Engineering Microwave Links

Jeremy D. Ruck, PE

WBA Broadcasters Clinic - October 12, 2016


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Main Topics

- Emission designators.
- Path profiles.
- Fresnel zone.
- Propagation.
- Link budgeting.
- Reliability.
- Diversity.
- Coordination and rules.

Emission Designators

- Series of 9 characters describing transmission.
- Current scheme in place since 1990s.
- Necessitated by new modes.
- Last two characters not used by FCC.
- First four characters describe bandwidth.
- Fifth character describes main carrier modulation type.
- Sixth character describes nature of modulating signal.
- Seventh character describes type of information.
- Eighth character (if used) describes details of signal.
- Ninth character (if used) describes nature of multiplexing.

Emission Designators

- First four are three numerals and one letter.
- Letter occupies decimal point location.
- Letter describes unit of bandwidth.
- First character cannot be zero, K, M, or G.
- Bandwidth of 0.001 to 999 Hz is expressed in Hertz (H).
- Bandwidth of 1.00 to 999 kHz is expressed in kHz (K).
- Bandwidth of 1.00 to 999 MHz is expressed in MHz (M).
- Bandwidth of 1.00 to 999 GHz is expressed in GHz (G).

Emission Designators

- Bandwidth Examples

0.002 Hz = H002

500 kHz = 500K

1.25 MHz = 1M25

180.5 kHz = 181K

6 kHz = 6K00

5.65 GHz = 5G65

25 MHz = 25M0

180.7 kHz = 181K

Emission Designators

- Fifth symbol type of main carrier modulation.
- Seven main breakdowns.
- 1. Emission of an unmodulated carrier.
- 2. Emission of amplitude modulated main carrier.
- 3. Emission of angle modulated main carrier.
- 4. Emission of amplitude & angle modulated main carrier.
- 5. Emission of pulses.
- 6. Cases not covered above where main carrier is modulated in two or more modes.
- 7. Cases not otherwise covered.

Emission Designators

- Fifth symbol is a letter.

Emission of unmodulated carrier	N	**Main carrier is amplitude and angle modulated simultaneously or in sequence**	D
Amplitude Modulated Main Carrier:		**Emission of Pulses:**	
Double-sideband	A	Sequence of unmodulated pulses	P
Single-sideband, full carrier	H	Pulse sequence modulated in amplitude	K
Single-sideband, reduced or variable carrier	R	Pulse sequence modulated in width/duration	L
Single-sideband, supressed carrier	J	Pulse sequence modulated in position/phase	M
Independent sidebands	B	Pulse sequence where carrier is angle modulated during pulse period	Q
Vestigial sidebands	C	Pulse sequence as combination of foregoing or produced by other	V
Angle-Modulated Main Carrier:		**Cases not covered above, in which an emission consists of the main carrier modulated, either simultaneously or in sequency, a combination of two or more of**	W
Frequency Modulation	F		
Phase Modulation	G	**Cases not otherwise covered**	X

Emission Designators

- Sixth symbol is (generally) a number.
- Seventh symbol is a letter.

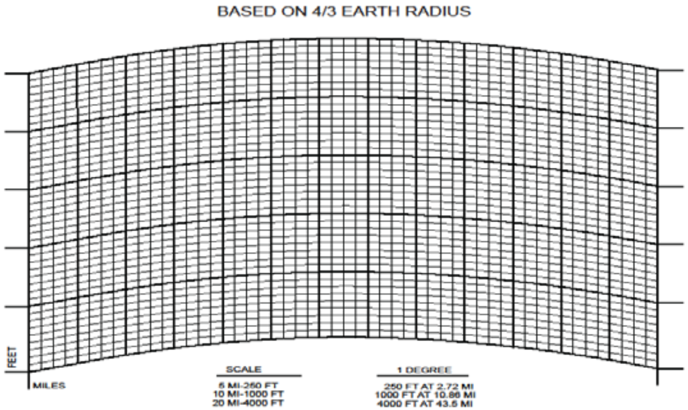
Nature of Signal(s) Modulating Main Carrier (sixth character)		Type of Information to be Transmitted (seventh character)	
No modulating signal	0	No information transmitted	N
A single channel containing quantized or digital information without the use of a modulating sub-carrier, excluding time-division multiplex	1	Telegraphy - for aural reception	A
A single channel containing quanitized or digital information with the use of a modulating sub-carrier, excluding time-division multiplex	2	Telegraphy - for automatic reception	B
A single channel containing analog information	3	Facsimile	C
Two or more channels containing quanitized or digital information	7	Data transmission, telemetry, telecommand	D
Two or more channels containing analog information	8	Telephony (including sound broadcasting)	E
Composite system with one or more channels containing quanitized or digital information, together with one or more channels containing analog information	9	Television (video)	F
Cases not otherwise covered	X	Combination of the above	W
		Cases not otherwise covered	X

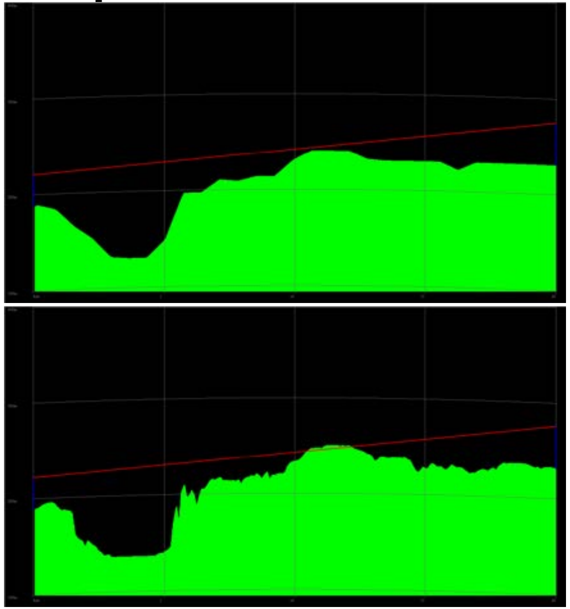
Emission Designators

- 6K00A3E – Double sideband AM voice
- 200KF3E – Broadcast FM
- 5M75C3F – NTSC Video
- 25K0F3E – NTSC Aural Carrier
- 6M00C7W – ATSC Video
- 180KF3E – Mono Aural STL
- 300KF8E – Typical Stereo Aural FM STL
- 500KD7W – Digital Aural STL system
- 25M0F9W – TV STL System

