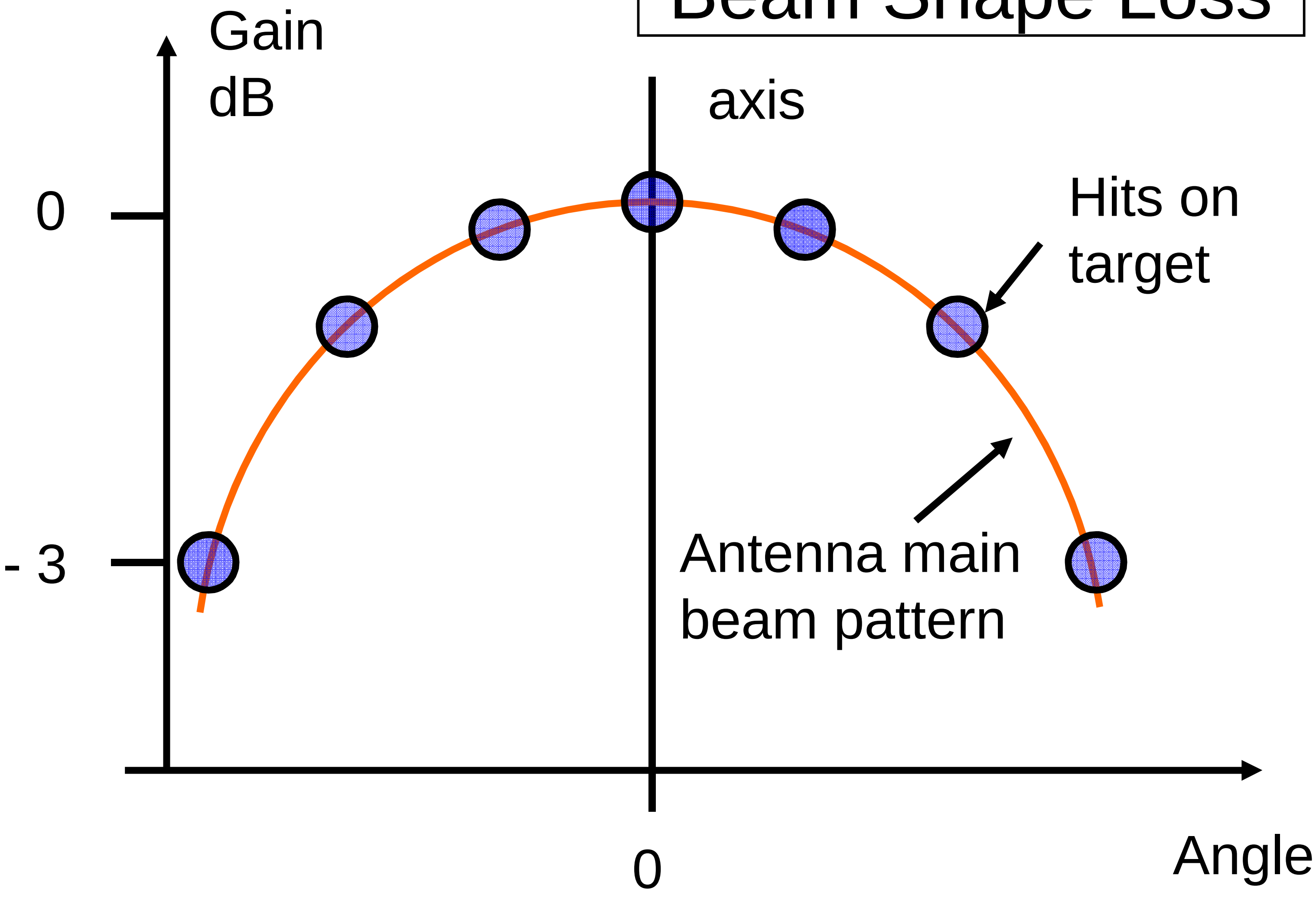
# RF Loss Example

- S band radar:  one way RF loss = 4.5 dB
- Loss occurs from transmitter to antenna
  from antenna to receiver
- Hence system loss is   2 x 4.5  =  9 dB
- We must include this loss in the radar equation

