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Microwave Path Engineering

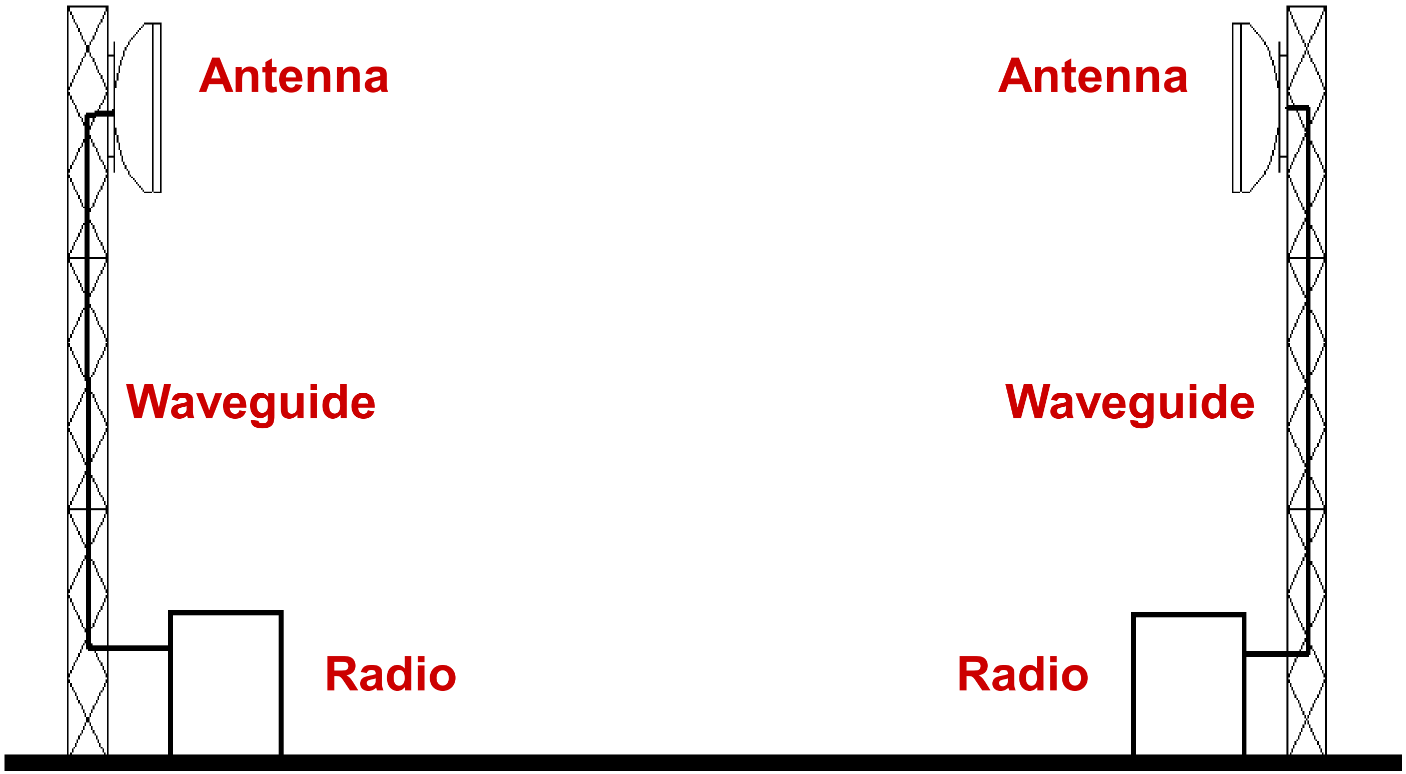
USTTI Course 19-311

September 24, 2019

Course Outline

1. **Microwave Components**
2. **RF Propagation**
3. **Link Budget**
4. **Reliability**
5. **Interference Analysis**

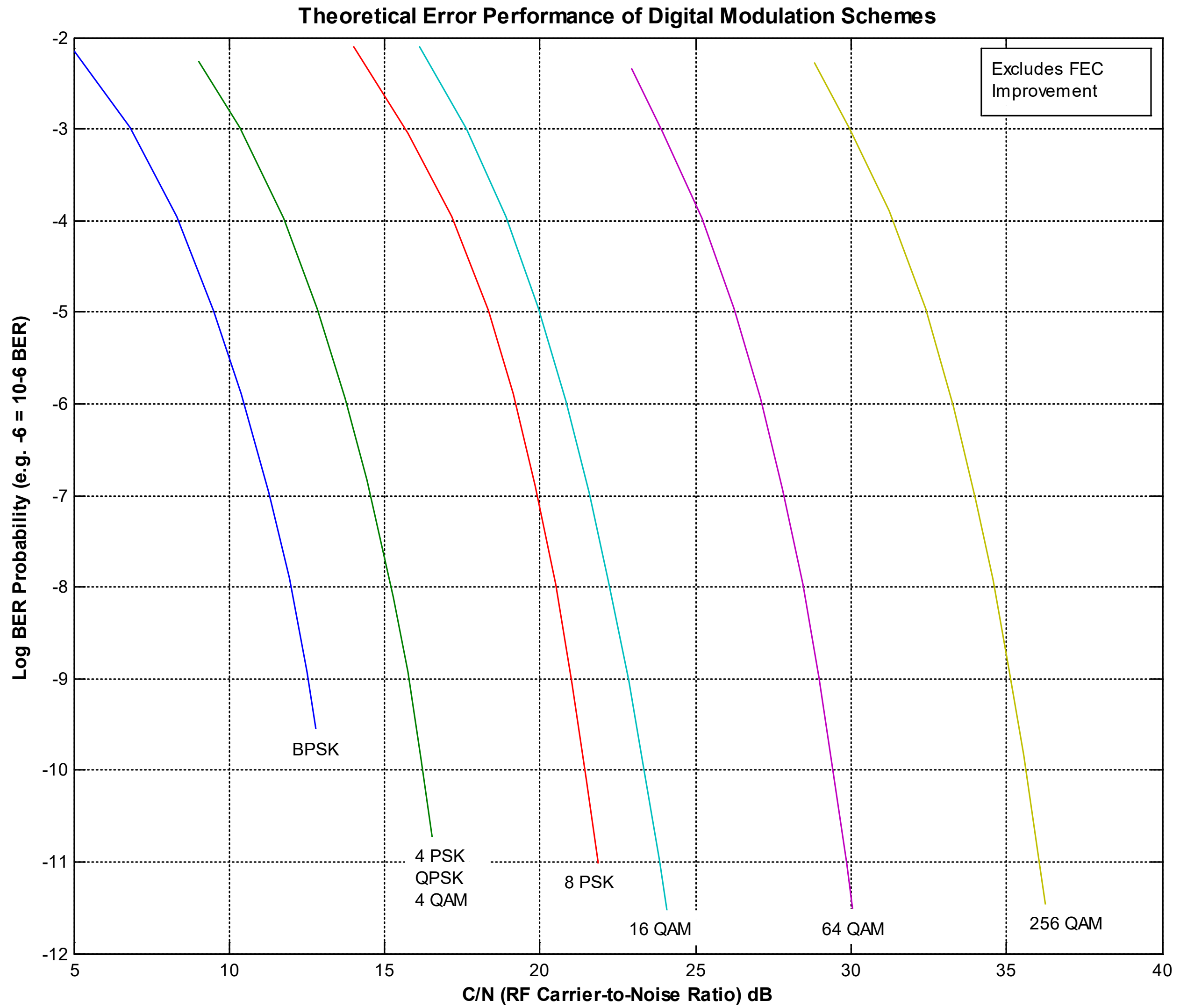
Microwave Diagram



Radio Equipment

Radio Equipment

- "Waterfall" Curves



Radio Equipment

- **Threshold**
  - Minimum receiver input level below which BER becomes excessive due to thermal noise
    - The 10^{-6} BER threshold is called the *Static Threshold*
    - The 10^{-3} BER threshold is called the *Dynamic* or *Outage Threshold*
- **Oversaturation Level**
  - Maximum receiver input level above which BER becomes excessive due to overdriving electronics into saturation (distortion)
- **Receiver can operate with low error rate between threshold and oversaturation → dynamic range**

Radio Equipment - Data Rates of Common Interfaces

North American Digital Hierarchy		
Designation	Data Rate	DS0's (# of VC)
DS1 (T1)	1.544 Mb/s	24
DS2 (T2)	6.312 Mb/s	96
DS3 (T3)	45 Mb/s	672
3xDS3	135 Mb/s	2016
DS5 (T5)	400 Mb/s	5760

European Digital Hierarchy		
Designation	Data Rate	DS0's (# of VC)
E1	2.048 Mb/s	32
E2	8.448 Mb/s	128
E3	34.4 Mb/s	512
E4	139.3 Mb/s	2048
E5	565 Mb/s	8192

Optical Signal Hierarchy		
SONET Designation	SDH Designation	Data Rate
STS-3	STM-1	155.52 Mb/s
STS-12	STM-4	622.08 Mb/s
STS-48	STM-16	2488.32 Mb/s
STS-192	STM-64	9953.28 Mb/s

Transmission Lines

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Transmission Lines

- Maximum useful frequency is f_{max}, above which electromagnetic modes in addition to the fundamental mode can propagate introducing dispersion (distortion)

- Waveguides have a cutoff frequency f_{co}, the lowest frequency that will propagate along the waveguide without dying out

- Useful Frequency Ranges:
  - Coax: 0 to f_{max}
  - Waveguide: f_{co} to f_{max}

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Transmission Lines

SFX-500 (3/8")

FXL-540 (1/2")

FXL-780 (7/8")

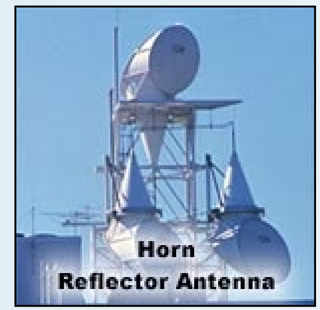
FXL-1480 (1-1/4")

FXL-1873 (1-5/8")

	Transmission Line Loss (dB/100 ft)			
	Coaxial Cable			
	3/8" (SFX-500)	7/8" (FXL-780)	1-5/8" (FXL-1873)	Elliptical Waveguide
960 MHz	3.12	1.16	0.66	x
2.1 GHz	4.72	1.79	1.05	0.35 (EW17)
3.7 GHz	6.41	2.48	x	0.92 (EW37)
6.2 GHz	8.51	x	x	1.43 (EW63)
11 GHz	11.90	x	x	3.06 (EW90)
18 GHz	x	x	x	5.91 (EW180)
23 GHz	x	x	x	8.34 (EW220)

Microwave Antennas

Direct Radiating Antennas focus the radio beam generally by using a feed source to illuminate a curved (Parabolic) reflecting surface.



Increasing Weight

Increasing Quality

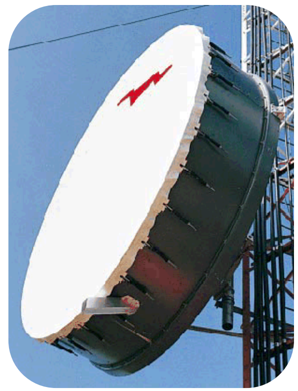
Increasing $$$

Microwave Antennas

Parabolic Reflector Antenna: a feed illuminates a parabolic reflector to focus the radio beam in the desired direction

Grid (ULine)

Standard (PL, PAR)



Ultra High Performance (UHP, UHX)

ValuLine High Performance Low Profile (VHLP)

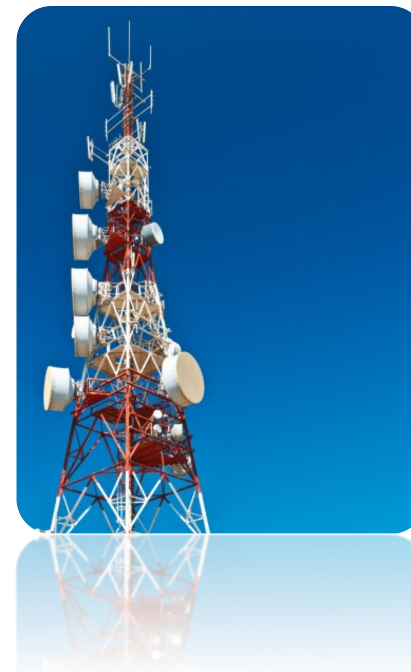
Super High Performance (Sentinel SHP)

Microwave Antennas

- **Antenna Gain (Maximum Power Gain)**

$$G = (efficiency) * \left(\frac{maximum\ radiation\ intensity}{isotropic\ radiation\ intensity} \right)$$

  - Gain is inversely proportional to beamwidth
  - Gain is directly proportional to reflector size, operating frequency and efficiency



Microwave Antennas

- **Antenna Gain**

$$G = 10\log\left(\frac{4\pi e A}{\lambda^2}\right) dBi$$

$$= 10\log e\left(\frac{\pi d f}{c}\right)^2 dBi$$

G = Antenna Gain in dBi (reference to *isotropic* radiator)

e = Antenna efficiency: $0.5 < e < 0.7$, typically 0.55

A = Area of aperture (reflective surface) in units of wavelength

λ = Wavelength = c/f

c = Speed of light $\approx 3.0 \times 10^8$ m/s

f = Frequency (hz)

