Terrestrial fixed links

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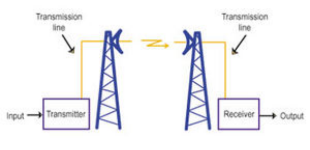
Outline

Point-to-point terrestrial link

What they are and why we do care



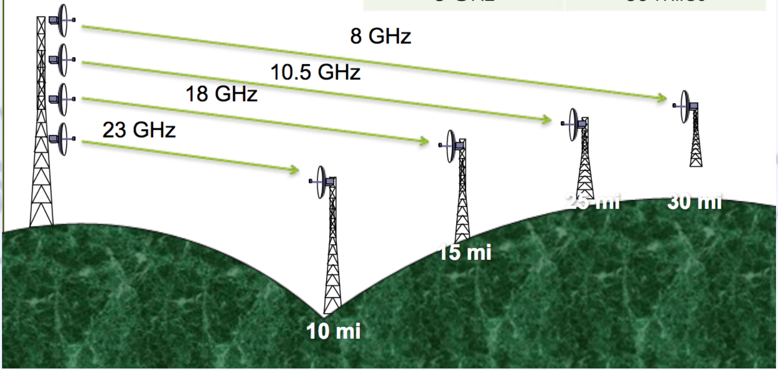
- It consists of two antennas mounted on tall masts.
- Antennas (high directivity) are separated by tens or hundreds of km.
- TX/RX antennas are located in places free of any clutter.
- It provides reliable and high speed data links.
- It may serve as main communication link or as back-up configuration.
- It usually exploits VHF and above.

High-frequency

- High frequency beams of radio waves provide high speed wireless connections that can send and receive voice, video, and data information.
- Microwave links are are widely used for point-to-point communications because their small wavelength allows conveniently-sized antennas to direct them in narrow beams, which can be pointed directly at the receiving antenna.
- The high frequency of microwaves gives the microwave band a very large information-carrying capacity; the microwave band has a bandwidth 30 times that of all the rest of the radio spectrum below it.

Frequency planning

Frequency	Path Length
23 GHz	10 miles
18 GHz	15 miles
10.5 GHz	25 miles
8 GHz	30 miles



Long-haul

- The most commonly used frequencies for common-carrier long-haul communications are the 4 GHz, 6 GHz and 11 GHz bands.
- The 12 GHz band is used as a component of the cable TV (CATV) system. Microwave links are used to provide TV signals to local CATV installations, and the signals are then distributed to individual subscribers via coaxial cable.
- For short point-to-point links between buildings, the 22 GHz band is typically used.
- The higher frequencies are less useful for longer distances because of attenuation, but are adequate for short distances.
- In addition, antennae are smaller and cheaper for the higher frequencies.

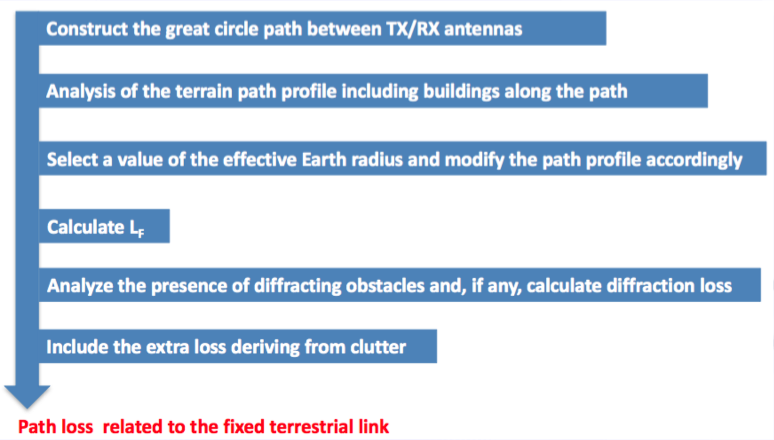
The longest microwave link

In 2016, the longest microwave link (189 km) ever turned up in a public mobile phone network went live in Tonga, Oceania.

- Key challenge of this project remained the 189km link. Not only the distance but also lack of height to provide predictable propagation.

Tonga has a perfect radio site - a 1000m high extinct volcano: Kao Island.

Key items to predict path loss



Outline

Construct the great circle path between TX/RX antennas

- It is the shortest path between TX/RX antennas along the Earth profile.
- It will not coincide with the straight-line TX/RX path drawn on a map, due to Earth's curvature. However, the difference is generally small.
- The analysis of propagation is restricted to phenomena arising from objects that are located along with the great circle path.
- This is a reasonable assumption at high frequency (Fresnel's zones relatively small) and/or for high directive antennas.

