Fixed Systems

Course notes – © Dr Mike Willis

Plan

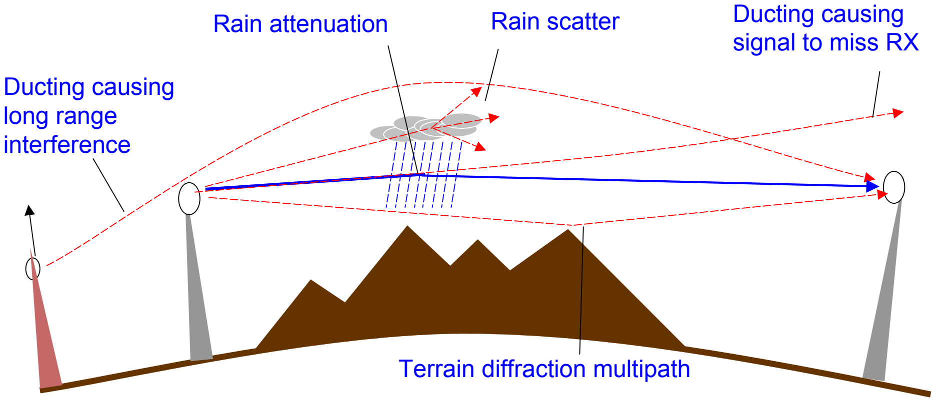
- In this section we will look in particular at the effects of propagation on systems in the fixed services.
  - We covered the mechanisms in the previous lectures, now we will put it together for predictions and look at the standard models used for assessing propagation

Terrestrial line of sight

Microwave links
Wireless networks - WiMAX

A terrestrial fixed link

A few of the propagation effects



Rain attenuation

Rain scatter

Ducting causing signal to miss RX

Ducting causing long range interference

Terrain diffraction multipath

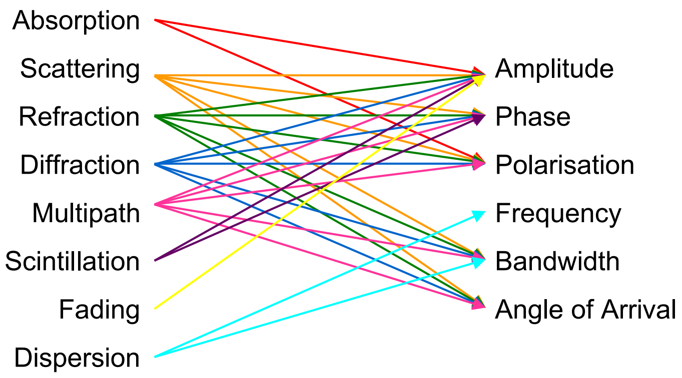
Also:

Tropospheric multipath - Gaseous attenuation - Blockage by buildings

Mechanisms

Propagation mechanisms and their effects

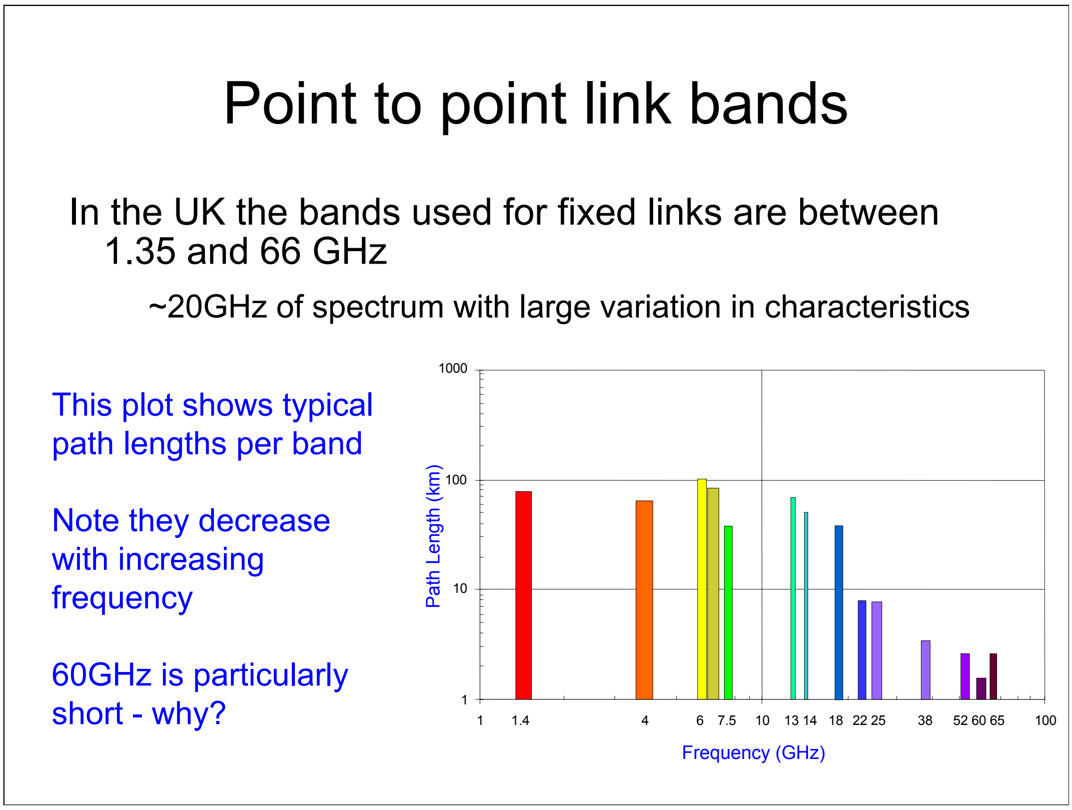
This grid gives some idea of how various signal parameters are effected by propagation



Absorption
Scattering
Refraction
Diffraction
Multipath
Scintillation
Fading
Dispersion

Amplitude
Phase
Polarisation
Frequency
Bandwidth
Angle of Arrival

It varies greatly with frequency and path length



Point to point link bands

In the UK the bands used for fixed links are between 1.35 and 66 GHz

~20GHz of spectrum with large variation in characteristics

This plot shows typical path lengths per band

Note they decrease with increasing frequency

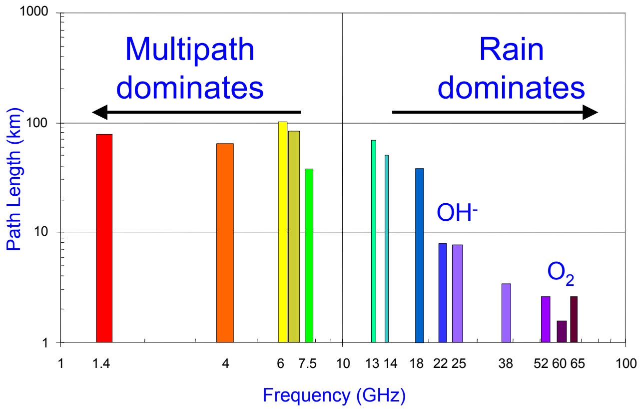
60GHz is particularly short - why?

The main reason for the decrease in length with frequency is because of rain attenuation. The reason 60GHz is so short is that Oxygen attenuation at ground level can be 10dB/km. This severely limits the range of the link - or ensures privacy if you prefer.

Point to point link bands

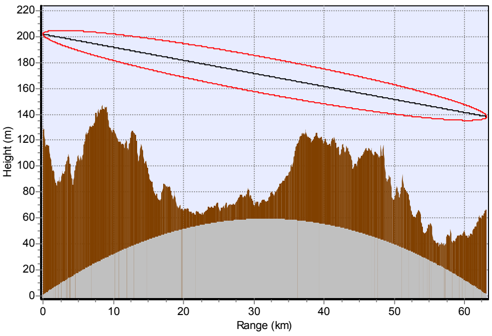
The lower frequencies tend to be dominated by multipath with the higher frequencies dominated by rain fading

- at 60GHz Oxygen attenuation dominates - 10dB/km
- at 23 GHz there is a water vapour resonance, but it is only a few dB

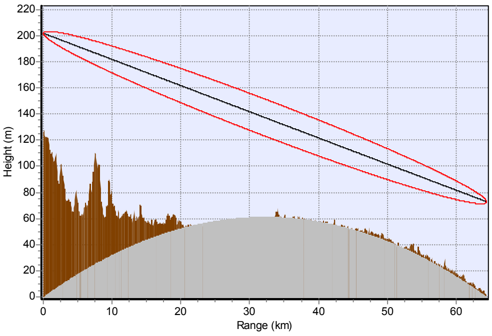


Planning the link

Tend to use high masts to obtain good Fresnel zone clearance from terrain



Hilly Terrain

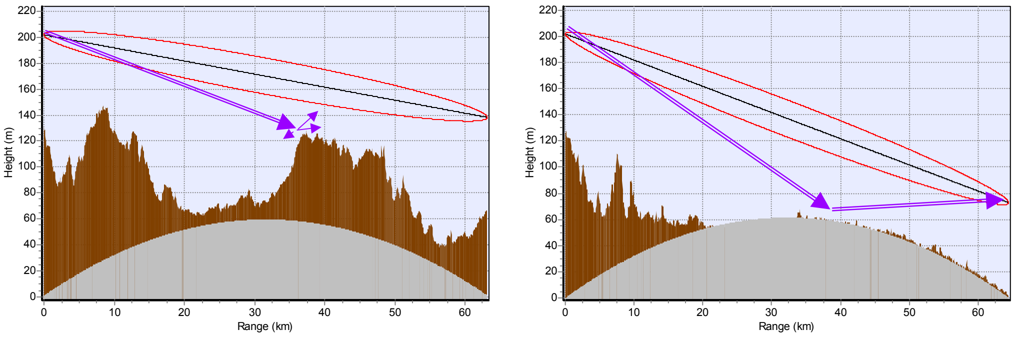


Flat Terrain

The need to get good Fresnel clearance is because of k-factor variation. Designers will typically aim for up to 4th Fresnel zone clearance assuming a k-factor of 0.9 or less.

Planning the link

- Nice to use terrain to avoid ground reflections if possible
  - If not - can get severe multipath issues



Hilly Terrain

Flat Terrain

In practice it is often impossible to avoid ground reflections on longer paths in flat areas and with reasonable antenna sizes. The solution to this is usually to deploy two receiver antennas at different heights - the best signal being used at any time. The reason this works is that the phase difference of the multipath interference will vary with height and as a result, the spectral null will appear at a slightly different frequency for each antenna. As the k-factor varies, the received channel at one or other of the receive antennas will not be in the null.

What you need to do is to calculate the range of path length differences between the direct and reflected path as the k-factor varies, if this is always less than a wavelength appropriate transmit and receive antenna heights can be selected so cancellation never occurs on the link. Otherwise, diversity antennas may be needed.

Reliability

Fixed links tend to have high availability requirements

- A 99.99% requirement is not unusual
  - Under an hour a year outage
- Rare propagation events are important
  - Fading
  - Interference

Will look at this first - Multipath and Rain

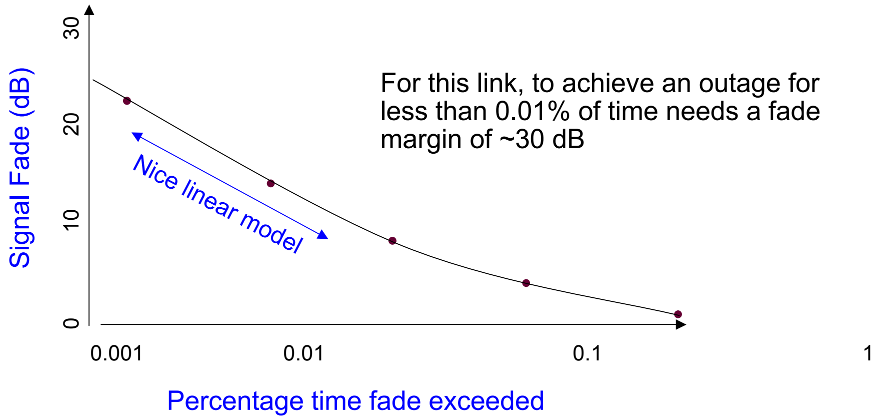
Whether the operators really need 99.99% or 99.999% is open to debate, especially if the hardware failure rate is much higher, but it is traditional. Lower frequencies tend to be dominated by multipath and higher frequencies by rain fading.

