Radar Systems Engineering
Lecture 5
Propagation through the Atmosphere

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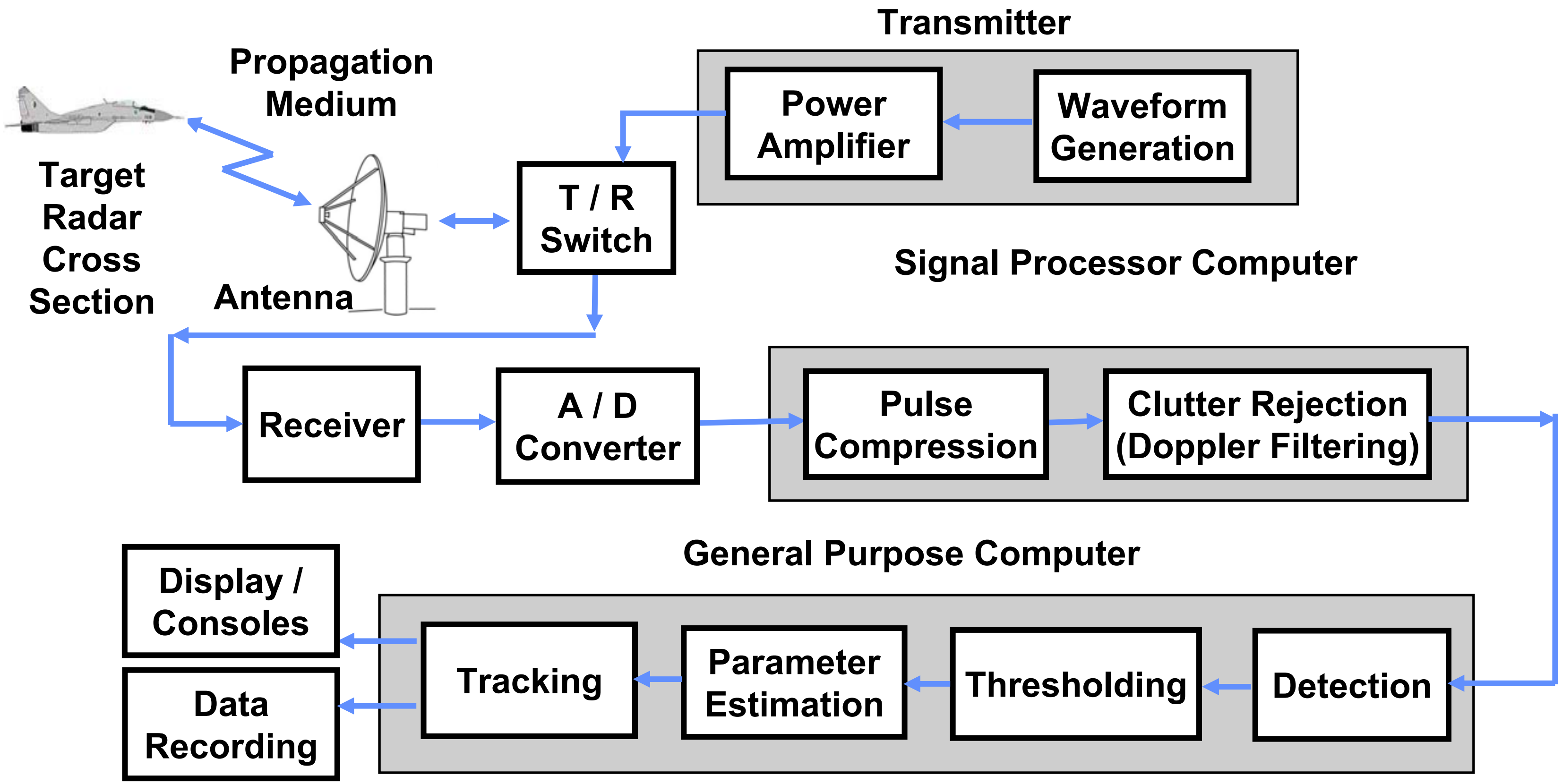
Guest Lecturer

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)

General Purpose Computer

Detection

Thresholding

Parameter Estimation

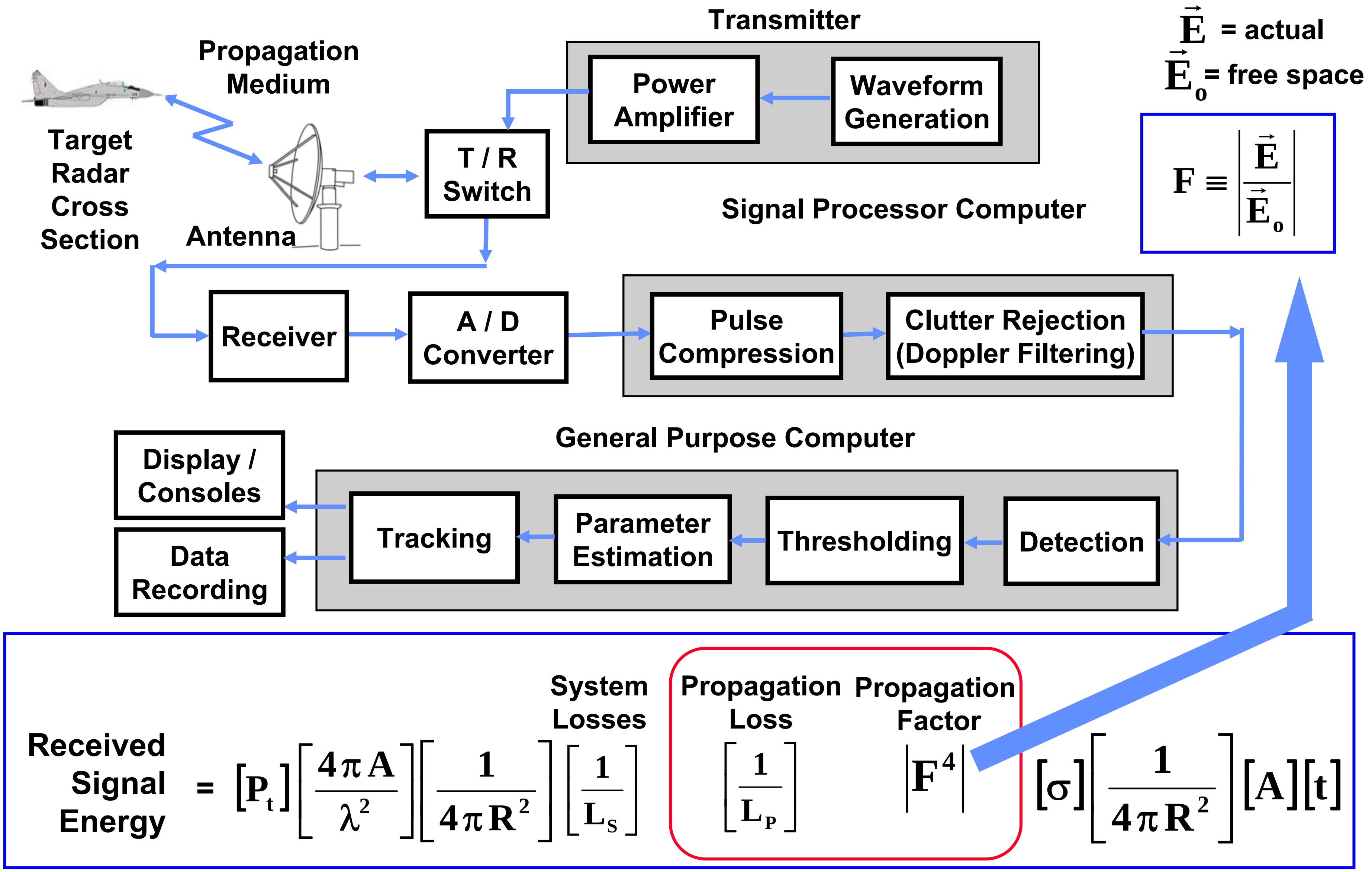
Tracking

Display / Consoles

Data Recording

$$\text{Received Signal Energy} = [P_t]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\overset{\text{System Losses}}{\left[\frac{1}{L_S}\right]}\boxed{\overset{\text{Propagation Loss}}{\left[\frac{1}{L_P}\right]}\;\overset{\text{Propagation Factor}}{\left|F^4\right|}}[\sigma]\left[\frac{1}{4\pi R^2}\right][A][t]$$

Block Diagram of Radar System



$\vec{E}$ = actual

$\vec{E}_o$ = free space

$$F \equiv \left| \frac{\vec{E}}{\vec{E}_o} \right|$$

Received Signal Energy

$$= \left[P_t\right]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L_S}\right]\left[\frac{1}{L_P}\right]\left|F^4\right|\left[\sigma\right]\left[\frac{1}{4\pi R^2}\right]\left[A\right]\left[t\right]$$

Introduction and Motivation

- **Ground based**
- **Sea based**
- **Airborne**

Patriot

Courtesy of US MDA

AWACS

Courtesy of U.S. Air Force.

AEGIS

Courtesy of U.S. Navy.

Almost all radar systems operate through the atmosphere and near the Earth's surface

Effect of the Atmosphere on Radar Performance

- Attenuation of radar beam
- Refraction (bend) of the radar beam as it passes through the atmosphere
- "Multipath" effect
  - Reflection of energy from the lower part of the radar beam off of the earth's surface
  - Result is an interference effect
- Over the horizon diffraction of the radar beam over ground obstacles
- Propagation effects vary with:
  - Changing atmospheric conditions and wavelength
  - Temporal and geographical variations

A Multiplicity of Atmospheric and Geographic Parameters

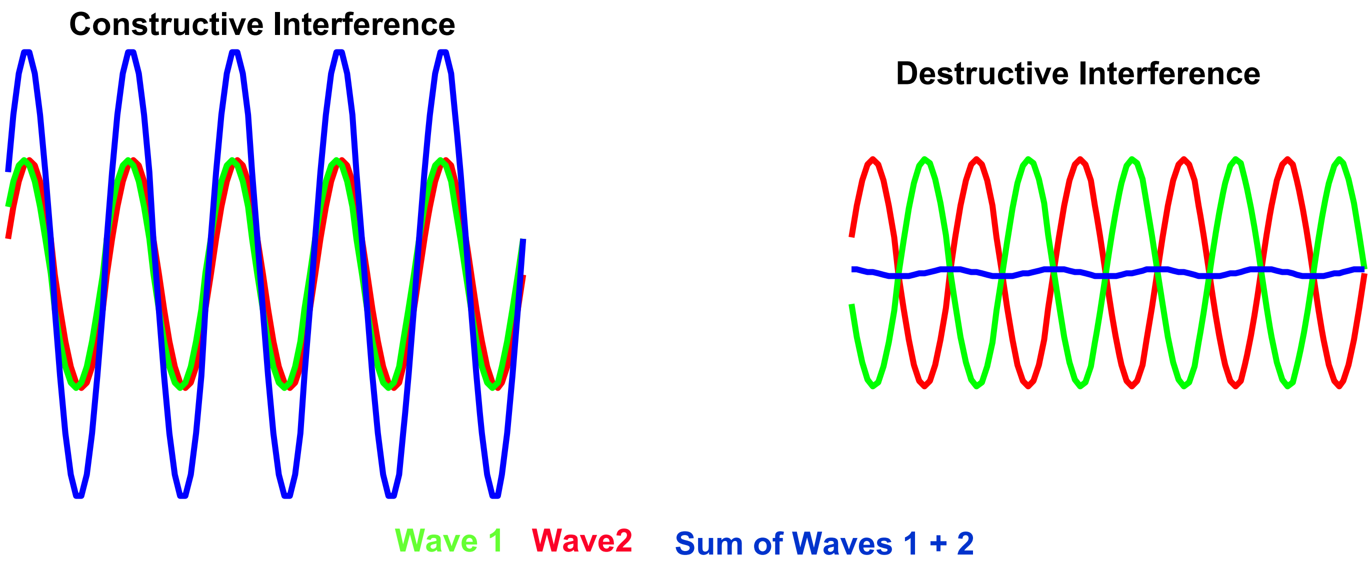
- Atmospheric parameters vary with altitude
  - Index of refraction
  - Rain rate
  - Air density and humidity
  - Fog/cloud water content

- Earth's surface
  - Curvature of the earth
  - Surface material (sea / land)
  - Surface roughness (waves, mountains / flat, vegetation)

Outline

- ➡ Reflection from the Earth’s surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Review of Interference Effect



- Two waves can interfere constructively or destructively
- Resulting field strength depends only on relative amplitude and phase of the two waves
  - Radar voltage can range from 0-2 times single wave
  - Radar power is proportional to $(\text{voltage})^2$ for 0-4 times the power
  - Interference operates both on outbound and return trips for 0-16 times the power

Courtesy of MIT Lincoln Laboratory
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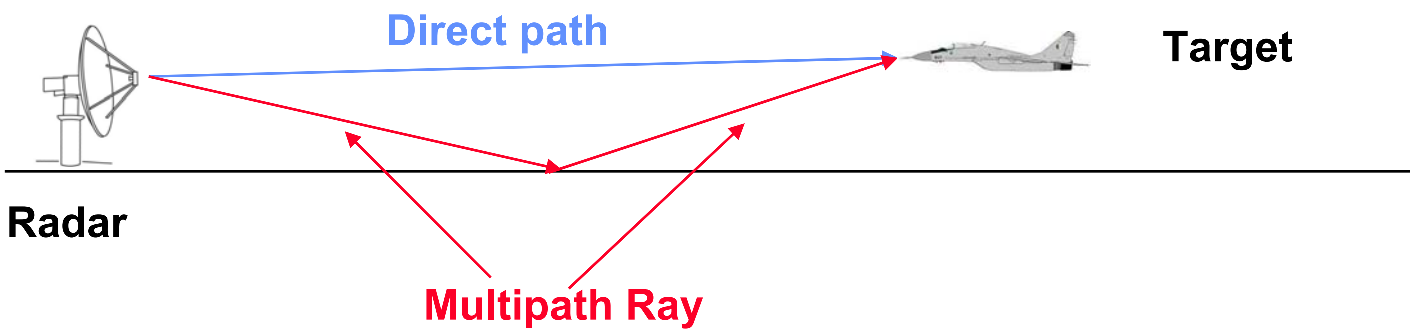
Overview - Propagation over a Plane Earth



- **Reflection from the Earth's surface results in interference of the direct radar signal with the signal reflected off of the surface**
  - **Total propagation effect expressed by propagation factor $|F|^4$**
- **Surface reflection coefficient (Γ) determines relative signal amplitudes**
  - **Dependent on: surface material, roughness, polarization, frequency**
  - **Close to 1 for smooth ocean, close to 0 for rough land**
- **Relative phase determined by path length difference and phase shift on reflection**
  - **Dependent on: height, range and frequency**

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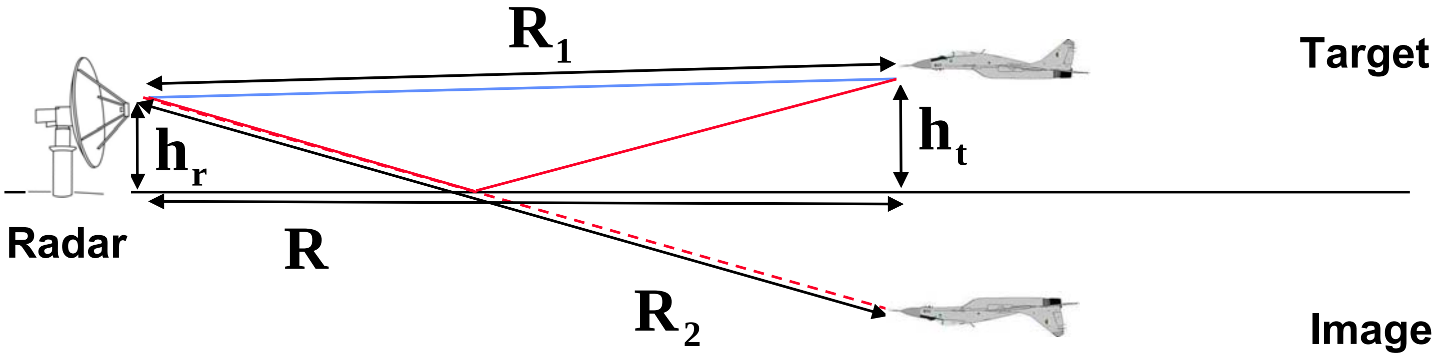
Relative Phase Calculation



$$R_1 = \sqrt{R^2 + (h_r - h_t)^2}$$

$$R_2 = \sqrt{R^2 + (h_r + h_t)^2}$$

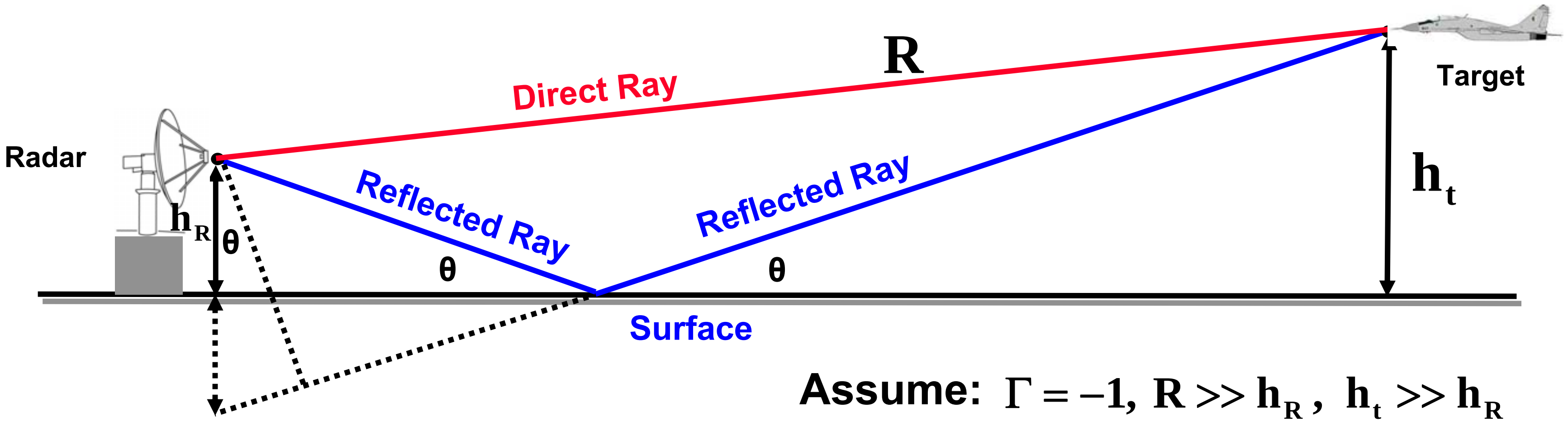
$$\Delta\varphi = \frac{2\pi}{\lambda}(R_1 - R_2) \approx \frac{4\pi h_r h_t}{\lambda R}$$