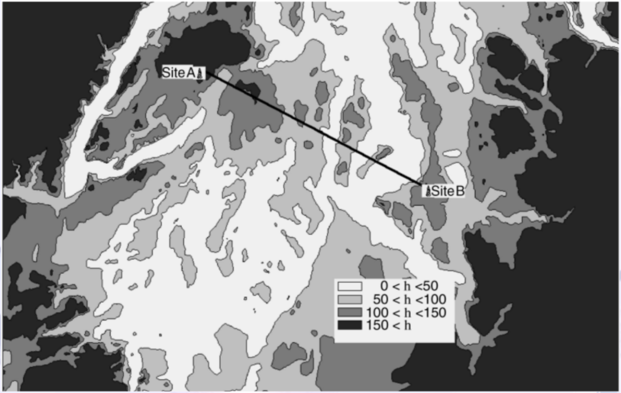
Great circle path - http://www.gcmap.com

Map Style: Plain Light Blue Marble

Distances

From	To	Initial Heading	Magnetic Heading	Distance
NAP (40°53'10"N 14°17'27"E)	MXP (45°37'50"N 8°43'41"E)	321° (NW)	318° (NW)	431 mi

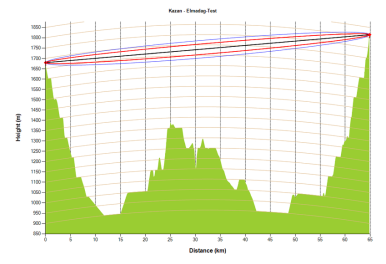
Great circle path - path profile



Great circle path between two sites “A” and “B”. Contours are marked with heights in meters asl.

Deriving the terrain path profile

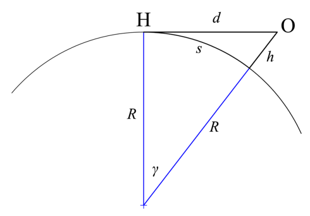
It consists of extracting the path profile (terrain heights) along with the constructed great circle path.



- It is based on photogrammetric maps.
- The terrain height is uplifted according to the Earth bulge, i.e.; the height of the Earth at mean sea level, to include the obstructing effects of the Earth curvature.

Correcting for the Earth's curvature

Earth's curvature must be accounted for since it limits the horizon distance of TX/RX antennas, even without obstacles.



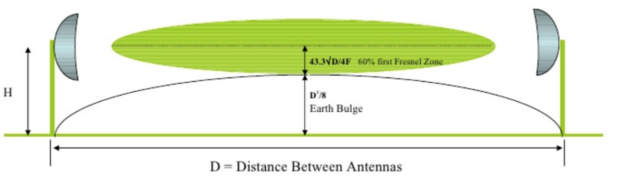
- The horizon distance is the largest distance on the Earth's surface that is visible from an antenna located at height h above the mean sea level:

$$d \approx \sqrt{2Rh} \qquad (1)$$

where $R \approx 6375\text{km}$ is the Earth radius.

Correcting for the Earth bulge

The Earth bulge, i.e.; the height of the Earth at mean sea level is used to uplift the terrain profile to include obstructing effects of the Earth curvature.



The Earth bulge is the main obstruction for long-range terrestrial communication systems in case of gentle variations of terrain.

Outline

Tropospheric refraction

- The refractive index of the Earth's atmosphere is slightly different from the free space one.

Atmospheric refractivity

- To better manage this slight difference, the atmospheric refractivity N is defined as follows:

$$N = (n - 1) \times 10^6. \quad (2)$$

- Hence, at Earth's surface $n = 1.000315$ becomes $N = 315$ N units.

Tropospheric refraction

- N varies both with height and with location. However, the variability with the height of the atmosphere is the most significant.

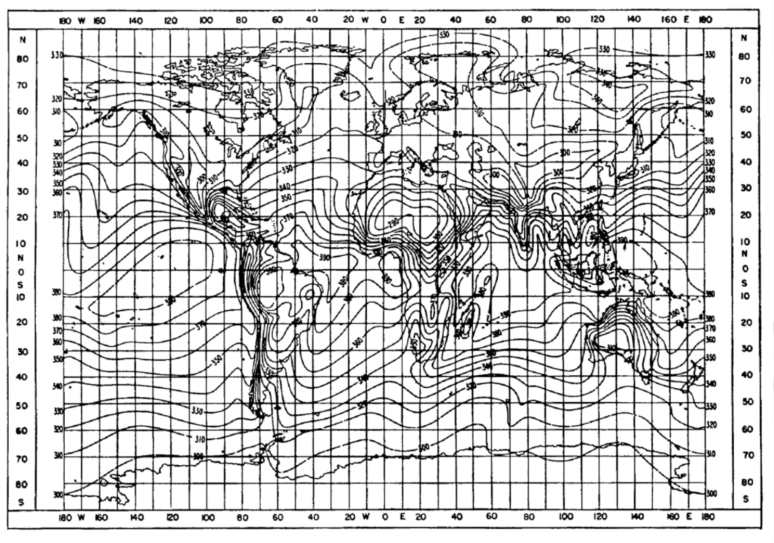
Standard atmosphere

- Within the troposphere, the following exponential law is assumed (standard atmosphere):