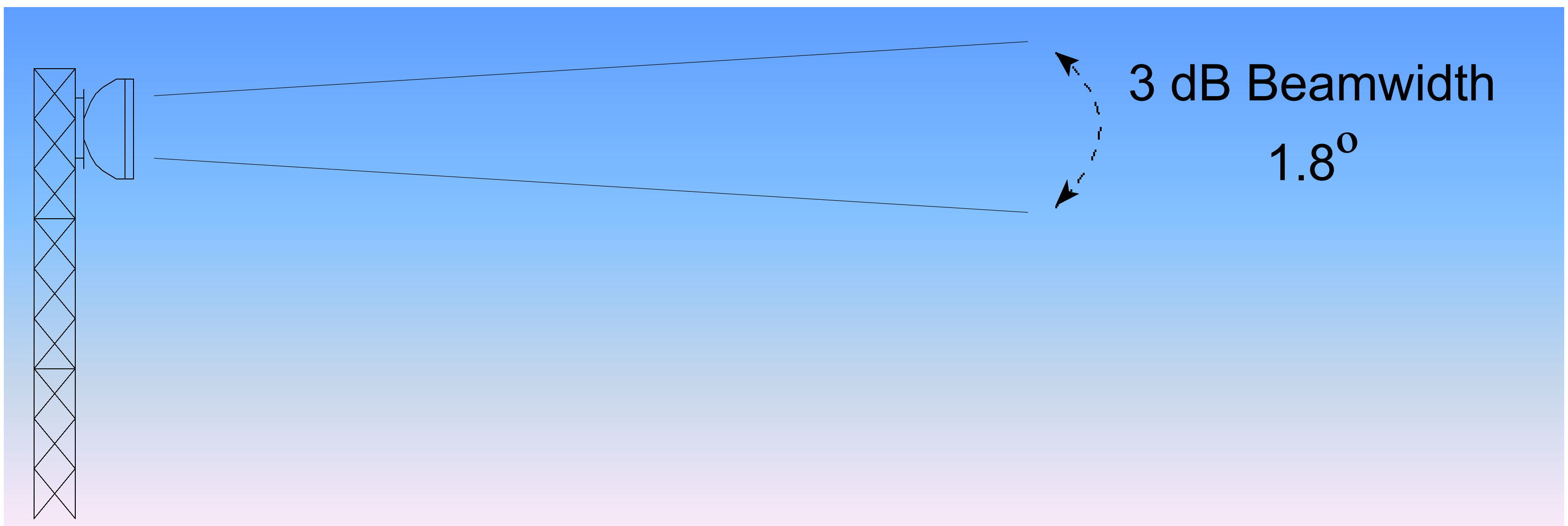
d = antenna diameter

Microwave Antennas

- **Not possible to construct perfect antennas**
  - Highest gain concentrated in region near main beam, but lower gains exist in other directions
  - The off-axis response presents a potential for interference from or into the antenna
- **Discrimination**
  - Ratio (expressed in dB) of the gain at an off-axis angle to the main beam (maximum on-axis) gain
  - Influenced by
    - Quality / Performance Level of antenna
    - Direction (Discrimination Angle)
    - Polarization (Vertical or Horizontal)

Microwave Antennas

- **Beamwidth**
  - Angle between the half-power (3 dB) points of the main beam
  - Figure-of-merit on how effectively the antenna concentrates the radiated power in the desired direction

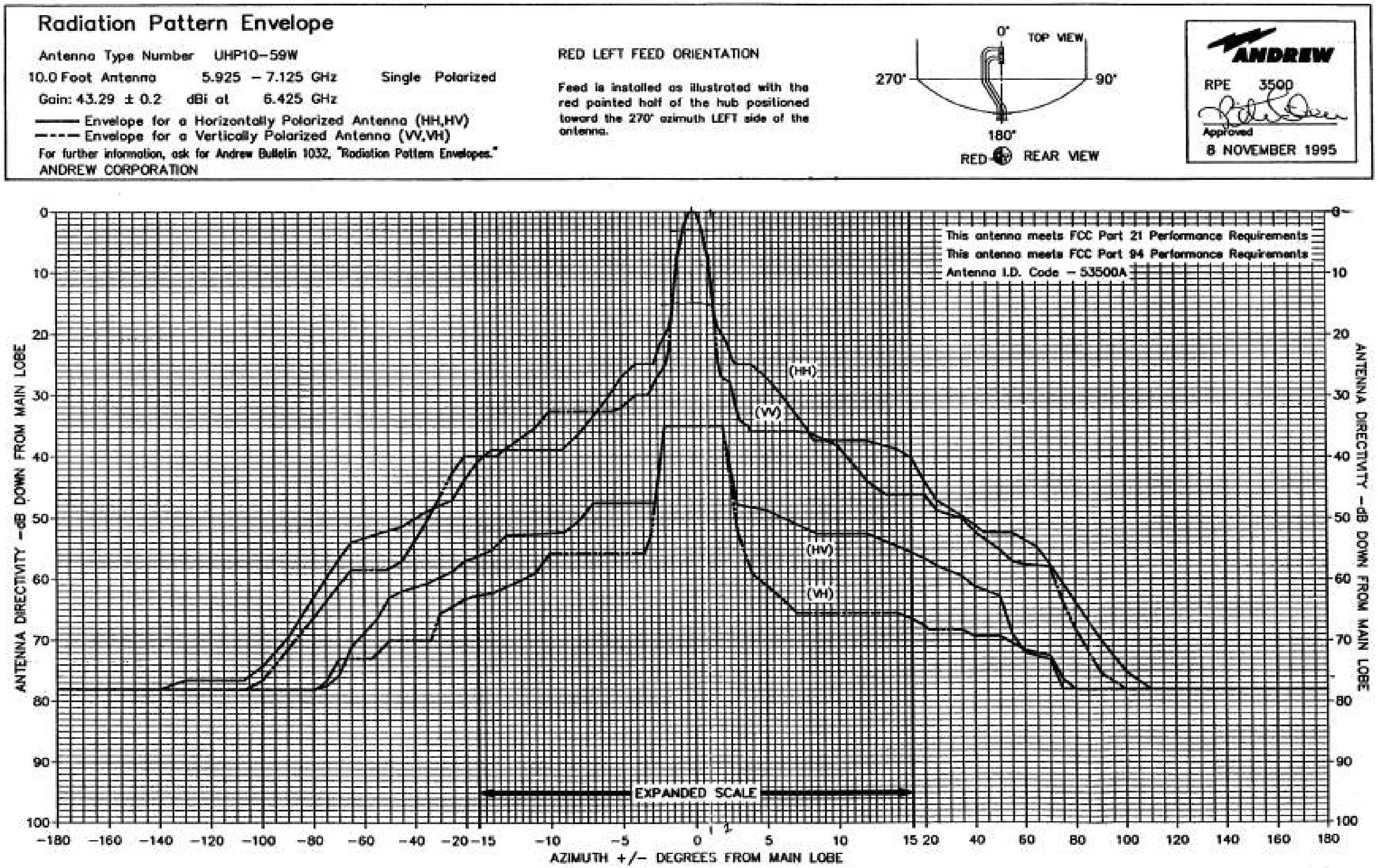


Microwave Antennas

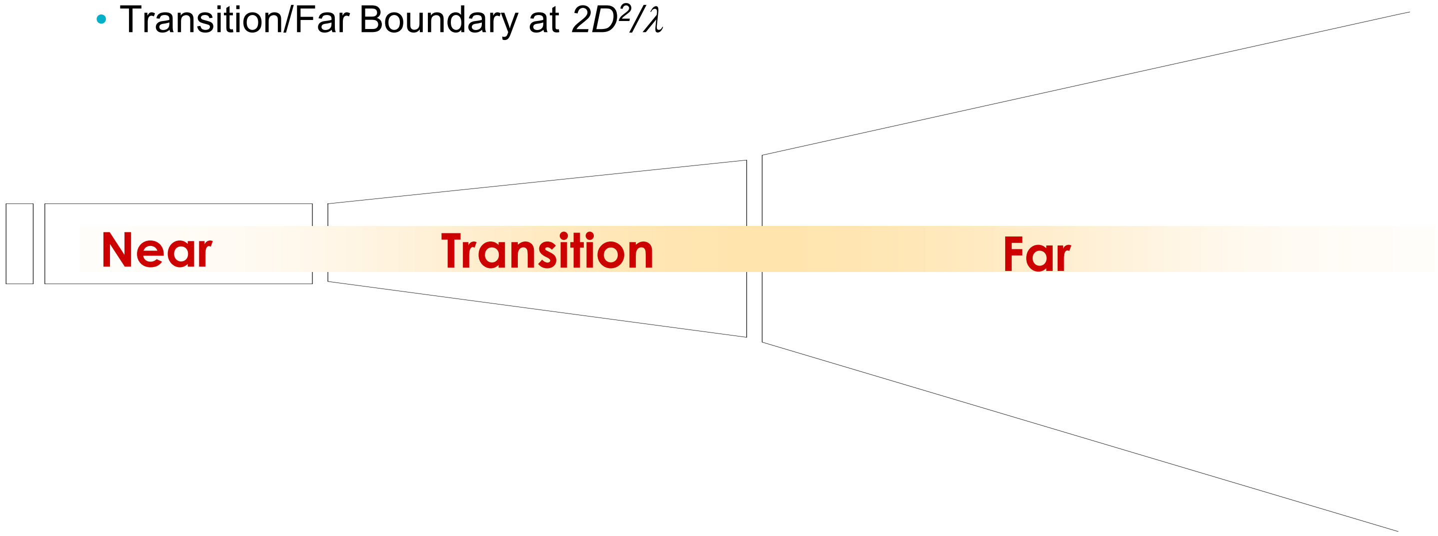
- **For a Given Antenna Size, Directionality Depends on:**
  - Frequency
  - Performance Category

Parabolic Diameter (ft)	Performance	Band (GHz)	Gain (dBi)	Beamwidth (deg)	F/B Ratio (dB)
6	Standard	6.2	38.9	1.8	46.0
6	Ultra High	6.2	38.8	1.8	75.0
6	Standard	11	44.0	1.0	51.0
6	Ultra High	11	44.0	1.1	80.0

Microwave Antennas



- **Antenna Field Patterns**
  - Near field: Radiation Pattern not well formed
  - Transition: Pattern begins to form but still depends on distance
    - Near/Transition Boundary $\pi D^2/(8\lambda)$
  - Far field: Pattern fully formed and independent of distance
    - Transition/Far Boundary at $2D^2/\lambda$

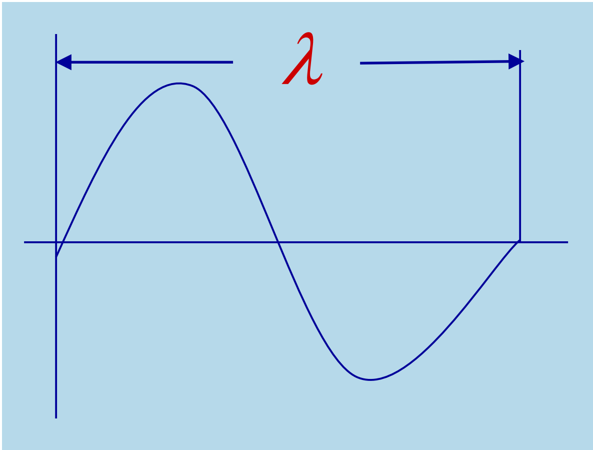


RF Propagation

RF Propagation

- **Some Basics**
  - Frequency (f)—Number of repetitions (cycles) per second (Hz)
  - Period (τ)—Duration of a Single Cycle (seconds)
  - Wavelength (λ)—Distance wave travels in one period
  - Speed of Light (c) = 2.99792458×10^8 m/s

$$f = 1/\tau = c/\lambda$$



Free Space Path Loss

- **The difference between power transmitted & power received is called *Path Loss***
- **The portion of Path Loss attributed to the spreading effect of signal is referred to as Free Space Path Loss**
- **Free Space Path Loss is inversely proportional to the square of the wavelength**