Direct wave **Reflected wave**

$$F = 1 + |\Gamma| \exp(i\,\Delta\varphi)$$

$$\text{Two way propagation factor} = |F|^4$$

Propagation over a Plane Earth



Assume: $\Gamma = -1,\ R >> h_R\,,\ \ h_t >> h_R$

- The (reflected path) - (directed path) : $\Delta = 2h_R \sin\theta$
- For small θ , $\sin\theta = \dfrac{h_R + h_t}{R}, \Delta = \dfrac{2\,h_R h_t}{R}$
- The phase difference due to path length difference is:

$$\phi = \left(\frac{2\pi}{\lambda}\right)\left(\frac{2h_R h_t}{R}\right)$$

Reflection at surface

- The total phase difference is $\phi = \left(\dfrac{2\pi}{\lambda}\right)\left(\dfrac{2h_R h_t}{R}\right) + \pi$

Propagation over a Plane Earth (continued)

- **The sum of two signals, each of unity amplitude, but with phase difference:**

$$\eta = \sqrt{\left((1+\cos\phi)^2 + (\sin\phi)^2\right)} = \sqrt{2\left(1+\cos\left(\frac{4\pi h_R h_t}{\lambda R}\right)\right)}$$

- **The one way power ratio is:**

$$\eta^2_{1WAY} = 2\left[1-\cos\left(\frac{4\pi h_R h_t}{\lambda R}\right)\right] = 4\sin^2\left(\frac{2\pi h_R h_t}{\lambda R}\right)$$

- **The two way power ratio is:**

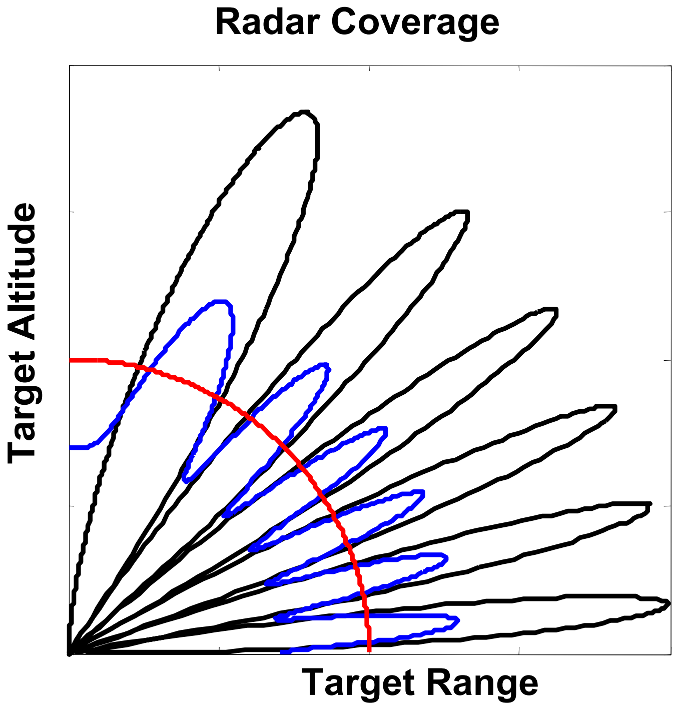
$$\eta^4_{1WAY} = 16\sin^4\left(\frac{2\pi h_R h_t}{\lambda R}\right)$$

- **Maxima occur when** $(\quad) = (2n+1)\frac{\pi}{2}$ **, minima when** $(\quad) = n\pi$

- **Multipath Maxima and Minima:**

Maxima $$\frac{4h_R h_t}{\lambda R} = 2n+1$$ **Minima** $$\frac{2h_R h_t}{\lambda R} = n$$

Multipath Effect on Radar Detection Range



Reflection Coefficient

Γ =-1

Γ =-0.3

Γ =0

First maxima at angle

$$\approx \frac{\lambda}{4h_R}$$

- Multipath causes elevation coverage to be broken up into a lobed structure
- A target located at the maximum of a lobe will be detected as far as twice the free-space detection range
- At other angles the detection range will be less than free space and in a null no echo signal will be received

Courtesy of MIT Lincoln Laboratory
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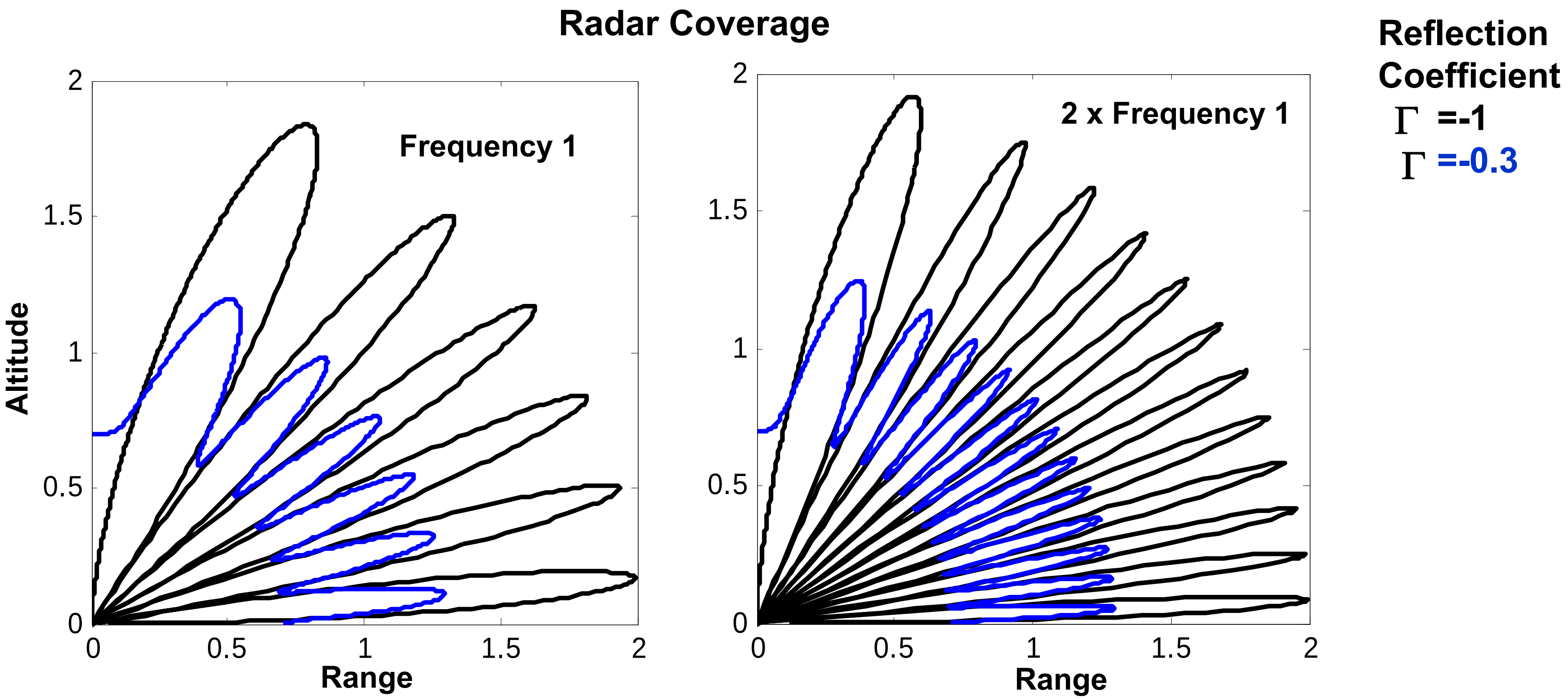
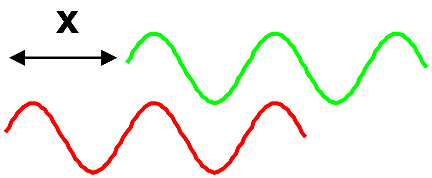
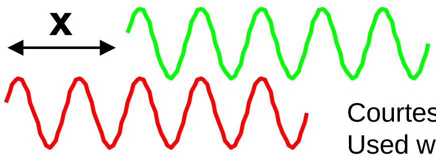
Multipath is Frequency Dependent



Radar Coverage



1 lobe over distance x :



2 lobes over distance x :

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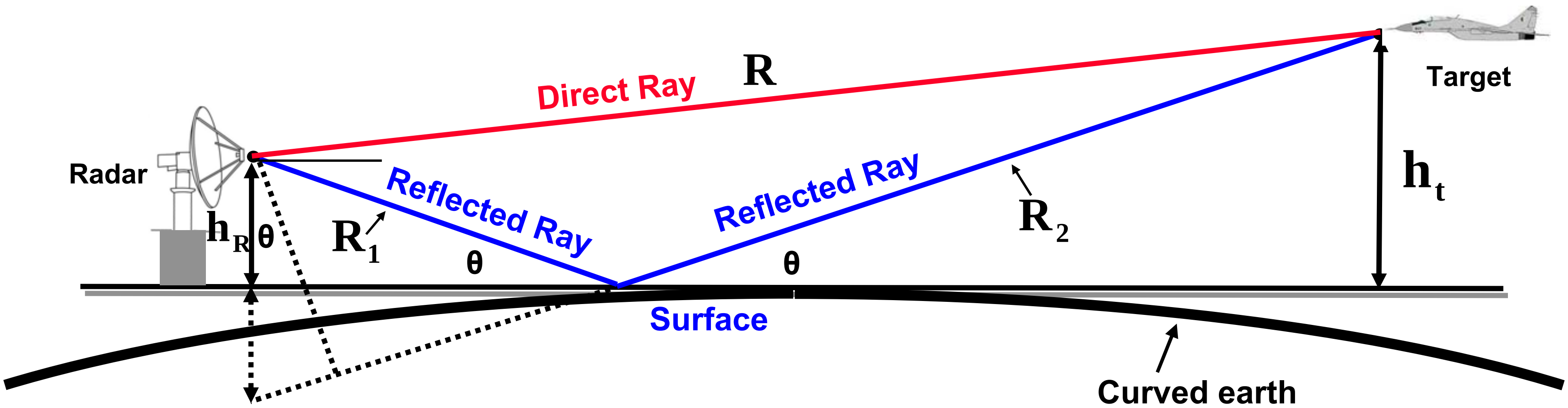
Lobing density increases with increasing radar frequency

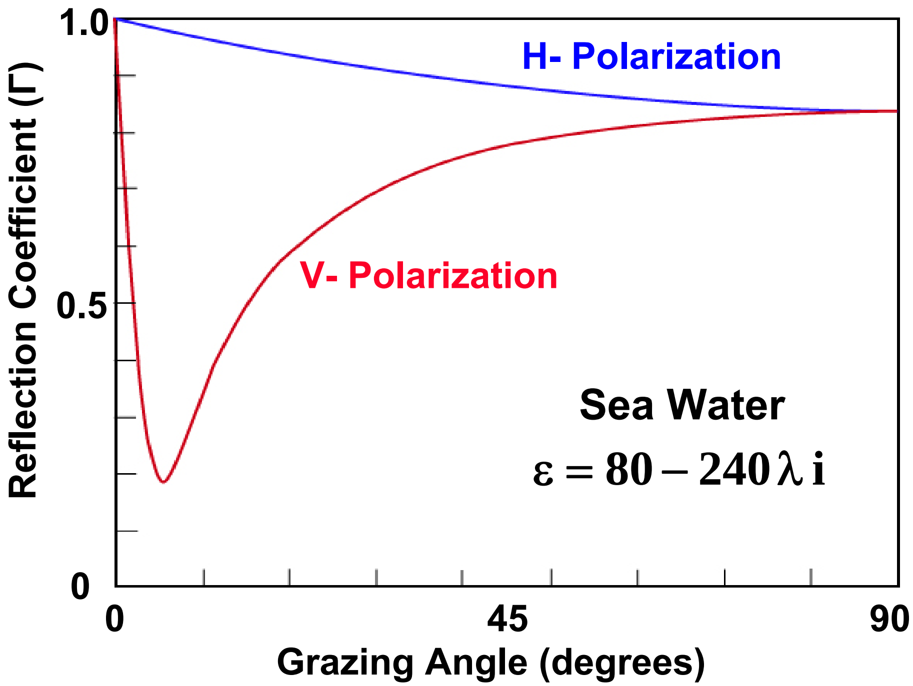
Propagation over Round Earth

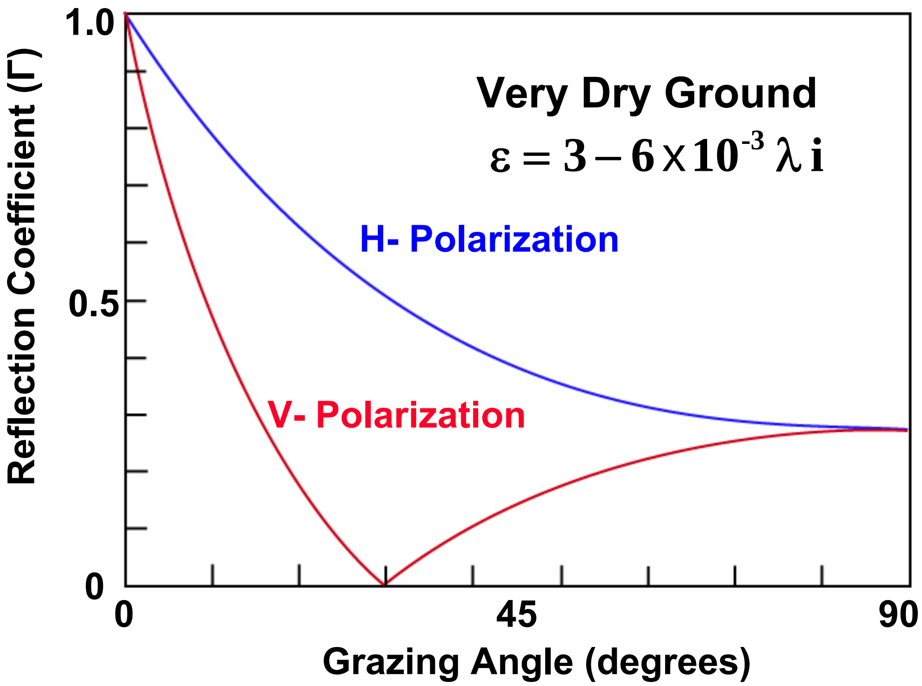


- Reflection coefficient from a round earth is less than that from a flat earth
- Propagation calculations with a round earth are somewhat more complicated
  - Computer programs exist to perform this straightforward but tedious task
  - Algebra is worked out in detail in Blake (Reference 4)
- As with a flat earth, with a round earth lobing structure will occur

Adapted from Blake, Reference 4

Examples - L-Band Reflection Coefficient





ε = Complex dielectric constant

$$\varepsilon = \varepsilon_r - i\,\varepsilon_i = \varepsilon_r - i\,60\,\lambda\,\sigma$$

σ = Conductivity

α = Grazing angle

λ = Wavelength

$$\Gamma_H = \frac{\sin\alpha - \sqrt{\varepsilon - \cos^2\alpha}}{\sin\alpha + \sqrt{\varepsilon - \cos^2\alpha}} \qquad \Gamma_V = \frac{\varepsilon\sin\alpha - \sqrt{\varepsilon - \cos^2\alpha}}{\varepsilon\sin\alpha + \sqrt{\varepsilon - \cos^2\alpha}}$$

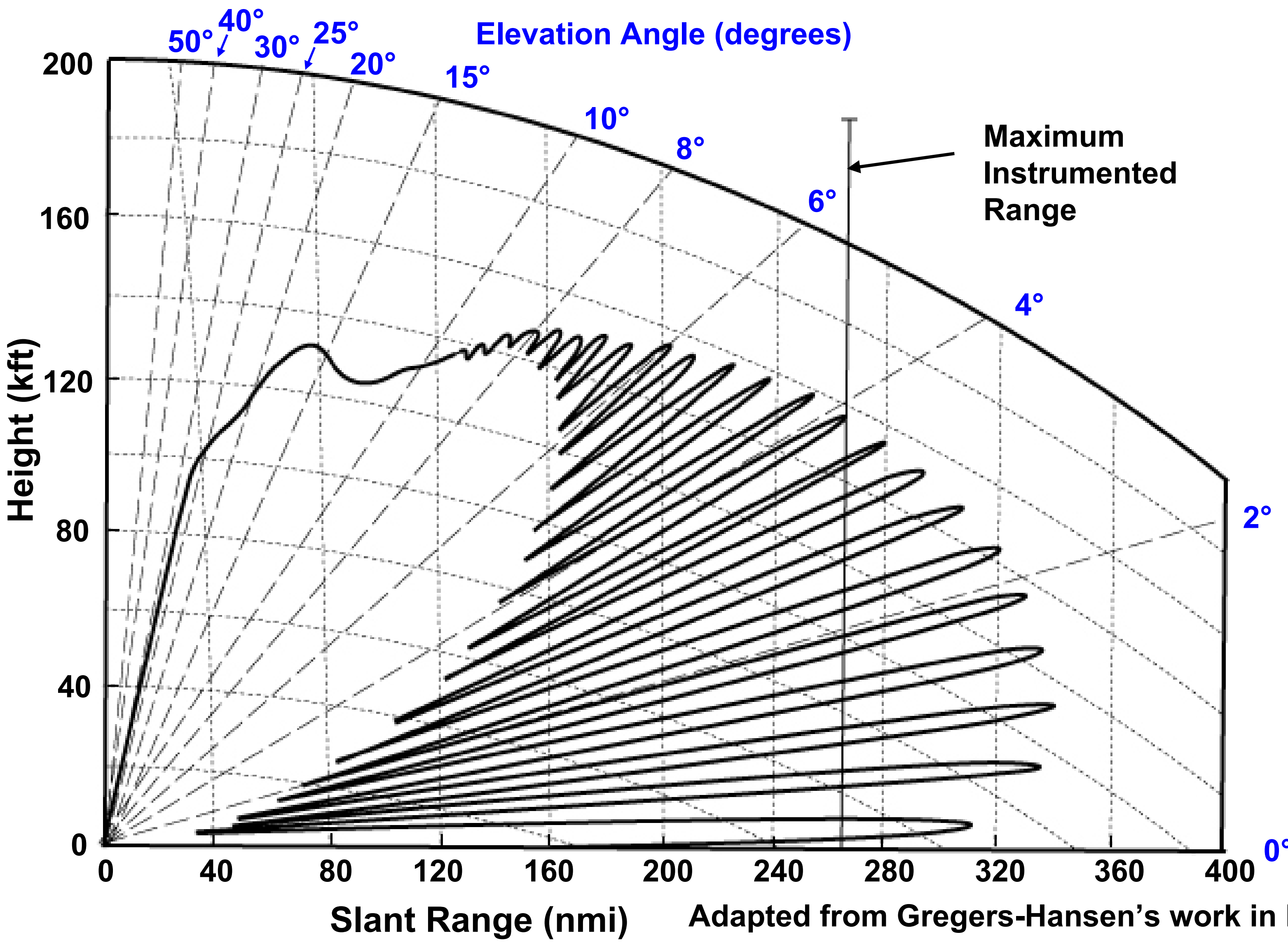
SPS-49 Ship Borne Surveillance Radar

Courtesy of US Navy

USS Abraham Lincoln

- Radar Parameters
  - Average Power 13 kW
  - Frequency 850-942 MHz
  - Antenna
    - Gain 29 dB
    - Rotation Rate 6RPM
  - Target $\sigma = 1\ m^2$
    - Swerling Case I
  - P_D 0.5
  - PFA 10^{-6}
  - Antenna Height 75 ft
  - Sea State 3