Path profiles

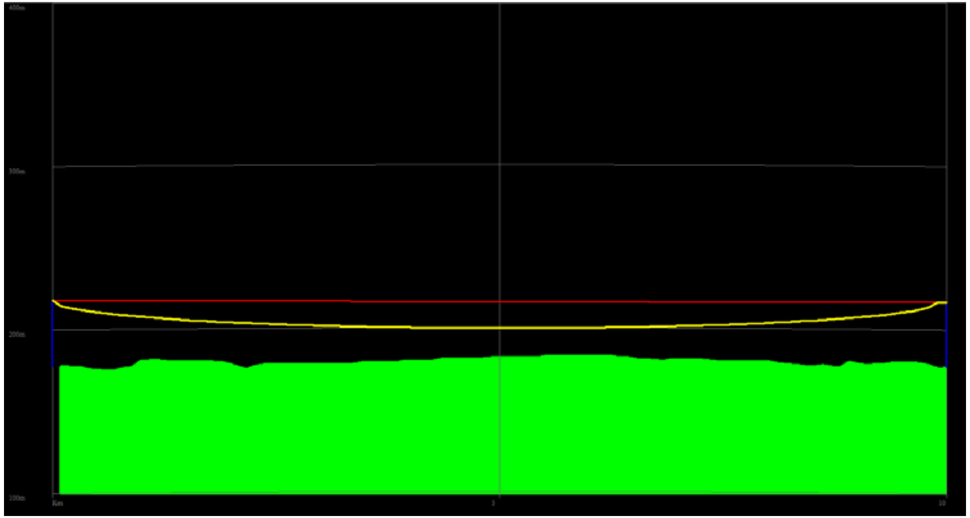
- Digitized terrain databases.
- Old method picked elevations from maps.
- Earth radius graph paper.





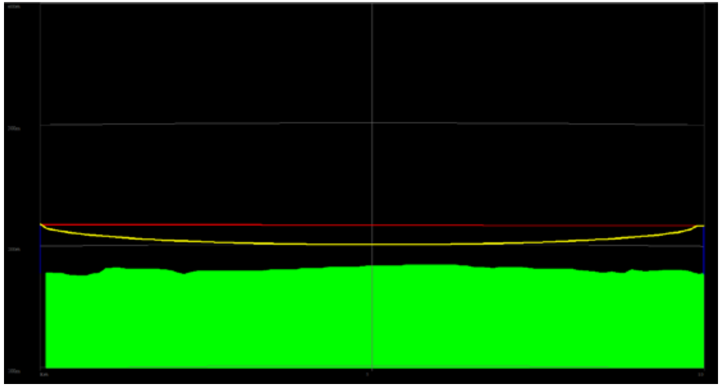
Path profiles

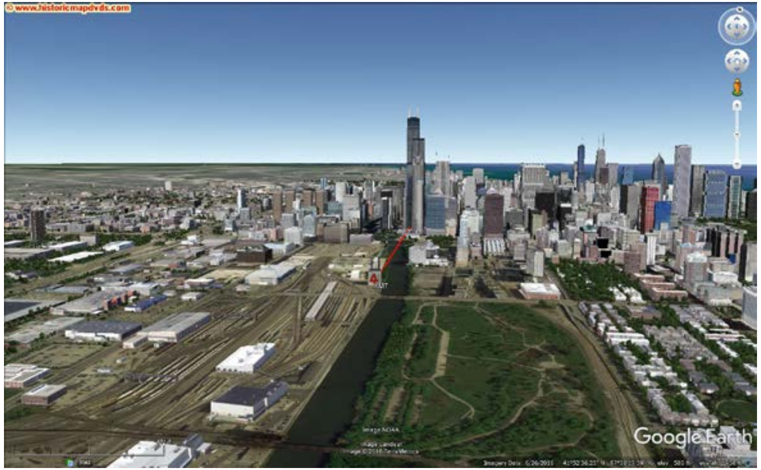
- Check path for accuracy.
- Check path for obstructions.
- Do not rely 100% on databases.



Path profiles

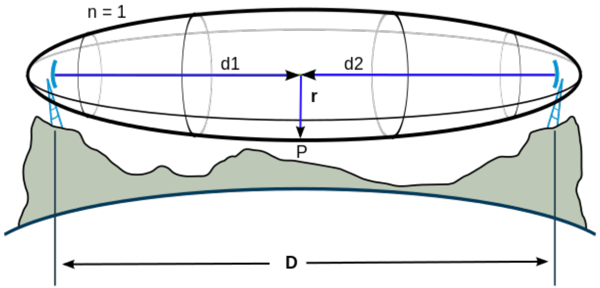
- Note significant man made obstructions.

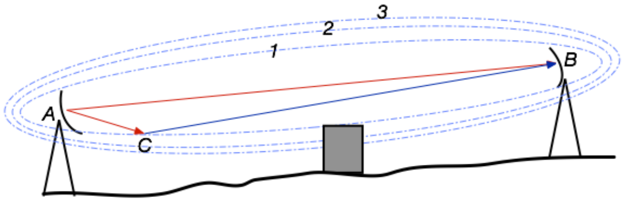




Path Profiles

- Lack of path obstructions is not sufficient.
- Optical line of sight versus radio line of sight.
- Radio line of sight takes into account Fresnel ellipsoids.
- Electromagnetic waves near objects are refracted.
- Refraction affects strength of received signal.
- Avoid line of sight issues in path designs.



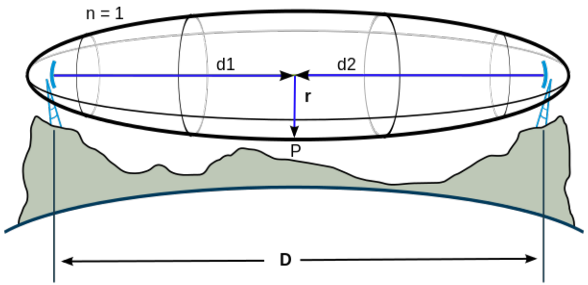


Fresnel Zones or Radii

- Concentric ellipses.
- Zones are multiples of λ/2 path length differences.
- Zone radius is frequency dependent, and in general:

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

$$d_1, d_2 >> n\lambda$$



- First Fresnel Radius:

$$F_1 = 8.656\sqrt{\frac{D(km)}{f\,(GHz)}}m$$

$$F_1 = 36.03\sqrt{\frac{D(mi)}{f\,(GHz)}}ft$$

Fresnel Zones or Radii

- Higher order Fresnel radii are also important.
- Even numbered zones radius are $\lambda/2$ multiples.
- Check even numbered zones for smooth tangential paths.
- Large bodies of water are a particular problem.
- Ground clearance of 60% of first Fresnel zone radius.
- Remember to account for foliage and structures.