# Beam Shape Loss

- Surveillance radar must rotate antenna
- Antenna beam sweeps past target
- Multiple radar pulses are spread across antenna pattern between 3 dB points
- Antenna gain is less than $G_{\mathbf{max}}$ except on axis
- For N > 10, loss is 1.6 to 2 dB
- See text, Figure 2-4, p. 70 for more discussion

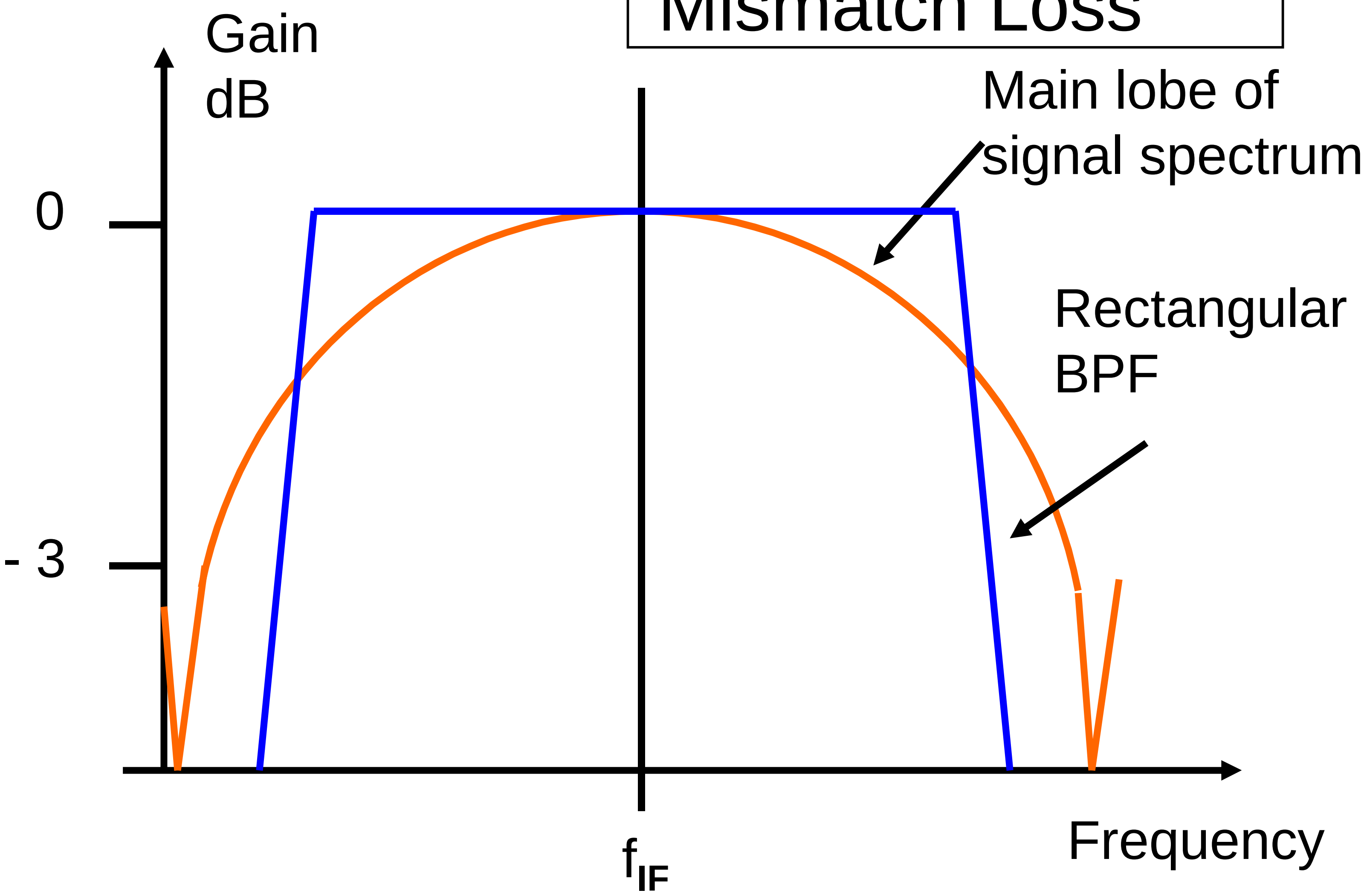
# Beam Shape Loss



# Other System Losses

- Rx filter mismatch loss
- Radar pulse has sin X / X spectrum
- Rx bandpass filter is ~ rectangular
- Mismatch loss is 0.9 dB
- Radome Loss
- If antenna has radome, there will be RF loss
- Typical value (text) is 1.2 dB two way
- Other signal processing losses - see text

# Mismatch Loss



# S-band Surveillance Radar Example

- Add up all losses:
- RF losses 9.0 dB
- Beam shape loss 2.0 dB
- Mismatch loss 0.9 dB
- Total 11.9 dB
- Miscellaneous losses 3.1 dB
- Estimated losses 15.0 dB

# Radar Design Example

- We will next design a radar system for a particular application
- Our design work will utilize the RE modified for integration gain and system loss (in dB units):

$$P_r = P_t + 2\,G + 2\,\lambda + \sigma + G_{int} - L_s - 33 - 4\,R$$