Vertical Coverage of SPS-49 Surveillance Radar



Adapted from Gregers-Hansen's work in Reference 1

Outline

- Reflection from the Earth’s surface
- ➡ Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Refraction of Radar Beams

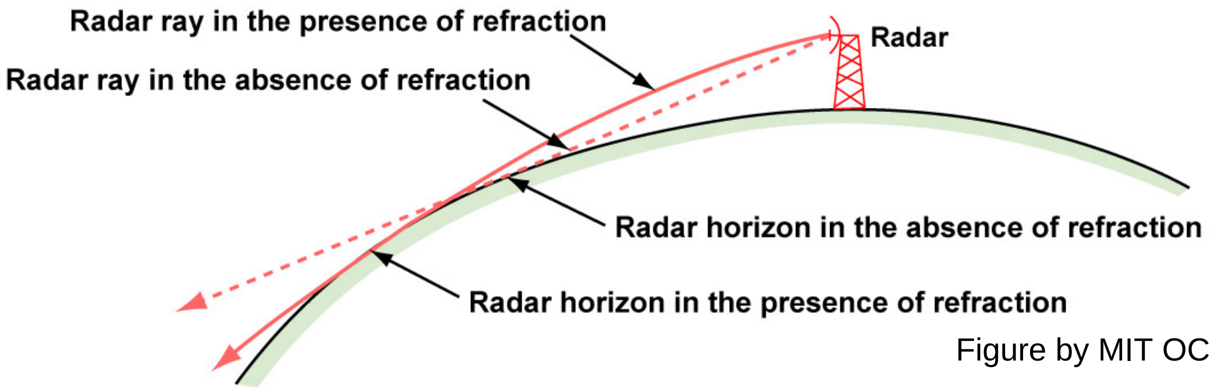


Figure by MIT OCW.

- The index of refraction, $\mathbf{n}$, and refractivity, $\mathbf{N}$, are measures of the velocity of propagation of electromagnetic waves

$$\mathbf{n} = \frac{\mathbf{v}_{\mathbf{Vacuum}}}{\mathbf{v}_{\mathbf{Air}}} \qquad \mathbf{N} = (\mathbf{n}-1)10^{+6} \qquad \mathbf{n} = 1.000335 \qquad \mathbf{N} = 335$$

- The index of refraction depends on a number of environmental quantities:

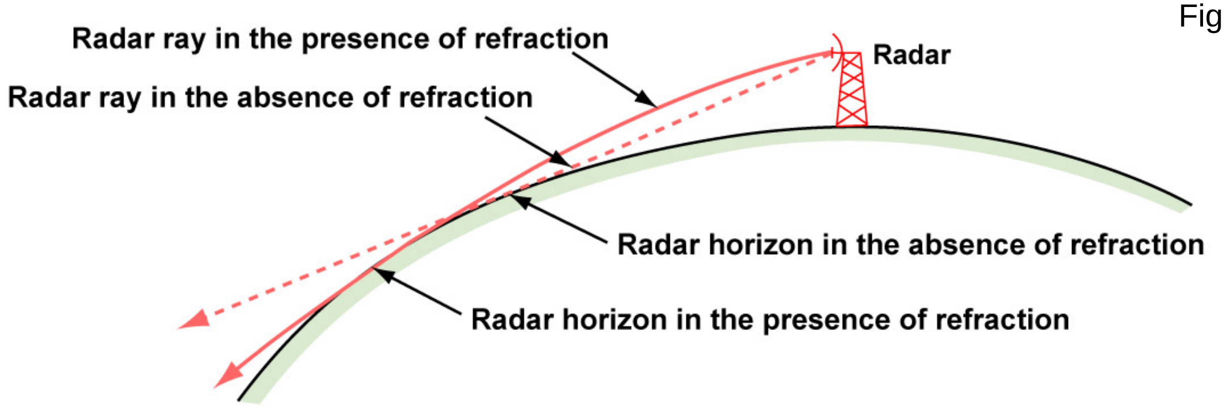
$$\mathbf{N} = \frac{77.6}{\mathbf{T}}\left[\mathbf{p} + \frac{4810\,\mathbf{e}}{\mathbf{T}}\right]$$

$\mathbf{p}$ = barometric pressure (mbar)
$\mathbf{e}$ = partial pressure of water in (mbar)
$\mathbf{T}$ = absolute temperature, (°K)
(1 mm Hg = 1.3332 mbar)

Adapted from Skolnik, Reference 1

Refraction of Radar Beams

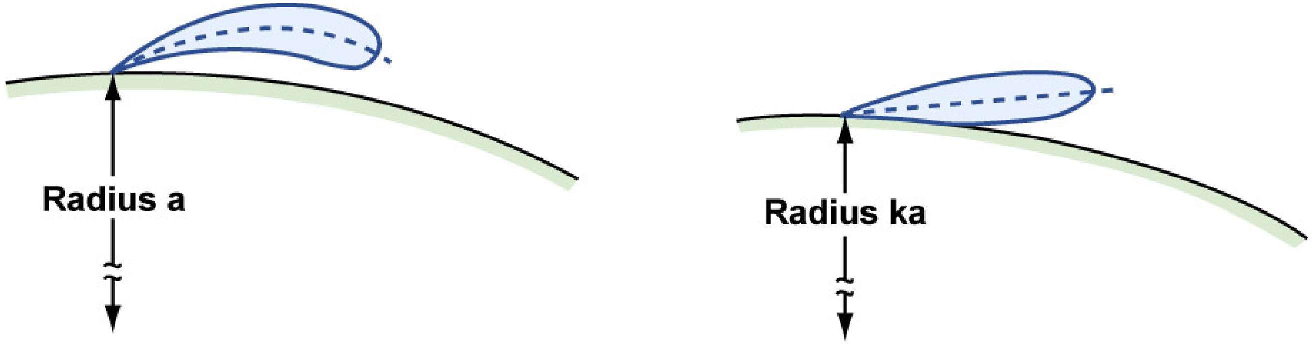
Figure by MIT OCW.



- **The index of refraction (refractivity) decreases with increasing altitude**
- **Velocity of propagation increases with altitude**
- **The decrease is usually well modeled by an exponential**
- **Radar beam to bends downward due to decreasing index of refraction**

Earth’s Radius Modified to Account for Refraction Effects

Figure by MIT OCW.



Antenna beam bent due to refraction by the Earth’s atmosphere

Shape of beam in equivalent Earth representation with radius ka

- **Atmospheric refraction can be accounted for by replacing the actual Earth radius a, in calculations, by an equivalent earth radius ka and assuming straight line propagation**
  - **A typical value for k is 4/3 (It varies from 0.5 to 6)**
  - **Average propagation is referred to as a “4/3 Earth”**

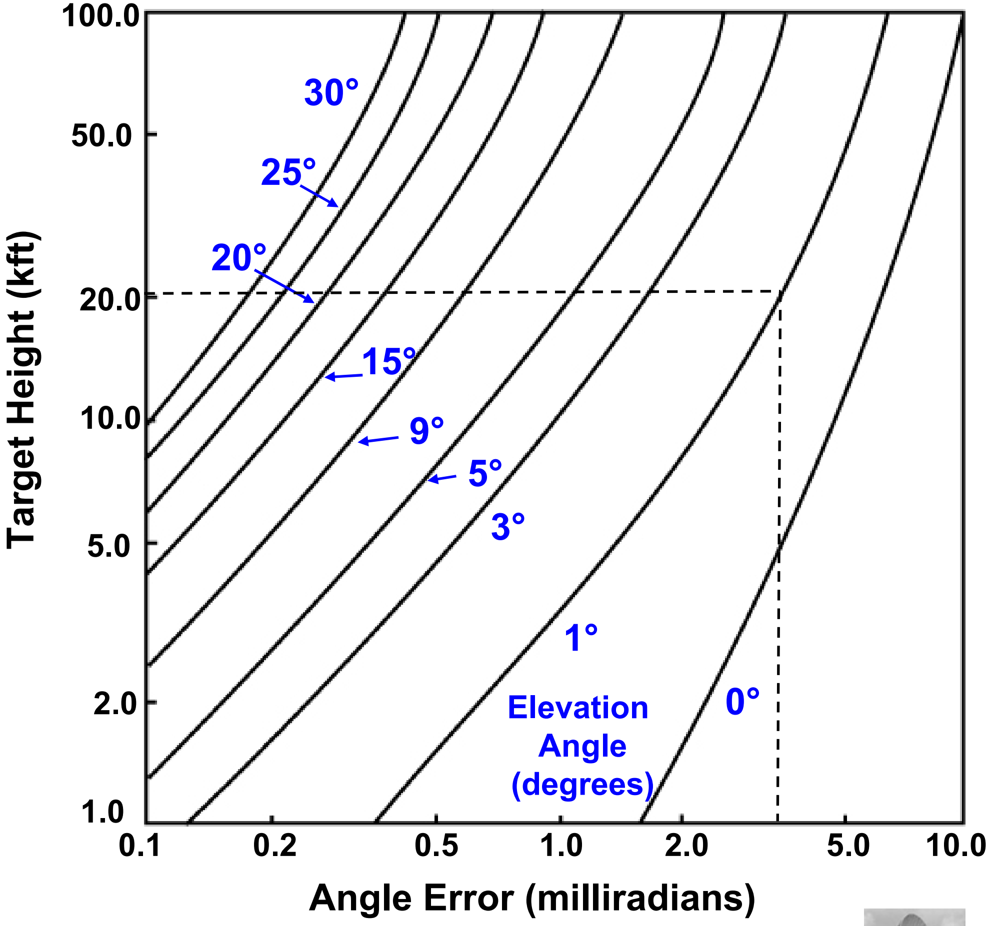
- **The distance, $\mathbf{d}$, to the horizon can be calculated using simple geometry as:**

$$d = \sqrt{2kah}$$

$\mathbf{h}$ **= height of radar above ground**

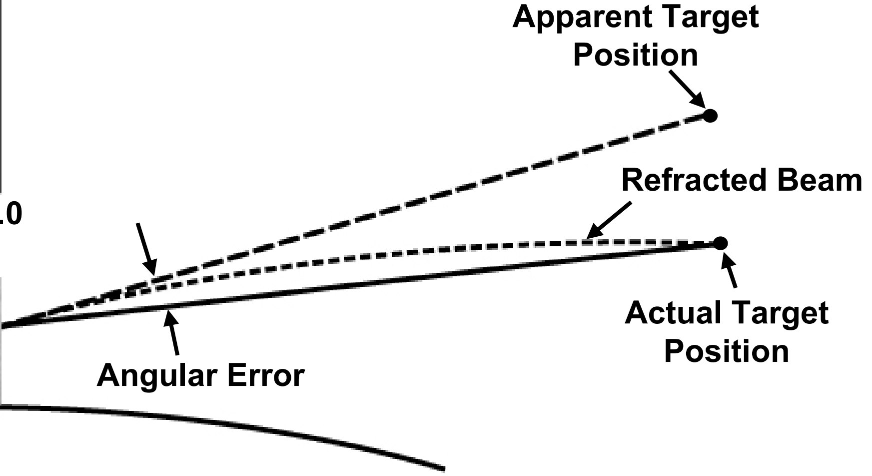
Assuming 4/3 earth: $d(\text{nmi}) = 1.23\sqrt{h(\text{ft})}$ $d(\text{km}) = 4.12\sqrt{h(\text{m})}$

Effects of Refraction of Radar Beam



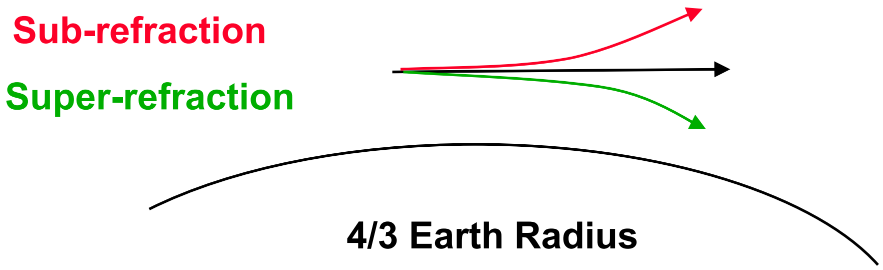
Refraction causes an error in radar angle measurement.

For a target at an altitude of 20,000 ft and an elevation angle of 1°, the angle error ~3.5 milliradians



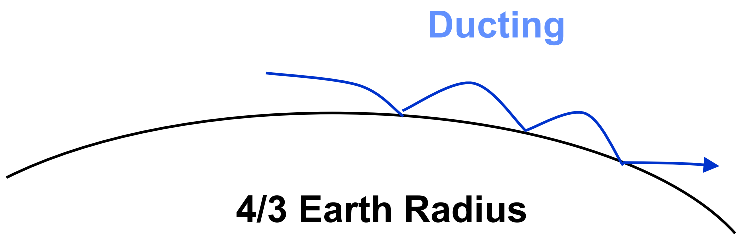
Adapted from Skolnik, Reference 1

Non-Standard Propagation


Sub-refraction

Super-refraction

4/3 Earth Radius


Ducting

4/3 Earth Radius

- Using Snell's law, it can be derived that $k = \dfrac{1}{1 + a\left(dn/dh\right)}$
- Non standard propagation occurs when k not equal to 4/3
- Refractivity gradient for different propagation

Condition	N units per km
– Sub-refraction	positive gradient
– No refraction	0
– Standard refraction	-39
– Normal refraction (4/3 earth radius)	0 to -79
– Super-refraction	-79 to -157
– Trapping (ducting)	-157 to $-\infty$

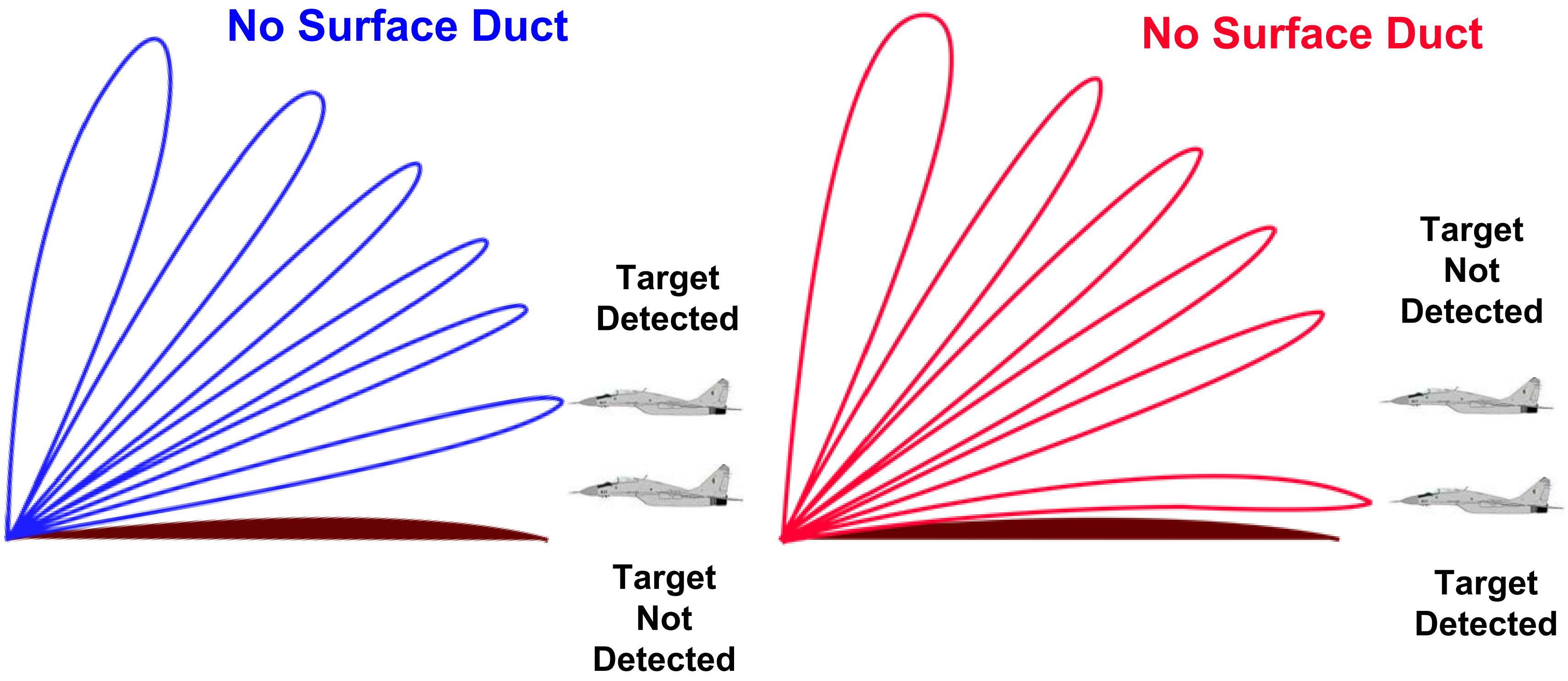
Anomalous Propagation

- Anomalous propagation occurs when effective earth radius is greater than 2. When dn/dh is greater than $-1.57 \times 10^{-7}\ \text{m}^{-1}$
- This non-standard propagation of electromagnetic waves is called anomalous propagation, superrefraction, trapping, or ducting.
  - Radar ranges with ducted propagation are greatly extended.
  - Extended ranges during ducting conditions means that ground clutter will be present at greater ranges
  - Holes in radar coverage can occur.