Propagation Stuff

- Refraction occurs. Results in bending of beam.
- Described by index of refraction.
- Depends on humidity, temperature, and pressure.
- Varies location to location and time to time.
- Refractivity can be calculated. Our interest is in gradient.
- We use gradient (G) to calculate earth-radius factor (k)

$$k = \frac{157}{157 + G}$$

G (N-unit/km)	k	Conditions
79	0.67 (2/3)	Subrefraction
0	1	Normal
-39	1.33 (4/3)	Normal
-79	2	Normal
-157	∞	Superrefraction
<-157	< 0	Trapping (ducting)

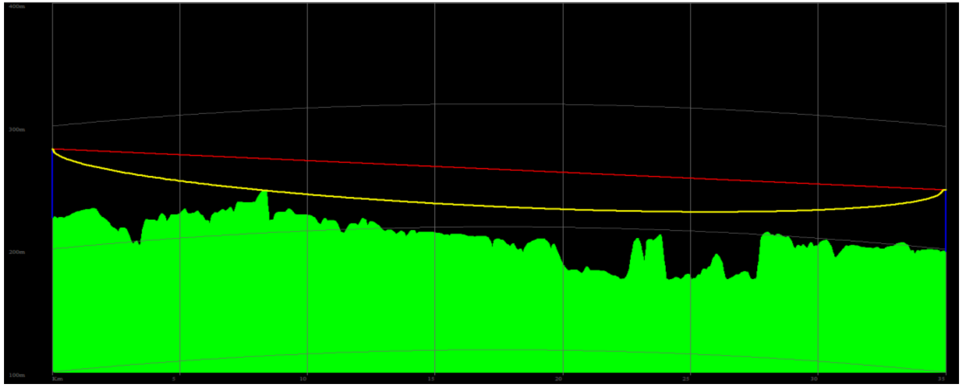
Propagation Stuff

- k factor compensates for refraction in atmosphere.
- Application to true radius yields effective earth radius.
- Standard value is 4/3. Use if no local value provided.
- Lower values lower line of sight.
- This necessitates greater antenna heights.
- Typical k values in the United States:

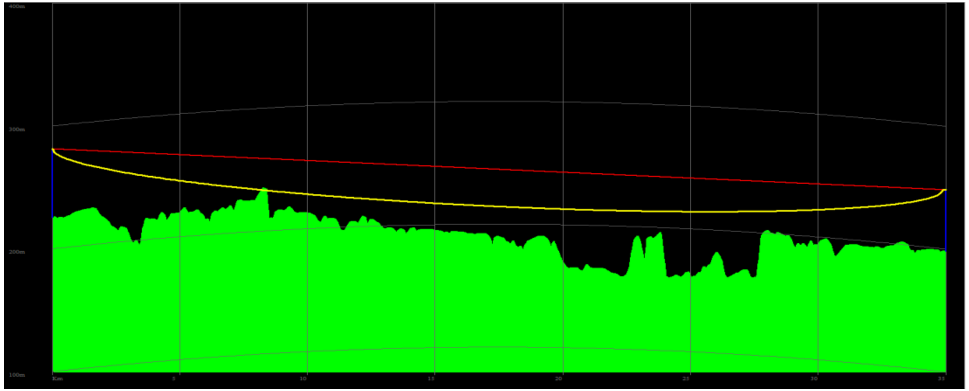
	Summer	Winter
Dry mountains (above 1,500 m)	1.20	1.20
Mountains (to 1,500 m)	1.25	1.25
Midwest and Northeast	1.50	1.30
South and West Coast	1.55	1.35
Southern Coast	1.60	1.50

Propagation Stuff

- k = 1.33



- k = 1.20

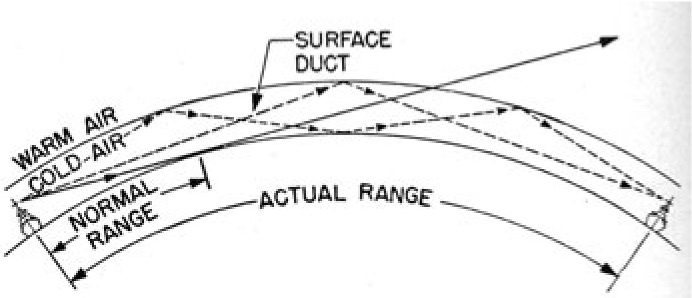


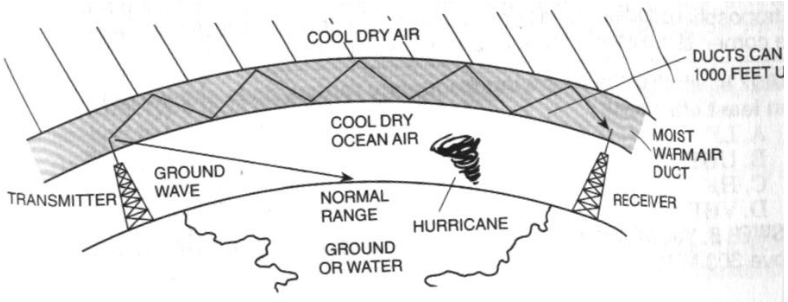
Propagation Stuff

- Free-Space – isotropic, homogeneous, lossless media.
- Reflection – surface based, especially water.
- Diffraction – path obstruction by impenetrable body.
- Scattering – objects in path smaller than wavelength.
- Subrefraction – ray bends away from earth. Rare.
- Superrefraction – ray bends down. Inversion.
- Ducting – related to superrefraction.

Ducting

- Incident angle approximately 1°.
- Aloft air warm and dry for surface based.
- Surface based on leeward side of land.
- Surface based may extend long distances.
- Elevated ducts are caused same way.
- Land based typically lowest 200 meters.