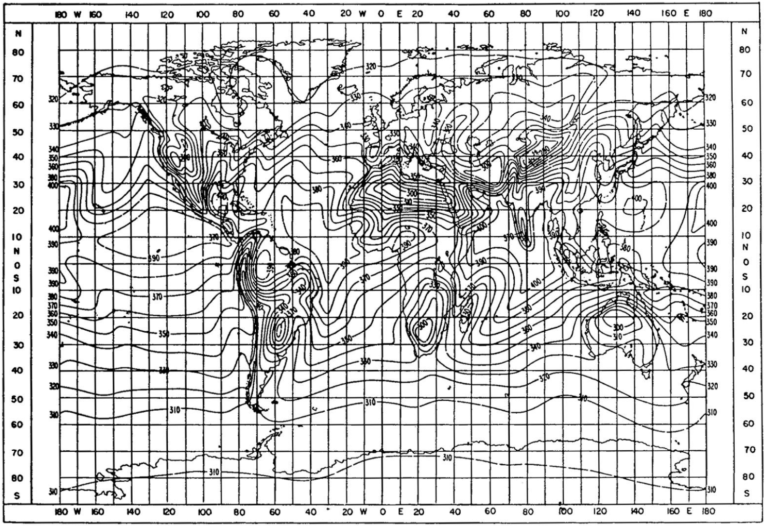
$$N = N_s e^{-\frac{h}{H}} \tag{3}$$

where h is the altitude; while $N_s \approx 315$ and $H = 7.35$km are the reference values for the height scale and the N value measured at the surface level, respectively. They both depend on the geographic area.

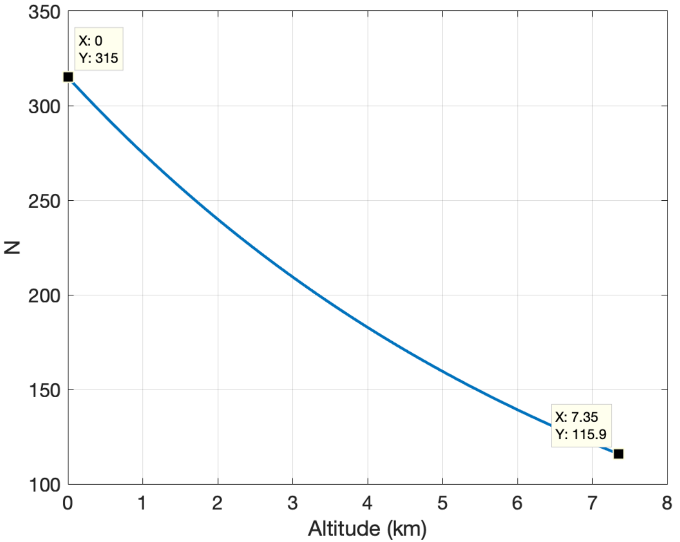
Average (5y) variability of N_s in February - ITU



Average (5y) variability of N_s in August - ITU

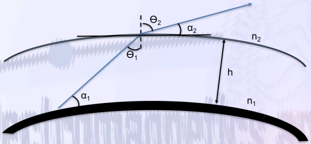


Standard atmosphere



Rays tend to curve towards the ground

Since $v_f = \frac{c}{n}$, em waves are slower when approaching the Earth's surface.



- This makes ray paths be no longer straights. They tend to curve towards the Earth's surface.
- Snell's law allows calculating this curvature assuming two layers calling for $n_2 > n_1$.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_1}{n_2} \tag{4}$$

Em waves and the interface are assumed to be locally plane.

Rays tend to curve towards the ground

Geometric optic (GO) considerations allow deriving a formula that expresses the curvature of the ray ρ at any point as a function of the height variability of n.

$$\frac{1}{\rho} = -\frac{\cos\alpha}{n}\frac{dn}{dh} \tag{5}$$

with α being the elevation angle at the refraction point.

The range of the antenna is extended

Although the ray curvature is not as large as the Earth's one, it is enough to make the ray propagating beyond the geometrical horizon distance calculated using eq.(1).

The lowest layer of the atm

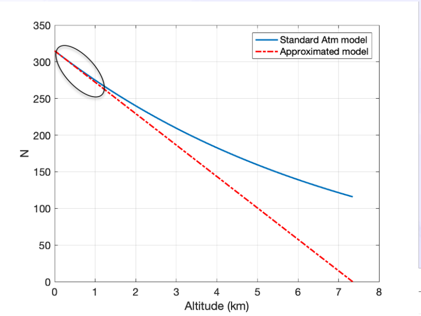
The statistics of the vertical gradient of radio refractivity in the lowest layer of the atmosphere are important parameters for the estimation of path clearance and propagation associated effects.