$$N = \frac{77.6}{T}\left[p + \frac{4810\,e}{T}\right]$$

- Often caused by temperature inversion
  - Temperature usually decreases with altitude
  - Under certain conditions, a warm air layer is on top of a cooler layer
  - Typical duct thickness ~few hundred meters

Effect of Ducting on Target Detection



No Surface Duct

Target
Detected

Target
Not
Detected

No Surface Duct

Target
Not
Detected

Target
Detected

- **Ducting :**
  - – Can cause gaps in elevation coverage of radar
  - – Can allow low altitude aircraft detection at greater ranges
  - – Increase the backscatter from the ground

Adapted from Skolnik, Reference 1

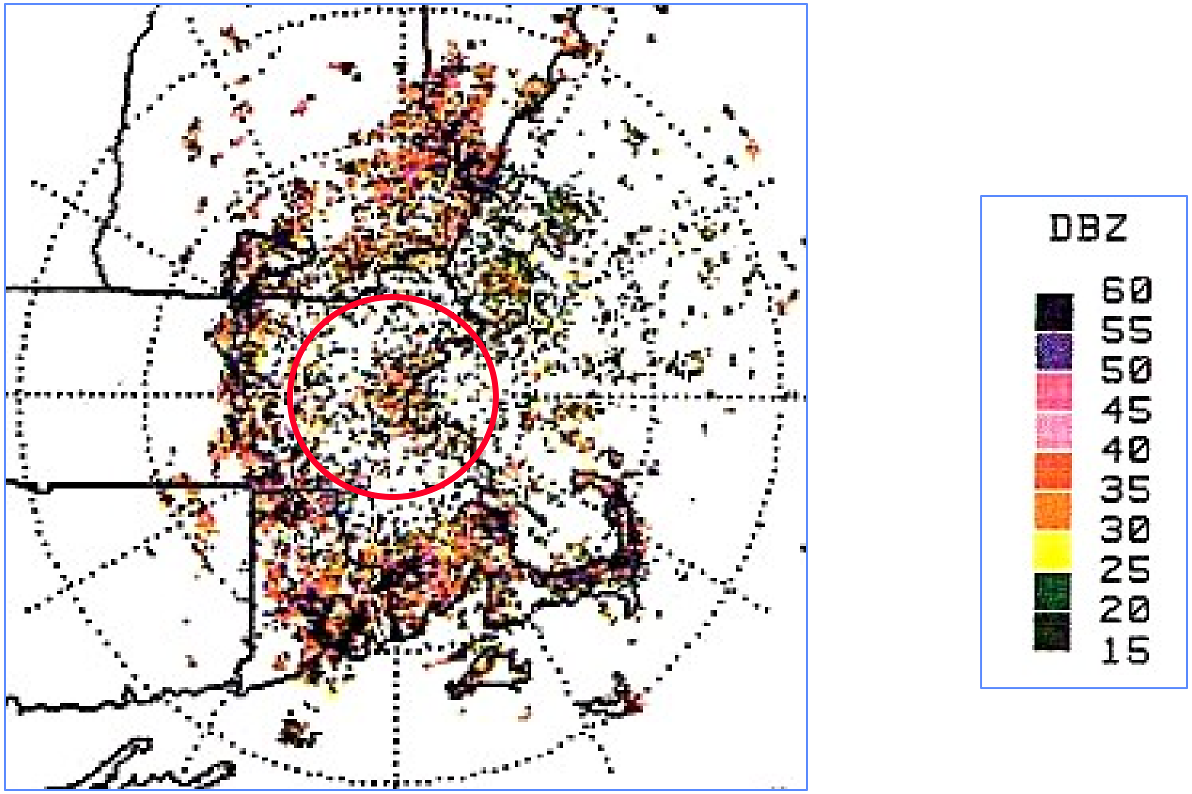
Anomalous Propagation

- Balloon borne radiosondes are often used to measure water vapor pressure, atmospheric pressure and temperature as a function of height above the ground to analyze anomalous propagation

- When ducting occurs, significant amounts of the radar's energy can become trapped in these "ducts"
  - These ducts may be near the surface or elevated
  - "Leaky" waveguide model for ducting phenomena gives good results
    - Low frequency cutoff for propagation

- Climactic conditions such as temperature inversions can cause ducting conditions to last for long periods in certain geographic areas.
  - Southern California coast near San Diego
  - The Persian Gulf

Ducted Clutter from New England


PPI Display

50 km range rings

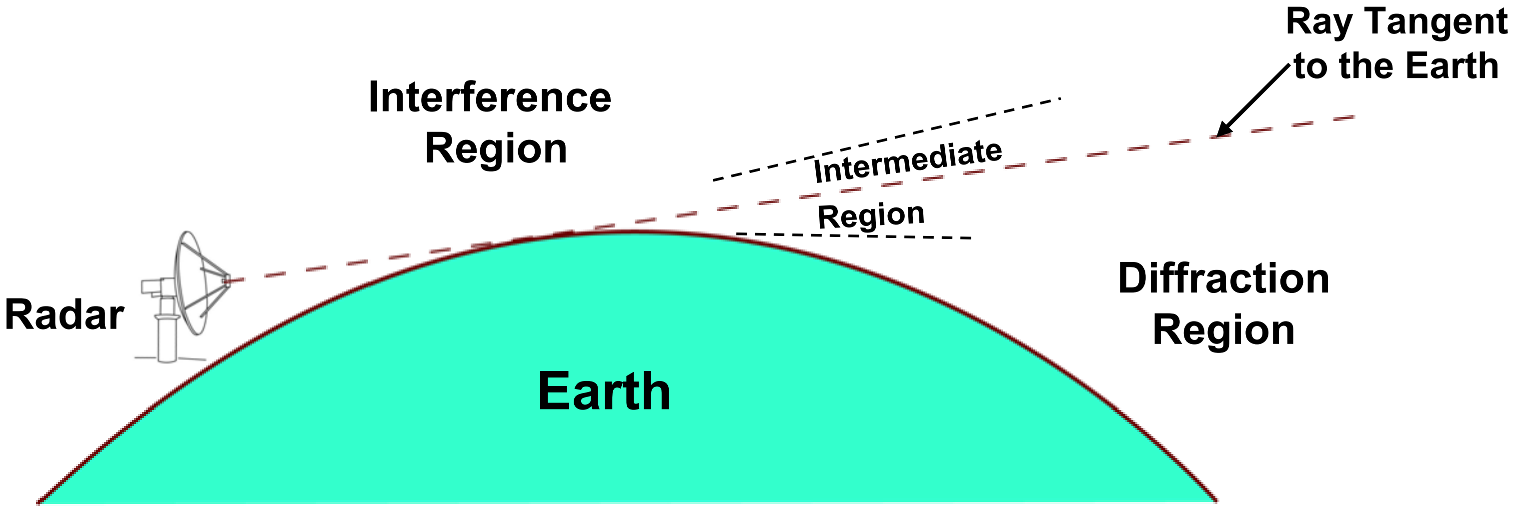
Courtesy of MIT Lincoln Laboratory
Used with Permission

Ducting conditions can extend horizon to extreme ranges

Outline

- Reflection from the Earth’s surface
- Atmospheric refraction
- ➡ Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Propagation Over Round Earth



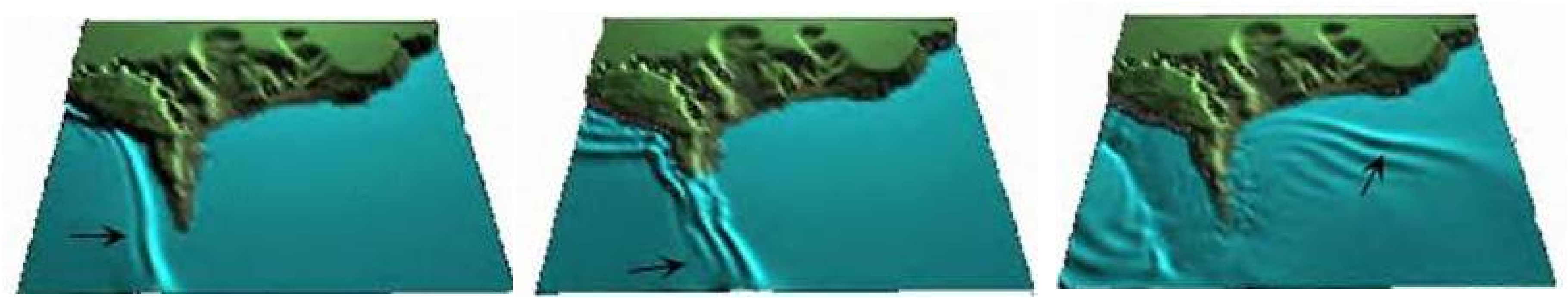
- **Interference region**
  - **Located within line of sight radar**
  - **Ray optics assumed**

- **Diffraction region**
  - **Below radar line of sight**
  - **Direct solution to Maxwell's Equations must be used**
  - **Signals are severely attenuated**

- **Intermediate region**
  - **Interpolation used**

Adapted from Blake, Reference 2

Diffraction



Tsunami Diffracting around Peninsula

Courtesy of NOAA / PMEL / Center for Tsunami Research.
See animation at http://nctr.pmel.noaa.gov/animations/Aonae.all.mpg

- **Radar waves are diffracted around the curved Earth just as light is diffracted by a straight edge and ocean waves are bent by an obstacle (peninsula)**

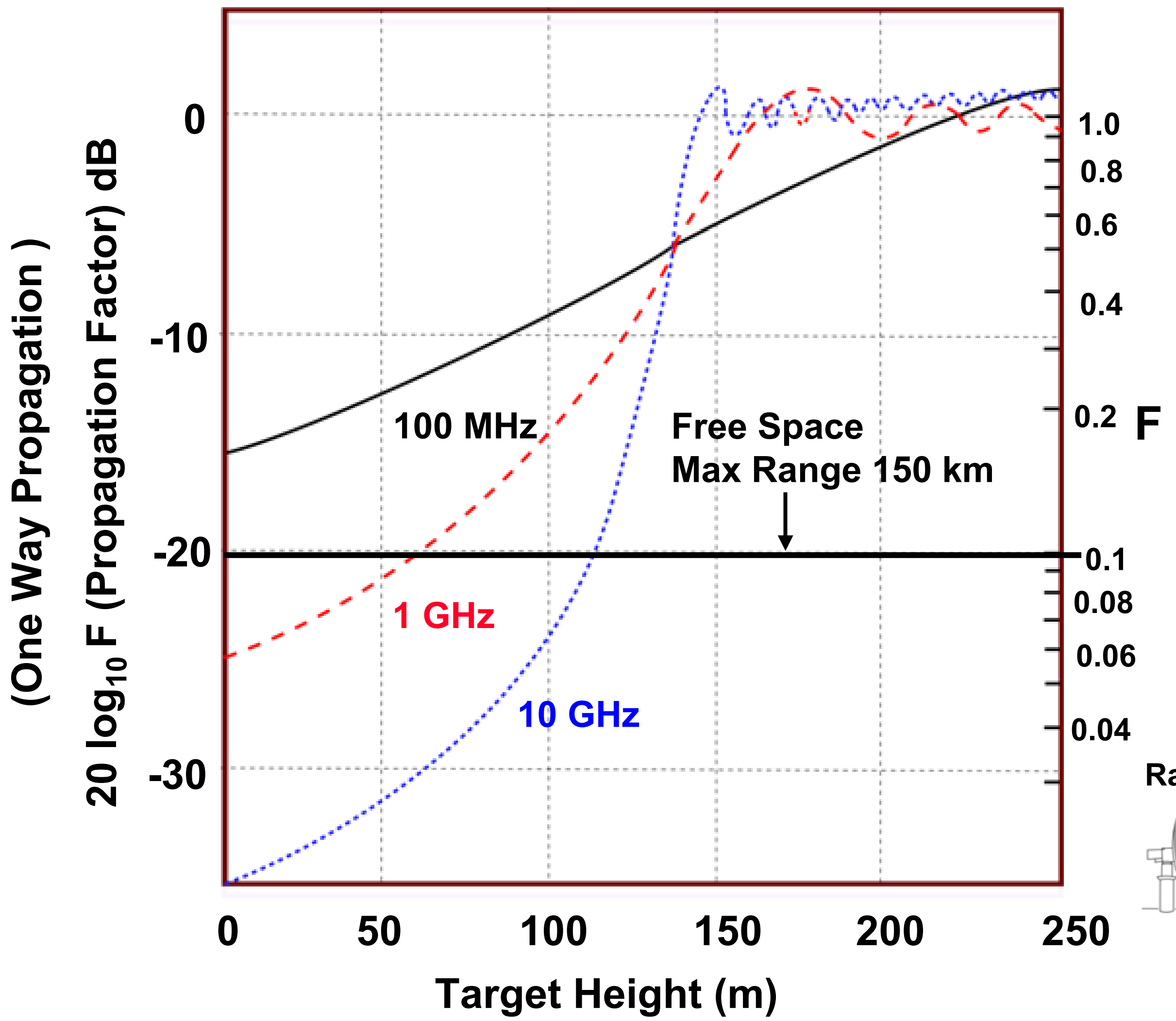
- **Web reference for excellent water wave photographic example:**
  - **http://upload.wikimedia.org/wikipedia/commons/b/b5/Water_diffraction.jpg**

- **The ability of radar to propagate beyond the horizon depends upon frequency (the lower the better) and radar height**

- **For over the horizon detection, significant radar power is necessary to overcome the loss caused by diffraction**

Knife Edge Diffraction Model

Propagation Factor vs. Target Height

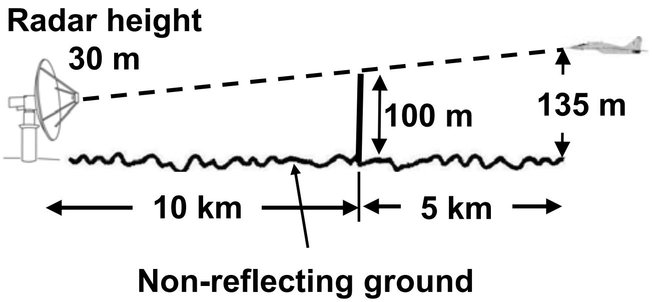


Adapted from Meeks, Reference 6

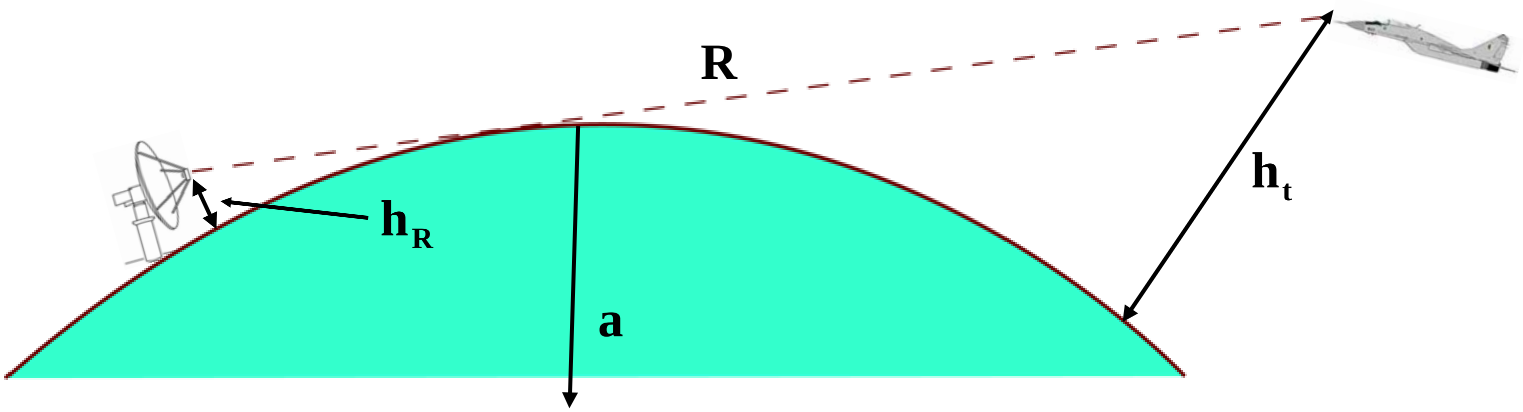
F = Propagation factor

Radar height = 30 m
Target height = 135 m
Obstacle height = 100 m

Over the horizon propagation is enhanced at lower frequencies



Target Detection Near the Horizon

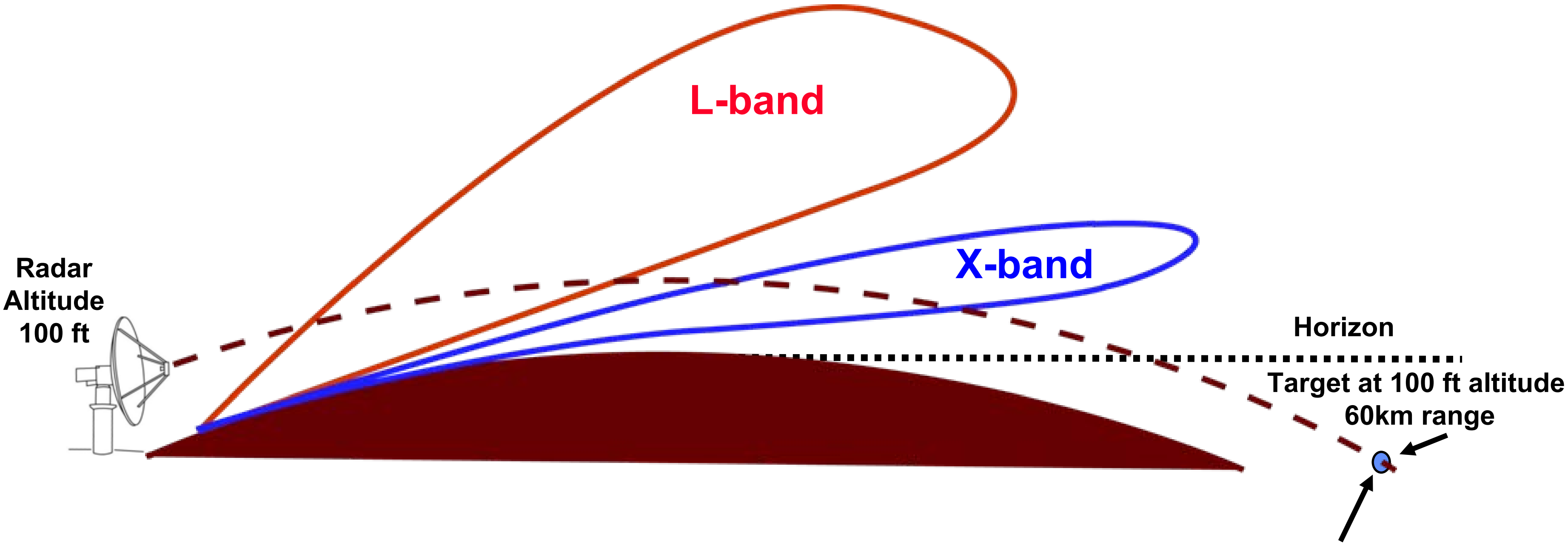


$$R \cong \sqrt{2kah_R} + \sqrt{2kah_t}$$

a = radius of the Earth
k = 4/3 for normal atmosphere

- The expression relates, for a ray grazing the earth at the horizon, (radar beam tangential to earth): the maximum range that a radar at height, h_R, may detect a target at height, h_t
- For targets below the horizon, there are always a target detection loss, due to diffraction effects, that may vary from 10 to > 30 dB, resulting in a signal to noise ratio below that of the free space value.