- Note: True design work is not covered in POMR – pay attention to this slide presentation!

# Radar Design Example

- We have to meet a sensitivity spec, e.g., obtain $(S/N)_{\mathbf{min}}$ for a certain target at range $R_{\mathbf{max}}$
- Relate the S/N spec to $S_{\mathbf{min}}$ by

$$S_{\mathbf{min}} = N \text{ dBW} + (S/N)_{\mathbf{min}}$$

$$S_{\mathbf{min}} = k\, T_{\mathbf{s}}\, B_{\mathbf{n}} \text{ dBW} + (S/N)_{\mathbf{min}}$$

- Write the RE for the test target as

$$S_{\mathbf{min}} = P_{\mathbf{t}} + 2\,G + 2\,\lambda + \sigma + G_{\mathbf{int}} - L_{\mathbf{s}} - 33 - 4\,R_{\mathbf{max}}$$

# Radar System Design Example

- There are many parameters in a radar system

  $B$, $G_{int}$ , $\Delta R$, $P_t$ , $G$, $\lambda$, $\sigma$, $R_{max}$ , $L_s$ , $S_{min}$

  $k$, $T_s$ , $B_n$ , $\theta_B$ , PRF

- Of the many parameters only Boltzmann's constant is fixed
- We cannot set all the parameters values at the start of the designing

# Radar System Design Example

- Design is an iterative process
- Begins with a *specification*
- Step 1. Start with a few key parameters