Free Space Path Loss

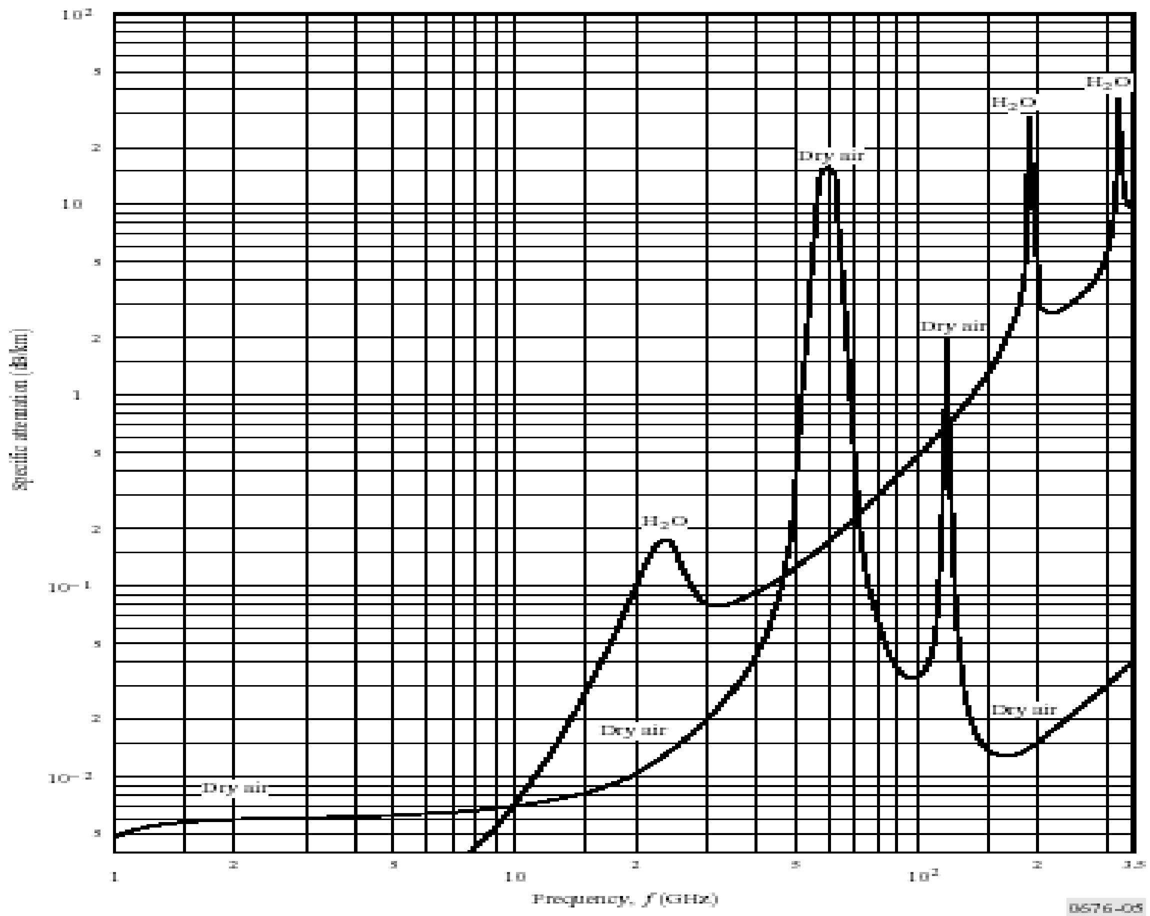
- **The Free Space Path Loss Equation(s):**
  - $FSPL_{mi} = 96.6 + 20\log(f_{GHz}) + 20\log(d_{mi})$ dB
  - $FSPL_{km} = 92.4 + 20\log(f_{GHz}) + 20\log(d_{km})$ dB

  - **Example:**
    - What's the FSPL for a 20 mi path at 6.175 GHz?
    - $FSPL = 96.6 + 20\log(6.175) + 20\log(20)$ dB = 138.4 dB
    - What's the FSPL at 10 mi? 40 mi?

Atmospheric Absorption

FIGURE 5

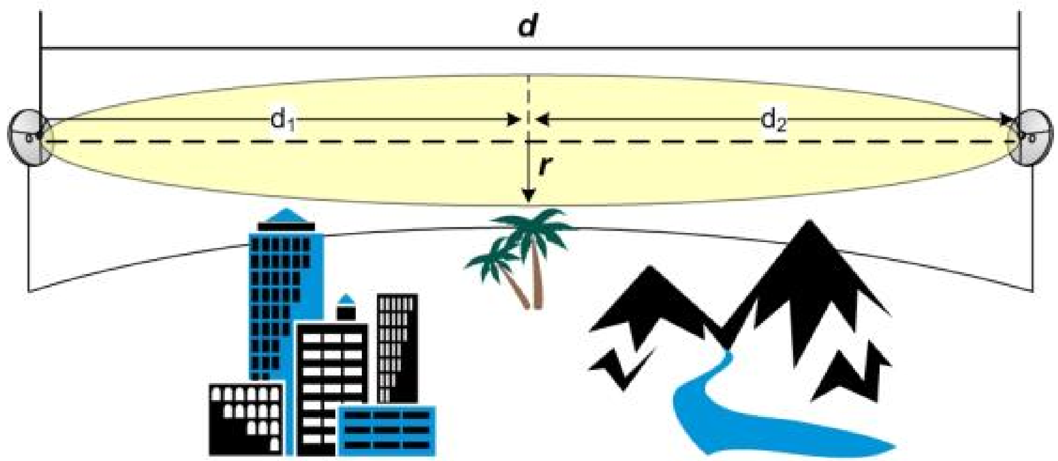
Specific attenuation due to atmospheric gases



Pressure: 1 013 hPa
Temperature: 15° C
Water vapour: 7.5 g/m³

Fresnel Zone

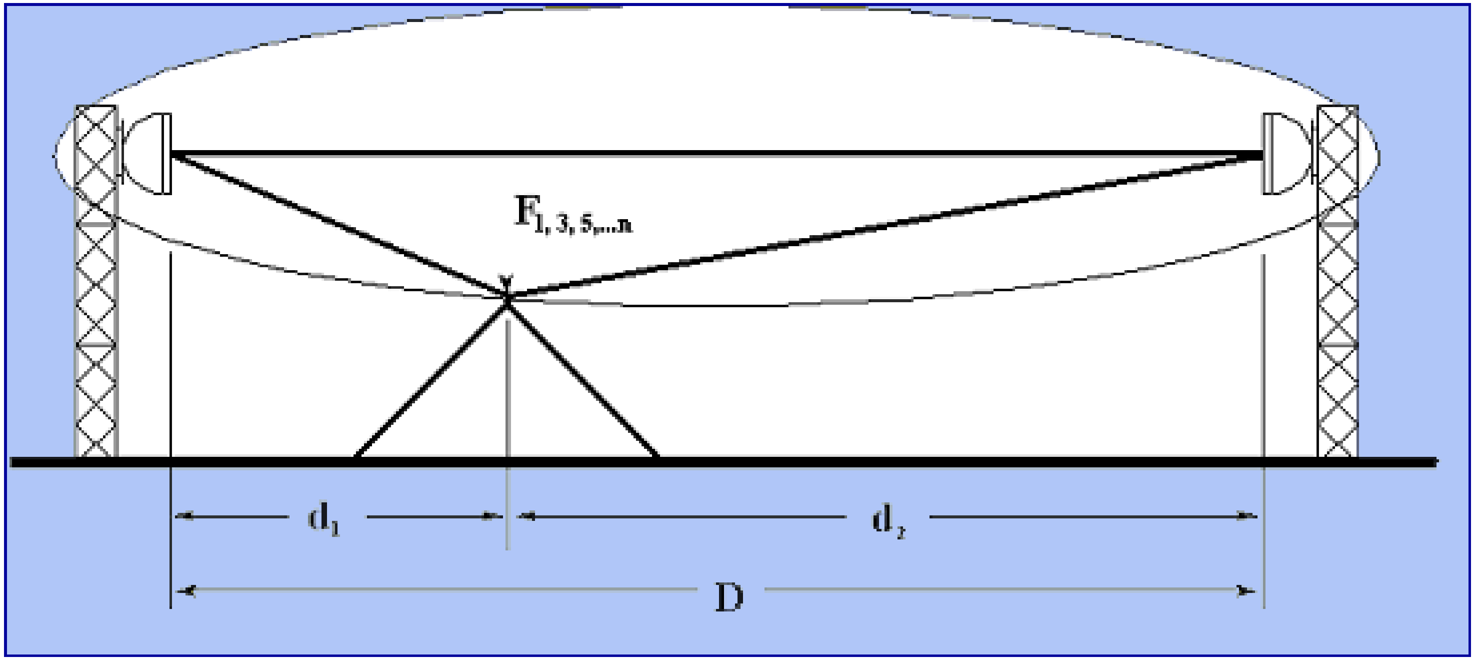
$$r = 17.3 \sqrt{\frac{(d_1 \cdot d_2)}{F\,(d_1 + d_2)}}$$



d = Distance between antenna d_1 = Distance to point-of-interest from antenna 1 d_2 = Distance to point-of-interest from antenna 2	***r*** = Radius of Fresnel Zone at point-of-interest F = Frequency in GHz

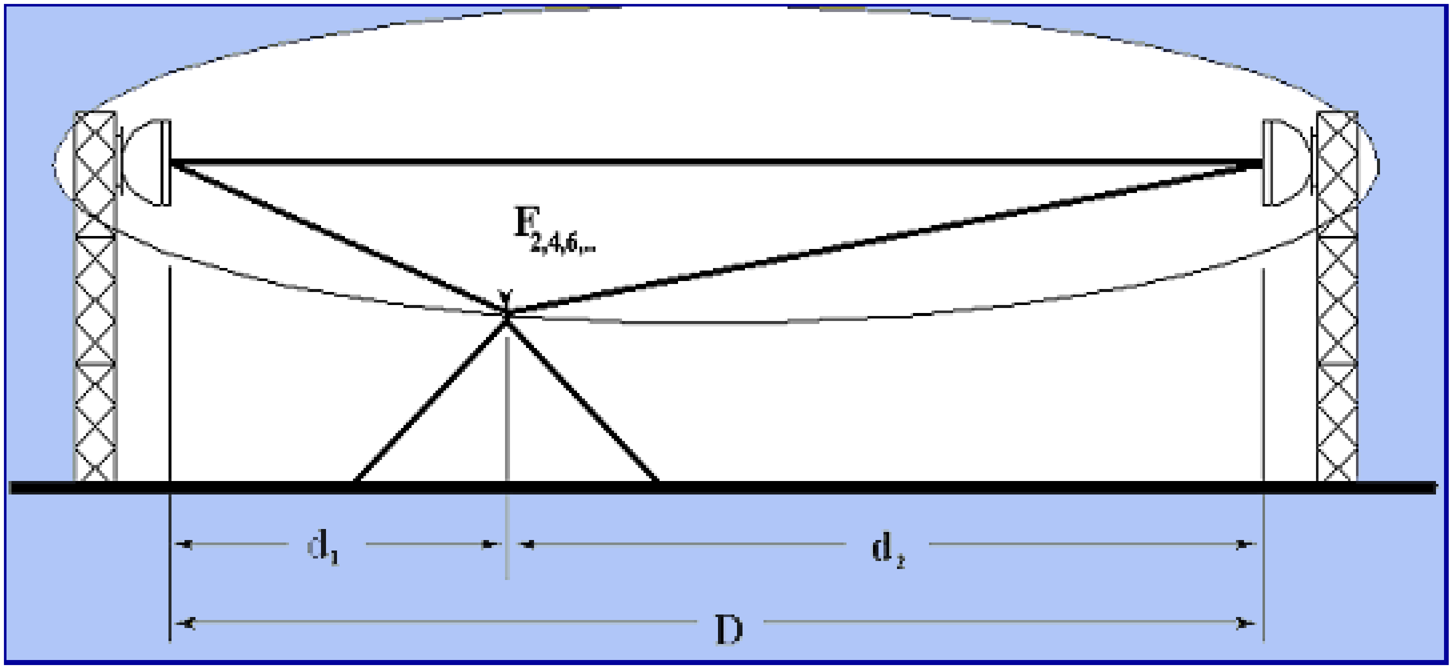
Fresnel Zones

- **Reflections from objects at the surface of *odd* numbered Fresnel zones will add *in phase* at the receiver**
  - (180º shift + n x ½ wavelengths)

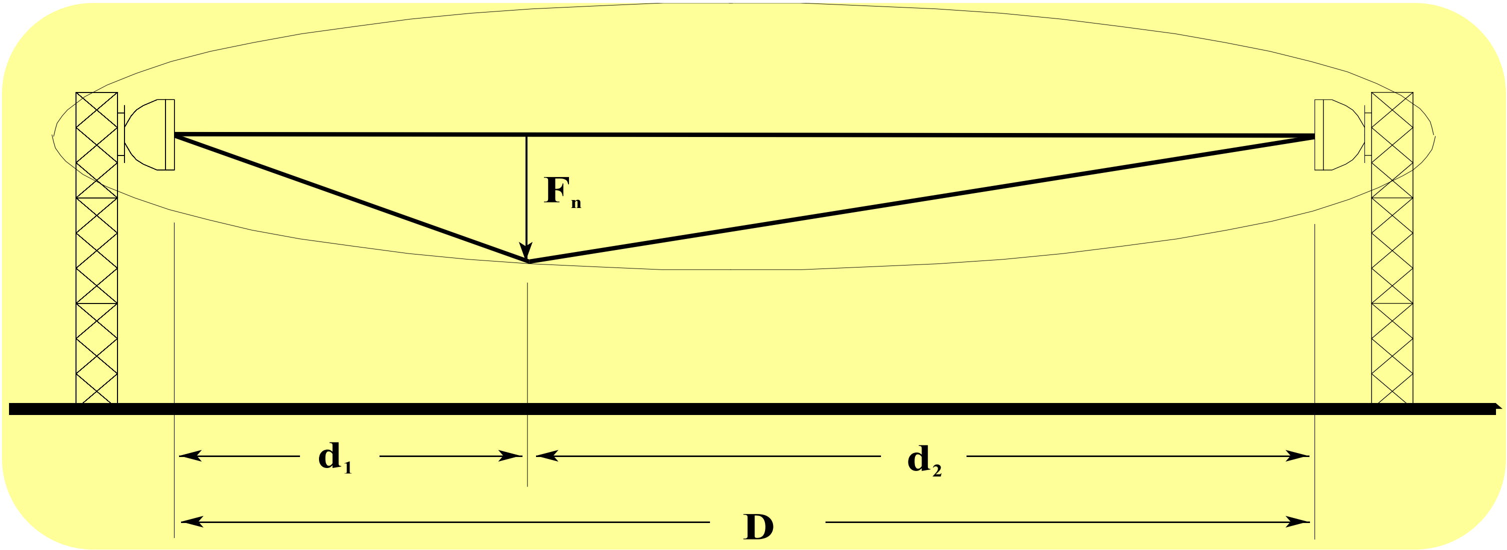


Fresnel Zones

- **Reflections from objects at the surface of *even* numbered Fresnel zones will be *anti-phase* at the receiver**
  - (180º shift + n wavelengths)