Frequency Dependence of Combined Diffraction and Multipath Effects



Loss

80 dB at X-Band

60 dB at L-Band

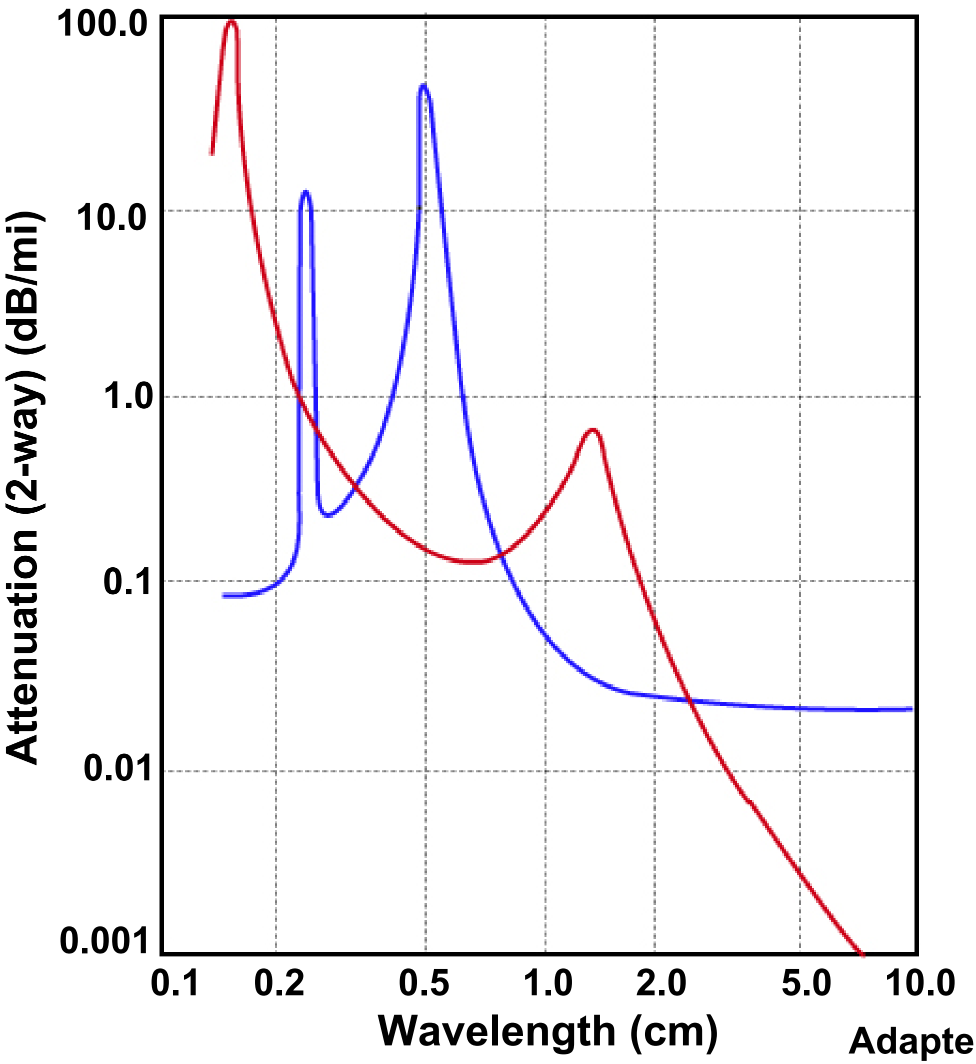
- Multipath effects result in good detection of low altitude targets at higher frequencies

- Diffraction Effects
  - Favors lower frequencies
  - Difficult at any frequency

Outline

- Reflection from the Earth’s surface
- Atmospheric refraction
- Over-the-horizon diffraction
- ➡ Atmospheric attenuation
- Ionospheric propagation

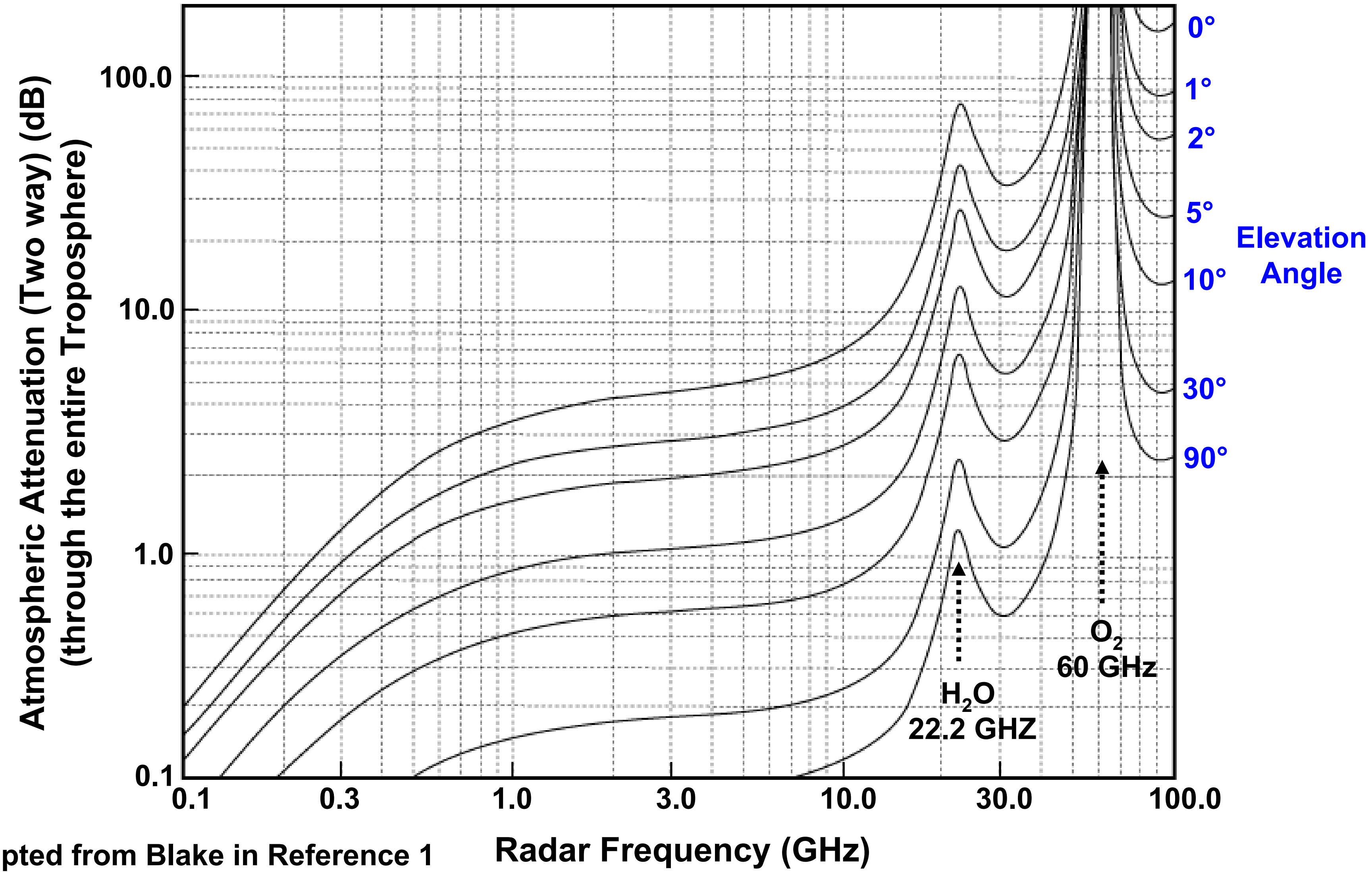
Theoretical Values of Atmospheric Attenuation Due to H_2O and O_2



- The attenuation associated with the H_2O and O_2 resonances dominate the attenuation at short wavelengths
  - Attenuation is negligible at long wavelengths
  - It is significant in the microwave band
  - It imposes severe limits at millimeter wave bands
- At wavelengths at or below 3 cm (X-Band), clear air attenuation is a major issue in radar analysis
- At millimeter wavelengths and above, radars operate in atmospheric "windows".