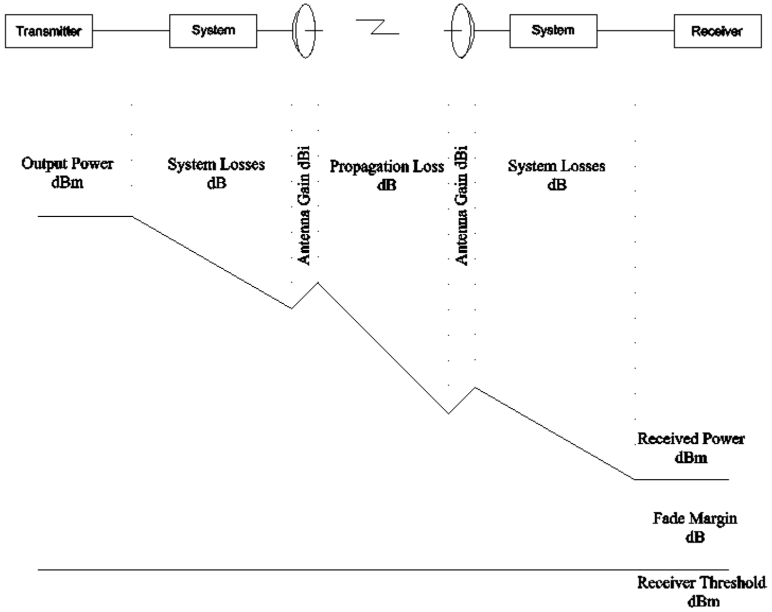




Tropospheric Ducting

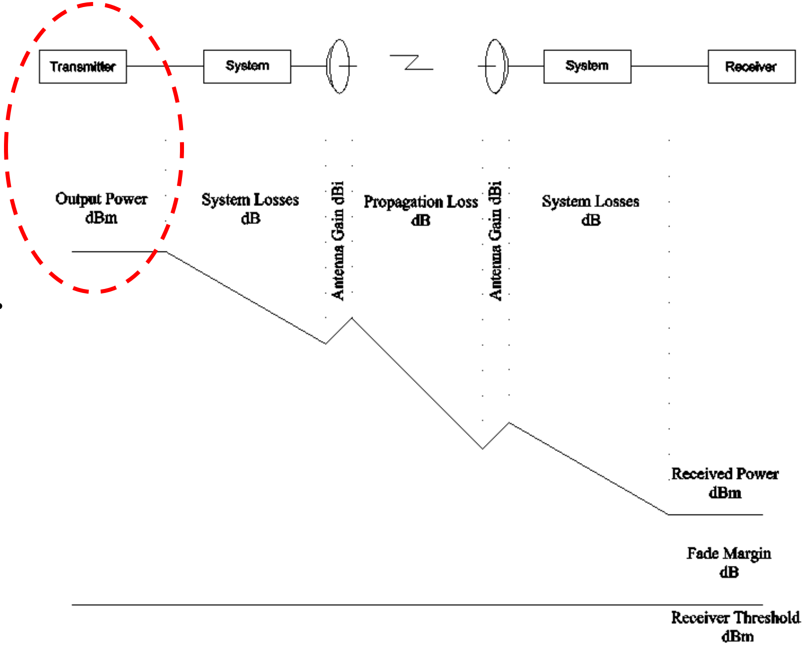
Link Budget

- The heart of a link design.
- Start with transmitter power.
- Subtract system losses on transmit side.
- Add transmit antenna gain.
- Subtract propagation losses.
- Add receive antenna gain.
- Subtract system loss on receive side.
- Received power level obtained.
- Subtract receiver threshold for fade margin.



Link Budget

- Transmit power specified in dBm.
- dBm is decibels relative to one milliwatt.
- Convert watts to milliwatts.
- Base 10 logarithm of power in milliwatts.
- Multiply this value by 10. Result is dBm.



- Example: Convert 10 Watts to dBm

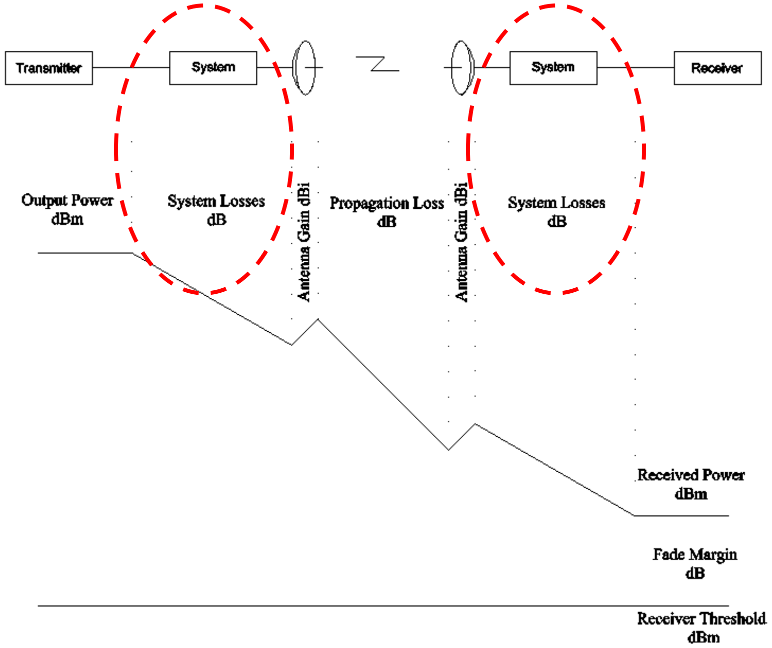
$$P_{(dBm)} = 10 \cdot \log_{10}(1000 \cdot 10)$$