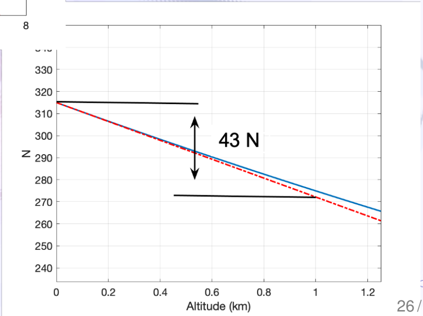
- For small heights, eq.(3) can be approximated as follows:

$$N \approx N_s \left(1 - \frac{h}{H}\right) \tag{6}$$

- This formula shows that, near the ground, N has approximately a constant gradient: $\Delta N = -43$ N units per km.

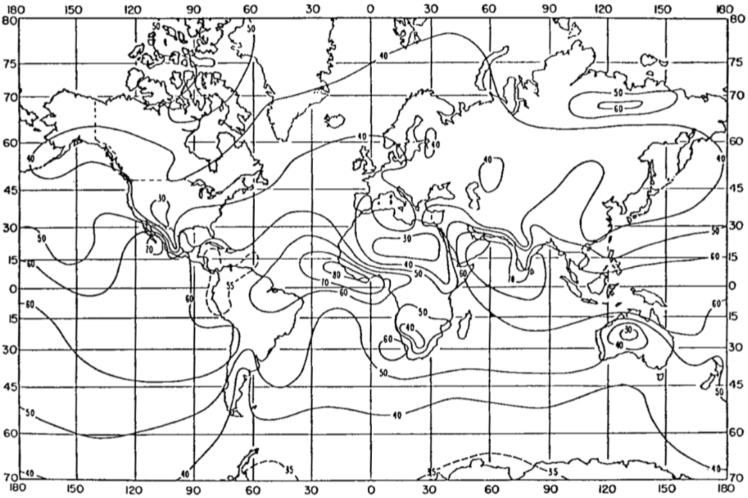
The lowest layer of the atm





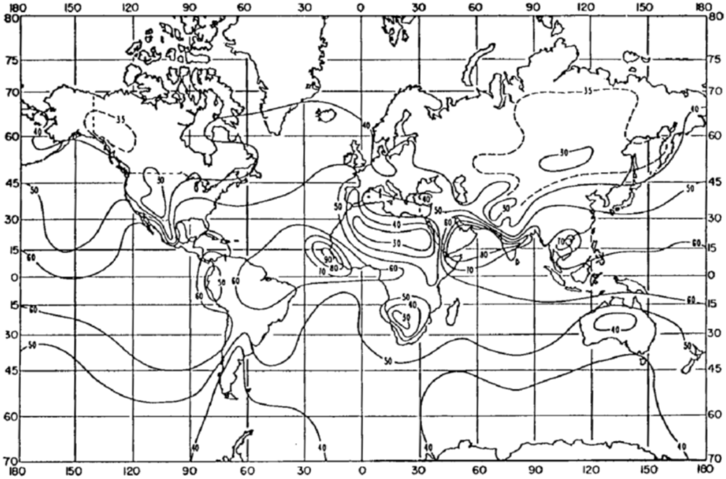
The lowest layer of the atm - ΔN variability

Monthly mean values of ΔN: February



The lowest layer of the atm - ΔN variability

Monthly mean values of ΔN: May



Rays tend to curve towards the ground

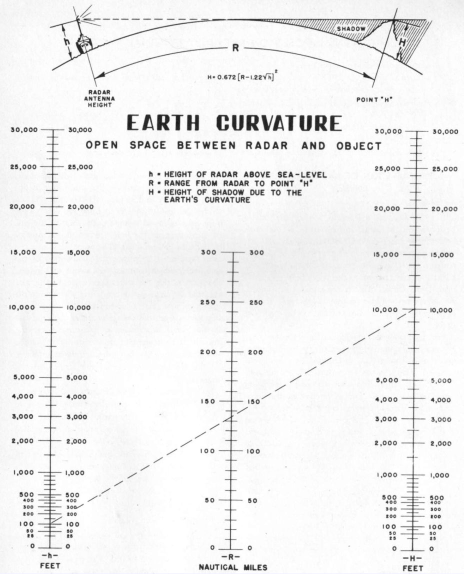
Near the ground, N has approximately a constant gradient: -43 N units per km. Hence:

- For low elevation angles, eq.(5) exhibits a constant curvature.
- This implies that the ray path is an arc of a circle.

Effective Earth radius factor k_e

Instead of considering the curved ray path, it is more convenient to recalculate the Earth's bulge and the horizon distance replacing R with an increased Earth radius $R_{eff} = k_e R$. The ray appears now to follow a straight path.