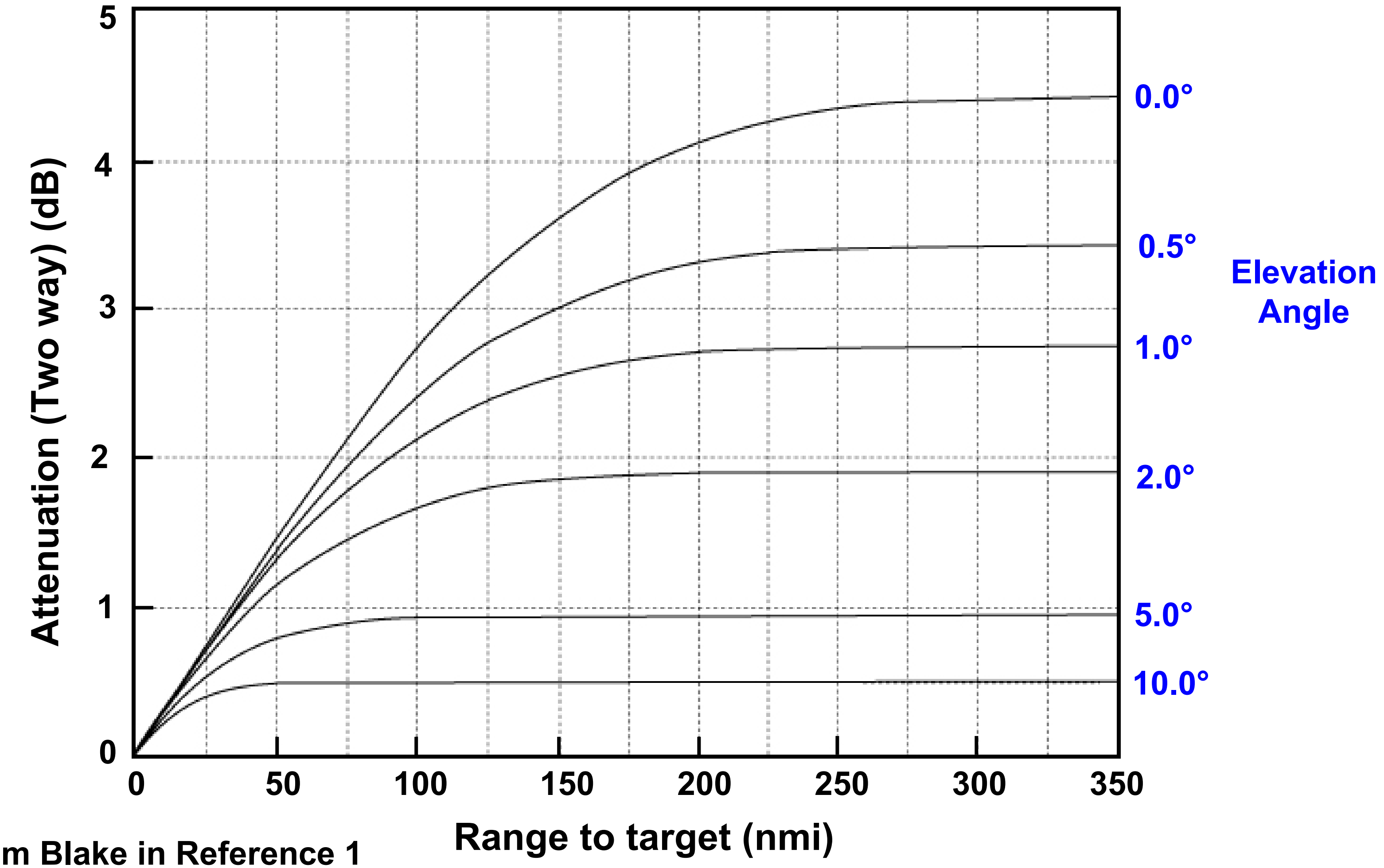
Adapted from Skolnik, Reference 1

Atmospheric Attenuation in the Troposphere



Adapted from Blake in Reference 1

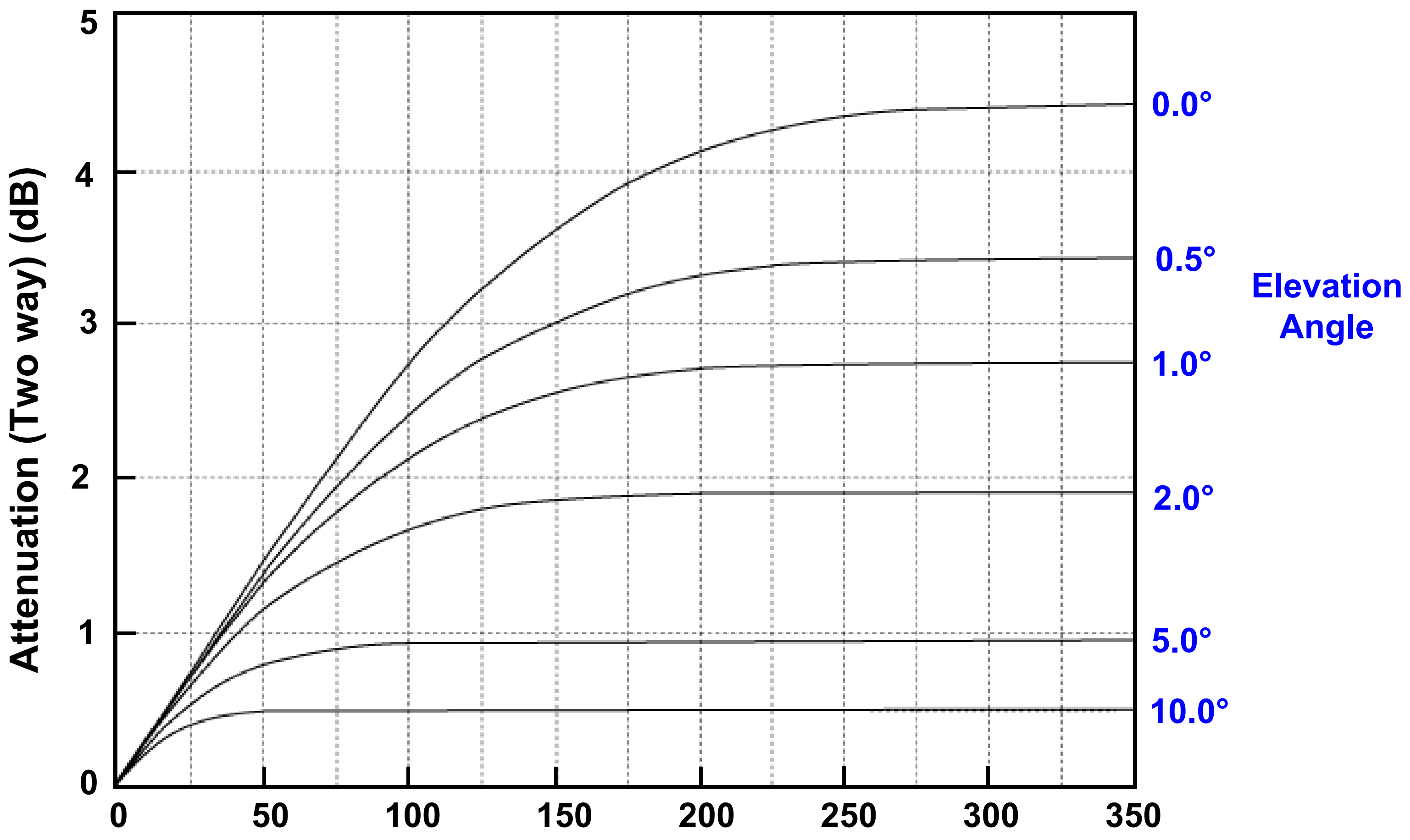
Atmospheric Attenuation at 3 GHz



Adapted from Blake in Reference 1

- **Attenuation becomes constant after beam passes through troposphere**

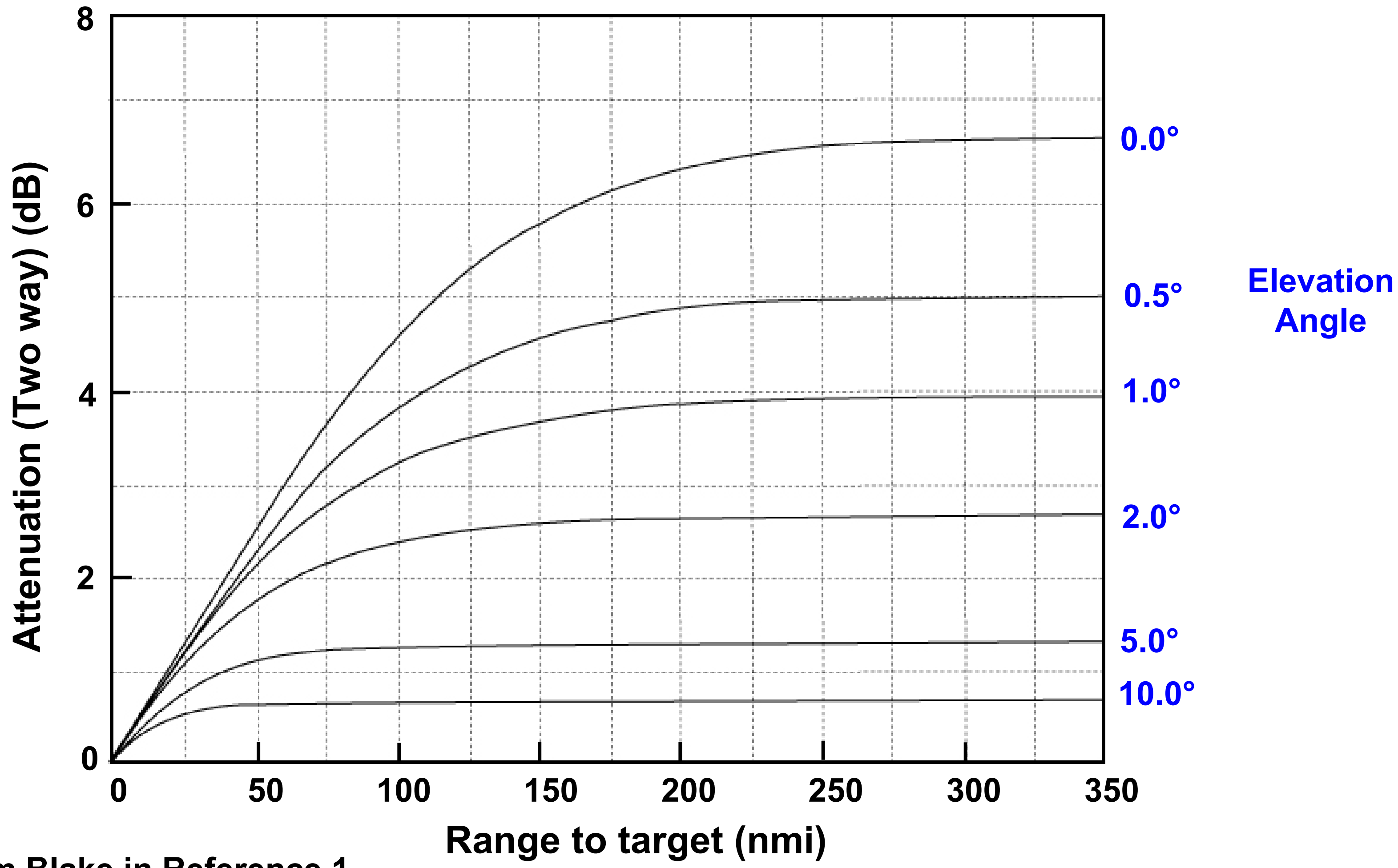
Atmospheric Attenuation at 3 GHz



Adapted from Blake in Reference 1

- Attenuation 4.4 dB at 0° elevation vs. 1.0 dB at 5°

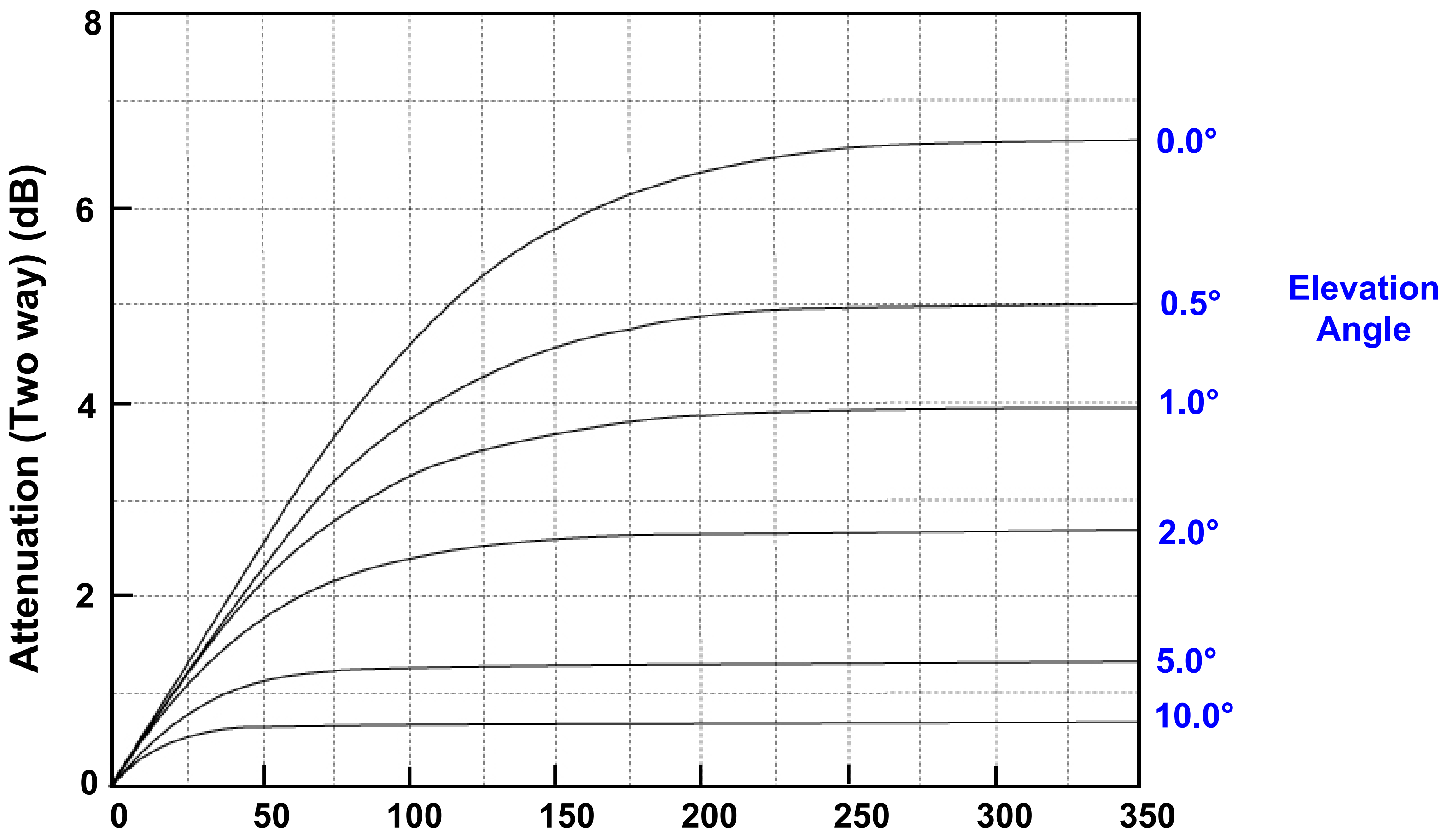
Atmospheric Attenuation at 10 GHz



Adapted from Blake in Reference 1

- **Attenuation: 6.6 dB at 10 GHz vs. 4.4 dB at 3 GHz**

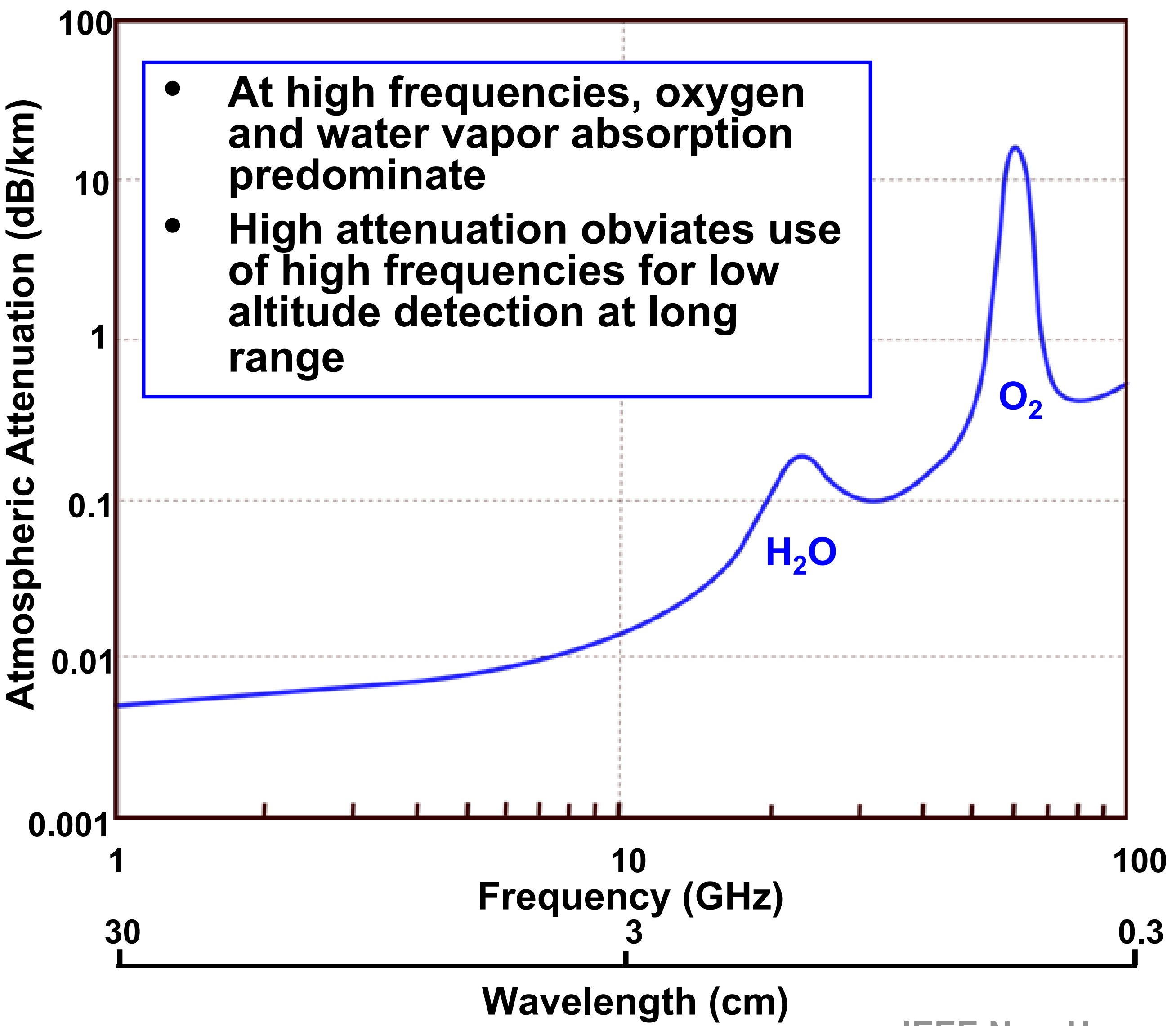
Atmospheric Attenuation at 10 GHz



Adapted from Blake in Reference 1

- **For targets in the atmosphere, radar equation calculations require a iterative approach to determine correct value of the atmospheric attenuation loss**

Atmospheric Attenuation at Sea Level



- At high frequencies, oxygen and water vapor absorption predominate
- High attenuation obviates use of high frequencies for low altitude detection at long range

Attenuation Due to Rain and Fog

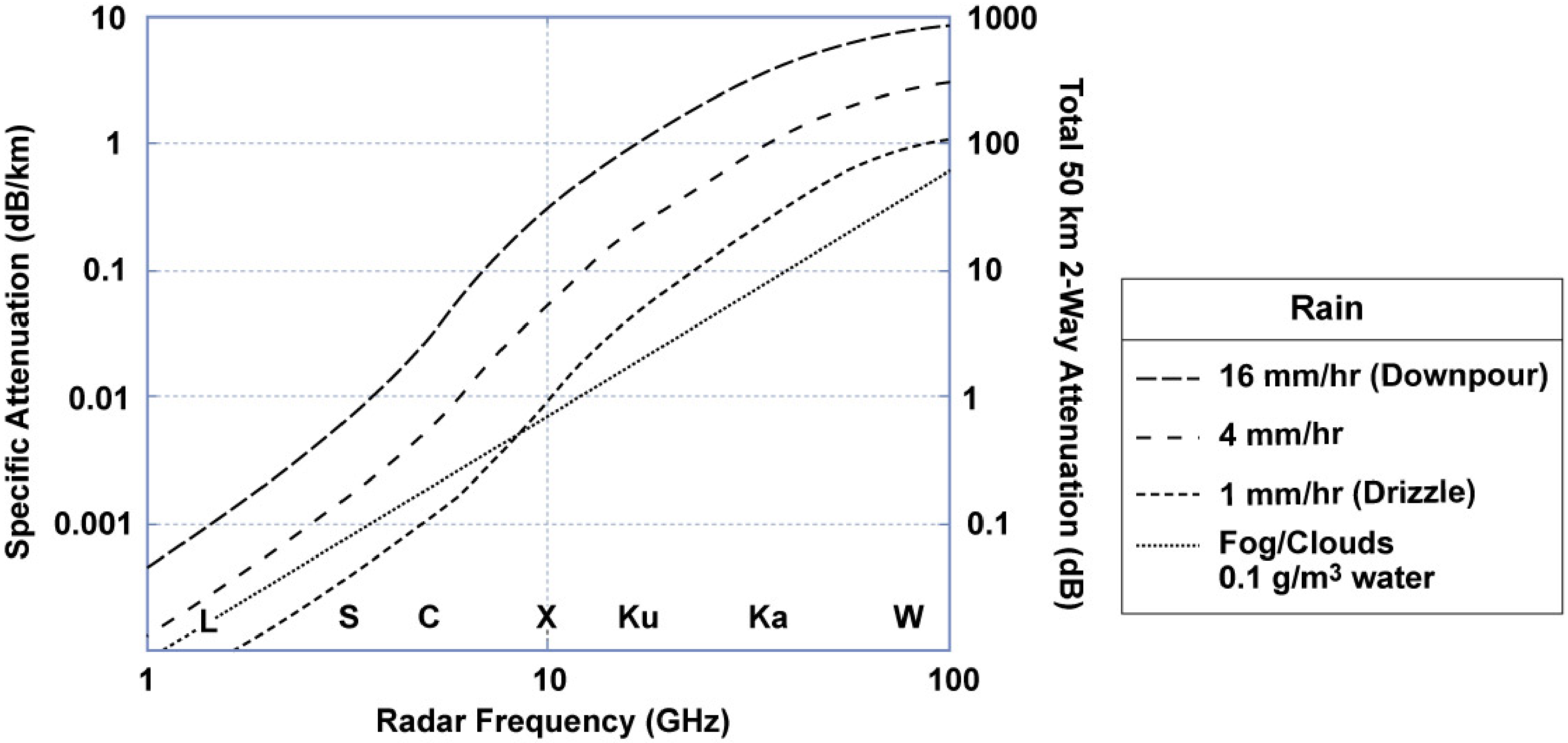
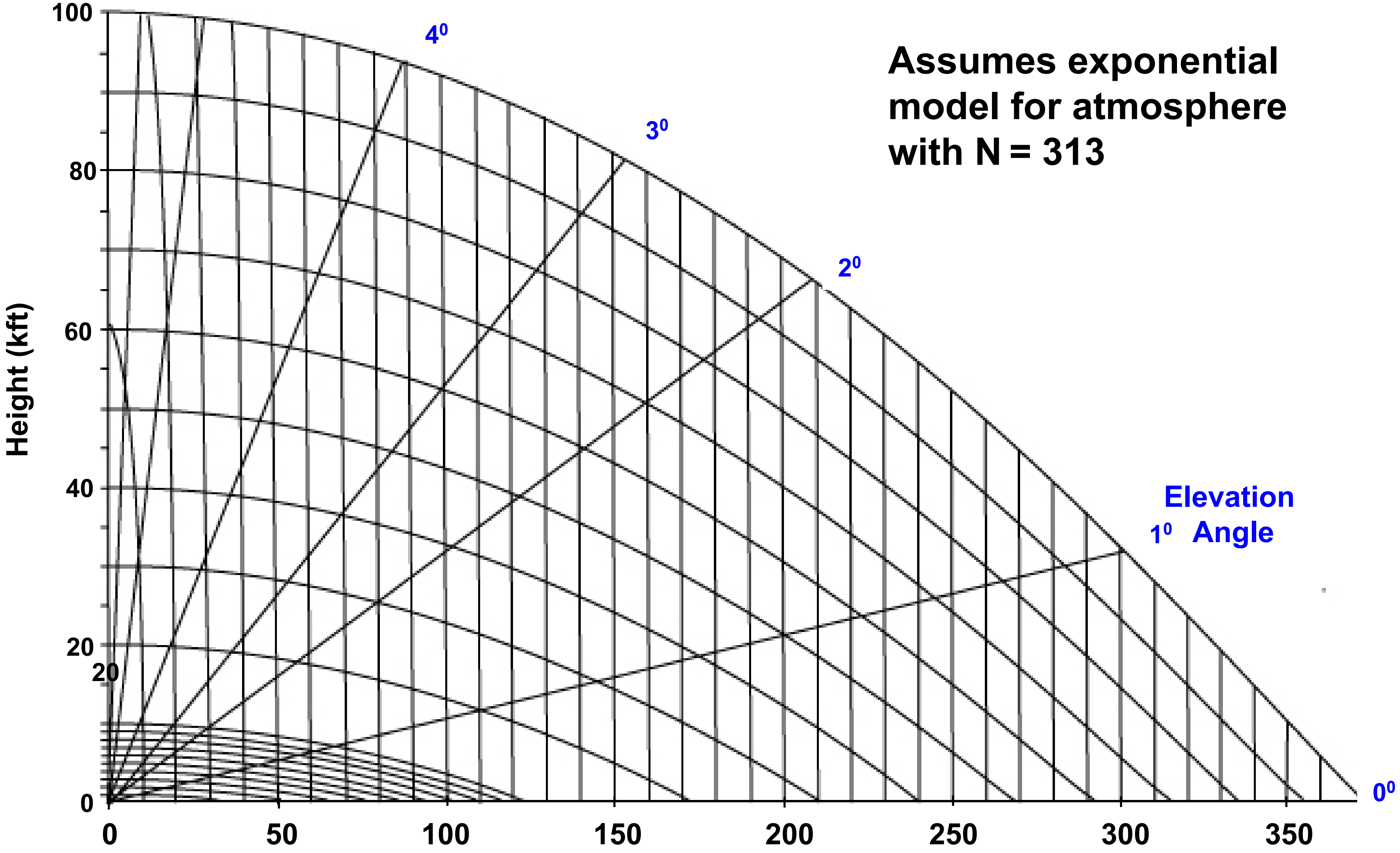


Figure by MIT OCW.