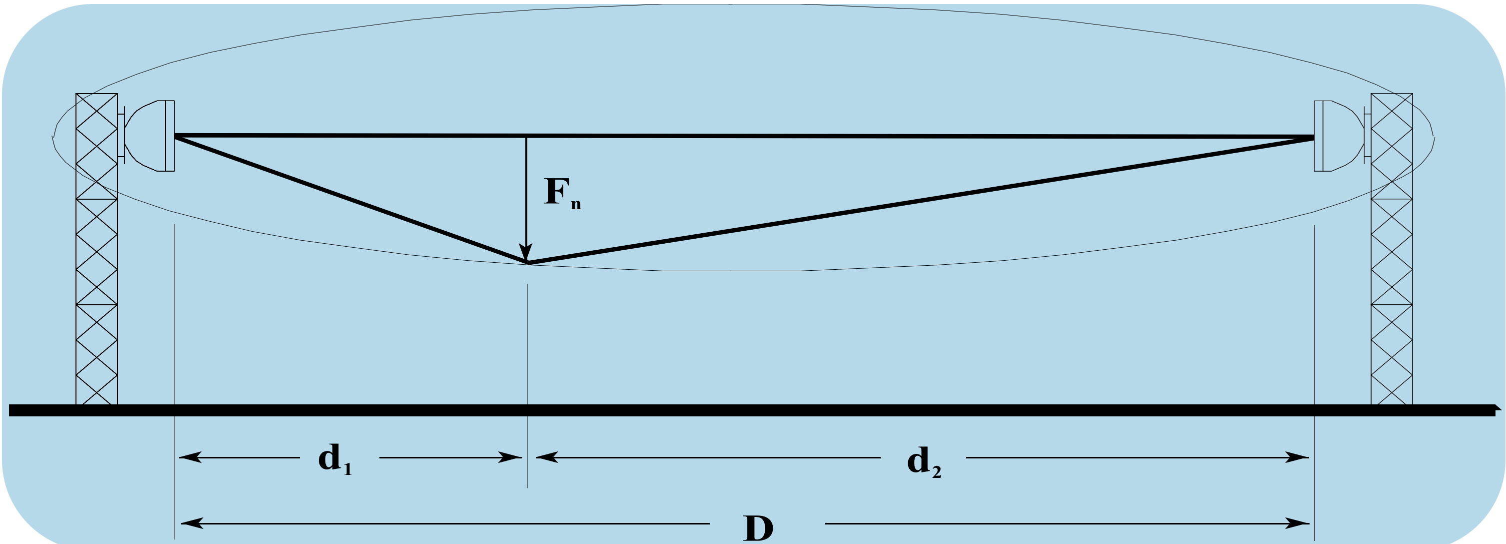
Fresnel Zone Diagram



$$F_n = 72.1\sqrt{\frac{nd_1d_2}{fD}}$$

Where: F_n = n^{th} Fresnel Zone radius in feet
d_1 = distance from one end of the path to the reflection point in miles
D = total path length
d_2 = D - d_1
f = frequency in GHz

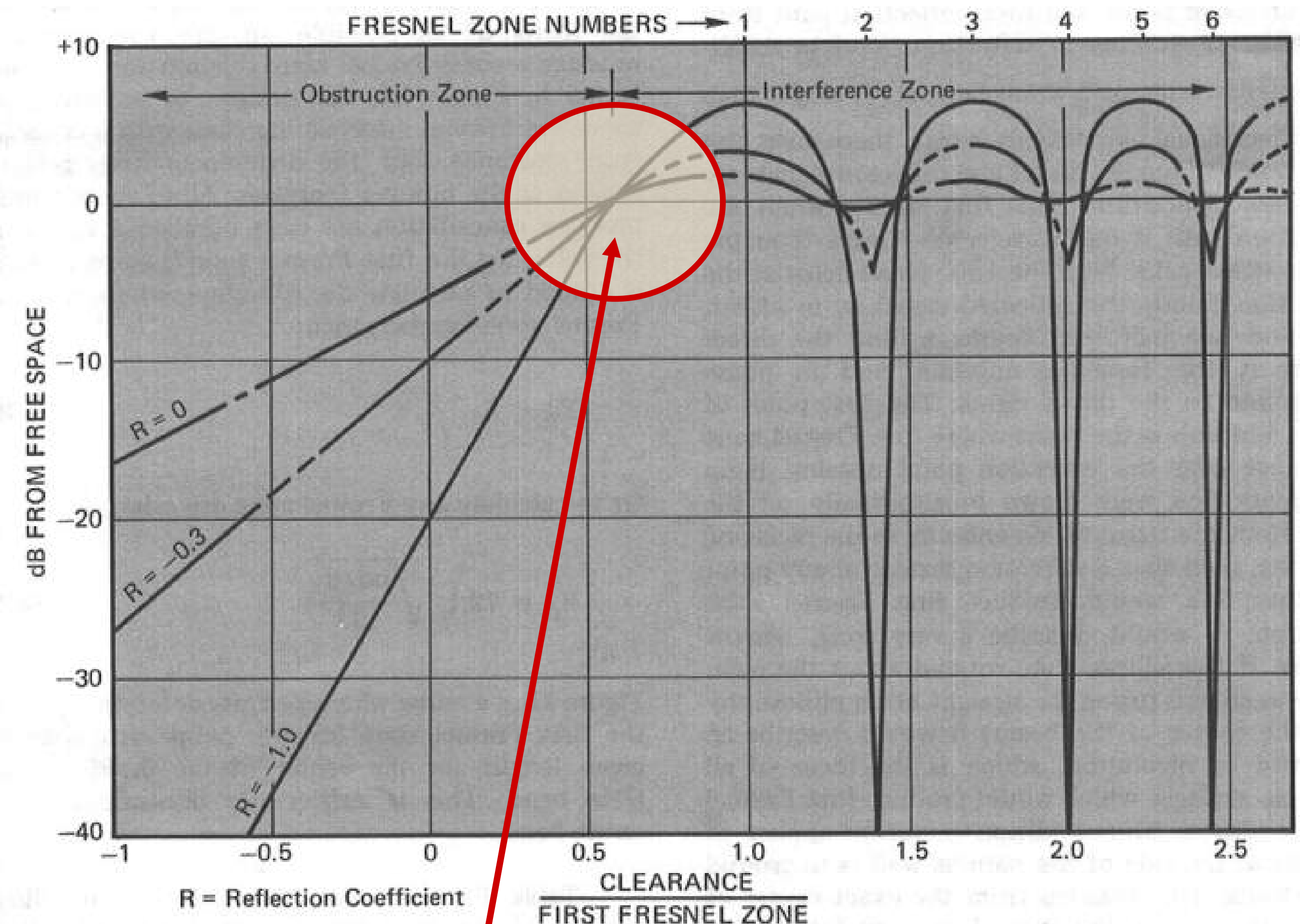
Fresnel Zone Examples



$$F_n = 72.1\sqrt{\frac{n d_1 d_2}{fD}}$$

If :	D = 30 mi	D = 30 mi	D = 8 mi	D = 3 mi
	d1 = d2 = 15 mi	d1 = d2 = 15 mi	d1 = d2 = 4 mi	d1 = d2 = 1.5 mi
	f = 1.9 GHz	f = 6.7 GHz	f = 23 GHz	f = 38 GHz
Then:	F1 = 143.25 ft	F1 = 76.3 ft	F1 = 21.3 ft	F1 = 10.3 ft

Fresnel Zones

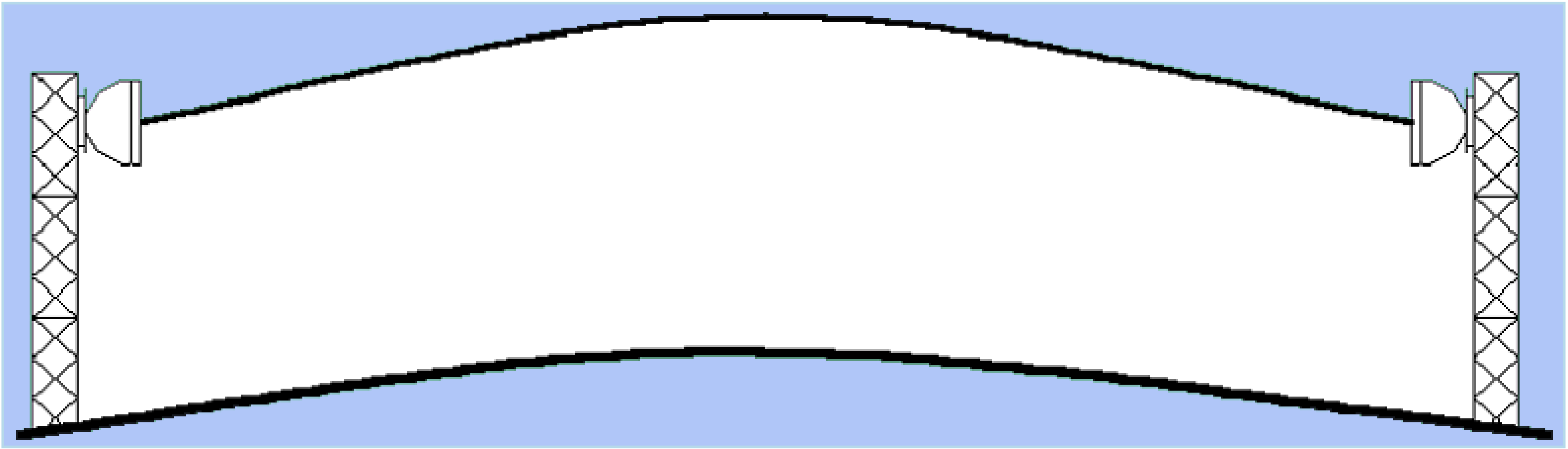


Path clearance less than $0.6*F_1$ can result in additional path loss due to diffraction

K Factor

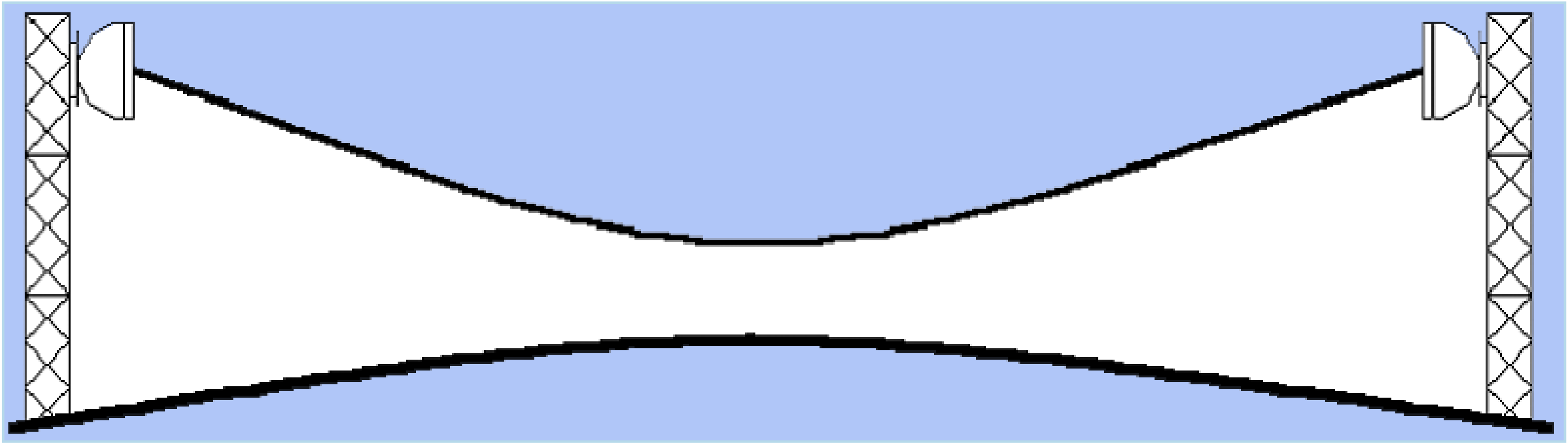
K Factor

- **This causes a bending of the rays from the transmitter to the receiver**
  - The ray bends up for typically negative dn/dh



K Factor

- However, if dn/dh is positive, the ray bends down towards the ground



K Factor

- Worldwide map of dN/dh (ΔN)