Normogram - Optical horizon

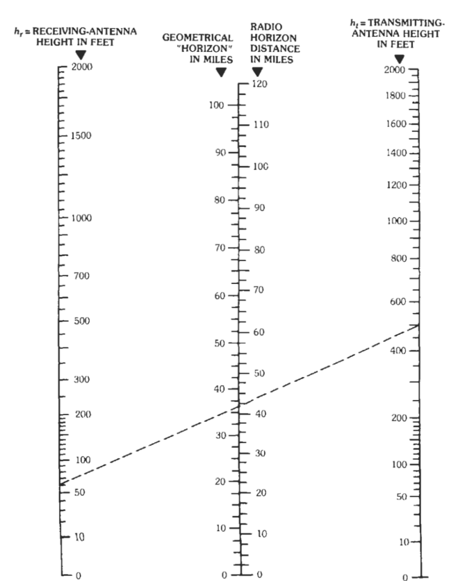


Normogram - Optical horizon

The normogram correlates radar antenna height and target altitude with the maximum range of the target as determined by the optical horizon

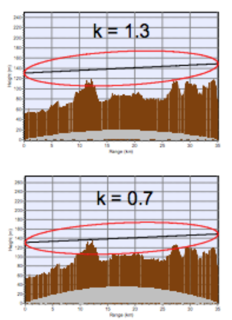
- How does it work ?
  - Let's have a TX antenna at 100ft asl.
  - Which is the max range to detect a target at 10000ft asl ?
  - Just draw a line between the 100ft point on the leftmost side vertical bar and the 10000ft point on the rightmost vertical bar.
  - The intersection with the middle vertical line just shows the maximum rage according to the optical horizon.

Normogram - radio horizon using $k_e = 1.33$



k_e

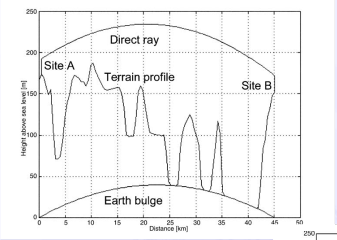
The median value of k_e is taken to be $\frac{4}{3}$. Hence, R_{eff} (for 50% of the time) is $\frac{4}{3}R = 8500$km.



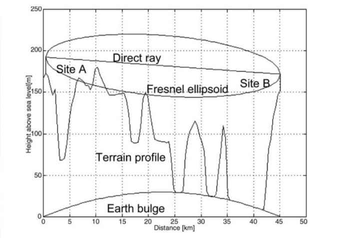
- Using R_{eff}, the Earth's bulge and the terrain profile are reduced making the ray to follow a straight path.
- Note that terrain obstructions within the Fresnel zone do not change.

Now, the free space path loss L_F can be calculated.

Path profile



without Earth radius correction

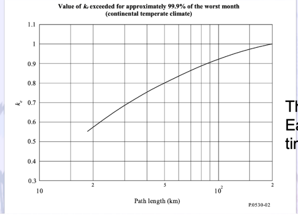


with Earth radius correction

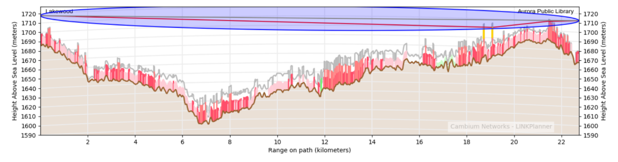
The Earth bulge and terrain profile is reduced and the ray path can now be drawn as straight, without changing the obstruction of the Fresnel ellipsoid by the terrain.

k_e: time variability

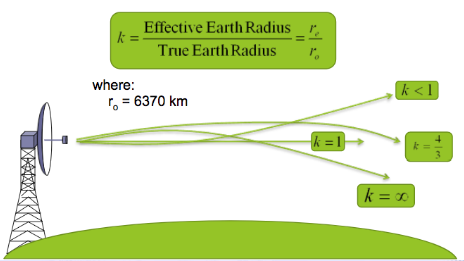
$k_e = \frac{4}{3}$ is the median value only, i.e.; the value exceeded for 50% of the time in a typical year! Accurate links need to be designed according to the desired availability of the link.



The gray line stands for the worst case Earth bulge which occurs up to 0.1% of the time.



k_e different scenarios are possible



- $k_e < 1$: The mw beam is bent away from the Earth.
- $k_e = 4/3$: The fictitious Earth radius appears to mw beams to be longer than the actual one.
- $k_e > 4/3$: The equivalent Earth's curvature is flattened.
- $k_e = \infty$: The mw beam follows the Earth's curvature.

In a nutshell

Effective Earth curvature

Uniform bending may be represented by straight-line propagation, but with the radius of the earth modified so that the relative curvature between the ray and the earth remains unchanged.

- The new radius of the earth is known as the effective earth radius.
- The ratio of the effective earth radius to true earth radius is usually denoted by K_e.
- The average value of K_e in temperate climates is about 1.33.
- Values from about 0.6 to 5.0 are to be expected.