$$P_{(dBm)} = 10 \cdot \log_{10}(10000) = 10 \cdot 4$$

$$P_{(dBm)} = 40$$

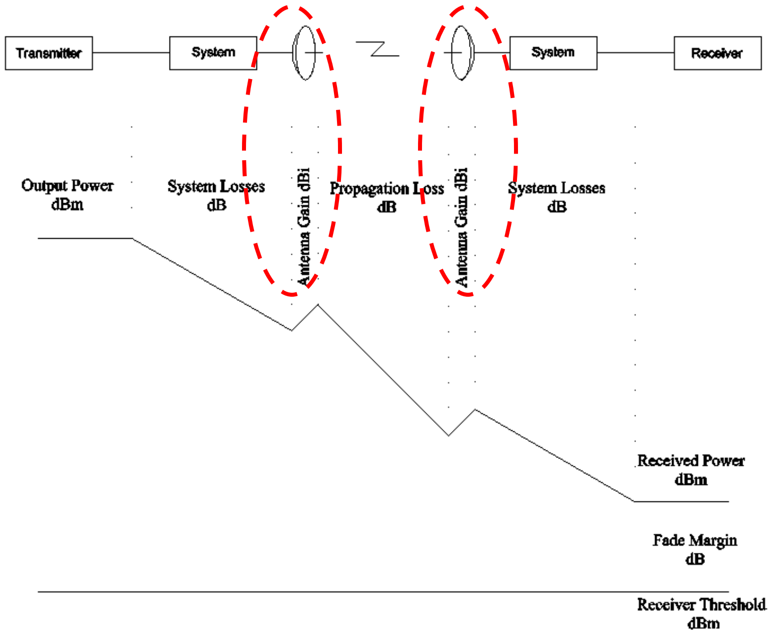
Link Budget

- Transmitter to antenna components.
- Attenuation values specified in dB.
- Sum losses of all components.
- Transmission line.
- Connectors.
- Splitters.
- Circulators.
- Filters.
- Same procedure on other side.



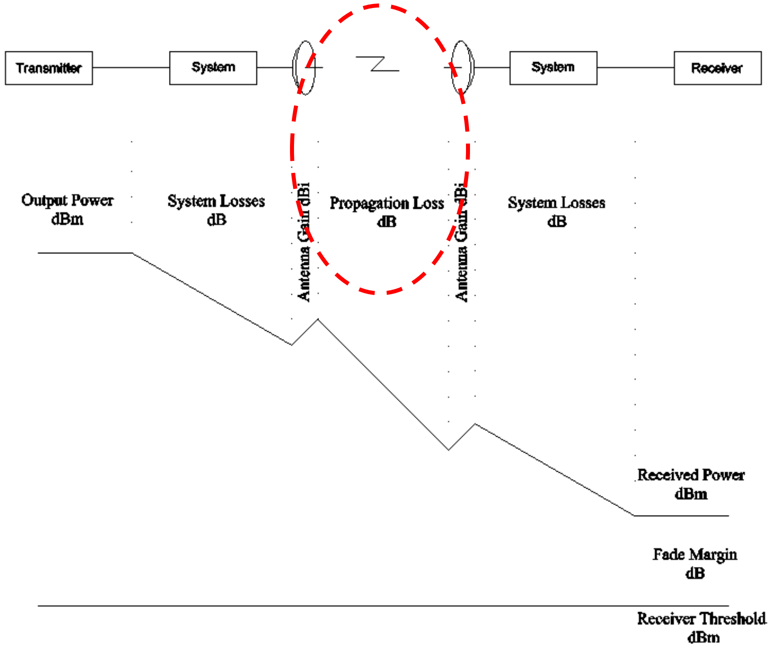
Link Budget

- Antenna gain typically specified dBi.
- Isotropic gain 2.15 dB above dipole gain.
- Antenna gain subtracted from losses.
- Larger antennas = higher gain.



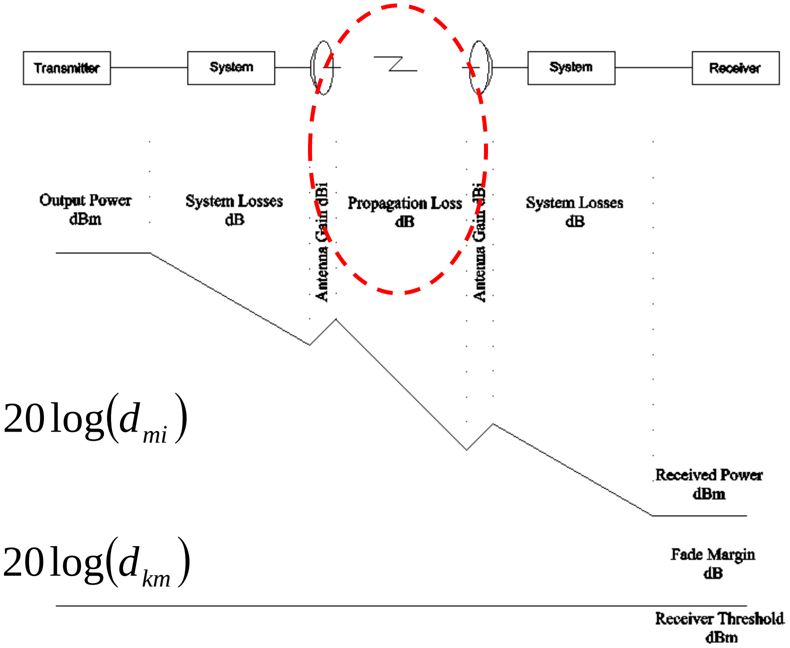
Link Budget

- Free-space losses.
- Vegetation absorption.
- Gas absorption.
- Obstacle losses.



Link Budget – Free Space Loss

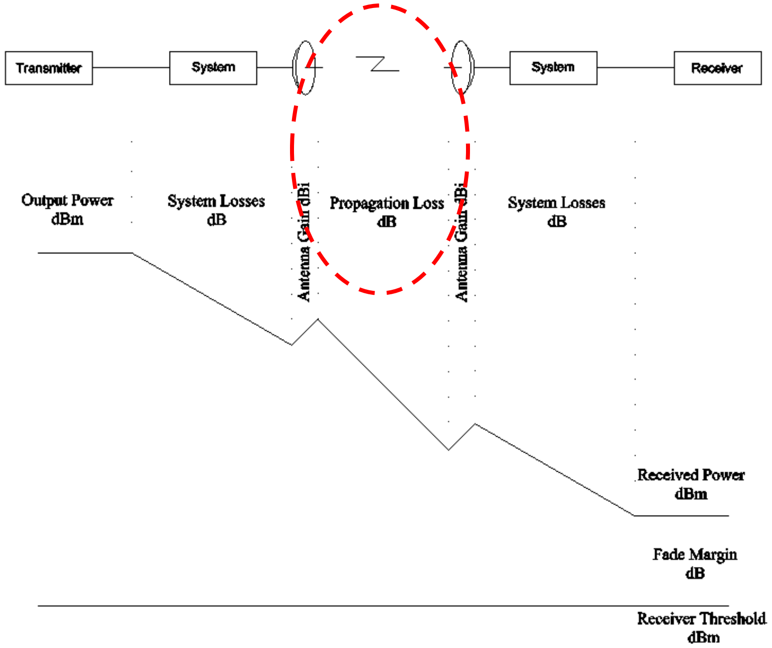
- Free-space loss always present.
- Dependent on distance and frequency.