  Calculate related quantities
- Step 2. Estimate radar performance

  Does performance meet specification?
- Step 3. Modify design

# Radar Design Example

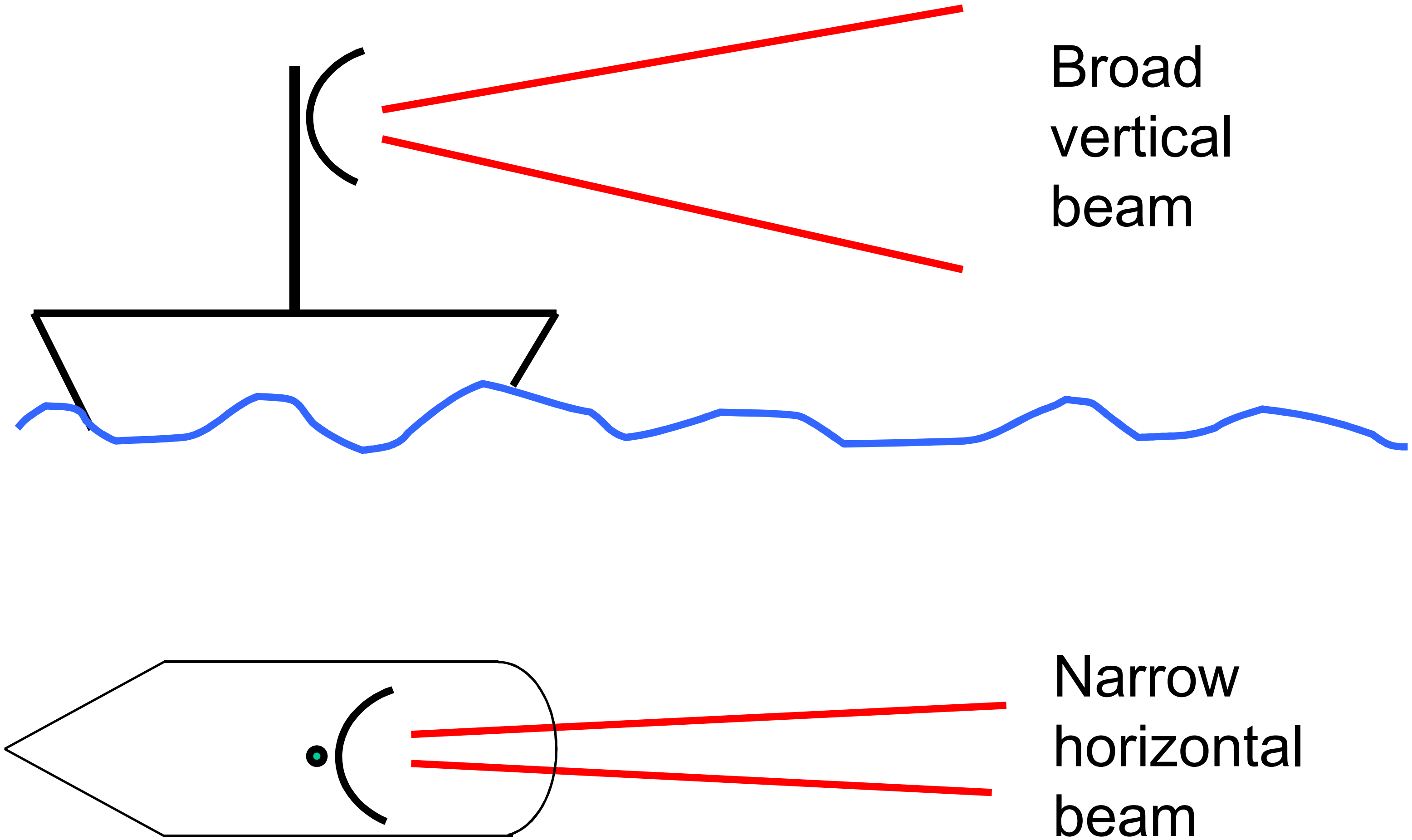
- Radar is X-band pulse radar for use on a boat
- General requirements:
  - Antenna must be small enough to fit on boat
  - Pulse power should be as low as possible
  - See large ships long way off
  - See small boats close in
- This simple Example will take many slides!