Outline

Multipath

It may cause severe degradation in the signal level at the receiver. It arises from:

- Significant ground reflections: This may happen when a reflecting surface, e.g.; ground or sea, results in a significant contribution to the received wave. In this case, a scenario similar to the plane earth model applies. Hence, the coherent combination of the direct and the reflected signals may severely degrade the received signal in case of destructive interference.
- Ducting: It occurs under unusual atmospheric conditions that generate abrupt changes in *n* over some height interval. Under this circumstances, it happens that a ray launched with a high elevation angle (which is normally expected to be lost in the space) reaches the receiver and combines with the direct signal generating multipath.

Obstruction loss

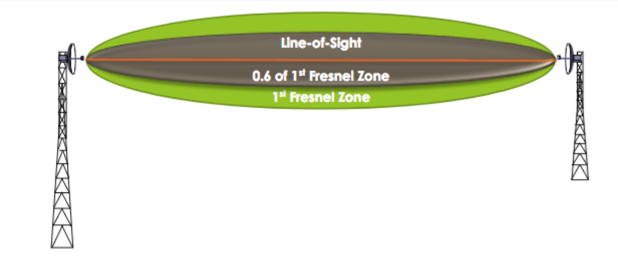
Terrain peaks entering the 0.6 first Fresnel zone generate obstruction loss in excess to L_F.

- Very high frequency links (> tens of GHz) must be conceived to avoid any obstruction loss.
- Links operated at lower frequencies (since the radius of the Fresnel zone is too big to ensure the absence of obstacles) must be designed accounting for the presence of obstacles.

The obstruction loss

Several methods are available to predict obstruction loss. The trade off is between accuracy of predictions and processing time.

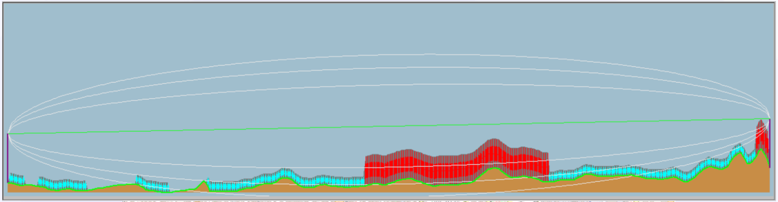
Ray of the first Fresnel zone



$$F_1 = 17.3\sqrt{\frac{d_1 d_2}{D f_{GHz}}} \tag{7}$$

- d_1 is the distance (km) from one end of the path.
- d_2 is the distance (km) from the other end of the path.
- D is the total distance (km).
- f is the em frequency (GHz).

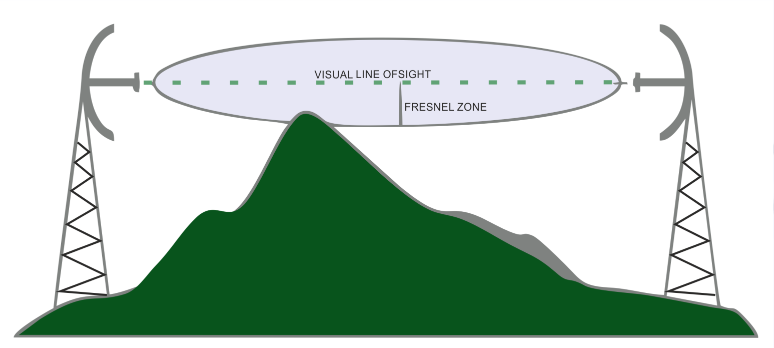
Do it yourself - https://www.ve2dbe.com/



Do it yourself - http://www.radiofresnel.com/

Terrain peaks

Terrain peaks are usually represented as absorbing knife edges. This assumption relies on the fact that terrain peaks must be sharp enough.



Knife edges

Diffraction loss must be considered as excess with respect to L_F.

A single knife-edge is present within the 0.6 first Fresnel zone

In this case $L_{ke}(\nu)$ can be calculated using basic reference methods.

Multiple knife-edges are in place

This case cannot be treated by simply adding the obstruction loss from each edge individually.
Each edge perturbs the field and makes the wavefronts incident on the next edge non plane.

Knife edge diffraction loss

L_{ke} can be calculated:

- By numerically calculating the Fresnel integrals.
- By an approximate formula (whose accuracy is better than 1 dB) that applies when $\nu > 1$:

$$L_{ke}(\nu_2) = -20 \log \frac{0.225}{\nu_2} \tag{8}$$

Outline

Geometrical-based methods

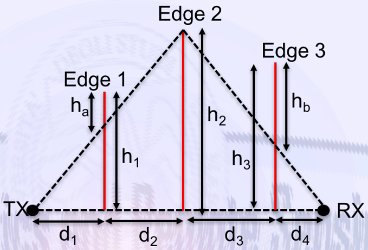
The predicted obstruction loss relies on simplifications that involve the path geometry, which is assumed to be made of simple geometrical constructions. Hence, the total diffraction loss is calculated as combinations of single diffractions between adjacent edges.

Methods

- The most simple method is the one developed by Deygout.
- Based on the Deygout method, two approaches were proposed to increase its accuracy: The Causebrook correction and the Giovannelli method.