- Absolute numbers: $$L_{FSL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$$
- In terms of km: $$L_{FSL} = 96.60 + 20\log(f_{GHz}) + 20\log(d_{mi})$$
- In terms of miles: $$L_{FSL} = 92.45 + 20\log(f_{GHz}) + 20\log(d_{km})$$
- +6 dB EIRP ~ doubling of range

Link Budget – Vegetation Absorption

- Avoid foliage if possible.
- Consider growth of foliage.
- Path surveys critical.
- Foliage Loss in dB: $L = 0.2 f^{0.3} d^{0.6}$
- Early empirical model.
- Valid for f = 200 MHz to 95 GHz.
- Depth < 400 m.
- Example: 1 GHz path, foliage depth 3 m:



$$L = 0.2 f^{0.3} d^{0.6} = 0.2 \cdot (1000)^{0.3} (3)^{0.6} = 0.2 \cdot (7.94) \cdot (1.93) = 3.1$$

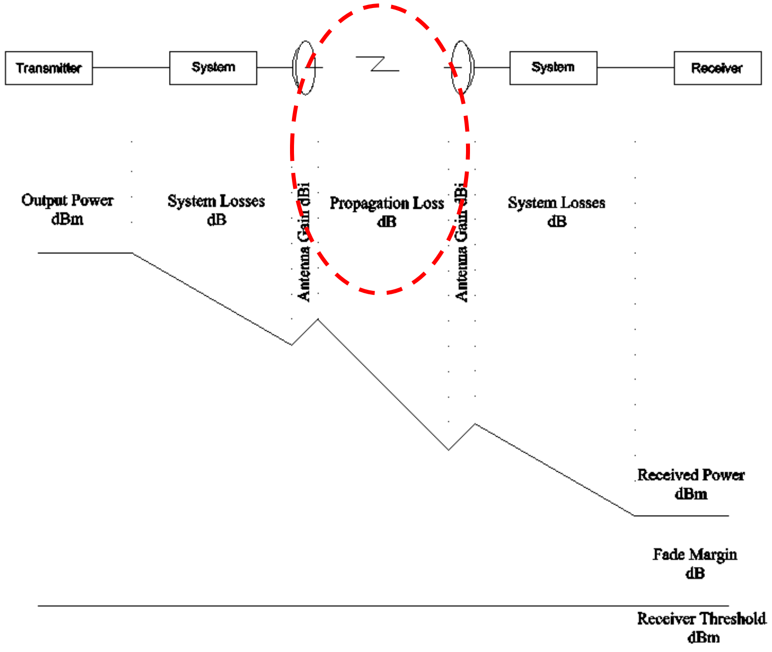
Link Budget – Vegetation Absorption

- Weissberger model is alternate.
- Yields slightly different results.

$$L = 0.45 f^{0.284} d \qquad 0 < d \le 14m$$

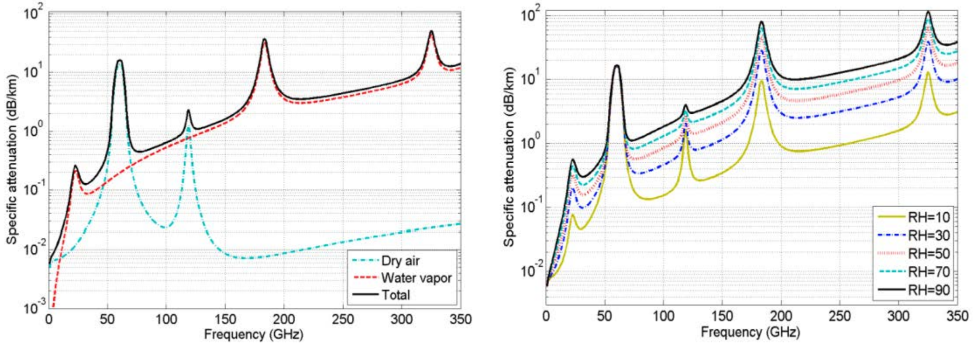
$$L = 1.33 f^{0.284} d^{0.588} \qquad 14 < d \le 400m$$

- Applicable for dense, dry, in-leaf trees.
- Applicable for temperate latitude forests.
- Other newer models developed.

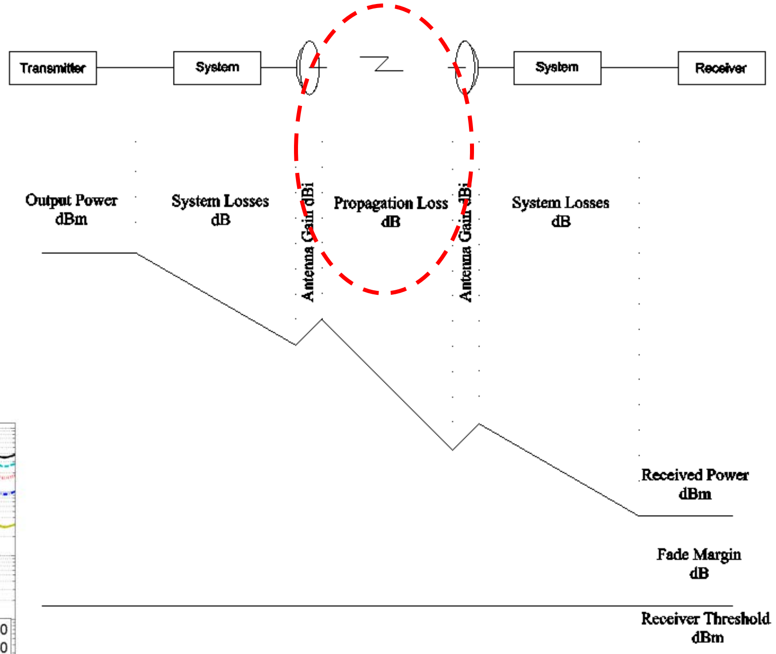


Link Budget – Gas Absorption

- Nitrogen and Oxygen 99% volume.
- Nitrogen can be neglected.
- Assume atmosphere O2 and H2O.
- Water vapor absorption ~23 GHz.
- Oxygen (dry air) absorption ~60 GHz.