Interference is of special significance as there is great pressure on spectrum in some fixed links bands. We will come on to that later.

Typical fixed link CDF

The fading end of the distribution

- This is what you might get for a low frequency link where multipath dominates

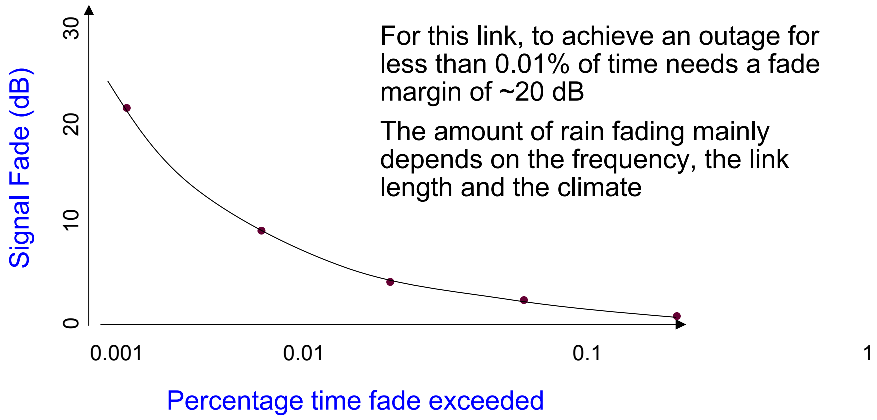


For this link, to achieve an outage for less than 0.01% of time needs a fade margin of ~30 dB

Another typical fixed link CDF

The fading end of the distribution

- This is what you might get for a high frequency link where rain fading dominates



For this link, to achieve an outage for less than 0.01% of time needs a fade margin of ~20 dB

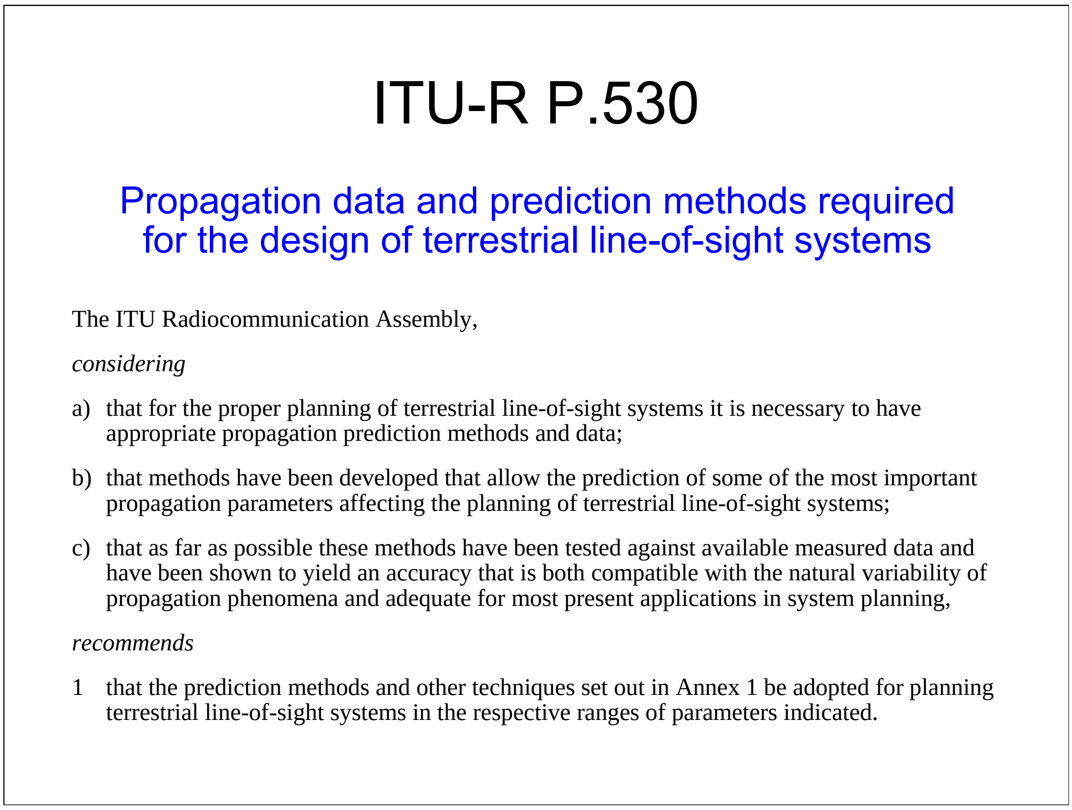
The amount of rain fading mainly depends on the frequency, the link length and the climate

Models for fixed link planning

To calculate the amount of fading a link will experience needs a model

- The standard model used is ITU-R P.530
    - Advises which models to use for free space loss, gaseous loss etc.
    - Gives advice on sub-path diffraction fading if full Fresnel zone is clearance not possible
    - Provides model for evaluating multipath fading
        - Advises how to overcome ground reflection with antenna diversity
    - Provides a model for evaluating rain fading
    - Provides a model for degradations in cross polar discrimination (XPD)

P530 is a long and detailed recommendation - here we will look at a few of the models it contains.



ITU-R P.530

Propagation data and prediction methods required for the design of terrestrial line-of-sight systems

The ITU Radiocommunication Assembly,

considering

a) that for the proper planning of terrestrial line-of-sight systems it is necessary to have appropriate propagation prediction methods and data;

b) that methods have been developed that allow the prediction of some of the most important propagation parameters affecting the planning of terrestrial line-of-sight systems;

c) that as far as possible these methods have been tested against available measured data and have been shown to yield an accuracy that is both compatible with the natural variability of propagation phenomena and adequate for most present applications in system planning,

recommends

1 that the prediction methods and other techniques set out in Annex 1 be adopted for planning terrestrial line-of-sight systems in the respective ranges of parameters indicated.

P530 Claims to inform on:

- diffraction fading due to obstruction of the path by terrain obstacles under adverse propagation conditions;
- attenuation due to atmospheric gases;
- fading due to atmospheric multipath or beam spreading (commonly referred to as defocusing) associated with abnormal refractive layers;
- fading due to multipath arising from surface reflection;
- attenuation due to precipitation or solid particles in the atmosphere;
- variation of the angle-of-arrival at the receiver terminal and angle-of-launch at the transmitter terminal due to refraction;
- reduction in cross-polarization discrimination (XPD) in multipath or precipitation conditions;
- signal distortion due to frequency selective fading and delay during multipath propagation.

ITU-R P.530

The fading mechanisms are divided into

- Clear air

  mainly from atmospheric layering
  - variable diffraction loss depending on k-factor
  - large fades through multipath effects through the atmosphere
  - small fades due to various de-focussing effects

- Precipitation

  rain, and other hydrometeors
  - absorption losses
  - scattering losses

Obviously both of these can occur at the same time along a link, especially if it is a long one.

P.530 - diffraction loss

Diffraction loss over average terrain is approximated as:

$$A_d = -20\, h / F_1 + 10 \quad \text{dB}$$

Valid for losses over 15dB

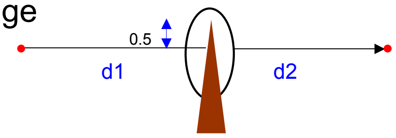
$$F_1 = 17.3 \sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}} \quad \text{m}$$

← Fresnel Ellipse radius

where *h* is the height difference (m) between most significant path blockage and the path trajectory.

h is negative if the obstruction cuts the line of sight.

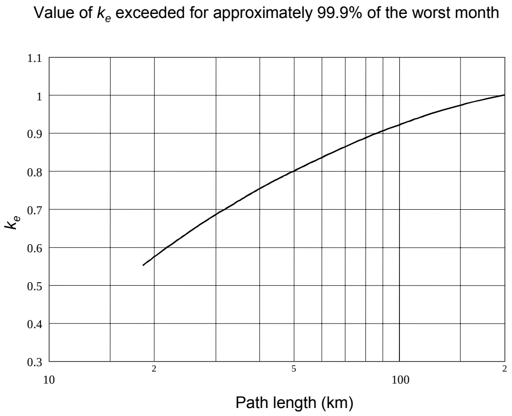
E.g. 3/4 blockage

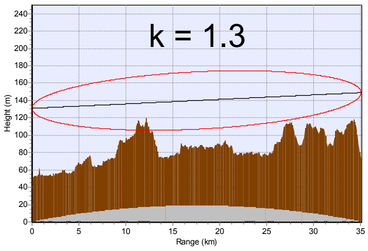


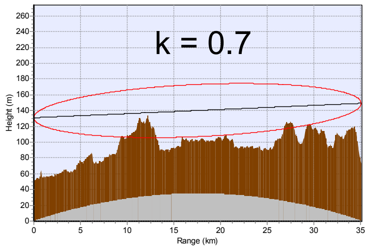
h/F1 = -0.5, A = 20 dB

P.530 - lowest k factor

- To check the path profile we need to know the worst value of k to use


Value of k_e exceeded for approximately 99.9% of the worst month





The two graphics show the effect of k-factor variations on the path blockage. In this case the path has sub path diffraction and the effect will not be very large. Other paths, especially at higher frequencies where the Fresnel radius is less can transition from being fully line of sight to fully blocked through k-factor variations.

It is also important to remember the limits of terrain data which may only be samples at 50m intervals. Even given good quality terrain information, path profiles do not give information on the height of ground cover - I.e. buildings and vegetation. Databases of clutter category, (Urban, Suburbs, Orchard, Lake, Fields etc.) are available and are usually accounted for using a mean clutter height which is added to the terrain height in checking for path clearance.

P.530 - Multipath fading at small time percentages

This model depends on a climate parameter, the path inclination, path length and the frequency:

Climate parameter $K = 10^{-4.2-0.0029 dN_1}$

Where dN_1 is the refractivity lapse rate in the first 65m not exceeded for 1% of the year (dN_1 =-100 in the UK)

K =3.2 x 10^{-5} is typical for the UK

The path inclination is $|\varepsilon_p| = |h_r - h_e| / d$

To give us the percentage of a worst month a specified attenuation A is exceeded

$$p_w = K d^{3.0} (1 + |\varepsilon_p|)^{-1.2} \times 10^{0.033f - 0.001h_L - A/10} \quad \%$$

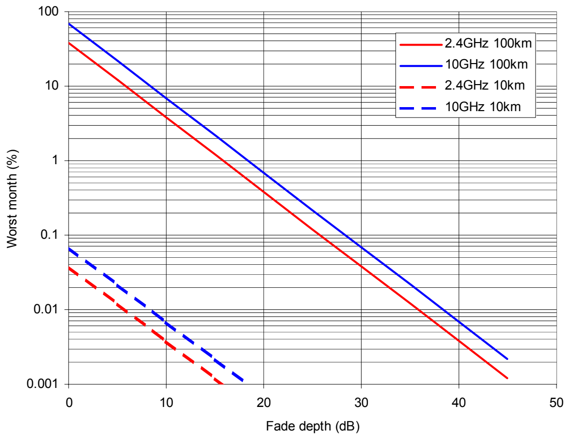
h_L is the altitude of the lowest antenna

f in GHz, h in m, d in km, A in dB

In the UK, N_0 is of the order of 320 N units. dN/dh is between -100 and -200 N units per km.