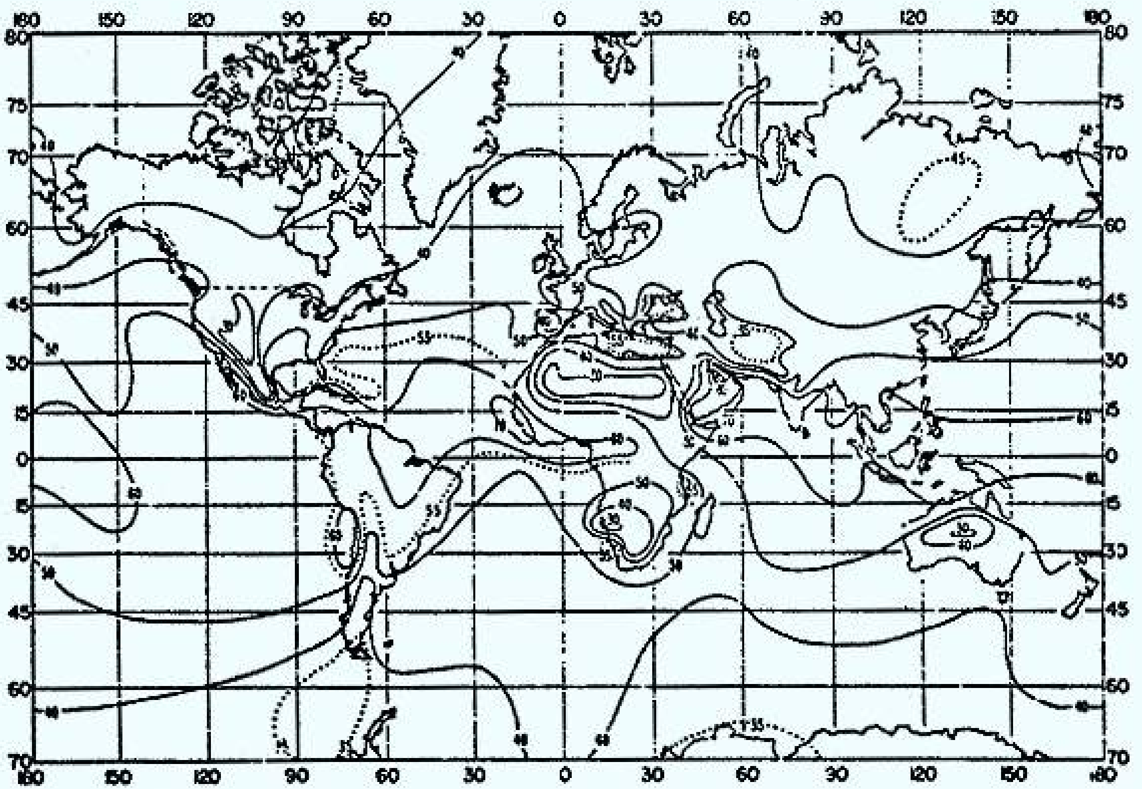
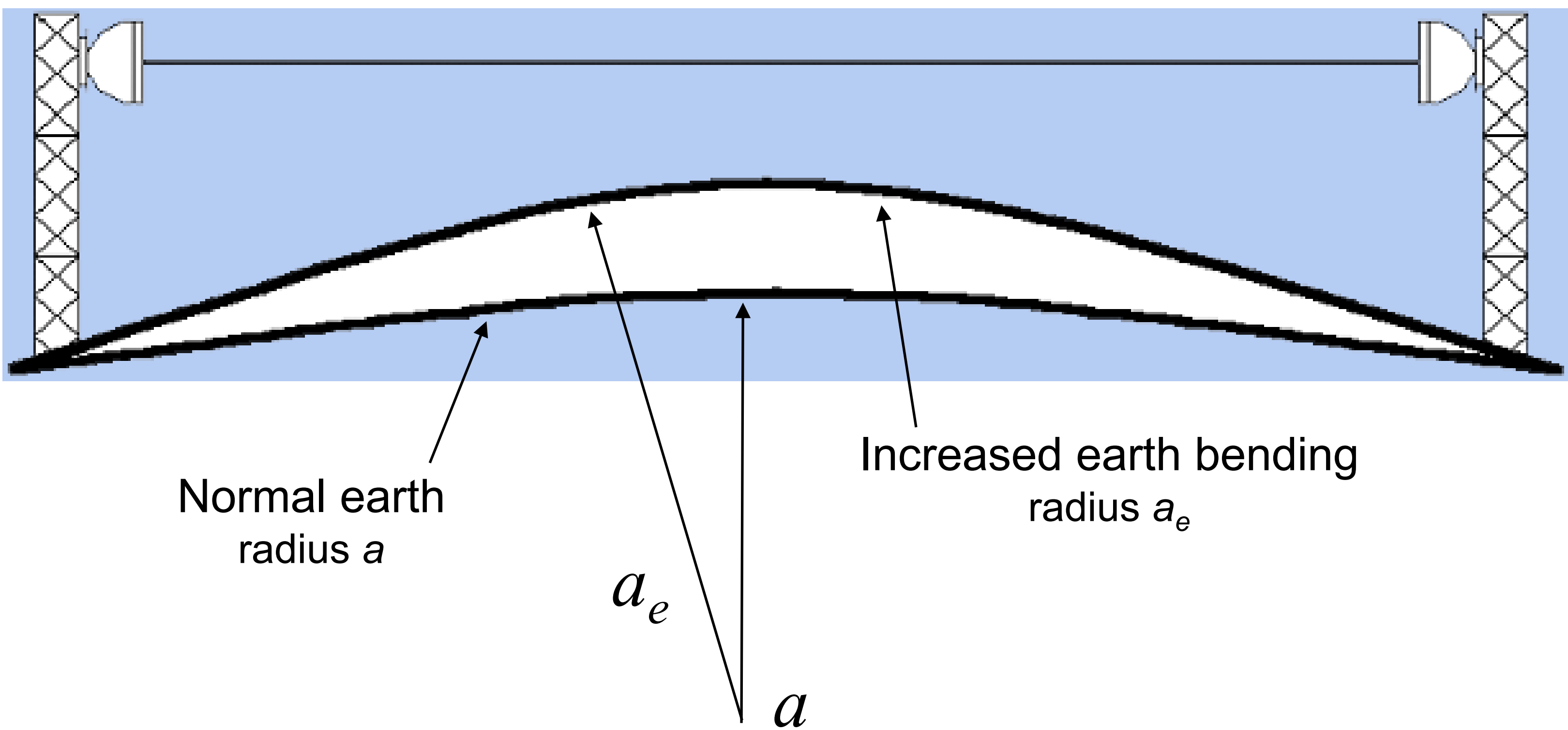


FIGURE B-15. Annual mean of refractivity gradient between surface and 1 km, ΔN.

K Factor

- It is convenient to model the bending ray as an increase in the curvature of the earth, leaving the ray straight



K Factor

- Now, we have a relationship between the effective earth radius, a_e and the actual earth radius a (6370 km):

$$a_e = ka$$

$$or$$

$$k = a / a_e$$

$$= 1/(1+a(dn/dh))$$

$$= 1/(1+a(dN/dh) \text{ x } 10^{-6})$$

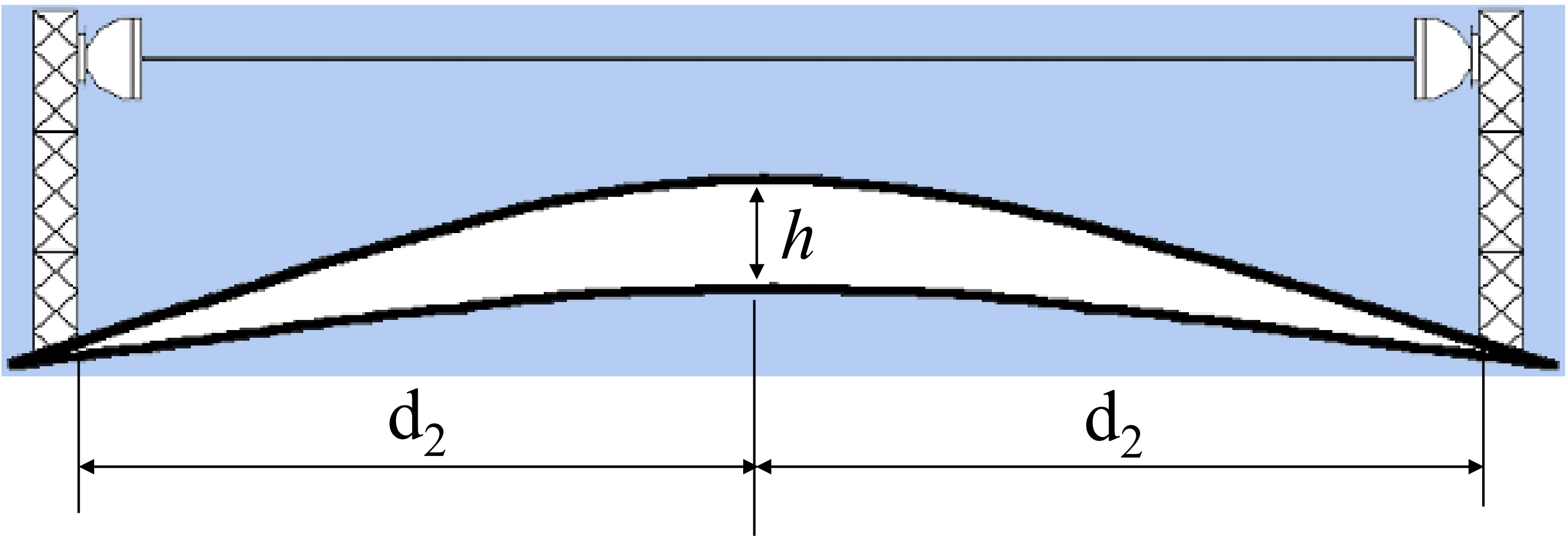
plugging for a:

$$\mathbf{k = 157 / (157 + dN/dh)}$$

K Factor

- **Earth bulge (h):**

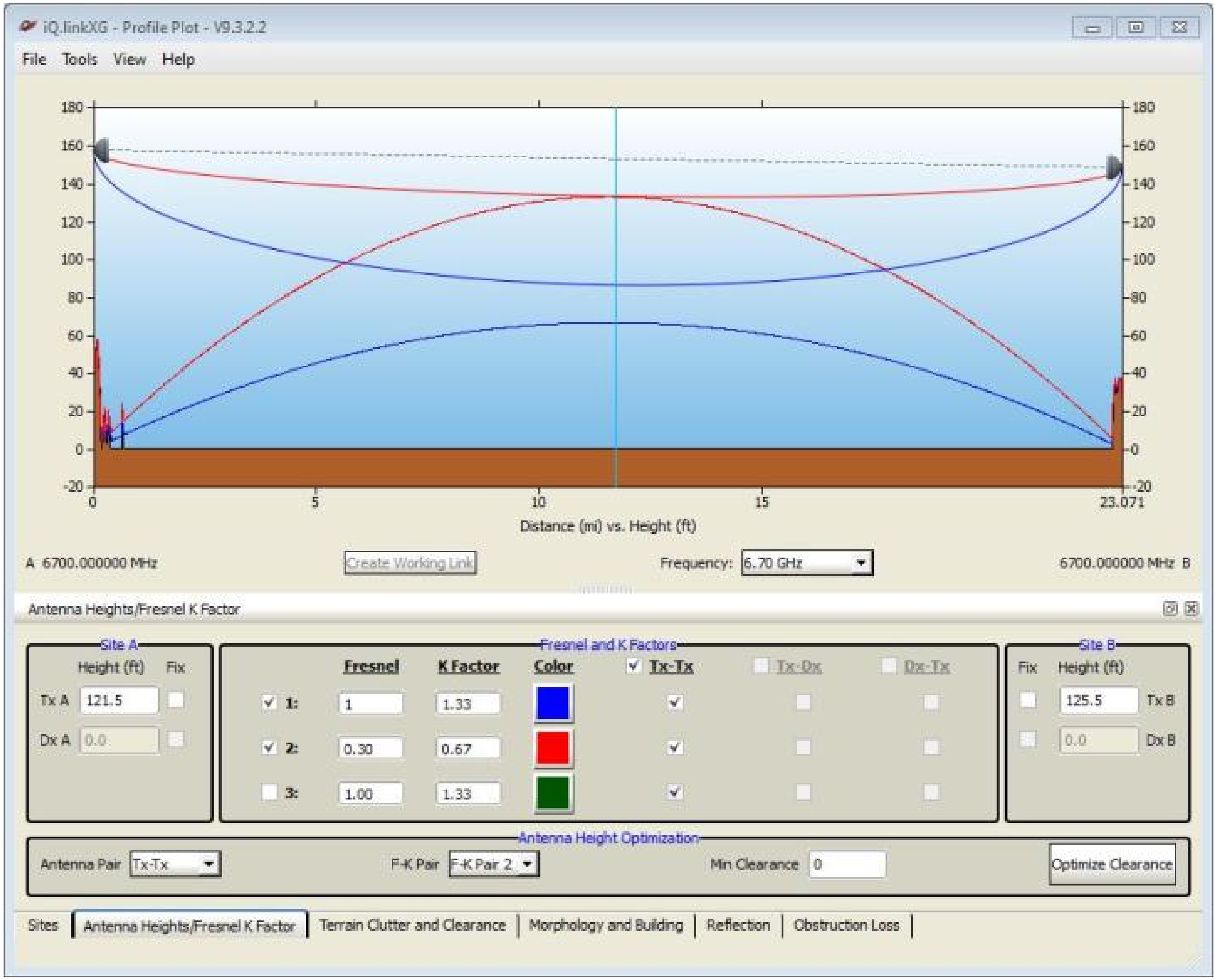
$$h = d_1 d_2 / 12.75k \quad \text{meters}$$
$$h = 0 \text{ for } k = \text{infinity}$$