The Deygout method

Assuming a simple geometry that consists of three knife-edges.



- Fresnel diffraction ν parameter for a single knife-edge is given by:

$$\nu(d_a, d_b, h) = h\sqrt{\frac{2(d_a + d_b)}{\lambda d_a d_b}} \tag{9}$$

The Deygout method - key steps

1- Calculate ν eq.(9) for each edge as if the edge were present alone:

$$\begin{aligned} \nu_1 &= \nu(d_1, d_2 + d_3 + d_4, h_1) \\ \nu_2 &= \nu(d_1 + d_2, d_3 + d_4, h_2) \\ \nu_3 &= \nu(d_1 + d_2 + d_3, d_4, h_3) \end{aligned} \tag{10}$$

2- Identify the main edge as the one resulting in the largest positive ν. In this case, the main edge is "Edge 2".

3- Calculate the diffraction loss associated with the main edge, using (8).

The Deygout method - key steps

4- Use the main edge to split the path into two sub-paths (in this case the two sub-paths are: $d_1 + d_2$ and $d_3 + d_4$).
With respect to the sub-path $d_1 + d_2$, the source point is TX while the new RX is on top of "Edge 2".
With respect to the sub-path $d_3 + d_4$, the source point is on top of "Edge 2", while the new RX coincides with the old one.

5- New ν parameters associated with obstacles within the first and the second sub-paths are evaluated:

$$\begin{aligned} \nu_1' &= \nu(d_1, d_2, h_a) \\ \nu_2' &= \nu(d_3, d_4, h_b) \end{aligned} \tag{11}$$

The Deygout method: total L_{ex}

Total excess loss

It is the combination of the losses associated with the main edge and the edges in the two sub-paths:

$$L_{ex} = L_{ke}(\nu_1') + L_{ke}(\nu_2) + L_{ke}(\nu_3') \tag{12}$$

The method can be easily extended to the case of more than three edges by applying the previous steps recursively.

- Deygout method overestimates the path loss when a large number of edges are present and/or when edges are close to each other.
- Cousebrook correction and the Giovannelli method aim at overcoming drawbacks of Deygout method.

All those methods fail in case of a large number of obstacles and at grazing incidence.

Outline

The multiple-edge diffraction integral

It consists of expressing the excess of diffraction loss due to n knife-edges as a multiple integral (n integrals) derived on the basis of the Huygens-Fresnel theory.

Diffraction integral method

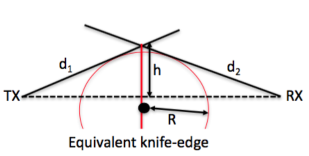
- It is very accurate, once efficient methods to evaluate the multiple integral are available.
- The evaluation of the integral is a very non-trivial issue.
- A possible solution consists of transforming the multiple-integral into an infinite series. This increases significantly the processing time that strongly depends on the number of edges.

Outline

The multiple-edge diffraction integral

Knife-edge approximation no longer applies when the terrain profile exhibits a significant curvature at its peak.

The obstacle is treated as a cylinder of finite radius.



- The cylinder is approximated with an equivalent knife-edge located at the intersection of the rays.
- The loss is calculated: $L_{ke}(v(d_1, d_2, h))$.
- An extra-loss term L_c is added that depends on geometrical parameters and frequency.

$$L_{ex} = L_{ke}(v(d_1, d_2, h)) + L_c(d_1, d_2, h, R, \lambda) \qquad (13)$$

Clutter

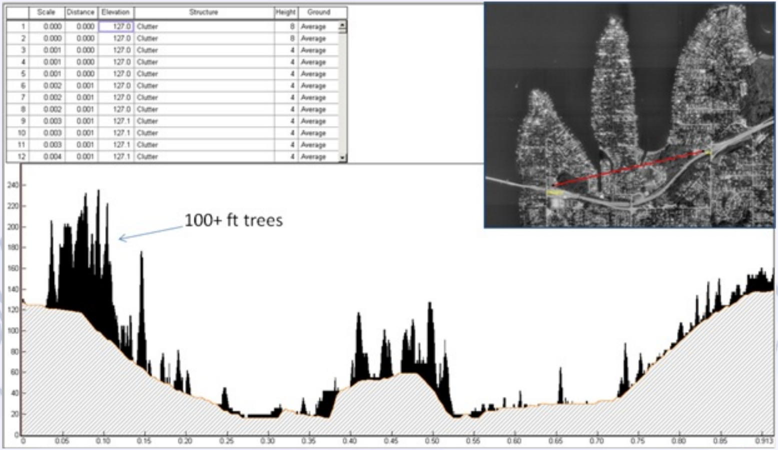
Although the link should be designed to be free of clutter, in some cases this is not possible.