P.530 - Multipath fading at small time percentages

Say we have a flat path at sea level across the UK:

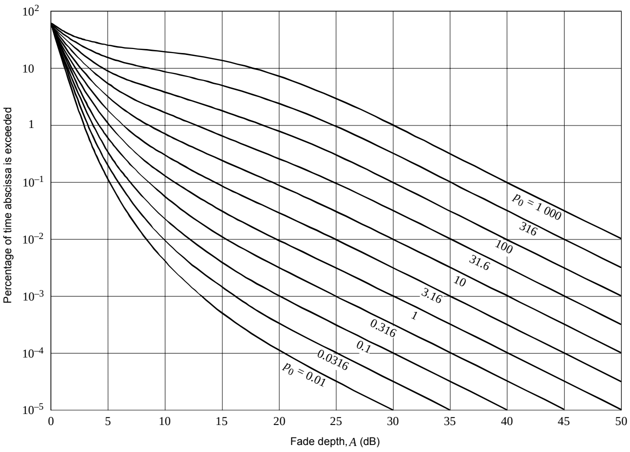


The 530 model for UK paths at short time percentages

The graph shows a couple of example paths to size the effect. At 0.01% for typical link lengths and frequencies multipath fading is 5 dB to 40dB.

P.530 - Multipath fading at all time percentages

This works for shallow fading - it is a blend between a deep and shallow fade model



It is based on the multipath occurrence factor, p_0

This percentage of time when the fading is just zero dB

the intercept of the deep-fading distribution with the percentage of time-axis

(note it is not constrained to 100%)

The actual method is simple but contains several equations which we will not go into here. The procedure is given in ITU-R P.530-11 section 2.3.2

P.530 - Multipath enhancements

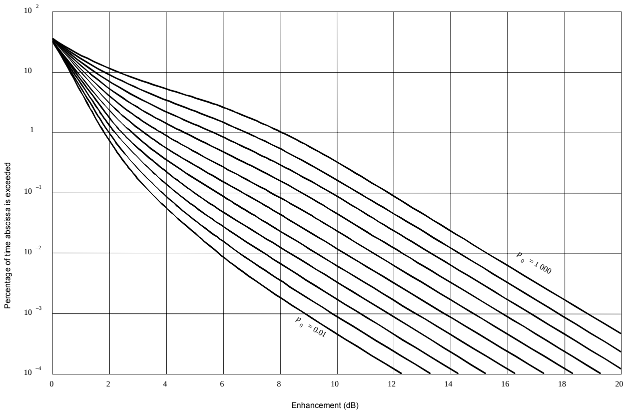
There is also a model for multipath enhancement

The worst month enhancement E can be found from:

$$p_w = 100 - 10^{(-1.7 + 0.2 A_{0.01} - E)/3.5} \ \% \quad \text{for} \quad E > 10 \text{ dB}$$

Where $A_{0.01}$ is the attenuation not exceeded for 0.01%

Again there is an empirical model for finding lower values of enhancement between 0 and E dB



This model works in a similar way to the fading model - the enhancement percentage at E = 10 dB is found and the enhancements between 0 and E are a set of curves.

P.530 - Worst month to Annual

The multipath models is P530 are geared towards worst month predictions there is a conversion formula provided

- It is based on a Geoclimatic factor

$$\Delta G = 10.5 - 5.6 \log\left(1.1 \pm |\cos 2\theta|^{0.7}\right) - 2.7 \log d + 1.7 \log\left(1 + |\varepsilon_p|\right) \quad \text{dB}$$

θ is the latitude N or S in degrees, d is path length in km,

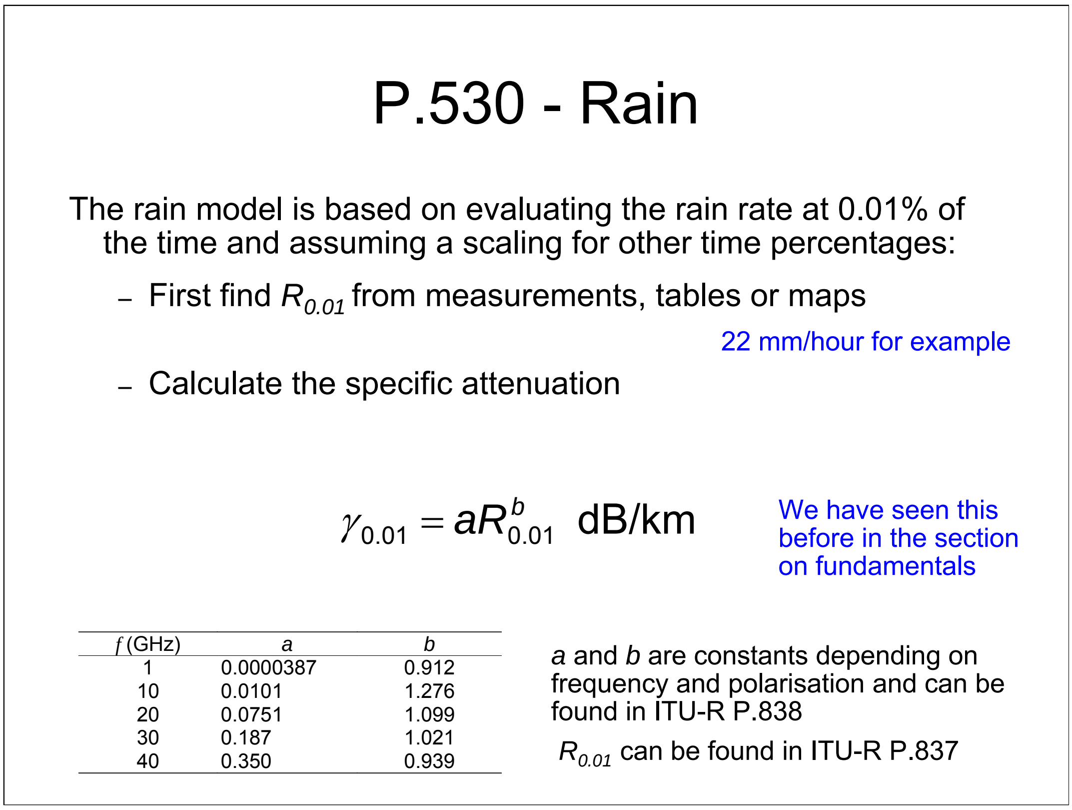
ε_p is the path inclination in milliradians

ΔG is limited to 10.8 dB and is positive for $\theta < 45^o$ and negative for $\theta > 45^o$

- The annual percentage can then be found from

$$p = 10^{-\Delta G / 10}\, p_w \quad \%$$

Again, this is an empirical conversion - to add to the uncertainty, there is considerable year to year variability in propagation. To be really sure of the statistics for percentages down below 0.01% really requires several years of measurements and the assumption that the climate has not changed over time. There is a fair amount of evidence, including results of long term radio link measurements, that the climate in the UK is changing.



P.530 - Rain

The rain model is based on evaluating the rain rate at 0.01% of the time and assuming a scaling for other time percentages:

- First find $R_{0.01}$ from measurements, tables or maps

22 mm/hour for example

- Calculate the specific attenuation

$$\gamma_{0.01} = aR_{0.01}^{b} \ \text{dB/km}$$

We have seen this before in the section on fundamentals

f (GHz)	*a*	*b*
1	0.0000387	0.912
10	0.0101	1.276
20	0.0751	1.099
30	0.187	1.021
40	0.350	0.939

a and *b* are constants depending on frequency and polarisation and can be found in ITU-R P.838

$R_{0.01}$ can be found in ITU-R P.837

The equation above for specific attenuation comes directly from scattering theory - it is therefore a Physical model. That means it should be a good match to what is measured in practice. The constants a and b have been calculated for many rain rate distributions and for stratiform and convective rain. A representative set applicable to most of the world is provided in ITU-R P.837. These values do not necessarily work very well outside the mid latitudes, for example in the tropics where the rain drop size distributions are quite different.

P.530 - Rain

We now need to work out how much of the path is in rain

- rain in not uniform
- Multiply the real distance by a "*path reduction factor*"

$$r = \frac{1}{1 + d/d_0}$$

Where $d_0 = 35e^{-0.015R_{0.01}}$
clipping $R_{0.01}$ to 100mm/hr

The attenuation is then:

$$\boxed{A_{0.01} = \gamma_{0.01}\, d\, r \quad \text{dB}}$$

A simple path reduction factor is a bodge. It works but as an Empirical model it takes no real account of the different rainfields experienced in practice. Local geography may mean that the point rainfall rate measured at one point on a link is quite different from that found at another point on the link. This is especially true for long links and those in mountainous terrain.

In the static storm model of rain, static storms arise uniformly and are advected across terrain by the wind. Over periods of 10s of minutes, over flat terrain, this theory and hence the path reduction factor are good.

P.530 - Rain Example

100km path at 10 GHz, Guildford (R = 22, a = 0.0101, b = 1.276)

$$\gamma_{0.01} = aR_{0.01}^{b} = 0.52 \text{ dB/km}$$

$$d_0 = 35e^{-0.015R_{0.01}} = 25 \text{ km}$$

$$r = \frac{1}{1 + d/d_0} = \frac{1}{1 + 100/25} = 0.2$$

The attenuation is then:

$$\boxed{A_{0.01} = \gamma_{0.01}\, d\, r = 10.4 \text{ dB}}$$

A simple path reduction factor is a bodge. It works but as an Empirical model it takes no real account of the different rainfields experienced in practice. Local geography may mean that the point rainfall rate measured at one point on a link is quite different from that found at another point on the link. This is especially true for long links and those in mountainous terrain.

In the static storm model of rain, static storms arise uniformly and are advected across terrain by the wind. Over periods of 10s of minutes, over flat terrain, this theory and hence the path reduction factor are good.

P.530 - Rain percentages

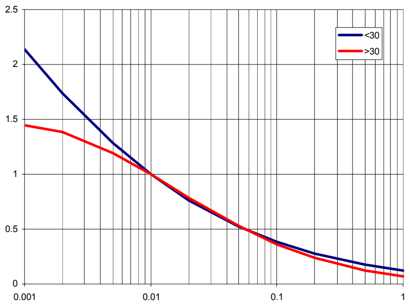
To get to other time percentages

- For links at latitudes equal or above 30°, the attenuation exceeded time percentages p in the range 0.001% to 1% is:

$$\frac{A_p}{A_{0.01}} = 0.12\, p^{-(0.546 + 0.043 \log_{10} p)}$$

- Below 30° use:

$$\frac{A_p}{A_{0.01}} = 0.07\, p^{-\left(0.855 + 0.139 \log_{10} p\right)}$$



Do not try and use this fit outside the 0.001 to 1% range - it will do strange things, the low latitude formula is not monotonic.

P.530 - Rain percentages

There are some weaknesses in the rain model

- The path reduction factor does not vary with rain rate
    - You might think it should, heavy rain being more confined in area
    - Should it vary with the prevailing wind direction?
- The percentage conversion from 0.01 is suspect
    - The climatic correction is quite crude
- No account is taken of passing through the melting layer
    - This occurs often in cold regions in the winter

- Do not assume the model is perfect
    - believe measurements in place of the model if you have them
    - but it is a good model and is used in UK planning

P.530 - Combining effects

There is fading caused by clear air and fading caused by rain

- To a first approximation, we can assume they do not occur at the same time
  - Frequently, one will dominate
- To find the total outage for a given margin, add the clear air and rain percentages together
  - You need to invert the model to do this
  - iterate or read off the graph

The assumption that the effects do not occur at the same time becomes progressively less safe at higher time percentages. As most engineers are interested in what is occurring on the link for small time percentages this to some extent does not matter.