(a) (b)



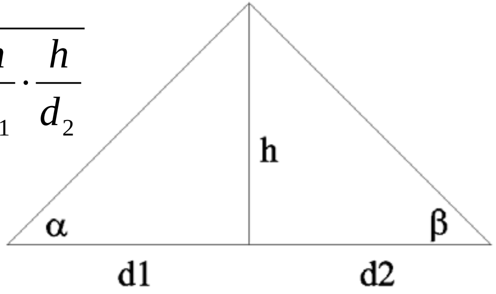
Link Budget – Obstacle Losses

- Calculations can be cumbersome.
- Estimate for single knife edge.

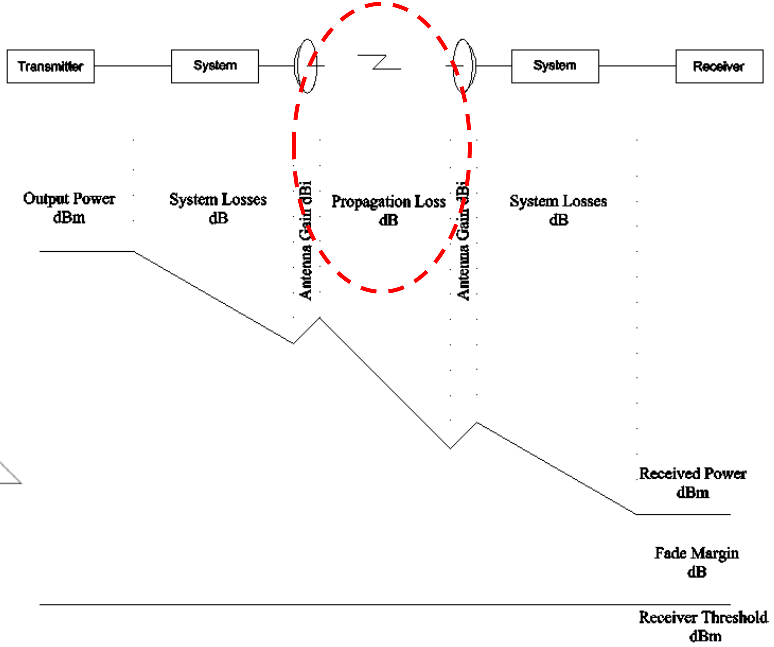
$$d = d_1 + d_2$$

$$\upsilon = \sqrt{\frac{2d}{\lambda}\tan\alpha\tan\beta} = \sqrt{\frac{2d}{\lambda}\cdot\frac{h}{d_1}\cdot\frac{h}{d_2}}$$

$$\upsilon = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}}$$



$$A(\upsilon) \approx \begin{cases} 6.02 + 9\upsilon + 1.65\upsilon^2 & -0.8 \le \upsilon \le 0 \\ 6.02 + 9.11\upsilon - 1.27\upsilon^2 & 0 < \upsilon \le 2.4 \\ 12.953 + 20\log\upsilon & \upsilon > 2.4 \end{cases}$$



Link Budget – Obstacle Losses

- Assume single tree on 7 GHz, 10 mile long path. Distance to the tree is 1 mile. The obstacle height is 30 feet above the center of the Fresnel zone. What is the diffraction attenuation?

$$1mi = 5280\,ft$$

$$d_1 = 1mi = 5280\,ft$$

$$d_2 = 9mi = 47520\,ft$$

$$\lambda = \frac{c}{f} = 0.1405\,ft$$

$$h = 30\,ft$$

$$\upsilon \approx 30\sqrt{\frac{2 \cdot 52800}{0.1405 \cdot 5280 \cdot 47520}} \approx 1.6$$

$$A(\upsilon) \approx 6.02 + 9.11(1.6) - 1.27(1.6)^2$$

$$A(\upsilon) \approx 6.02 + 14.58 - 3.25$$

$$A(\upsilon) \approx 17.35$$

Link Budget – Obstacle Losses

- Note this is for obstructed path. Not good idea.
- But note what happens for h=0 cases:

$$\upsilon = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} = 0$$

$$A(\upsilon) \approx 6.02 + 9\upsilon + 1.65\upsilon^2$$

$$A(\upsilon) \approx 6.02$$

- This is the case for grazing paths.
- Quick approximations.
- Other models are more rigorous.

Highly Variable Path Losses

- Ground reflections.
- Multipath fading.
- Flat fading.
- Rain/Precipitation fading.
- Refraction-Diffraction fading.

Path Reliability – Vigants model

- Primarily used in North America.
- Other models available.
- Frequency and distance dependent.
- Also dependent on climate and terrain.

$$P = 2.5\times10^{-6} cfd^{3} 10^{\frac{-CFM}{10}}$$

Path Reliability – Vigants model

$$P = 2.5 \times 10^{-6} c f d^{3} 10^{\frac{-CFM}{10}}$$

- P = one-way probability of fading
- f = frequency (GHz)
- d = path length (mi)
- CFM = composite fade margin
- c = climate/terrain factor
- c=4 over water/humid climate, 1 for average terrain/climate, 0.25 for mountains and dry climate.

Path Reliability – Vigants model

- Model allows up to find outage time.
- First calculate fade duration: $$T_0 = 8\times10^6 \cdot \frac{t}{50}$$
- Annual average temperature based. (35°F < t < 75°F)
- Outage time: $$SES = T_0 \cdot P$$
- Reliability: $$R_{\%} = 100 - \left(\frac{SES}{315576} \right)$$

Path Reliability - Example

- Determine reliability of 30 mile 7 GHz path, for average terrain and climate, with an average annual temperature of 40° F, and a composite fade margin of 36 dB.

$$P = 2.5\times10^{-6} cfd^3 10^{\frac{-CFM}{10}}$$

$$P = 2.5\cdot10^{-6}\cdot1\cdot7\cdot30^3\cdot10^{\frac{-36}{10}}$$

$$P = 1.19\times10^{-4} = 0.000119$$

$$T_0 = 8\times10^6\cdot\frac{40}{50} = 6.4\times10^6$$

$$SES = (0.000119)\times(6.4\times10^6)$$

$$SES = 762/yr$$

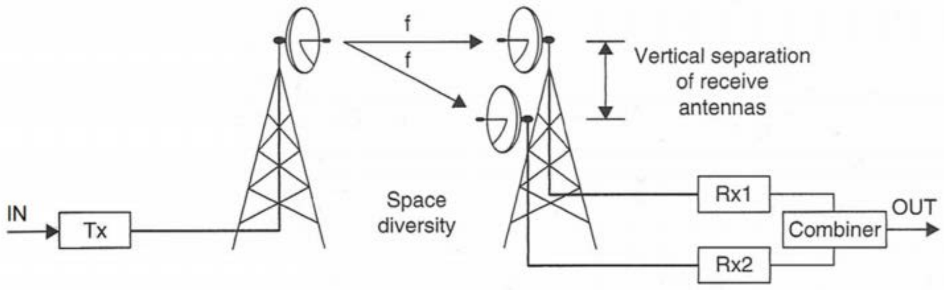
$$R_{\%} = 100 - \left(\frac{SES}{315576}\right) = 99.9976\%$$

- How does this compare with Ma Bell standards?