Radar performance at high frequencies is highly weather dependent

Radar Range - Height - Angle Chart
(Normal Atmosphere)



Assumes exponential model for atmosphere with N = 313

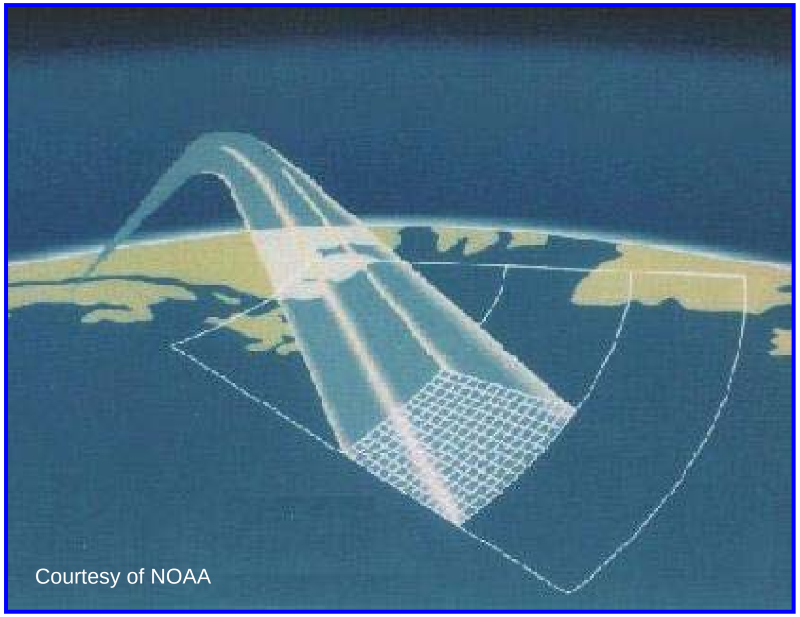
Adapted from Blake in Reference 4

Outline

- Reflection from the Earth’s surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- ➡ Ionospheric propagation

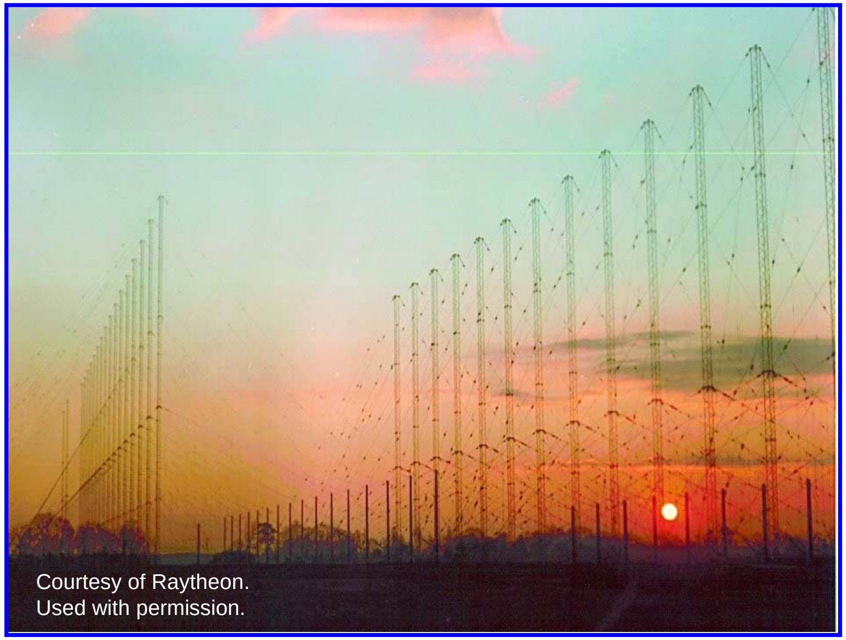
Over-the-Horizon Radars

OTH Radar Beam Paths



Courtesy of NOAA

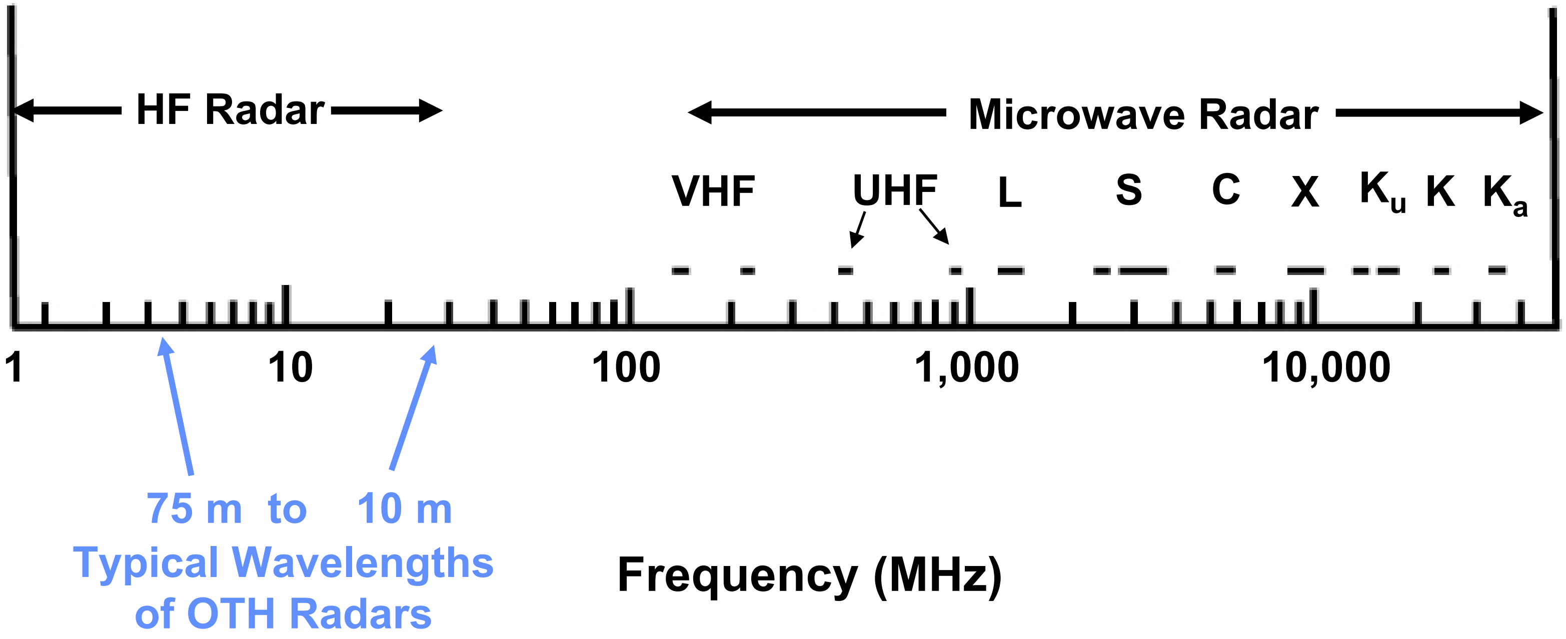
Example Relocatable OTH Radar (ROTHR) Transmit Array



Courtesy of Raytheon.
Used with permission.

- **Typically operate at 10 – 80 m wavelengths (3.5 – 30 MHz)**
- **OTH Radars can detect aircraft and ships at very long ranges (~ 2000 miles)**

Frequency Spectrum (HF and Microwave Bands)

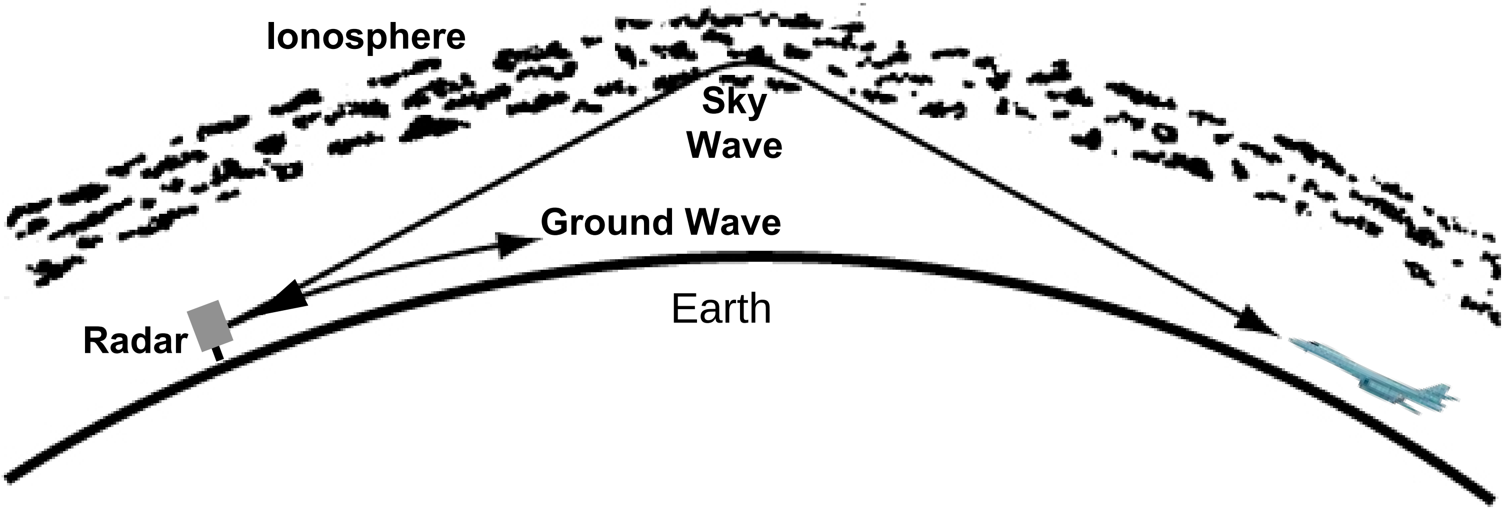


75 m to 10 m
Typical Wavelengths
of OTH Radars

Electromagnetic Propagation at High Frequencies (HF) is very different than at Microwave Frequencies

Adapted from Headrick and Skolnik in Reference 7

Ionospheric Propagation (How it Works- What are the Issues)



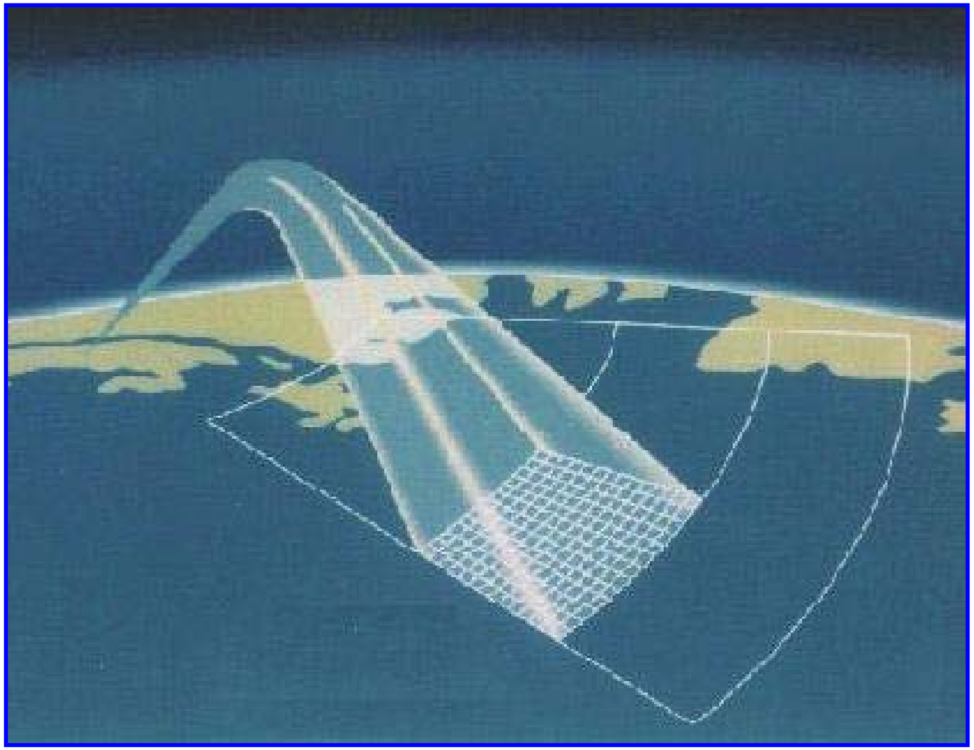
- **Sky wave OTH radars:**
  - Refract (bend) the radar beam in the ionosphere,
  - Reflecting back to earth,
  - Scattering it off the target, and finally,
  - Reflect the target echo back to the radar

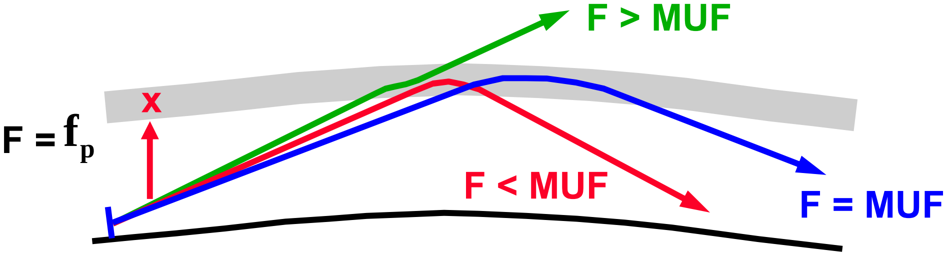
- **The performance of OTH radars vitally depends on the physical characteristics of the ionosphere, its stability and its predictability**

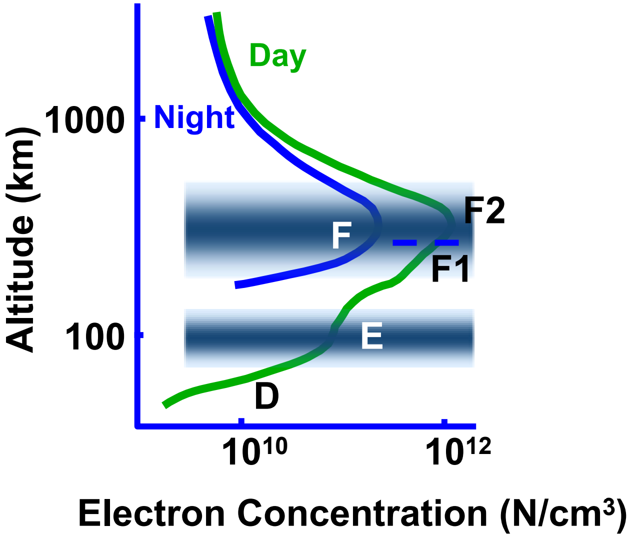
Adapted from Headrick and Skolnik in Reference 7