P.530 - XPD

The cross polar discrimination is degraded along a line of sight path:

- By clear air effects
  - Multipath, troposcatter and diffraction
- By rain
  - Scattering and radiative transfer
- Reduced XPD will not cause an outage unless cross polar frequency re-use is deployed
  - P530 Assumes an equal power interferer in the orthogonal polarisation

P.530 - Clear air XPD Outage

In clear air firstly find a baseline:

$$XPD_0 = \begin{cases} XPD_g + 5 & \text{for} \quad XPD_g \le 35 \\ 40 & \text{for} \quad XPD_g > 35 \end{cases}$$

Where XPD_g is the XPD spec of the antenna

Next find the “multipath activity” factor

$$\eta = 1 - e^{-0.2(P_0)^{0.75}}$$

where $P_0 = p_w/100$

This is the multipath occurrence factor corresponding to the percentage of the time p_w (%) of exceeding $A = 0$ dB in the average worst month

P.530 - Clear air XPD Outage

Then find Q:

$$Q = -10 \log \left(\frac{k_{XP} \ \eta}{P_0} \right)$$

where $k_{XP} = \begin{cases} 0.7 & \text{for one transmit antenna} \\ 1 - 0.3 \exp \left[-4 \times 10^{-6} \left(\frac{s_t}{\lambda} \right)^2 \right] & \text{for two transmit antennas} \end{cases}$

S_t = vertical separation (m)

Calculate the XPD margin M_{XPD}

$$M_{XPD} = \text{XPD}_0 + \text{Q} - \left(C / I \right)_0$$

$(C/I)_0$ is the minimum required signal to interference ratio

Probability of outage $P_{XP} = P_0 \times 10^{-\frac{M_{XPD}}{10}}$

P.530 - Clear air XPD Outage

E.g For our 2.4GHz 100km link $P_w = 40\%$

Lets assume we need a C/I of 16 dB for a long range WiFi link - can we use cross polar re-use?

$$XPD_0 = \begin{cases} XPD_g + 5 & \text{for} \quad XPD_g \le 35 \\ 40 & \text{for} \quad XPD_g > 35 \end{cases} \quad = 35 \text{ dB}$$

Assuming our antenna has a 30 dB XPD rating

$$\eta = 1 - e^{-0.2 (P_0)^{0.75}} \quad = 0.096$$

$P_0 = P_w / 100 = 0.4$

$$k_{XP} = \begin{cases} 0.7 & \text{for one transmit antenna} \\ 1 - 0.3 \exp\left[-4 \times 10^{-6} \left(\frac{s_t}{\lambda} \right)^2 \right] & \text{for two transmit antennas} \end{cases}$$

Assuming only one antenna

P.530 - Clear air XPD Outage

So

$$Q = -10 \log \left(\frac{k_{XP} \; \eta}{P_0} \right) \qquad = 7.75 \qquad Q = -10 \log \left(\frac{0.7 \times 0.96}{0.4} \right)$$

$$M_{XPD} = \mathrm{XPD}_0 + \mathrm{Q} - \left(C/I \right)_0 \qquad = 26.75$$

From 35 + 7.75 - 16

$$P_{XP} = P_0 \times 10^{-\frac{M_{XPD}}{10}} \qquad = 8 \times 10^{-4} \qquad P_{XP} = 0.4 \times 10^{-\frac{26.75}{10}}$$

That is, approximately 0.1%

P.530 - Rain XPD

The rain XPD is modelled using the co-polar attenuation (*CPA*):

$$XPD = U - V \log CPA \qquad \text{dB}$$

$U = U_0 + 30 \log f$

U_0 is typically 15 dB and does not go below 9 dB

$V(f) = 12.8\, f^{0.19}$ for $8 \le f \le 20$ GHz

$V(f) = 22.6$ for $20 < f \le 35$ GHz

This model does not go below 8 GHz, rain attenuation is low below this frequency (and hard to measure correctly)

We can get to 4 GHz using frequency scaling:

$$XPD_2 = XPD_1 - 20 \log (f_2 / f_1) \qquad \text{for} \quad 4 \le f_1, f_2 \le 30 \text{ GHz}$$

P.530 - Rain XPD

E.g. The 10 GHz path had 10.4 dB of attenuation

$$U = U_0 + 30 \log f \;\; = 15 + 30 \log 10 = 45$$

$$V(f) = 12.8 f^{0.19} = 12.8 \times 10.0^{0.19} = 19.8$$

$$XPD = U - V \log CPA = 45 - 19.8 \log 10.4 = 24.9 \quad \text{dB}$$

This will only cause an outage if the C/I becomes too low

The interferer in this case is the cross-polar signal which is attenuated by practically the same amount as the wanted signal

When the level of XPD is too low for higher order modulation schemes (256-QAM) some form of cross polar cancellation (XPIC) will be needed

P.530 - Other models

The recommendation gives us several other models (it has 45 pages)

- How to overcome multipath
  - Terrain screening
  - Optimum antenna height
  - Use of vertical polarisation

- How to evaluate multiple hop chains of links
  - cascaded unreliability

Not intending to go into these time is limited. These are important models for the system designer but fairly specific to fixed link systems.

Terrestrial non-line of sight

Trans-horizon links
Broadcasting
Interference

Why

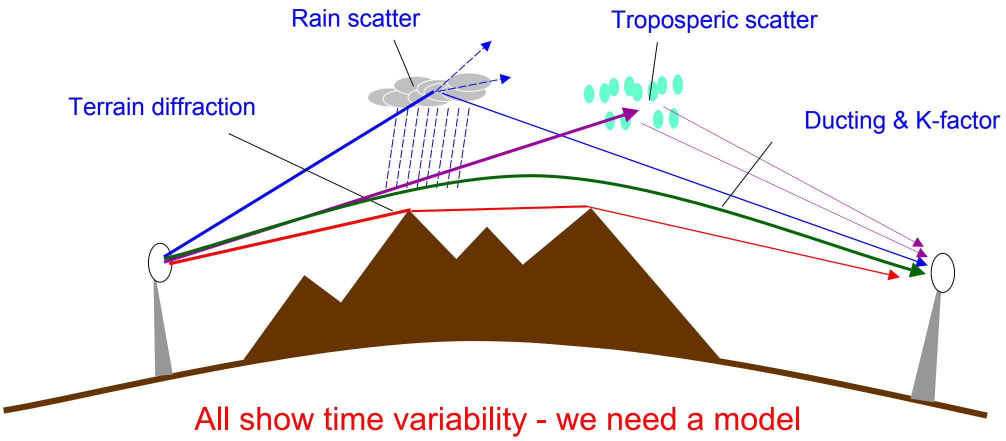
Not all links are line of sight

- Broadcasters for example are covering a population
  - UHF does propagate well beyond the horizon
- Troposcatter links are useful to skip over hostile terrain
  - e.g. linking to an oil rig or a ship at sea
- In the fixed point-point links service interference from systems over the horizon can still be a problem
  - We need to know the strength of the interference

A terrestrial non-LOS link

A few of the trans-horizon propagation effects

These can Enhance the signal



All show time variability - we need a model

Non-LOS models

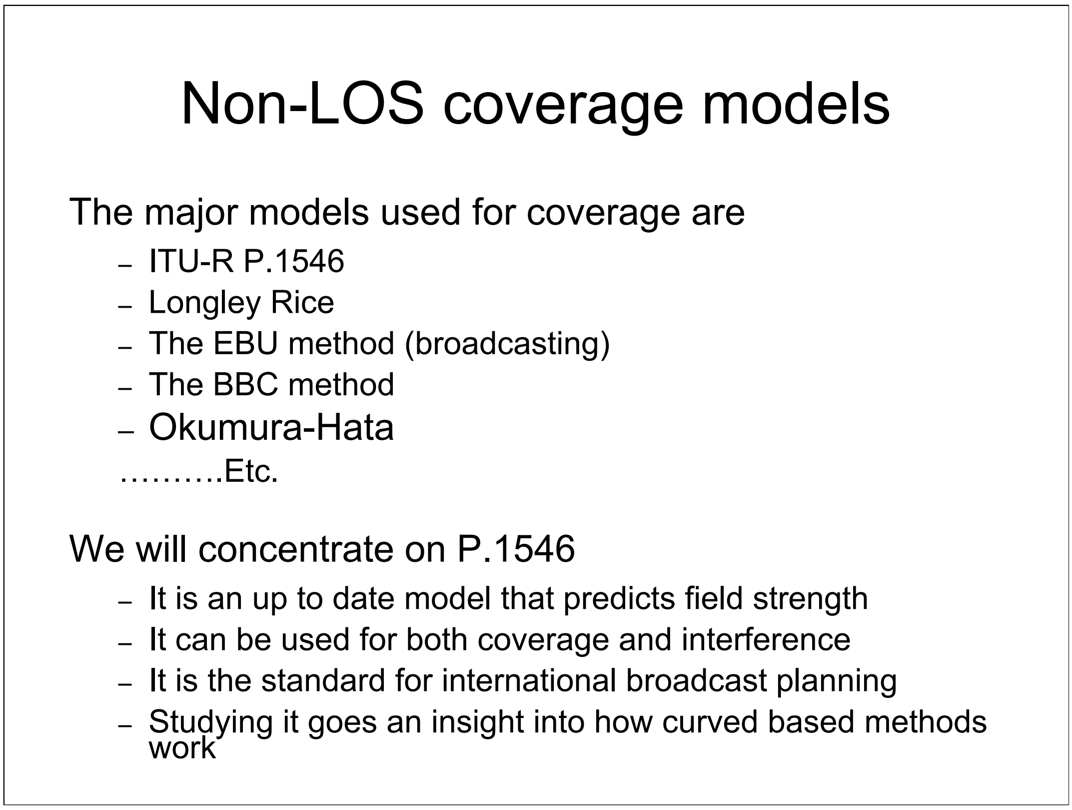
The models split into two categories

- those intended for predicting coverage
- those intended for predicting interference
    - *Models for interference can be used for coverage and vice versa, the difference is which end of the fading enhancement distribution is favoured by the model*

There are also different model types

- site specific using parameters based on location
- site general using generic parameters

Looking at these models will give us an insight into the relative importance of the physical processes taking place



Non-LOS coverage models

The major models used for coverage are

- ITU-R P.1546
- Longley Rice
- The EBU method (broadcasting)
- The BBC method
- Okumura-Hata

……….Etc.

We will concentrate on P.1546

- It is an up to date model that predicts field strength
- It can be used for both coverage and interference
- It is the standard for international broadcast planning
- Studying it goes an insight into how curved based methods work

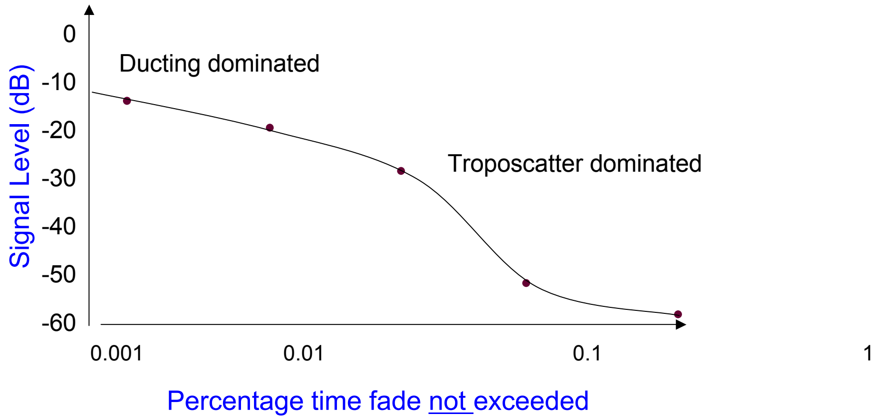
P1546 is in effect an Empirical model. It attempts to predict the result for an average location and covers location variability with an estimate of what that variability is. Given a good enough database it would be possible to plan a service like a TV transmitter coverage area or the coverage range of a PMR system using deterministic models for the terrain diffraction loss, the tropospheric scattering, and the variability in k-factor. It is also possible to predict interference through models of the incidence of anomalous propagation. The problem is the broadcaster does not know exactly where the reception points will be.