Path Reliability - Example

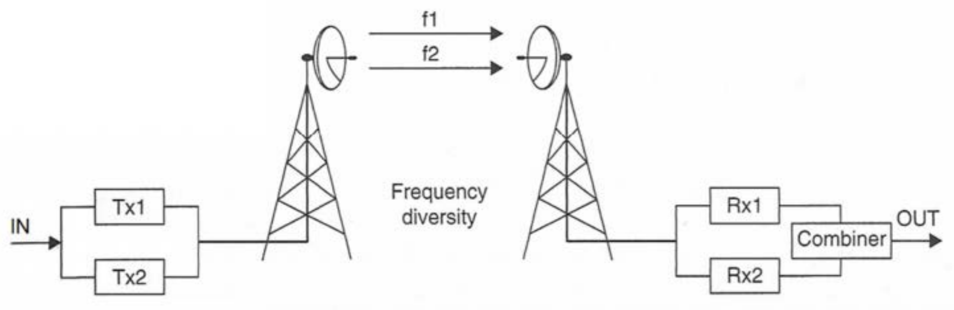
- 6.4 SES/mi/yr for <250 mile end-to end paths.
- 0.8 SES/mi/yr for >250 mile end-to end paths.
- In this case 192 SES/yr (6.4 SES/mi/yr x 30 miles)
- Yields reliability of 99.9994%
- Our reliability 99.9976%
- Nearly ten minutes difference in outage time.
- How do we fix?

Diversity Techniques



- Space diversity.
- Receive antennas vertically separated.
- Two paths are created.
- Path mechanics are variable.
- Separation can be hundreds of wavelengths in several feet.
- Paths are impacted differently.

Diversity Techniques



- Frequency diversity.
- Two different frequencies are utilized.
- Typical separation of 2% in frequency.
- Fading reduction of around 15 dB.

Coordination

- Licensed facilities must be coordinated.
- Coordination procedures in 74.502, 74.638, 101.103.
- Notification and Response.
- Expedited versus “regular” coordination.
- Coordination requires certification.
- Six month time frame.
- Major changes must be coordinated.

Major technical changes (see 47 CFR 1.929)

- Lat/Lon change greater than 5 seconds.
- Increase in frequency tolerance.
- Increase in bandwidth.
- Change in emission type.
- EiRP increase greater than 3 dB.
- Transmit antenna height increase of >3 meters AMSL.
- Increase in antenna beamwidth.
- Change to transmit antenna polarization.
- Azimuth changes of greater than one degree.
- Any change with all minor mods produce cumulative effect.

Thank You!

Comments and Questions?

Jeremy D. Ruck, PE

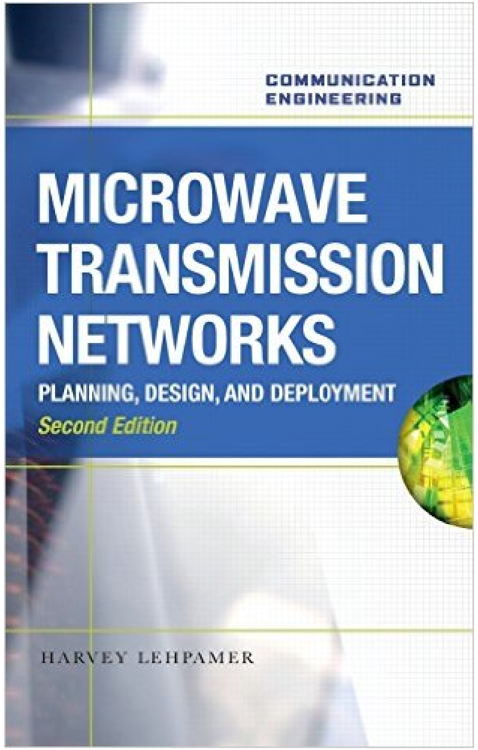
Jeremy Ruck & Associates, Inc.

jeremy@jeremyruck.com

309.647.1200

Recommended Reading

- Microwave Transmission Networks – Planning, Design, and Deployment.
- Second Edition.
- Author: Harvey Lehpamer.
- Publisher: McGraw-Hill
- ISBN 978-0-07-170122-8
- Available from NAB and SBE bookstores.



References

- Slides 12 & 13 - By Jcmcclurg (FresnelSVG.svg) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons"Available from: https://commons.wikimedia.org/wiki/File%3AFresnelSVG1.svg
- Slide 12 - By Jugandi [Public domain], via Wikimedia Commons="1st Fresnel Zone Avoidance" Available from: https://upload.wikimedia.org/wikipedia/commons/4/4b/1st_Fresnel_Zone_Avoidance.png
- Slide 19 - http://www.angelfire.com/sc/scannerpost/images/duct.jpg
- Slide 28 - Ali Mohammed Al-Saegh, A. Sali, J. S. Mandeep, Alyani Ismail, Abdulmajeed H.J. Al-Jumaily and Chandima Gomes (2014). Atmospheric Propagation Model for Satellite Communications, MATLAB Applications for the Practical Engineer, Mr Kelly Bennett (Ed.), InTech, DOI: 10.5772/58238. Available from: http://www.intechopen.com/books/matlab-applications-for-the-practical-engineer/atmospheric-propagation-model-for-satellite-communications.
- Slides 38 & 39 – Harvey Lehpamer (2010). Microwave Transmission Networks: Planning, Design, and Deployment, Second Edition. Published by McGraw-Hill. Figure 3.11 page 139. ISBN 978-0-07-170122-8.