Path Clearance

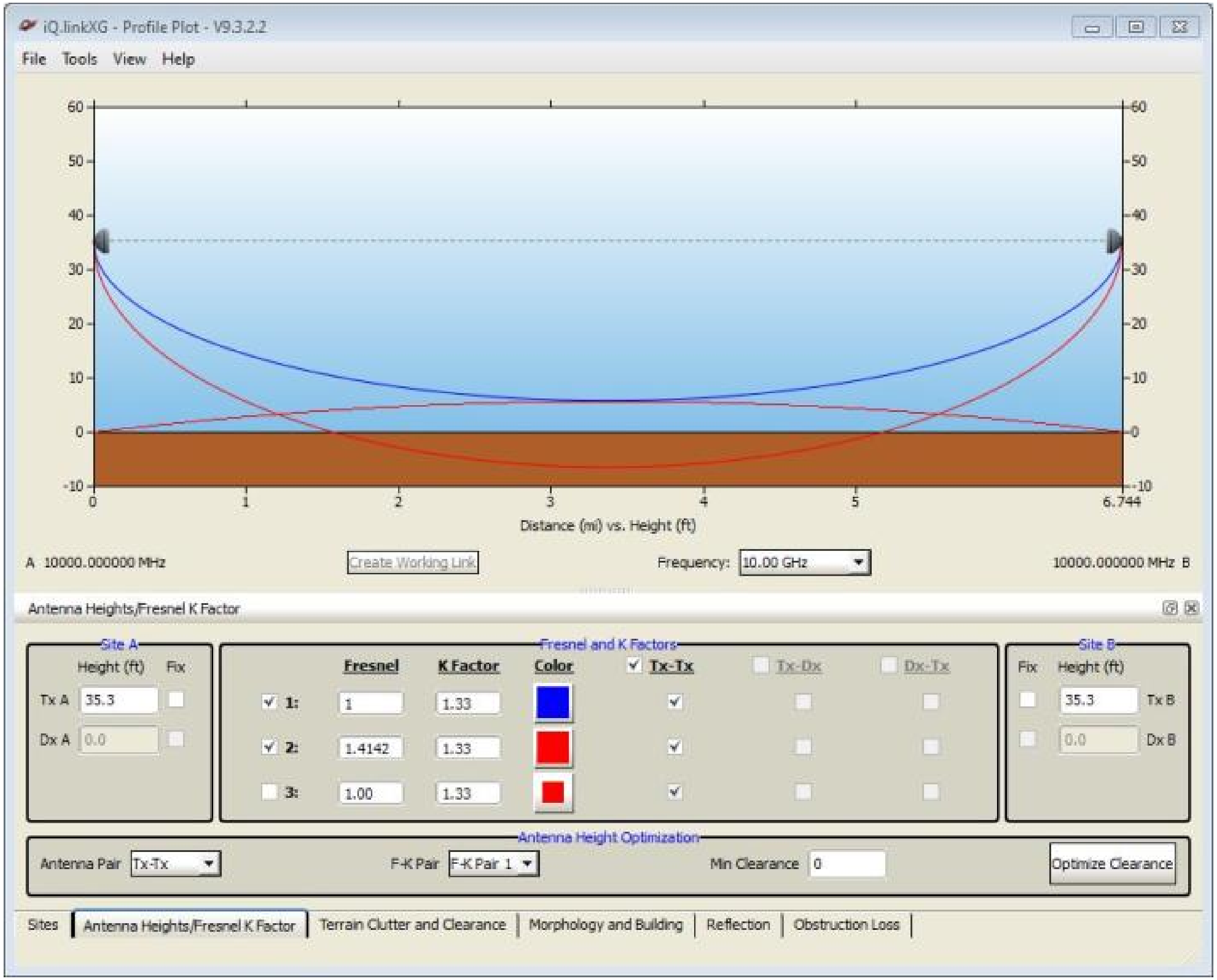
Path Clearance

- Path profile



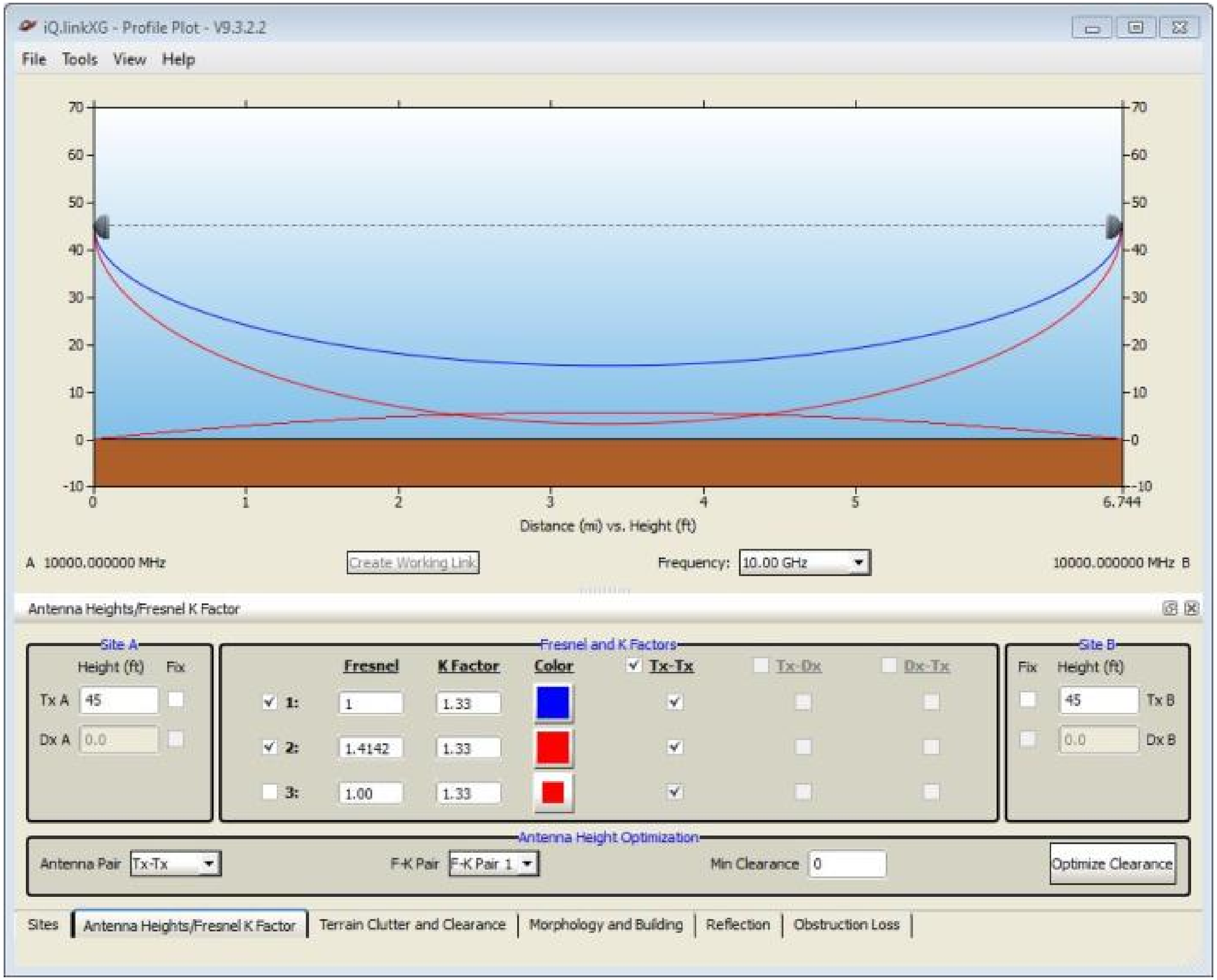
Path Clearance

- Proper Path Clearance



Path Clearance

- Excessive Path Clearance

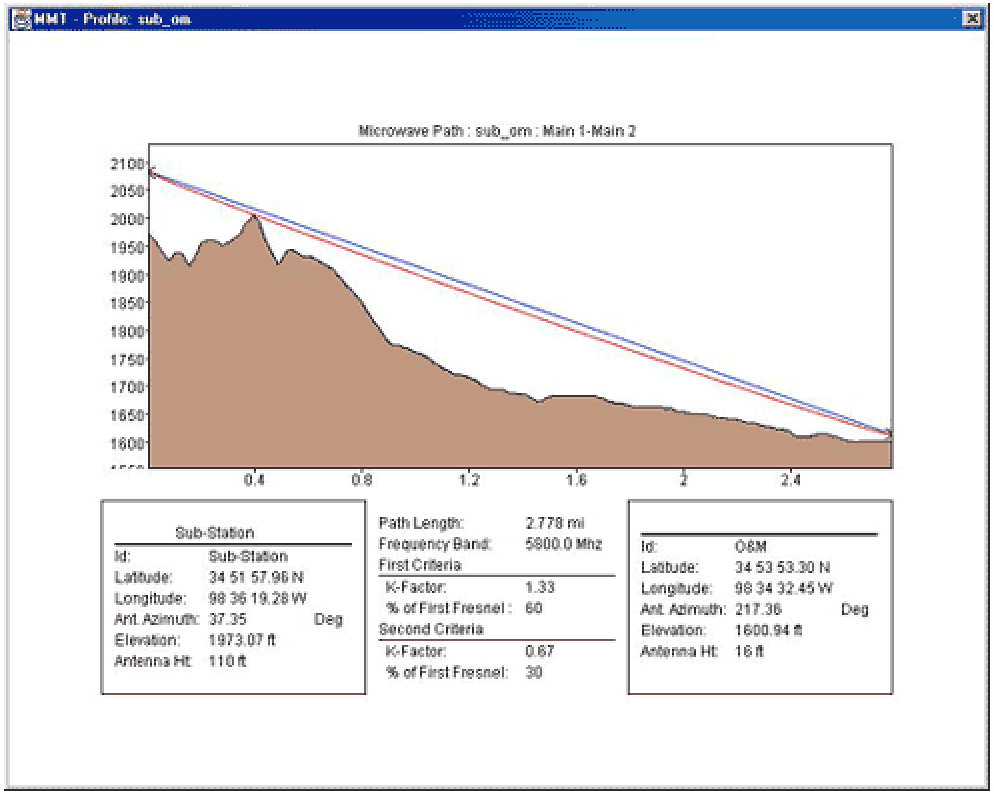


Reliability

Reliability

Outage

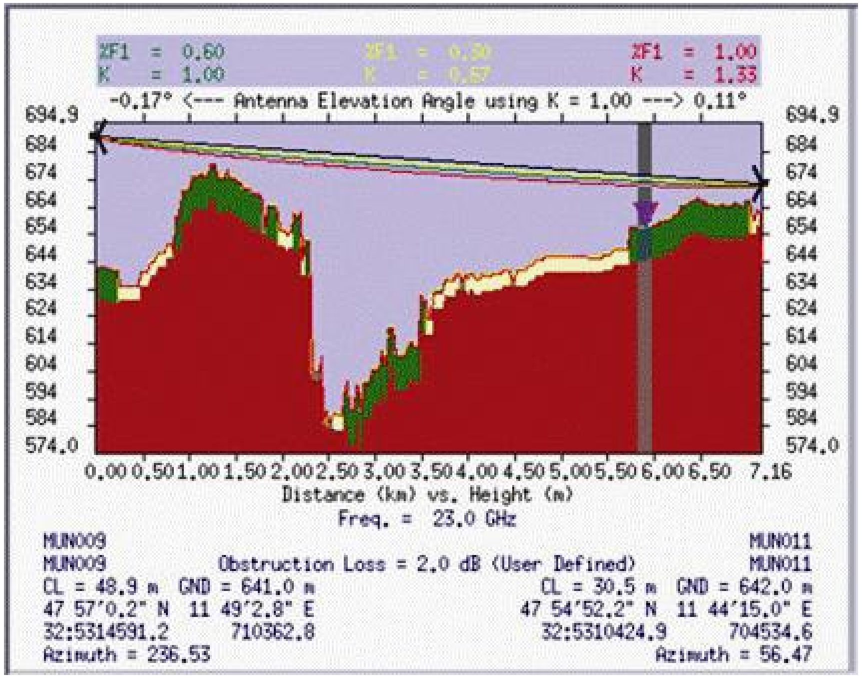
- Time that the RSL is faded below the Receiver Threshold is *outage*
- Outage is calculated as time below 10^{-6} BER for most purposes
- In the past, outage was calculated as time below 10^{-3} BER for telephony since the PCM multiplexers lose framing just below this BER



Reliability

Fade Margin

- The amount the signal may fade before a path outage results
- Digital—Composite Fade Margin
    - Includes a Thermal (or Flat) Fade Margin term that is the difference between the normal RSL and the minimum usable signal (Receiver Threshold) level. Also includes terms taking into account the effect of frequency selective fading in the channel (Dispersive Fade Margin) and the effect of interference (External Interference Fade Margin)



Reliability

- **Composite Fade Margin Equation**

$$CFM = -10\log\left(10^{-DFM/10} + 10^{-TFM/10} + 10^{-EIFM/10} + 10^{-AIFM/10}\right)$$

CFM = Composite fade margin

DFM = Dispersive fade margin

TFM = Thermal fade margin *(Receive level - Threshold)*

EIFM = External interference fade margin

AIFM = Adjacent-channel interference fade margin

Reliability

- **Example:**

If the RSL is -40 dBm, the Receiver Threshold is -75 dBm, the Dispersive Fade Margin is 50 dB, and the External Interference Fade Margin is 60 dB, what is the Composite Fade Margin of the link?