The solution is to assume that they are spread on a regular grid and calculate deterministically using physical models the propagation effects on the path from the transmitter to each point on the grid. This may later be weighted by population density, potential income, or some other metric regarding the target audience. Calculation over a large number of points takes a lot of computer time, but is becoming practical as computers get faster. There is now a move to develop more deterministic models that can take advantage of improved data sets and computer power. We will cover once of these more deterministic physical models, ITU-R P.452 later.

Typical trans-horizon link CDF

The curves that follow emphasise the enhancement end of the distribution useful for predicting interference

- E.g. Ducting/Troposcatter



ITU-R P.1546

This is a curve based model

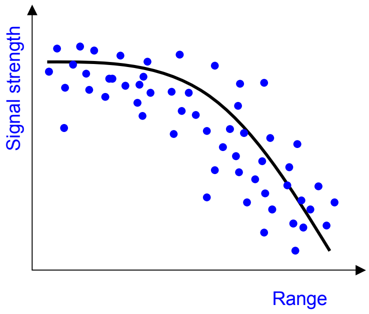
- The model uses lookup curves and scales the result based on input parameters E.g:
  - Frequency 30MHz - 3GHz
  - Percentage of time 50% to 1%
  - Mast heights 0 -1200m
  - Path lengths 1 - 1000km
  - Limited terrain data
  - Environment (Urban, Suburban etc)

Note:

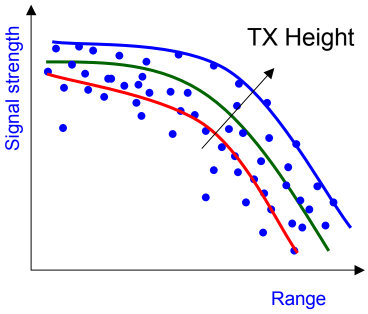
- Better results can be obtained using specific data and the methods discussed in the first section of the course (Terrain diffraction, Ray tracing etc.) but only with more computational effort and where the input data is available

Principle of curve based method

A set of curves are fitted to measurements



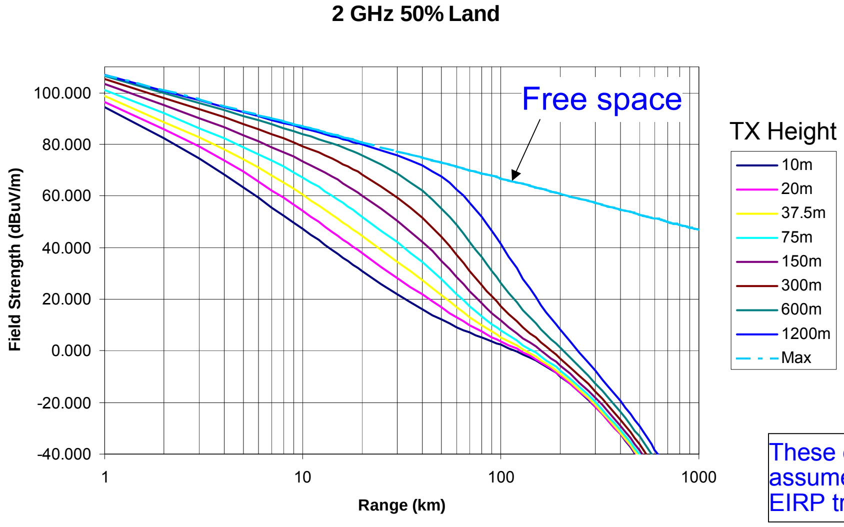
Usually there is
considerable spread



The spread can often be
reduced by using a
parameter select from a
family of curves

P.1546 Curves

An example set of curves from P1546



These curves assume a 1 kW EIRP transmitter

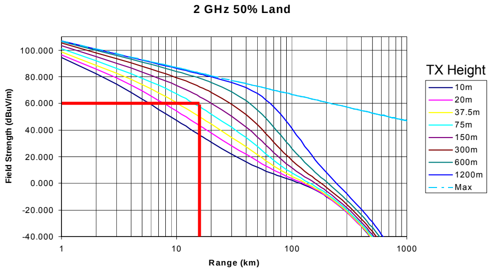
P.1546 Curves

Curves are provided for

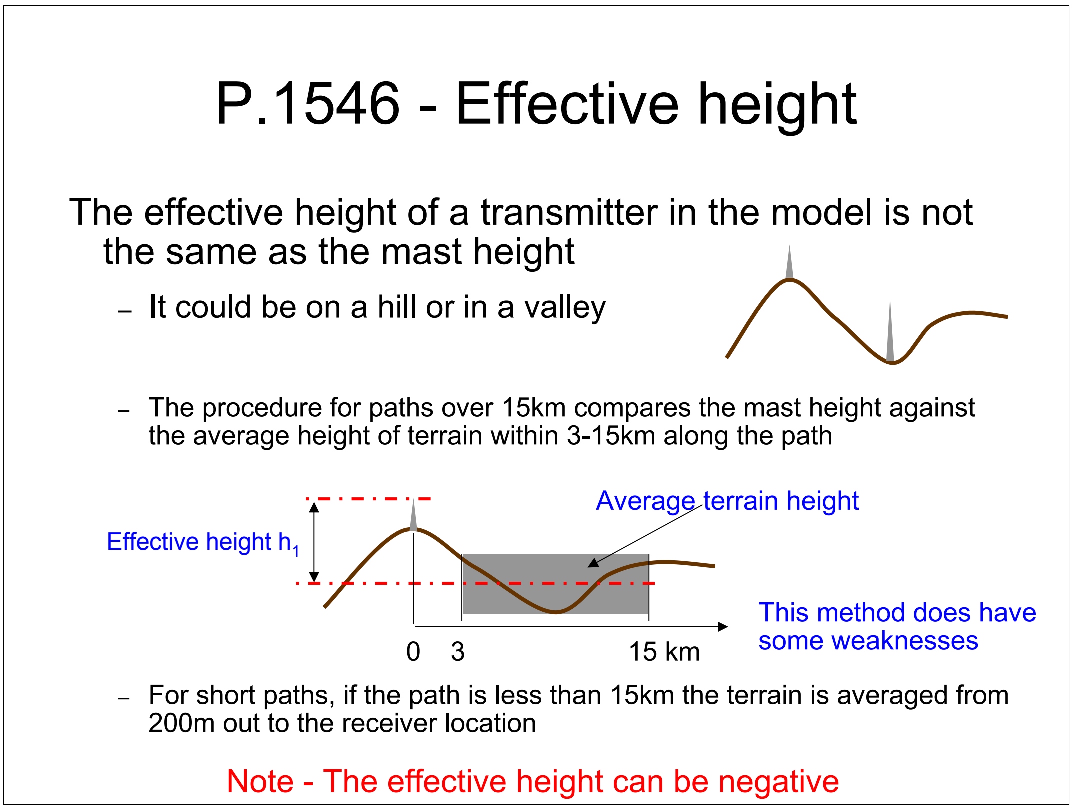
- 100MHz, 600MHz and 2 GHz
- 50%, 10% and 1% of the time
- Paths over Land, Warm Sea and Cold Sea

If a system matches perfectly with one of the curves we can use the curves for a prediction otherwise scaling and interpolation is required

This is the strength of the method, it can be tuned to better match the path in question



Just a few examples...



P.1546 - Effective height

The effective height of a transmitter in the model is not the same as the mast height

- It could be on a hill or in a valley
- The procedure for paths over 15km compares the mast height against the average height of terrain within 3-15km along the path

This method does have some weaknesses

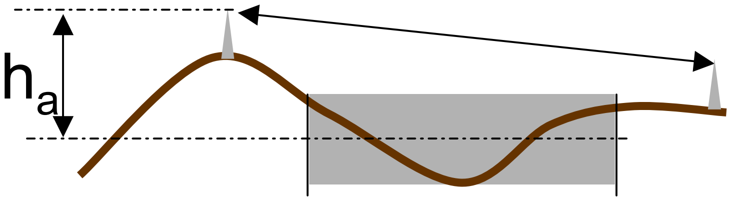
- For short paths, if the path is less than 15km the terrain is averaged from 200m out to the receiver location

Note - The effective height can be negative

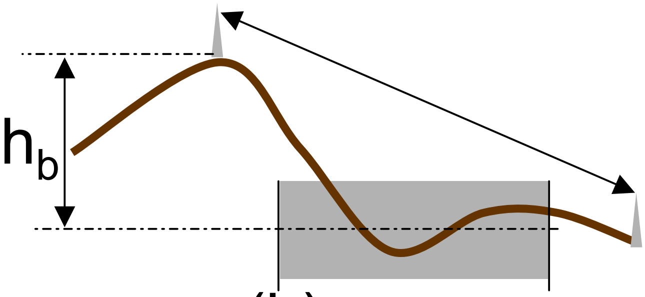
The method ignores terrain with the first 3km, this tends to assume the transmitter has a clear view out to at least 3km. This is likely to be true for broadcast systems for which the model was originally designed, but is not as likely to be for mobile systems with 10m masts.

There is also a problem with sloping ground. Paths (a) and (b) below are exactly the same, just rotated. The clearance is exactly the same, but the effective height for (b) is much greater.

The ITU-R are working on improving this part of the model.



(a)



(b)

P.1546 - Height interpolation

If the height does not lie on one of the curves an interpolation or extrapolation is used

For 10m to 3000m a logarithmic interpolation or extrapolation is used

$$E = E_{inf} + (E_{sup} - E_{inf}) \log(h_1 / h_{inf}) / \log(h_{sup} / h_{inf}) \quad \mathrm{dB}(\mu\mathrm{V/m})$$

inf relates to the curve below (inferior)

sup relates to the curve above (superior

If the value is above 1200m, inf should be the 600m curve and sup the 1200m curve

P.1546 - Height interpolation

For 0 - 10m the procedure is based on smooth-Earth horizon distance

$$d_H(h) = 4.1\sqrt{h}$$

$$E = E_{10}(d_H(10)) + E_{10}(d) - E_{10}(d_H(h_1)) \qquad \text{for } d < d_H(h_1)$$

$$E = E_{10}(d_H(10) + d - d_H(h_1)) \qquad \text{for } d \geq d_H(h_1)$$

For $h_1 < 0$m an correction is applied to account for diffraction losses and tropospheric scatter

This is based on a effective terrain clearance angle θ_e

P.1546 - Height interpolation

For h < 0m, a correction is applied to the value at h =0

C_{h1} = max[C_{h1d}, C_{h1t}]:

$$J(\nu) = \left[6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right)\right]$$

Diffraction $C_{h1d} = 6.03 - J(\nu)$

$\nu = K_\nu \theta_e$

$\theta_e = \arctan(-h_1/9000)$

$K_\nu =$ 1.35 for 100 MHz

$K_\nu =$ 3.31 for 600 MHz

$K_\nu =$ 6.00 for 2000 MHz

Troposcatter

$$C_{h1t} = 30\ \log\left[\frac{\theta_e}{\theta_e + \theta_{eff}}\right]$$

$$\theta_e = \frac{180d}{a\pi k}$$

d: path length (km)

a: 6 370 km, radius of the Earth

k: 4/3, effective Earth radius factor

P.1546 Frequency scaling

The model covers 30MHz to 3GHz

- curves are only supplied for 100, 600 and 2000MHz
- Log interpolation and extrapolation is used to get other frequencies similar to the height interpolation

$$E = E_{inf} + (E_{sup} - E_{inf}) \log(f / f_{inf}) / \log(f_{sup} / f_{inf}) \quad \text{dB}(\mu\text{V/m})$$

where:

f : frequency for which the prediction is required (MHz)
f_{inf} : lower nominal frequency (100 MHz if $f < 600$ MHz, 600 MHz otherwi
f_{sup} : higher nominal frequency (600 MHz if $f < 600$ MHz, 2 000 MHz otherwise)

There are exceptions, a different method is used when over sea below 100MHz

P.1546 Percentage time scaling

The model covers 50% to 1%

- But we only have curves for 50%, 10% and 1%
- An inverse complementary cumulative normal distribution function is used for this:

$$E = E_{sup}\,(Q_{inf} - Q_t)\,/\,(Q_{inf} - Q_{sup}) + E_{inf}\,(Q_t - Q_{sup})\,/\,(Q_{inf} - Q_{sup})$$

where:

t : percentage time for which the prediction is required

t_{inf} : lower nominal percentage time

t_{sup} :upper nominal percentage time

$Q_t = Q_i\,(t/100)$ $Q_{inf} = Q_i\,(t_{inf}/100)$ $Q_{sup} = Q_i\,(t_{sup}/100)$

$Q_i\,(x)$ = the inverse complementary cumulative normal distribution function provided as a table

P.1546 Other corrections

There are many other corrections for climate, clutter category, mixed paths and mobile antenna height, terrain at the receiver and advice on the location variability

- The implementation of P1546 is therefore quite complicated though can be implemented in a spreadsheet

This should give you a feeling of what has to be done with a curve based propagation prediction method

- It is not easy
- But it is a lot better than the really simple models

Deterministic models

- We have just discovered P1546 is quite a complicated model - but it is empirical
  - Basically is moves curves about a graph
  - Statistically it is good

- We expect models more based on physics to give a better result
  - Some models are ITU-R P.452, Longley Rice, Parabolic equation etc.