- The major source of clutter is due to trees.
- To estimate the loss associated to trees, the simplest approach is weighting the path length affected by trees by a specific attenuation [dB/m].
- Although this attenuation depends on frequency, tree density, etc., typically empirical approaches are adopted, such as the modified exponential decay model (which works in the range $0.2 - 95$GHz):

$$L = \eta f^{\nu} d^{\gamma} \tag{14}$$

with the carrier frequency f [MHz], $\nu = 0.284$, $\eta = 0.187$ and $\gamma = 0.588$.

Example of path profile characterized by high clutter heights



	Scale	Distance	Elevation	Structure	Height	Ground
1	0.000	0.000	127.0	Clutter	8	Average
2	0.000	0.000	127.0	Clutter	8	Average
3	0.001	0.000	127.0	Clutter	4	Average
4	0.001	0.000	127.0	Clutter	4	Average
5	0.001	0.000	127.0	Clutter	4	Average
6	0.002	0.001	127.0	Clutter	4	Average
7	0.002	0.001	127.0	Clutter	4	Average
8	0.002	0.001	127.0	Clutter	4	Average
9	0.003	0.001	127.1	Clutter	4	Average
10	0.003	0.001	127.1	Clutter	4	Average
11	0.003	0.001	127.1	Clutter	4	Average
12	0.004	0.001	127.1	Clutter	4	Average

Improving the microwave link

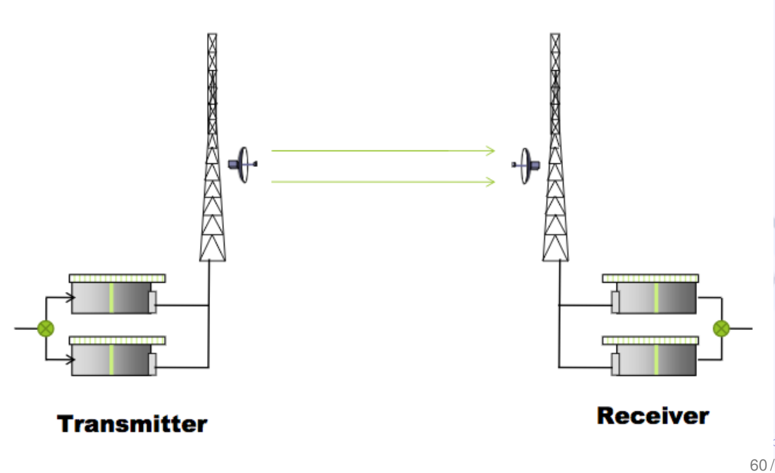
Multipath fading is the dominant propagation factor for fixed terrestrial microwave line-of-sight (LOS) radio links operating at frequencies below 10 GHz.

Multipath

- Fading due to multipath propagation attenuates received signals on line-of-sight links and thereby impairs the performance of point-to-point systems.
- Several methods are used to reduce the effects of multipath fading.
- Most of those methods are based on “Diversity” that aims at providing separate paths to transmit redundant information.

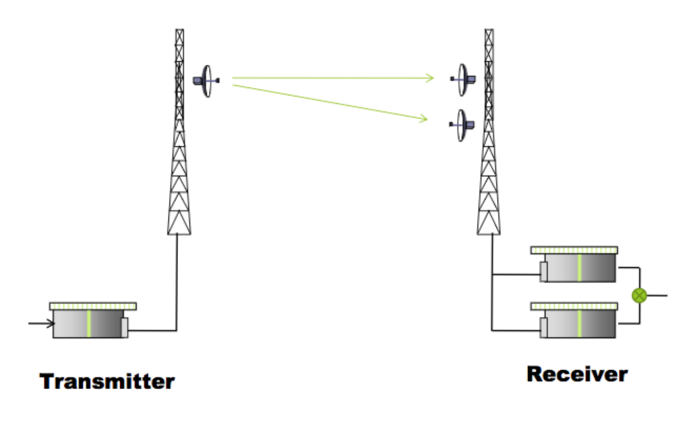
Frequency diversity

It consists of using two different frequencies to transmit the same information.

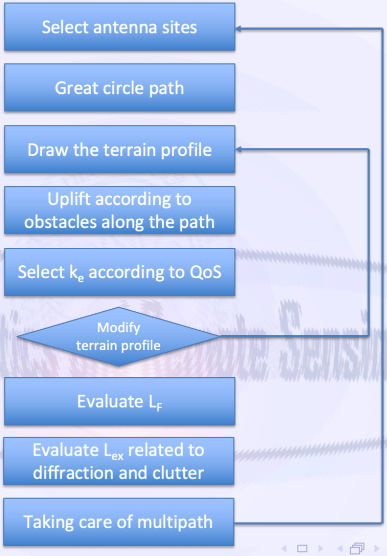


Space diversity

It consists of using two receiving antennas separated vertically on the same tower to build up two different physical paths separated in space.



To do list



Select antenna sites
Great circle path
Draw the terrain profile
Uplift according to obstacles along the path
Select k_e according to QoS
Modify terrain profile
Evaluate L_F
Evaluate L_{ex} related to diffraction and clutter
Taking care of multipath