  - TFM = -40 - (-75) = 35
  - CFM = $-10\log(10^{-5}+10^{-3.5}+10^{-6})$
    34.85 dB

Reliability

- The fade margin must be high enough to allow the path to meet the *reliability objective*
- Vigants (1975) gave a formula for predicting the link outage time based on the fade margin
- Outage time is dependent on:
  - climate, terrain, temperature, frequency, and path length
- Outage time can be greatly reduced by using frequency and/or space diversity

Reliability

- There are 31,536,000 seconds in a year
- An availability of 99.99% (four nines) means an outage of 3153.5 seconds per year, or about 53 minutes
- An availability of 99.999% (five nines) means an outage of 315.35 seconds per year, or about 5 minutes

Reliability

- **Vigants Multipath Outage Model**
  - Predicts *Atmospheric* Multipath Fading

$$T = \frac{rT_0 \times 10^{-\left(\frac{CFM}{10}\right)}}{I_0}$$

Where:

T	=	annual outage time (s)
r	=	fade occurrence factor
T_0	=	$(t/50)(8*10^6)$ = length of the fading season (s)
t	=	average annual temperature (F)
CFM	=	Composite Fade Margin (dB)
I_0	=	SD Improvement Factor (1 for non-diversity, >1 for diversity)

Reliability

- **Space Diversity Improvement Factor**

$$I_0 = 7 \times 10^{-5} s^2 \left(\frac{f}{D} \right) 10^{\left(\frac{CFM}{10} \right)}$$

Where:

s = vertical antenna spacing (ft) (s ≤ 50 feet)

f = frequency (GHz)

D = path length (mi)

CFM = composite fade margin (dB)

Reliability

- **Space Diversity Improvement Factor**
  - Example: Our 30 mile 6 GHz link has a Composite Fade Margin of 35 dB. If we add space diversity antennas 20 feet below the main antennas, by what factor do we predict that the atmospheric multipath fading outage will be reduced?
  - $Io = (7*10^{-5})(20^{2})(6/30)(10^{(3.5)}) = 17.7$

Reliability

- **Fade Occurrence Factor**

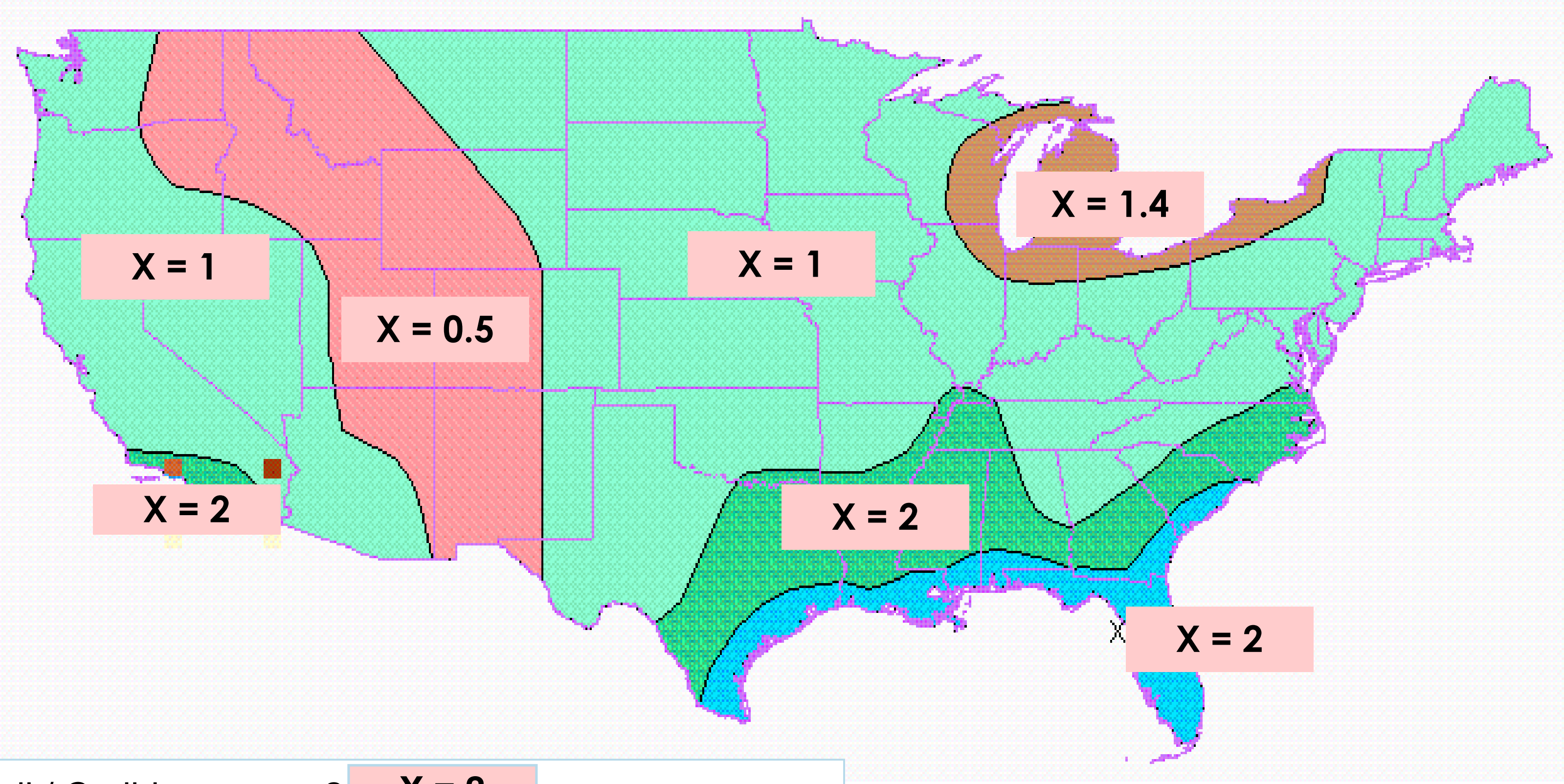
$$r = x\left(\frac{50}{w}\right)^{1.3}\left(\frac{f}{4}\right)D^{3}\times 10^{-5}$$

Where:

x = Climate factor (0.5 - 2 for poor - good areas, see map)
w = Terrain roughness (20 ≤ w ≤ 140 ft.)
f = frequency (GHz)
d = Path length (mi)

Reliability

- **Climate Factor**



Hawaii / Caribbean: **x = 2** **X = 2**

Alaska: **X = 0.5** for coastal & mountainous areas

X = 1 for flat, permafrost tundra areas

Reliability

- **Fade Occurrence Factor Example**
  - For an area of average propagation (x = 1) and a 30 mile path of average terrain roughness (w=50'), what is the fade occurrence factor at 6 Ghz?
  - $r = (1)(50/50)^{1.3}(6/4)(30^3)(10^{-5}) = 0.405$

Reliability

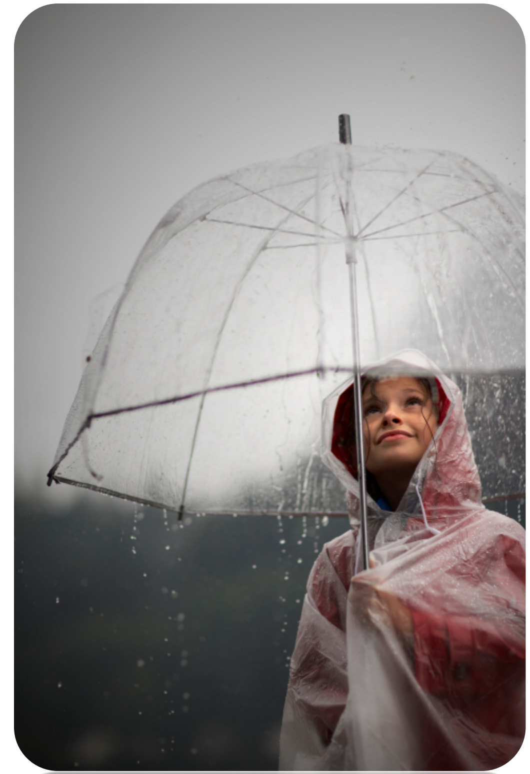
- **Outage Example**
  - Our link has a CFM of 35 dB and a fade occurrence factor of 0.405. If the average annual temperature is 60^o F, what is the expected annual outage due to atmospheric multipath fading without diversity?
  - $T_0 = (60/50)(8*10^6) = 9.6*10^6$ s
  - $T = (.405)(9.6*10^6)(10^{-3.5}) = 1230$ s

Reliability

- **Space Diversity Improvement Example**
  - The annual outage of 1230 s expected on this link doesn't meet the standard that we have established for our network. We calculate a space diversity improvement factor of 17.7 for a 20' antenna spacing. What annual outage do we expect with space diversity?
  - T = 1230/17.7 = 70 s

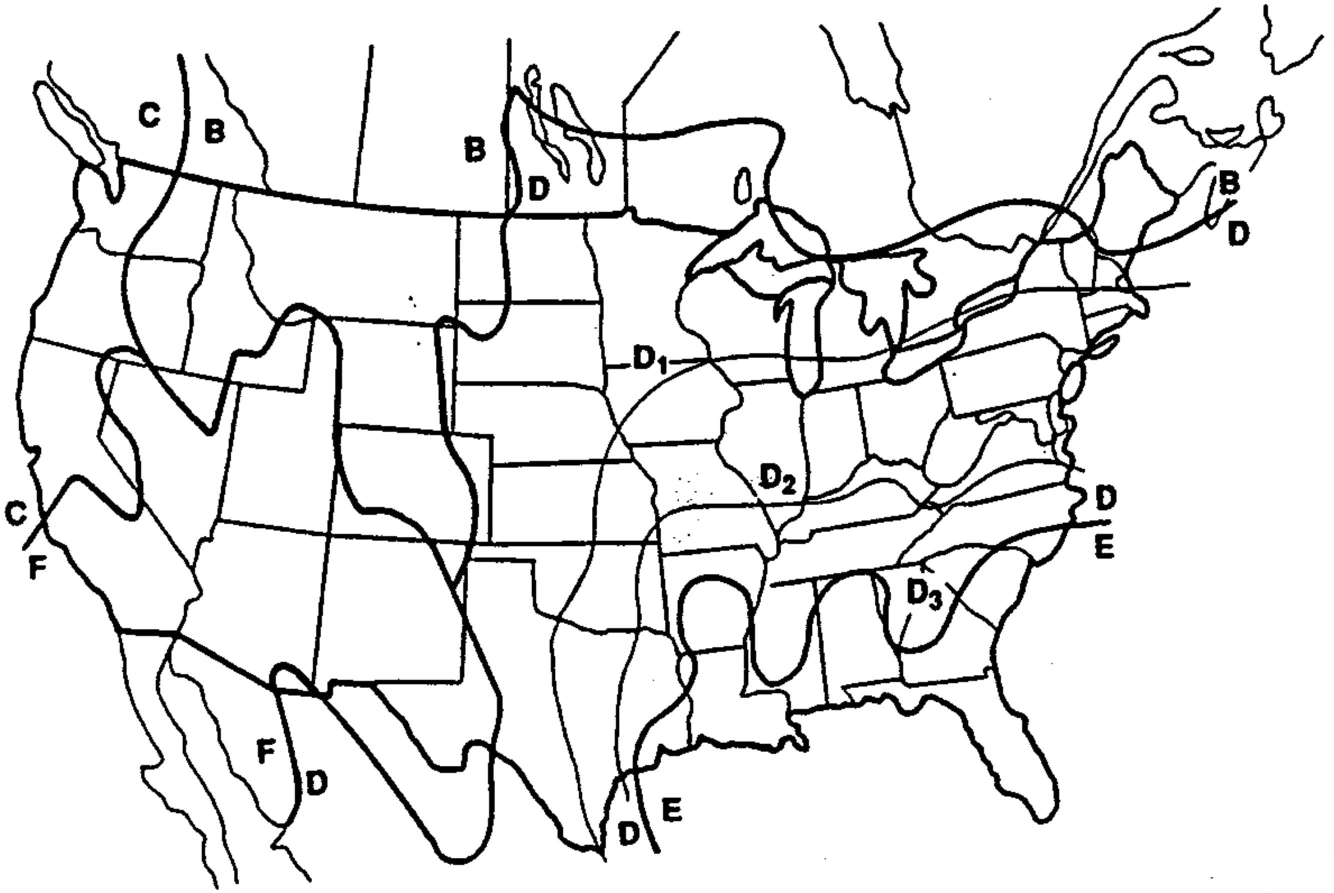
Reliability

- **Rain Outage**
  - Rain fades become significant when the frequency is above 10 GHz
  - Crane model predicts fade depth probability based on rainfall rate statistics by region (map)
  - Outage probability proportional to rain rate—*not* total annual rainfall