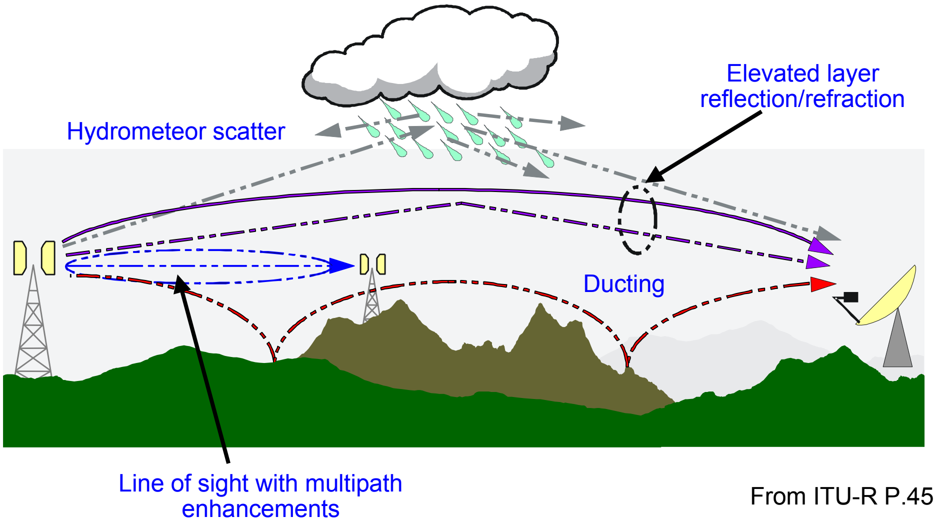
ITU-R P.452

This model is aimed at predicting interference enhancement

- It works for time percentages from 50% to 0.001%
- It covers 700MHz and up
- It is based on physical models for free space, diffraction, Troposcatter, ducting, elevated layers, and rainscatter
- The recommendation uses a path profile to categorise the path and evaluate the significance of each propagation mechanism

Short term propagation mechanisms

ITU-R P.452 presents a typical example of interference mechanisms affecting fixed links



From ITU-R P.452-12

ITU-R P.452 mechanisms

Now looking at each mechanism in turn

The line of sight mechanism

- Occurs when a line-of sight path exists under normal atmospheric conditions.
- Sub-path diffraction causes a slight increase in signal level
- On paths longer than about 5 km signal levels can often be significantly enhanced for short periods of time by multipath and focusing effects resulting from atmospheric stratification

ITU-R P.452 mechanisms

The diffraction mechanism

- Permits propagation beyond line-of-sight
- For high time percentages diffraction effects tend to dominate if signals are strong
  - Important as if we are not interested in short time percentages, the diffraction mechanism governs how closely we can space services sharing spectrum

ITU-R P.452 mechanisms

The Tropospheric scatter mechanism

- Permits propagation beyond line-of-sight
- Defines the "background" interference level for longer paths
  - e.g. more than 100-150 km
  - diffraction loss becomes very high
- Unless the high power is transmitted troposcatterd signals are weak

ITU-R P.452 mechanisms

The surface ducting mechanism

- Permits propagation beyond line-of-sight
- The most important short-term mechanism
  - Especially over water and in flat coastal land areas,
- Can give rise to high signal levels over long distances
  - more than 500 km over the sea
  - signals can exceed the equivalent "free-space" level under certain conditions.

ITU-R P.452 mechanisms

Elevated layer reflection and refraction mechanisms

- Permits propagation beyond line-of-sight
- Reflection and/or refraction from layers at heights up to a few hundred metres
    - Enables signals to bypass the diffraction loss of the terrain
    - The impact can be significant over long distances
        - up to 250-300 km

ITU-R P.452 mechanisms

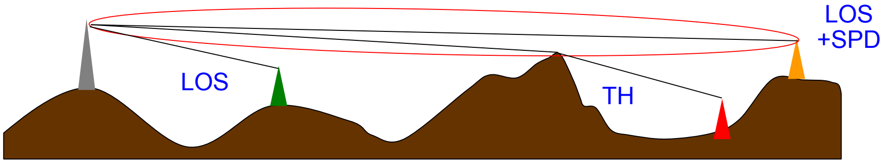
The hydrometeor scatter mechanism

- Permits propagation beyond line-of-sight
- A potential source of interference between terrestrial transmitters and earth stations
- Omnidirectional and can therefore effective the off the great-circle path
- Signal levels are quite low

ITU-R P.452 path type

This analyses the profile and categorises

- Line of sight
- Line of sight with sub-path diffraction
- Trans-horizon



P.452 models

For clear air

- line-of-sight including signal enhancements due to multipath and focusing effects
- diffraction embracing smooth-earth, irregular terrain and sub-path cases
- tropospheric scatter
- anomalous propagation - ducting and layer reflection/refraction
- height-gain variation in clutter

Hydrometeors

- based on common volume and rain cell model

Now look at a few of these

P.452 models

Inputs to the clear air models

- Climatic
  - N_0 (N-units), sea-level surface refractivity, used by troposcatter model
  - ΔN (N-units/km), the average radio-refractive index lapse-rate through the lowest 1 km of the atmosphere
  - β_0 (%), the time percentage refractive index lapse-rates exceed 100 N-units/km in the first 100 m of the atmosphere
- Path
  - Location (Latitude, Longitude, Elevation)
  - A path profile
  - Proportion of path over land, sea and coastal areas
- System
  - Frequency, Antenna gain mast heights

P.452 models

Clear air models -Line of sight

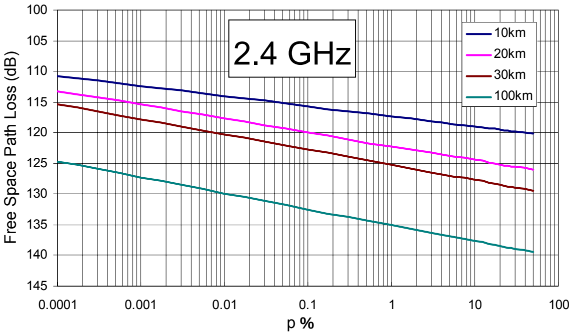
Gas loss

Multipath & focussing

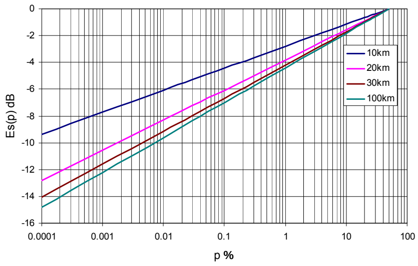
$$L_{b0}(p) = 92.5 + 20 \log f + 20 \log d + E_s(p) + A_g$$

$$E_s(p) = 2.6\,(1 - e^{-d/10}) \log(p/50)$$

We have seen this before apart from the $E_s(p)$ term



This is a fit to measurements



P.452 models

Clear air models - Diffraction

- First calculate the diffraction loss for 50% time K factor using Deygout on up to 3 most significant edges
- Do this again, using the k-factor for β_0 % time (but with the 50% knife edges to avoid finding different ones)

$$L_d(p) = L_d(50\%) - F_i(p)\left[L_d(50\%) - L_d(\beta_0)\right]$$

A log normal interpolation function

Where: $F_i\,(p) = \mathbf{I}(\,p/100) \,/\, \mathbf{I}(\beta_0\,/100)$

$\mathbf{I}$ () is the inverse cumulative normal function

Then the diffraction loss is:

$$L_{bd}\,(\,p) = 92.5 + 20 \log f + 20 \log d + L_d\,(\,p) + E_{sd}\,(\,p) + A_g \text{ dB}$$

Where $E_{sd}(p) = 2.6\left(1 - \mathrm{e}^{-(d_{lt}+d_{lr})/10}\right) \log\left(\frac{p}{50}\right)$

A multipath correction for the paths between the antennas and horizon

P.452 models

Clear air models - Tropospheric scatter

- This uses a scattering angle and the antenna gains

Surface refractivity
(typ 320 N)

$$L_{bs}(p) = 190 + L_f + 20 \log d + 0.573\,\theta - 0.15\,N_0 + L_c + A_g - 10.1\left[-\log(p/50)\right]^{0.7}$$

L_f is a frequency dependant loss $\quad L_f = 25 \log f - 2.5\,[\log(f/2)]^2$

L_c is the aperture to medium coupling loss $\quad L_c = 0.051 \cdot e^{0.055(G_t + G_r)}$

A_g is the gaseous absorption assuming $\rho = 3$ g/m^3

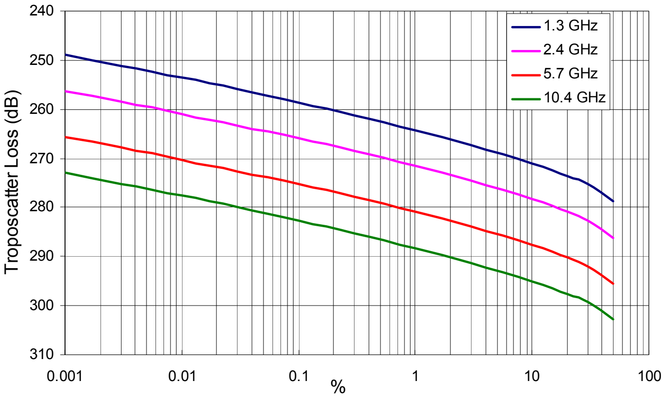
θ is the path angular distance in milliradians $\quad \theta = \theta_t + \theta_r + \dfrac{d}{k \cdot R_{earth}}$ rad

θ_t, θ_r are the transmit and receive elevation angles in milliradians

P.452 models

Clear air models

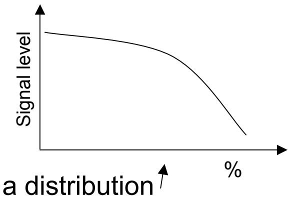
- Tropospheric scatter example
  - E.g. Say θ_t, θ_r *= 0, Gt = Gr = 20 dB, d = 500km*
  - So θ = 60 mrad A_g = 3 dB N_0 = 320 Nunits