# How to Proceed

- Stop:   Read specification
- Stop:   Decide what is important
- Stop:   Draw a block diagram of the radar
- Stop:   Decide where to start
- Do **not** begin by writing down the Radar Range Equation
- Make a trial design, then adjust parameters

# Radar Design Example

- Specification of radar for small sea going vessel
- X – band: 9.6 GHz
- $P_t$ = 10 kW (rms pulse power)
- Range resolution = 15 m
- Max range 40 km for 10 $m^2$ RCS target
- $(S/N)_{min}$ = 15 dB
- PPI synthesized display




Antenna beam requirements

# Radar Design Example

- Step 1. Find the bandwidth, B

  For $\Delta R = 15$ m, $\tau = 1\ \mu s \times 15 / 150 = 0.1\ \mu s$

  Use $B = 1/\tau = 10$ MHz

- Step 2. Find the $(S/N)_{min}$ required to meet specified target detection and false alarm probabilities, or adopt the value provided.

  We take $(S/N)_{min} = 15$ dB for detection of a 10 $m^2$ RCS target at a range of 40 km

- Need to mind the situation with small boats in close

# Radar Design Example

- Step 3. Select a fluctuation model of the target or assume a constant RCS, here

  $\sigma = 10\ \text{m}^2 = 10\ \text{dBmeter}^2$

- Step 4. Set the $R_{max}$ of the target

  $R_{max} = 40\ \text{km} = 46\ \text{dBm}$

- Step 5. Assume a value of Integration gain - how many pulses do we put on the target?

  Set $N = 20$, $G_{int} \sim 13$ dB (coherent)

# Radar Design Example

- Step 5. Find N and $S_{min}$

Assume $T_s = 1000$ K, then

$$N = -228.6 + 30 + 70 = -128.6 \text{ dBW}$$

With $(S/N)_{min} = 15.0$ dB

$$S_{min} = k\, T_s\, B_n \text{ in dBW} + (S/N)_{min}$$
$$= -128.6 + 15.0$$
$$= -113.6 \text{ dBW}$$

# Radar Design Example

- Step 6. Assign wavelength

$$\lambda = 0.03125 \text{ m} = -15.1 \text{ dBmeter}$$

- Consider RE with substitutions to this point

$$S_{\mathbf{min}} = P_{\mathbf{t}} + 2\,G + 2\,\lambda + \sigma + G_{\mathbf{int}}$$
$$- L_{\mathbf{s}} - 33 - 4\,R_{\mathbf{max}}$$

$$-113.6 = 40 + 2\,G - 30.2 + 10 + 13$$
$$- L_{\mathbf{s}} - 33 - 184$$

# Radar Design Example

- Estimate losses:
- RF - two way loss 4 dB
- Beam shape loss 2 dB
- Filter mismatch loss 1 dB
- Atmospheric loss ?
- Radome loss ?
- Total 7 dB

# Radar Design Example

- Step 7: Revised Radar Equation with $L_s$ = 7.0 dB

$$-113.6 = 40 + 2\,G - 30.2 + 10 + 13 - 7 - 33 - 184$$

- Step 8: Rearrange to solve for antenna gain

$$2\,G = -113.6 - 40 + 30.2 - 10 - 13 + 7 + 33 + 184$$

$$G = 38.8 \text{ dB}$$

# Radar Design Example

- For this design we need an antenna with a gain of 38.8 dB to meet the performance spec
- Consider the antenna on its own terms, suppose

  vertical beamwidth = 15º

  horizontal beamwidth = 1º

- Then G = 33,000 / (15 x 1) = 2200 = 33.4 dB
- Next consider the dimensions of the antenna from