Reliability

- **Rain Rate Climate Regions (Crane)**

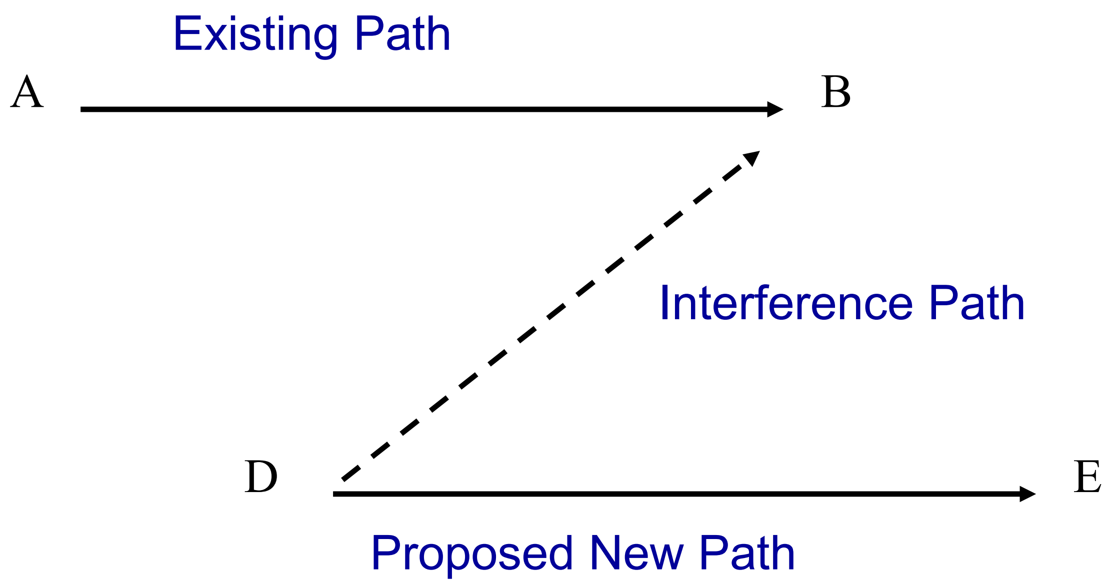


Interference Calculations

Interference Calculations

- **C/I: The ratio of desired signal power to interference power at the receiver input**

$$C/I = C(\text{dBm}) - I\ (\text{dBm})$$



Interference Calculations

- **Interference Level at B**

$$I_B = P_D + G_D - L_D - FSPL_{DB} + G_B - L_B - D_{Total}$$

P_D = Transmit Power at D
G_D = Antenna Gain at D
L_D = Fixed Losses at D
$FSPL_{DB}$ = Free Space Path Loss from D to B
G_B = Antenna Gain at B
L_B = Fixed Losses at B

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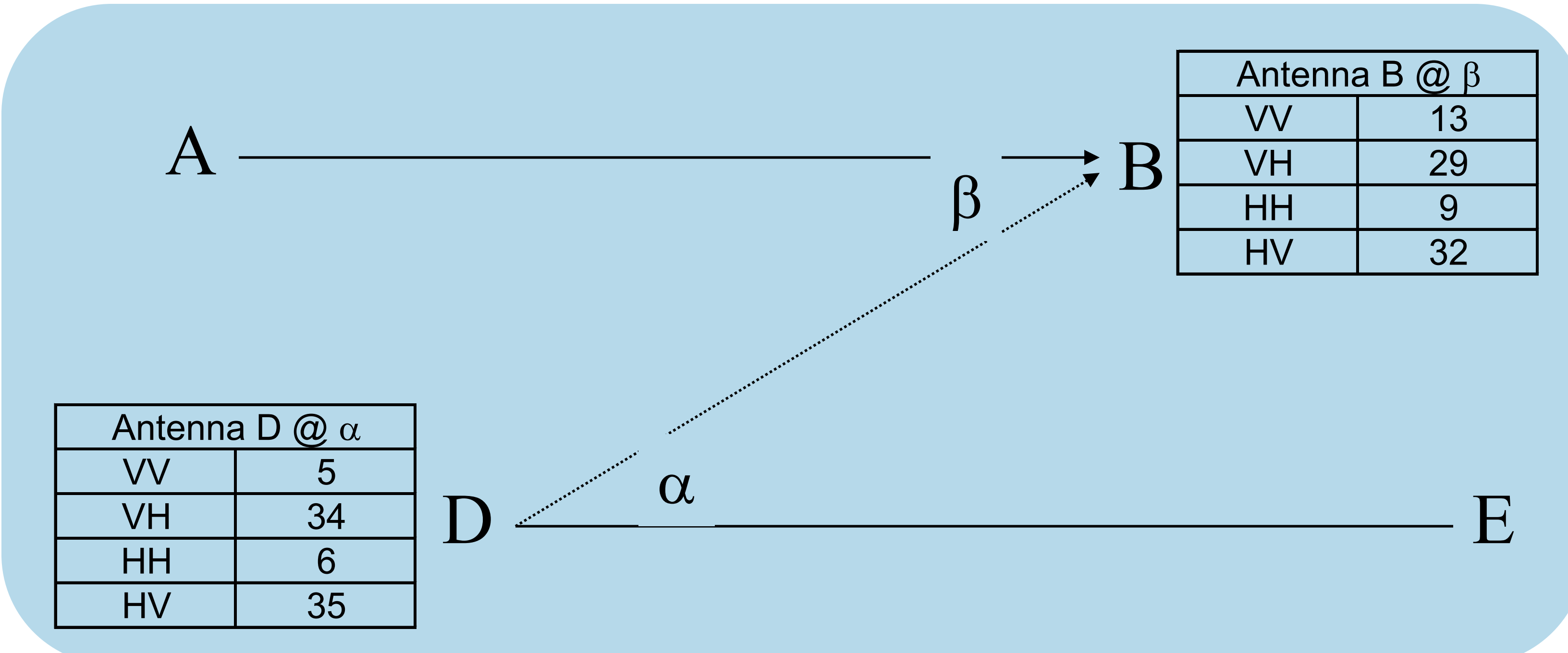
- **Total Discrimination**



Antenna B @ β	
VV	13
VH	29
HH	9
HV	32

Antenna D @ α	
VV	5
VH	34
HH	6
HV	35

Interference Calculations

- **Example**

  We suspect that a transmitter 40 miles away is a source of potential interference to a receiver on our 20 mile 6.175 GHz path. The power of both transmitters is 1 W (30 dBm). Assuming that all antenna gains are 40 dB, all line losses are 0 dB, that we are concerned about VV interference, and that the total discrimination is 18 dB as calculated on the previous slide, what is the C/I?

  - **C = 30+40-138.4+40 = -28.4 dBm**
  - **I = 30+40-144.4+40-18 = -52.4 dBm**
  - **C/I = -28.4 -(-52.4) = 24 dB**

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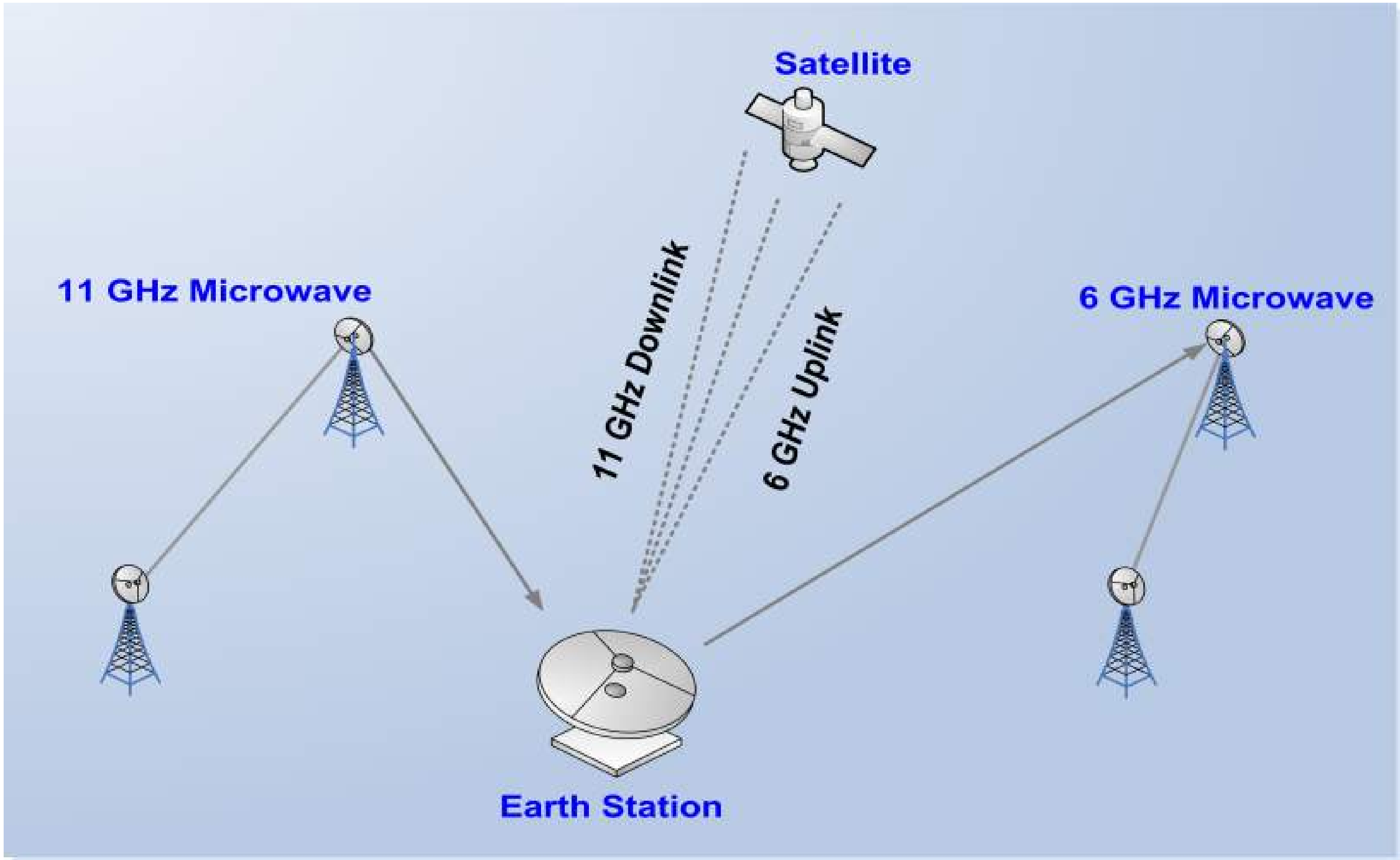
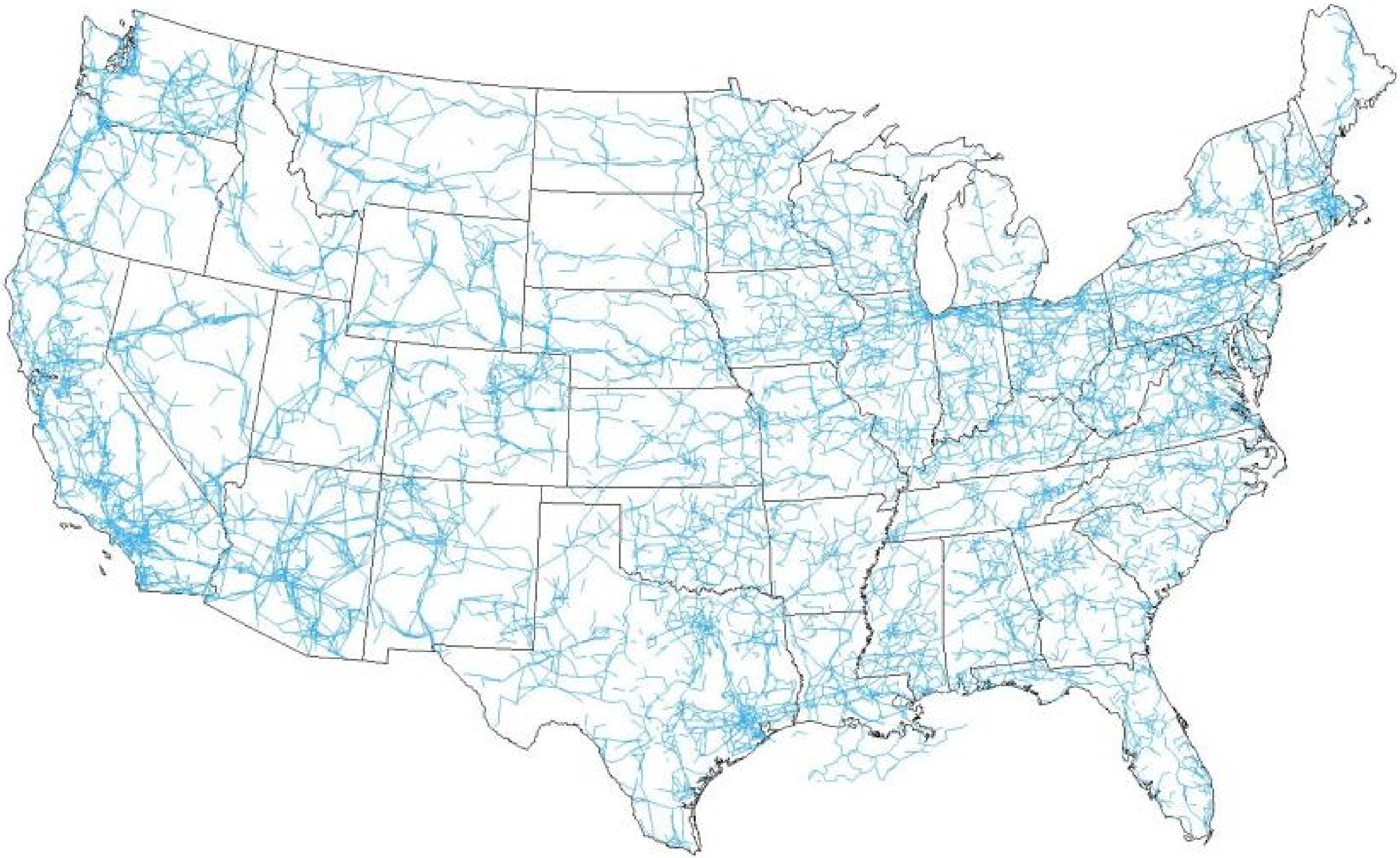
Frequency Planning

- **Earth Station Interference**



US 6.1 GHz Microwave Systems – May 2011



Thank You

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