P.452 models

Clear air models

- Ducting/ Layer reflection
  - The ducting model is difficult to describe quickly
  - It is based on the β_0 parameter
    - corrected for path geometry and terrain roughness
  - Takes into account frequency and path loss to scale a distribution
    - It is an empirical model, this is the time dependent part



$$A(p) = -12 + (1.2 + 3.7 \times 10^{-3} d) \log\left(\frac{p}{\beta}\right) + 12\left(\frac{p}{\beta}\right)^{\Gamma} \qquad \text{dB}$$

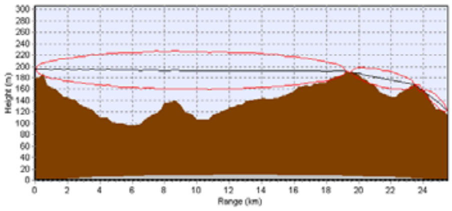
$$\Gamma = \frac{1.076}{(2.0058 - \log\beta)^{1.012}} \times e^{-\left(9.51 - 4.8\log\beta + 0.198\,(\log\beta)^2\right) \times 10^{-6} \cdot d^{1.13}}$$

Not particularly hard to do - but a long sequence of calculations best done in a computer programme

P.452 models

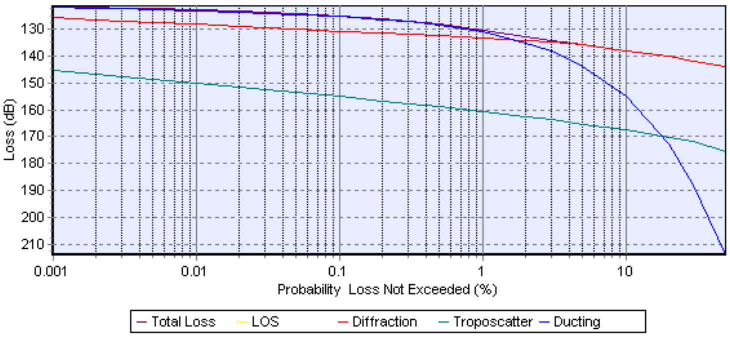
Combining the models

- The models are combined depending on the path type
  - we don't use the line of sight model for a trans-horizon path



A typical result for a 1.3 GHz path

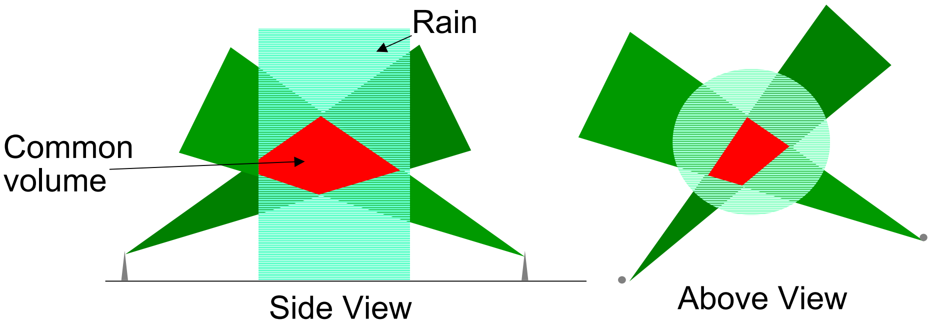
ducting dominates below 1% time



P.452 rainscatter

The rain scatter model is based on integrating the common volume of the antenna patterns through a approximation to a rain storm

- This is done in 3 dimensions using cylindrical co-ordinates

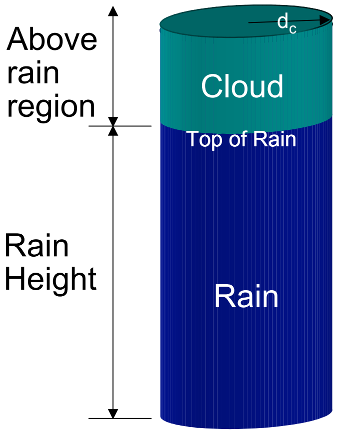


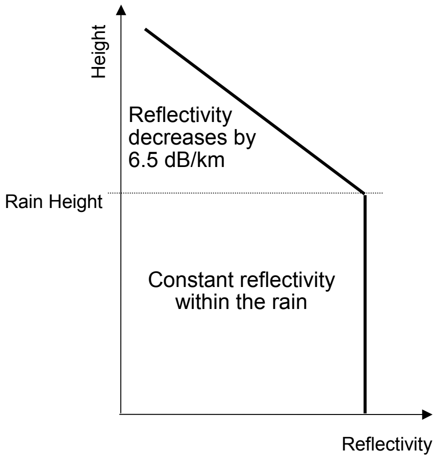
In practice, the integration has to be done numerically, the next slides show some of the important features

P.452 rainscatter

The rain cell is modelled as a Cylinder with radius dependent on the rain rate

$$d_c = 3.3R^{-0.08}$$

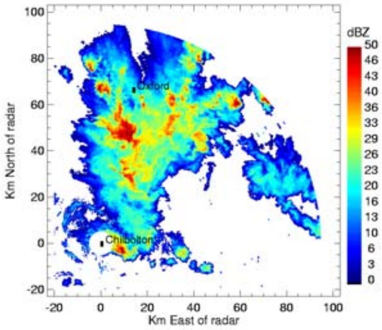




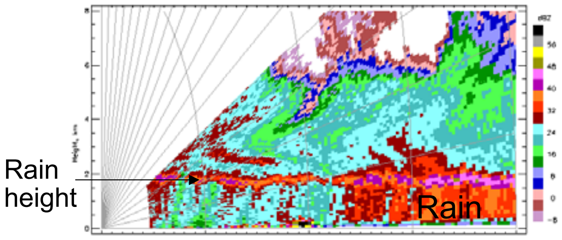
This simple model is used to make the integration tractable

Rain in practice

In real life, the reflectivity is not as in the model, here are some horizontal and vertical images of real rain



Horizontal radar scan showing that rainstorms are not cylindrical



Vertical radar scan showing the bright band

Images from Chilbolton Observatory

http://www.chilbolton.rl.ac.uk/

P.452 rainscatter

The path loss calculation is based on the bistatic radar equation:

$$P_r = P_t \frac{\lambda^2}{(4\pi)^3} \iiint_{\text{all space}} \frac{G(\theta,\phi)_t G(\theta,\phi)_r \eta A}{r_t^2 r_r^2} \mathrm{d}V$$

λ : wavelength
$G(\theta,\phi)_t$: gain of the transmitting antenna
$G(\theta,\phi)_r$: gain of the receiving antenna
η : scattering cross-section per unit volume
A : attenuation along the path from transmitter to receive
r_t : distance from the transmitter to the scattering volume

Solving this is best left as an exercise for a computer

P.452 rainscatter

In dB, the path loss can be formulated as:

$$L = 208 - 20\log f - 10\log Z_R - 10\log C + 10\log S + A_g$$

Where:

$\boldsymbol{Z_R}$ is the radar reflectivity at ground level which is related to the rainfall rate $Z_R = 400R^{1.4}$

S is a correction for Rayleigh scattering above 10 GHz and depends on the rainfall rate and scattering angle

$\boldsymbol{A_g}$ is the gaseous loss

C is the volume integral over the cell including the antenna patterns, the variation with height and the range to transmitter and receiver.

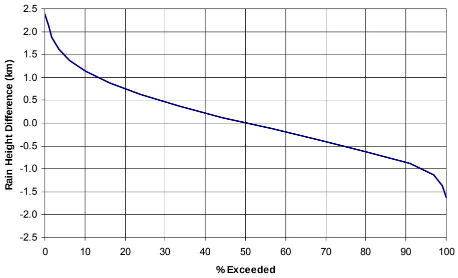
C is found by a fiendish combination of geometry and numerical integration

Two inputs to this model vary, the **Rain Rate** and the **Rain Height,** their statistical distributions govern the distribution of the Loss

P.452 rainscatter

Statistical distributions of rain

- We already know the distribution of rain rate v.s. percentage time
- The distribution of rain height relative to the median is assumed as below



This is claimed to work everywhere but is probably only valid in temperate regions

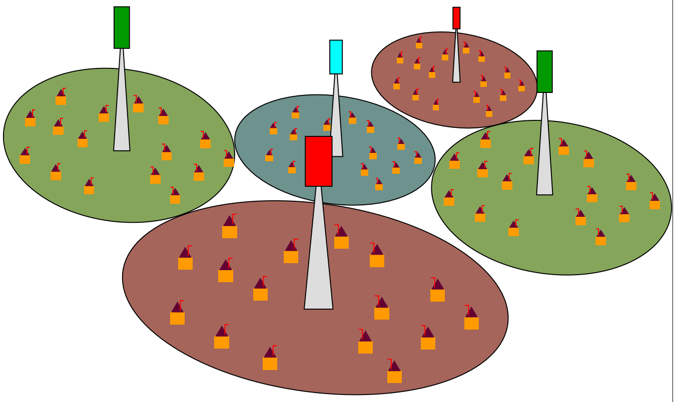
- It is also assumed that rainfall rate and rain height are statistically independent
  - the probability of occurrence for any given pair of rainfall-rate/rain-height combinations the product of the individual probabilities

Broadband Wireless Deployment

A broadband wireless concept

The problem is a point to area prediction

The links are just like short fixed links, but coverage and interference are the main concerns



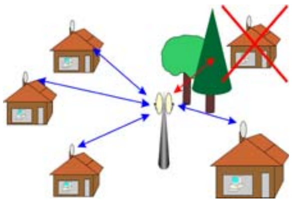
Systems have tended to operate in lower microwave bands with a move to mm-wave bands by regulators who would rather use the lower bands for mobiles

WiMAX/BFWA

Point to multi-point links ~3-50 GHz over short ranges fall into the “Broadband Wireless” category

- Propagation is the same as for terrestrial fixed links
  - The P.530, P.1546 and P.452 models can all be used
- but
  - main the issue is area coverage
  - path needs to be practically line of sight for reliable links
  - antennas are not likely to be on tall masts
  - service is likely to be blocked by buildings and vegetation

The problem is efficiently evaluating the performance of a large number of paths



Models for propagation effects are used in planning radio systems and for designing efficient ways of overcoming any limitations imposed by the path. Broadband wireless access systems tend to require models that cover link ranges of up to around 10km for the frequency bands where sufficient spectrum is available to provide high speed connections to many customers.

The main questions to be answered are can a customer be served, what are the channel characteristics and how does this vary over time. A secondary question that is very important if using spectrum efficiency concerns the interference environment. Systems need to be able to re-use spectrum and to do this a model for the relative strength of the wanted signal against all interferers is needed.

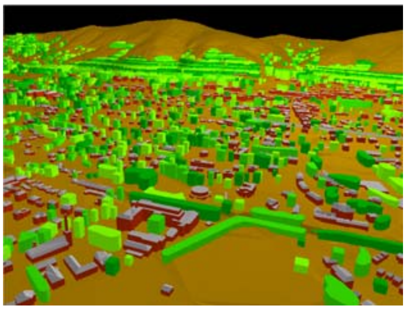
General statistical coverage models for broadband fixed wireless have been around for several years. The results of these models are useful in the initial stages of planning a system, answering questions such as how coverage changes with antenna height, what range can be expected from a link in a rural area compared to one in an urban area and how many base stations are needed in a point to multipoint system to cover a typical town.

Although statistical models can be run on a simple spreadsheet and they are very useful in initial system evaluation, they are less useful when implementing a service where the likelihood of coverage to a site is not specific enough. Sending out an installation engineer to find out is too expensive – so better models are required. As PC power has improved, these now tend to be based exclusively on Ray trace techniques.

Area coverage

Given a town, where and how high should the base station antennas be to obtain line of sight?