Physics of OTH Radar Propagation

Over the Horizon Propagation Enabled by Ionospheric Refraction







Plasma Frequency $f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_0}}$

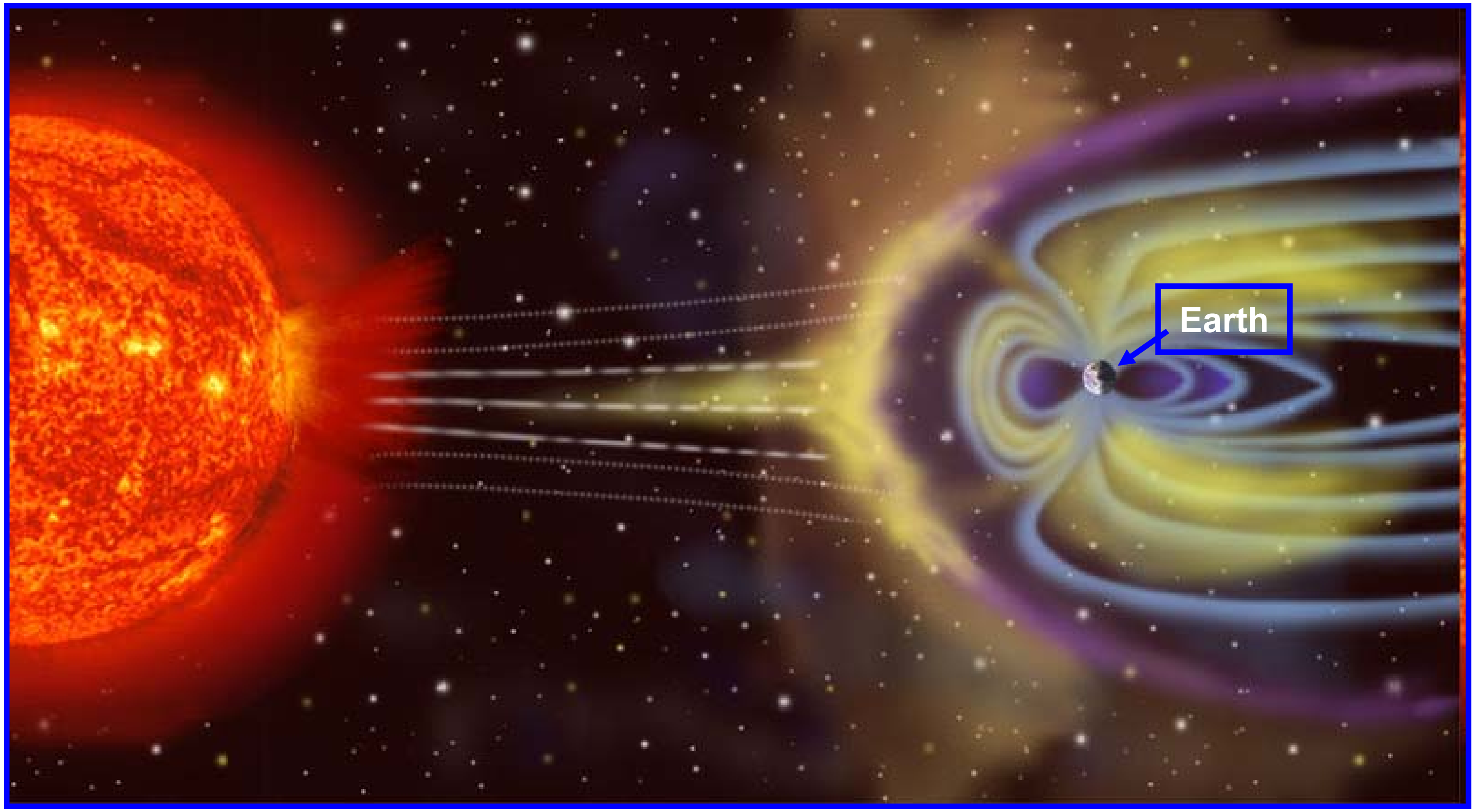
Maximum Usable Frequency (MUF)
Key for oblique incidence

$$\mathrm{MUF} = f_p \,\mathrm{secant}\left(\theta_{inc}\right)$$

MUF = Maximum Usable Frequenc

Regular Variation in the Ionosphere

- **Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere**



Courtesy of NASA

Different Layers of the Ionosphere

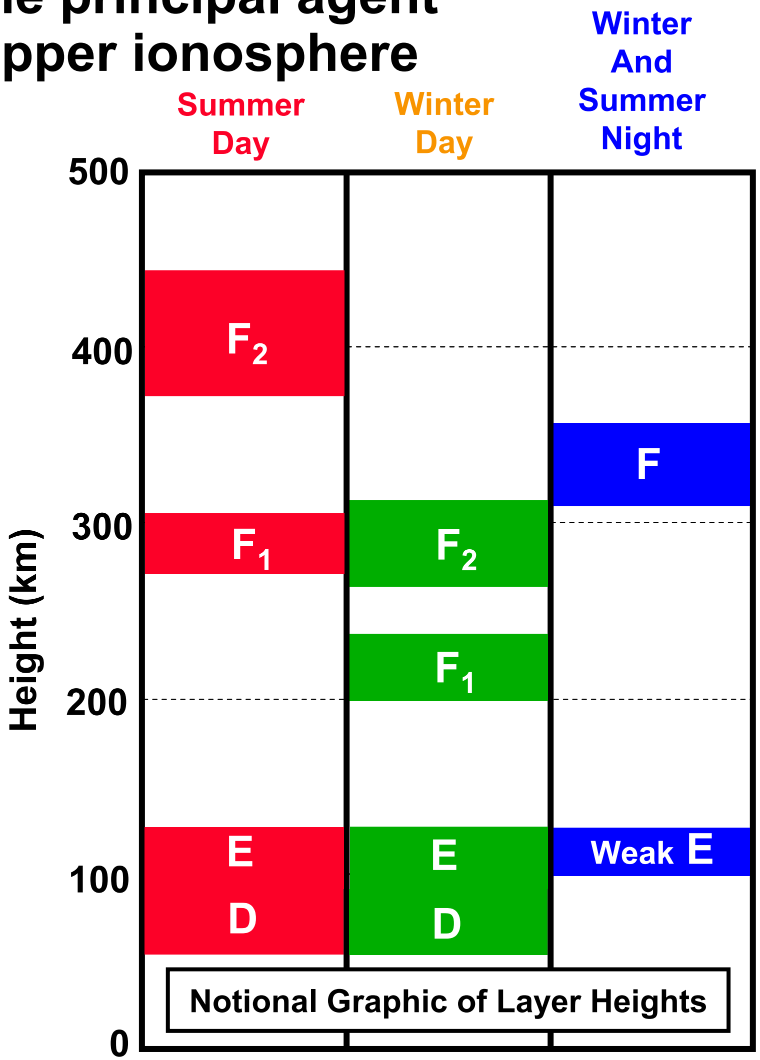
- Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere
- D layer (~50 to 90 km altitude
  - Responsible for major signal attenuation during the day

    Absorption proportional to $1/f^2$

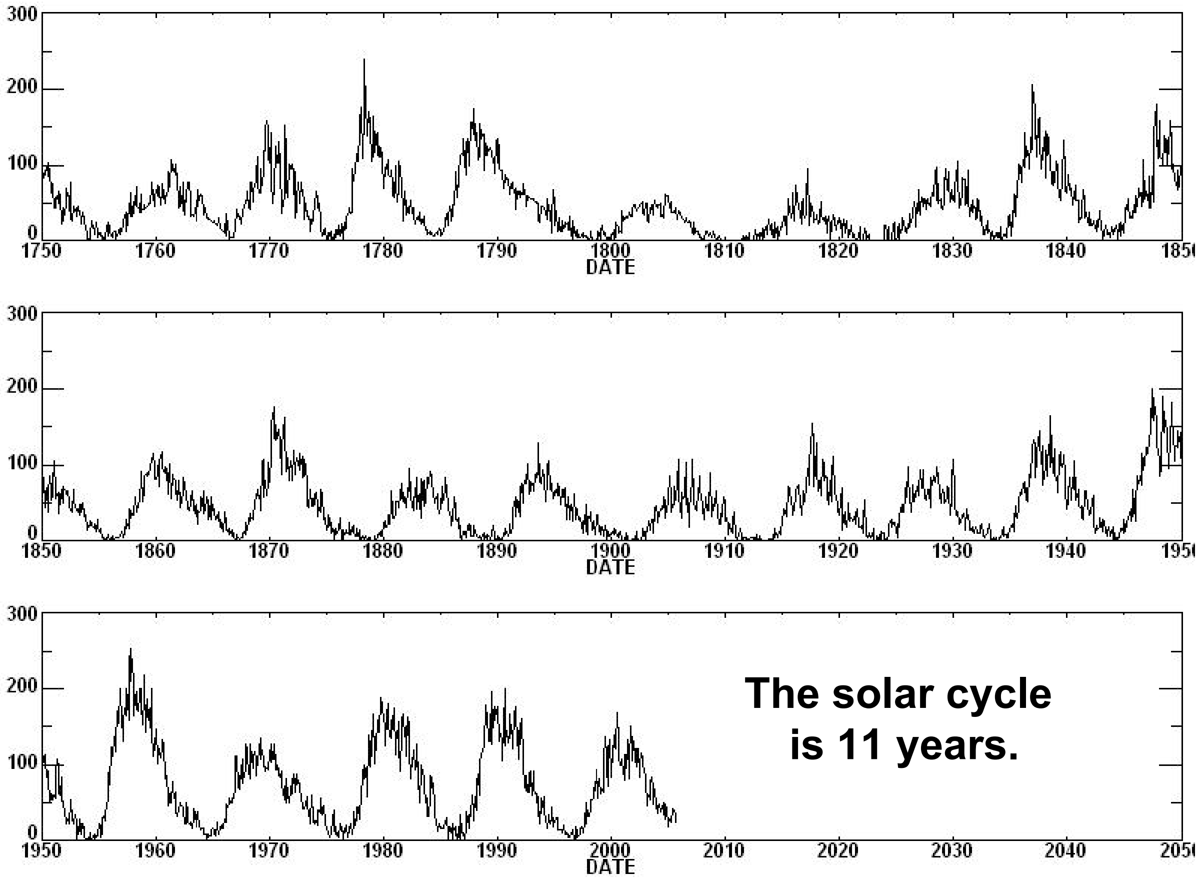
    Lower frequencies attenuated heavily
  - D layer disappears at night
- E layer (~90 to 130 km altitude)
  - Low altitude of layer=> short range
  - Sporadic-E layer – few km thick
- F layer (~200 to 500 km altitude
  - Most important layer for HF sky wave propagation
  - During daylight, F region splits into 2 layers, the F_1 and F_2 layers

    The F_1 and F_2 layers combine at night

    F_2 layer is in a continual state of flux



Average Sun Spot Number (1750 – present)

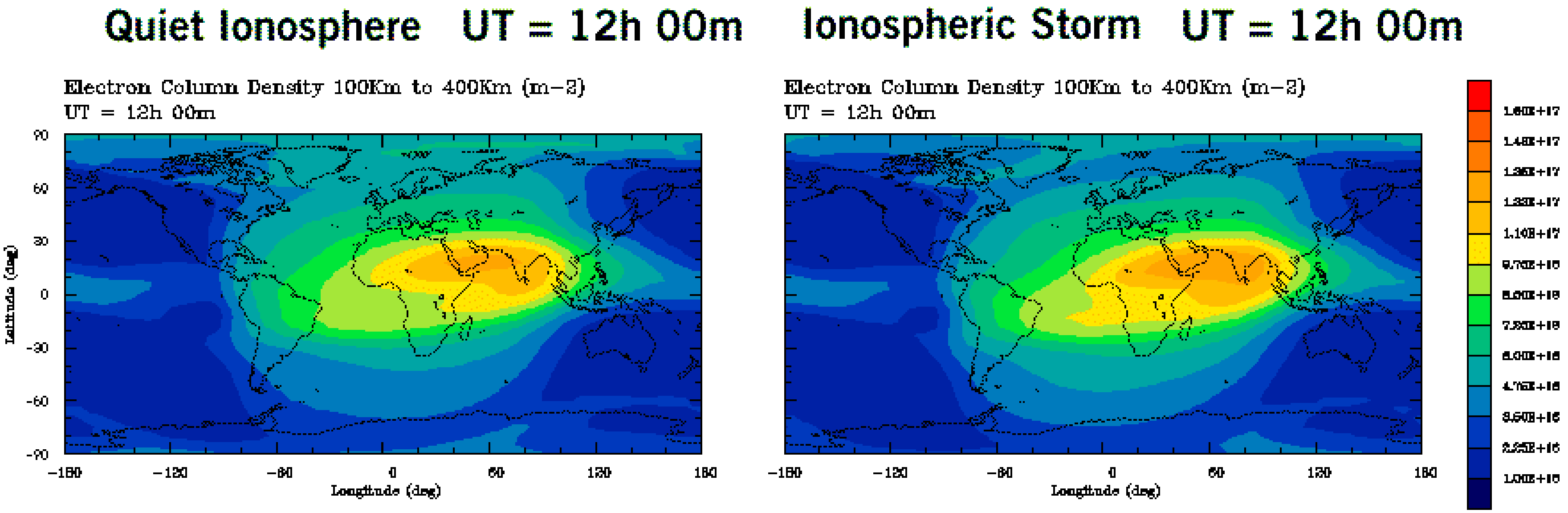


The solar cycle is 11 years.

Courtesy of NASA

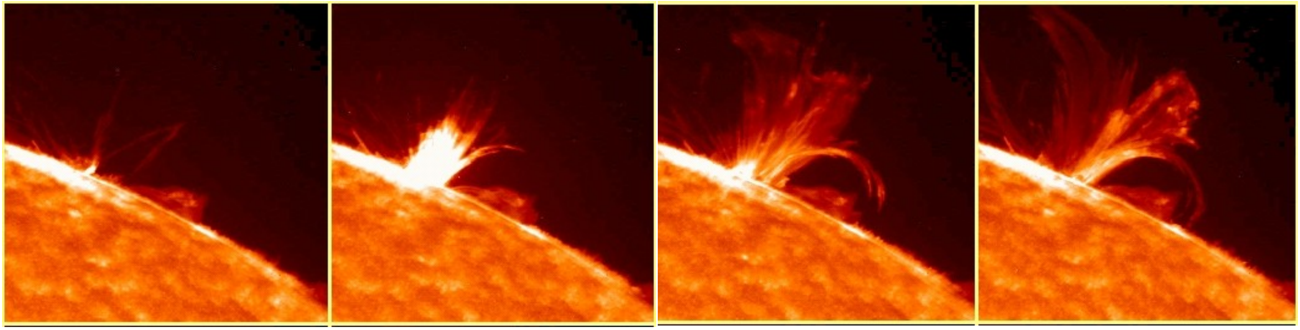
- Within each week, of each month, of each year there is significant variation in the Sun Spot number (solar flux), and thus, the electron density in the ionosphere

Variability of Ionospheric Electron Density



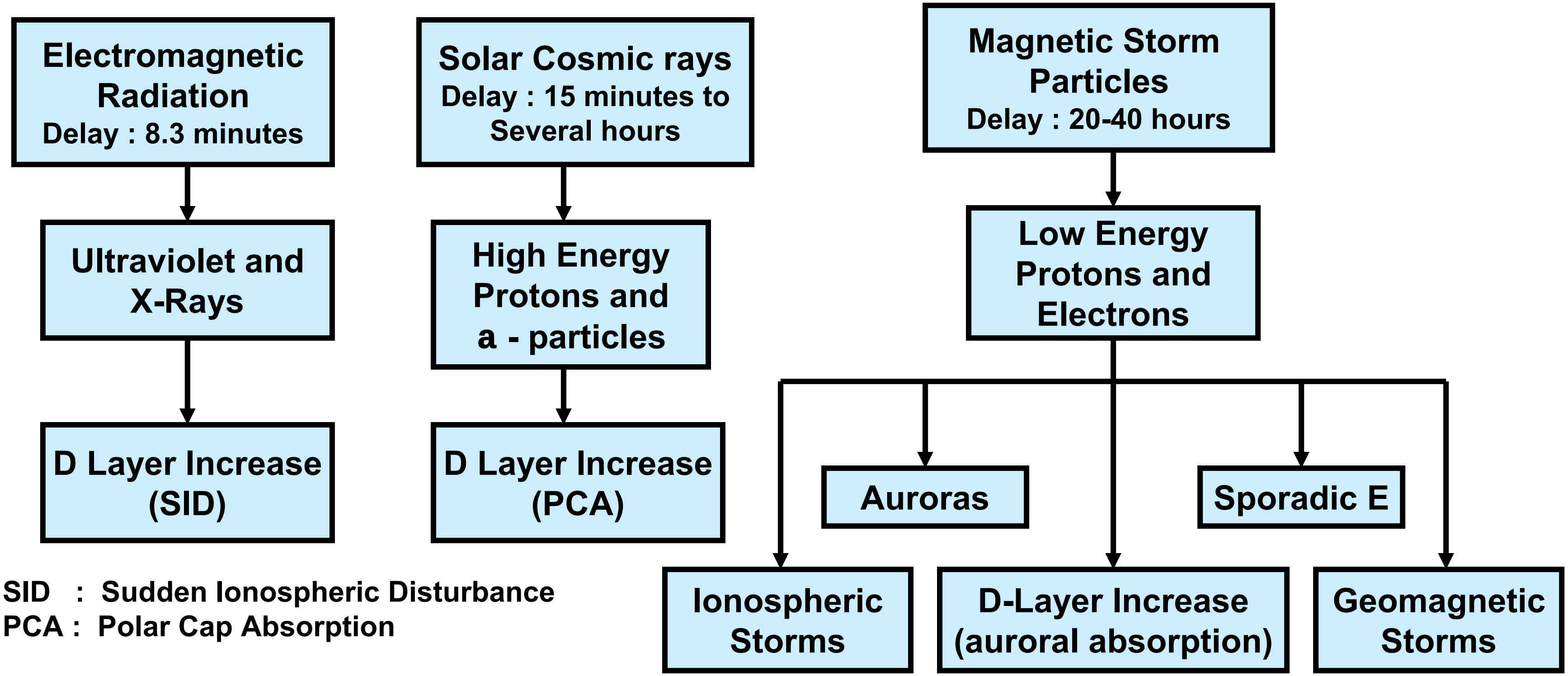
"Courtesy of Windows to the Universe, http://www.windows.ucar.edu"

Flare Emissions and Ionospheric Effects



May 19, 1998

Courtesy of NASA



Electromagnetic Radiation
Delay : 8.3 minutes

Ultraviolet and X-Rays

D Layer Increase (SID)

Solar Cosmic rays
Delay : 15 minutes to Several hours

High Energy Protons and a - particles

D Layer Increase (PCA)

Magnetic Storm Particles
Delay : 20-40 hours

Low Energy Protons and Electrons

Ionospheric Storms

Auroras

D-Layer Increase (auroral absorption)

Sporadic E

Geomagnetic Storms

SID : Sudden Ionospheric Disturbance
PCA : Polar Cap Absorption

Propagation Issues for OTH Radars

- OTH radar detection performance is dependent on many variables and is difficult to predict because of the variability and difficulty, of reliably predicting the characteristics of the ionosphere
  - Diurnal variations
  - Seasonal variations
  - Sun Spot cycle
  - Solar flares, coronal mass ejections, etc. from the sun

- Because OTH radars can detect targets at great ranges they have very large antennas and very high power transmitters

Summary

- The atmosphere can have a significant effect on radar performance
  - Attenuation and diffraction of radar beam
  - Refracting of the beam as it passes through the atmosphere
    - Causes angle measurement errors
  - Radar signal strength can vary significantly due to multipath effects
    - Reflections from the ground interfering with the main radar beam
  - Frequencies from 3 to 30 MHz can be used to propagate radar signals over the horizon
    - Via refraction by the ionosphere
  - The above effects vary with the wavelength of the radar, geographic and varying atmospheric conditions

References

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2. Skolnik, M., *Radar Handbook*, New York, NY, McGraw-Hill, 2rd Edition, 1990
3. Skolnik, M., *Radar Handbook*, New York, NY, McGraw-Hill, 3rd Edition, 2008
4. Blake, L. V. *Radar Range-Performance Analysis*, Munro, Silver Springs, MD,1991
5. Bougust, Jr., A. J., *Radar and the Atmosphere*, Artech House, Inc., Norwood, MA,1989
6. Meeks, M. L. ,*Radar Propagation at Low Altitudes*, Artech House, Inc., Norwood, MA,1982.
7. Headrick, J. M. and Skolnik, M. I., "Over-the-Horizon Radar in the HF Band", IEEE Proceedings, Vol. 62, No. 6, June 1974, pp 664-673

Homework Problems

- From Reference 1, Skolnik, M., Introduction to Radar Systems, 3rd Edition, 2001
  - Problem 8-1
  - Problem 8.8
  - Problem 8-11

Acknowledgements

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