$$\theta_{\mathbf{3\ dB}} \sim 75\ \lambda / D \text{ degrees}$$

# Radar Design Example

- Dimension in horizontal plane is

  $D_H$ = 75 $\lambda$ / 1 = 75 x 0.03125 m = 2.34 m

  $D_H$ = 7.7 feet - may be too large

- Set horizontal beamwidth = 1.5º

  $D_H$ = 1.56 m = 5.1 ft, G = 31.6 dB

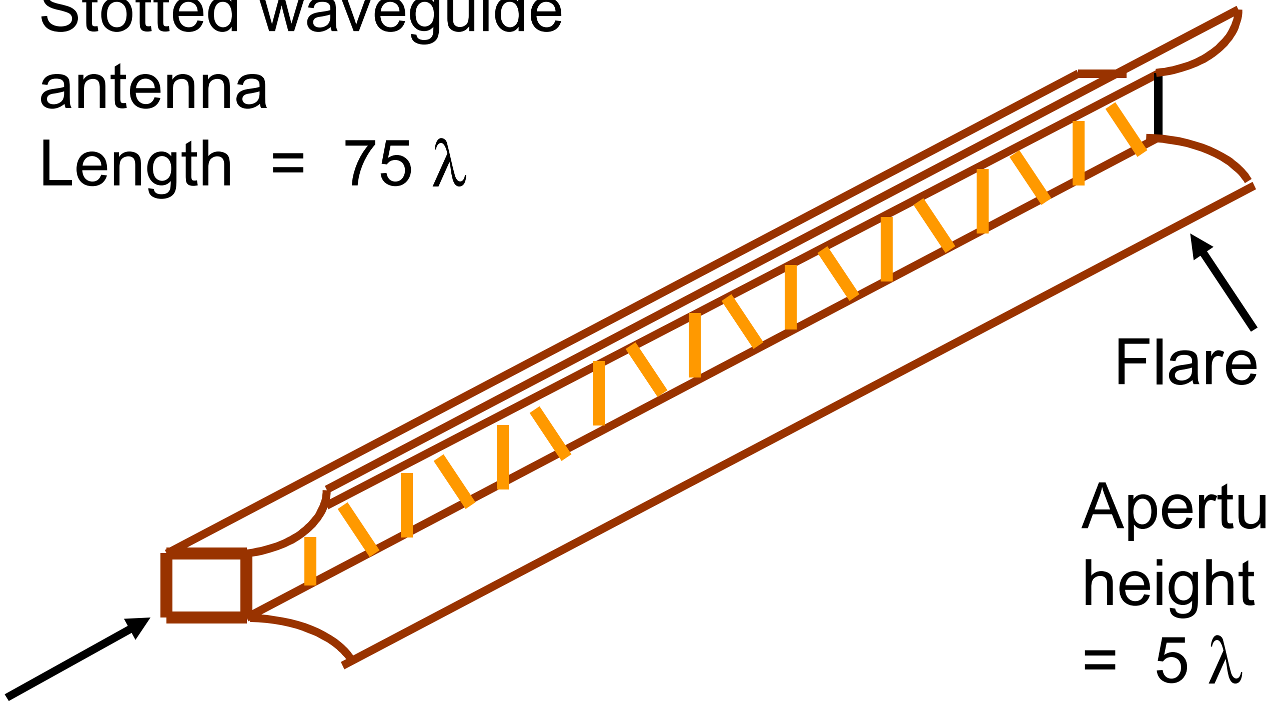
- Dimension in vertical plane is

  $D_V$ = 75 $\lambda$ / 15 = 5 x 0.03125 m = 0.16 m

  $D_V$ = 6 inches

# Typical small boat radar antenna

Stotted waveguide antenna
Length = 75 $\lambda$

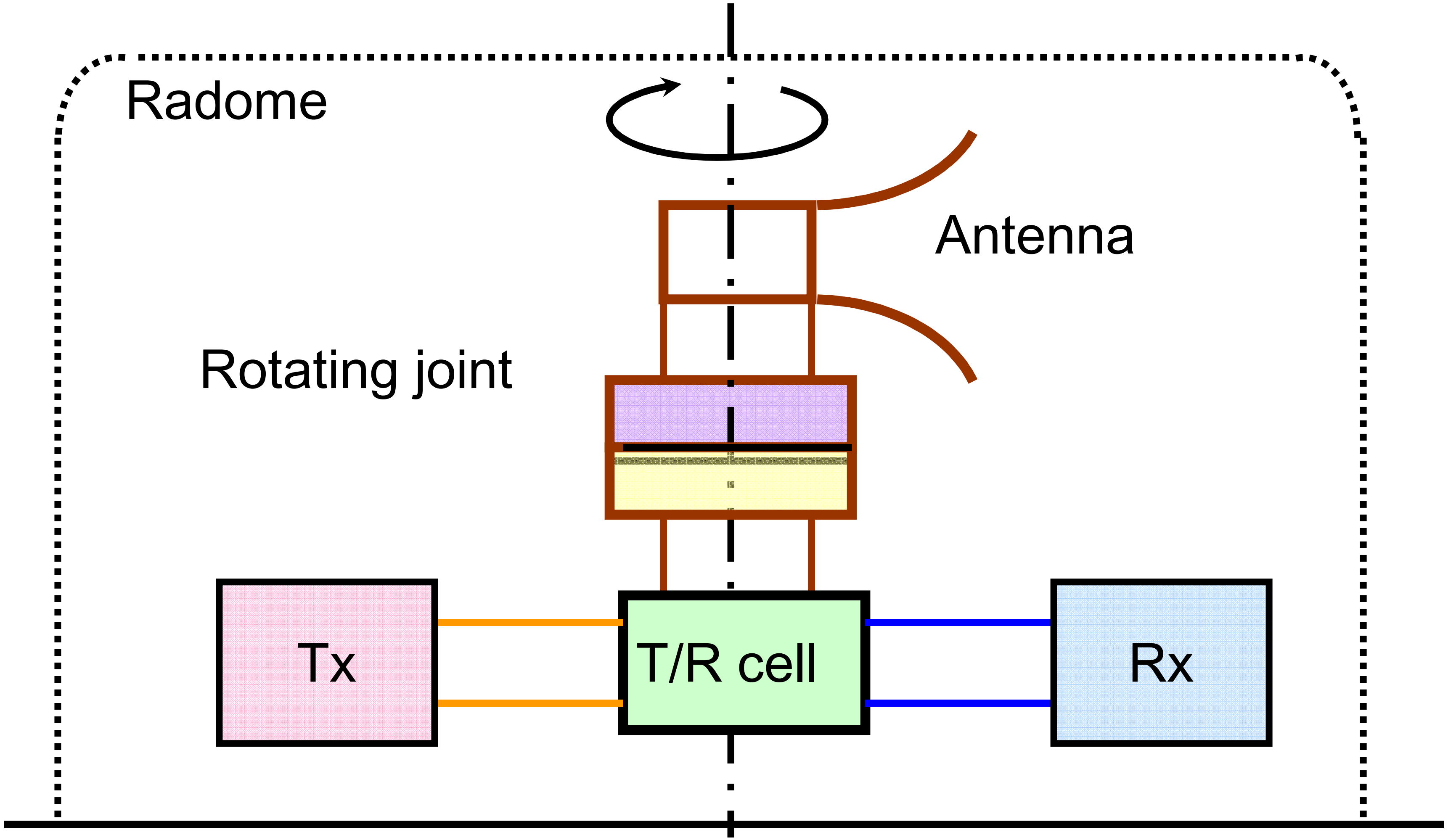


Flare

Aperture height = 5 $\lambda$

Power in

Beamwidths: $1^{o}$ Hor x $15^{o}$ Vert


Radome
Antenna
Rotating joint
Tx
T/R cell
Rx

# Radar Design Example

- Review design of X band radar:
- Antenna:

$$D_H = 1.56 \text{ m} = 5.1 \text{ ft}, \quad G = 31.6 \text{ dB}$$

- For our design we need $G = 38.8$ dB to meet the performance spec; we are short on antenna gain by

$$\Delta G = 38.8 - 31.6 = 7.2 \text{ dB}$$

- The dB shortfall in the radar equation is $2\,\Delta G$
- We need to find another 14.4 dB!