- You can find out with a database of all buildings and terrain
  - You could run a computer Ray Trace simulation over a building database



Sample terrain, building and vegetation database

But if you do not have a suitable database there are alternative ways of getting a good statistical estimate

By its nature, accurate clutter data is difficult to obtain and can date rapidly, especially the data for vegetation.

A system deployed in the winter may become unreliable in the spring when leaves appear on trees, or maybe a few years after installation on a new estate when the newly planted trees have grown.

Buildings have a large effect on the radio channel. They provide an opportunity to site an antenna and can block the line of sight. Reflections and diffraction around buildings can increase coverage and can cause multipath.

Until recently, detailed building vector data had to be produced by a manual extraction process based on stereo aerial photography; an expensive and time consuming task. The figure above shows a section of Malvern and was produced using this method.

The development of airborne Lidar surveying has greatly improved the availability of building data, which is now available for many major towns and cities or if not can be obtained quickly and reasonably cheaply. There is now much research being done on how to perform Ray trace predictions over large databases within a reasonable amount of CPU time.

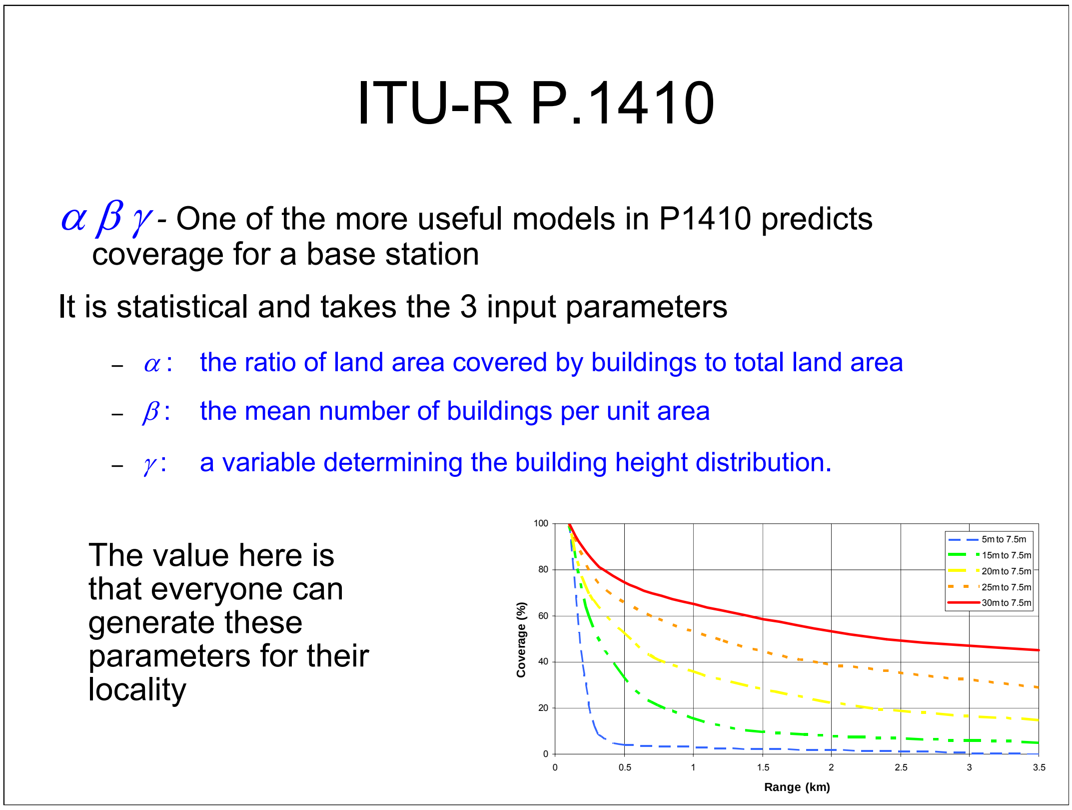
Coverage models based on ray tracing are also useful in indicating coverage on other paths. In a multi-user network, the closest viable link is not necessarily the best one to use; it is good to have a choice to avoid congestion bottlenecks. When rain fading is a limiting factor, the ability to use a backup link may be crucial to meeting the reliability specification.

ITU-R P.1410

Propagation data and prediction methods required for the planning of terrestrial broadband radio access systems operating in the frequency range 2 - 60GHz

This recommendation attempts to assist in planning broadband wireless systems

- Gives advice on
  - Coverage statistics vs base station and terminal heights
  - Area effects of rainfall & diversity
  - A model for reflections and scattering
- Statistics of
  - Dominant propagation mechanism
  - Relative levels of each coverage mechanism at a point



ITU-R P.1410

α β γ - One of the more useful models in P1410 predicts coverage for a base station

It is statistical and takes the 3 input parameters

- α : the ratio of land area covered by buildings to total land area
- β : the mean number of buildings per unit area
- γ : a variable determining the building height distribution.

The value here is that everyone can generate these parameters for their locality

To predict the likelihood of coverage to an area, only a statistical distribution of building characteristics is needed, ranging through for example a simple categorisation, “Urban”, Dense Urban”, Village” or as parameterized data α, β ,γ.

The models developed in ITU-R P.1410 that predict coverage probability can also be used in evaluating interference, which is analogous to unwanted coverage. Interference is usually modeled to greater distances than the intended coverage.

Coverage likelihood derived from empirical models like this is useful in the system design stage, but when attempting to determine if a given customer can be served a more specific prediction is needed. In order to make predictions to individual locations, detailed building data must be obtained to allow more advanced simulations, for example using ray tracing techniques.

Coverage

Line of sight coverage from a reasonable height base station is limited to a few km

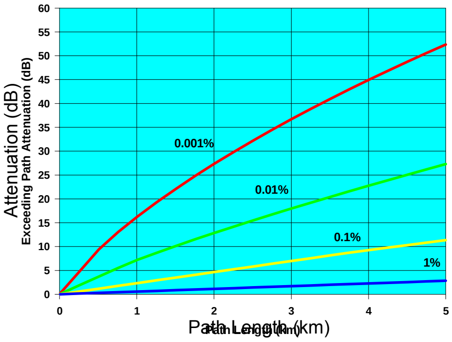
- This means that rain attenuation becomes less important
  - The limit is not the rain fading but coverage economics
  - So higher less congested frequencies can be used
  - This means more bandwidth

- For propagation modelling what matters is
  - Line of sight ?
  - What is the probability of line of sight interference ?
  - What is the probability of multipath ?
  - When it rains, what proportion of the coverage area has outage ?

Coverage

Line of sight coverage from a reasonable height base station is limited to a few km

- This means that rain attenuation becomes less important
  - E.g. a 2km path at 42 GHz will only see 5 dB of rain fading for 99.9% availability
    - The limit is not the rain fading but coverage economics
    - At 2km we expect only 50% coverage
  - So higher less congested frequencies can be used
    - This means more bandwidth



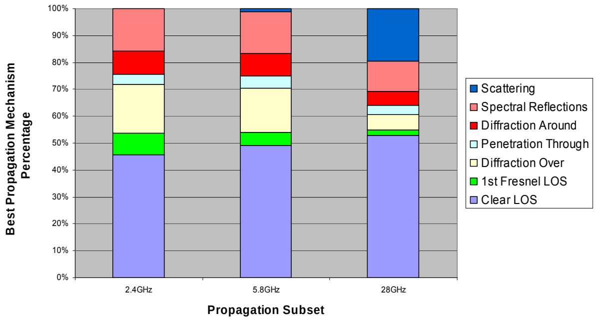
42 GHz rain attenuation (UK)

Radio links in the higher frequency bands are effected by fading when there is heavy rain. This generally limits the overall availability of the link. There is a well established and accurate rain fade model within the ITU-R P.530.

This model is based on the statistics of rainfall. As local climates can be so variable, rain rate statistics must be known or estimated for the area of interest based on the ITU-R rain rate maps.

Relative importance of propagation mechanisms

Results from EU BROADWAN project now incorporated into ITU-R P.1410



This simulation of each mechanism versus frequency band illustrates some important points

Line of sight coverage increases with frequency - Fresnel zones get smaller

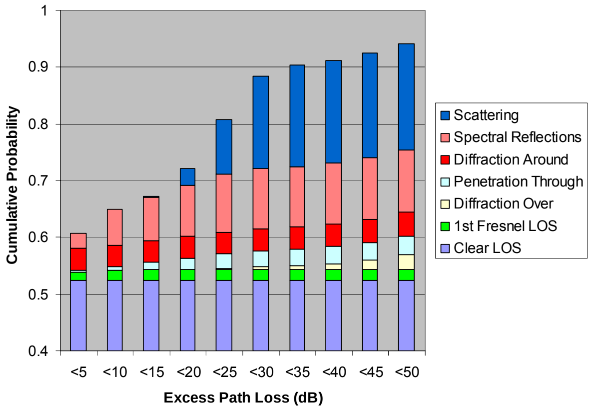
Diffraction becomes less important at higher frequencies – increased losses

Spectral reflections are more likely at lower frequencies - surface roughness

Images extracted from BROADWAN deliverable D17

Relative importance of propagation mechanisms

Results from EU BROADWAN project now incorporated into ITU-R P.1410



Relative path loss is important this plot shows the 2.4 GHz path loss against the cumulative probability, (coverage for up to 60 dB excess loss)

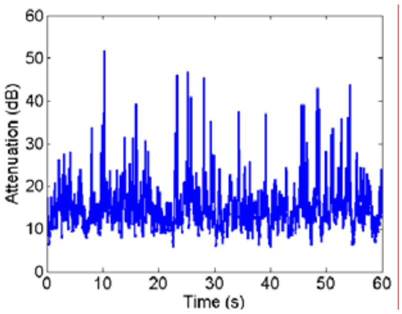
You can gain a lot of coverage from reflections and scattering, but with a high path loss penalty

Images extracted from BROADWAN deliverable D17

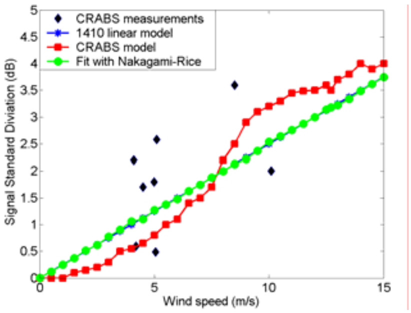
Vegetation fading

The practicalities of WiMAX deployments is that some links pass through limited vegetation

- The same models (ITU-R P.833) used for fixed links are appropriate



Measured time series of link passing through a single tree

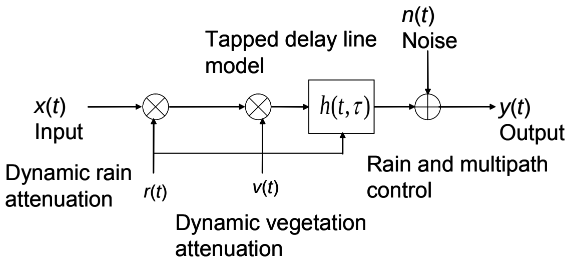


A selection of models for the standard deviation of fade depth

Dynamic channel model

WiMAX system developers need channel models to develop appropriate modulation and coding schemes

- As well as slow fading, links passing through vegetation suffer fast fading due to multipath
- ITU-R P.1410 contains a Tapped delay line model to aid in developing channel simulators



The functions controlling this model and some typical parameters are available from P.1410 and other ITU-R recommendations

In the combined model above, the rain attenuation function r(t) is derived from the synthetic rain field model or for a single link from the Maseng-Bakken[1] model.

The vegetation attenuation function v(t) is derived from the ITU-R P.833 vegetation model including the dynamic effects due to wind.

A tapped delay line model for multipath uses a function h(t,τ) which is derived from measurements from channel sounders.

Additive white Gaussian noise is introduced at the final stage, where interference signals can also be added if necessary.

---

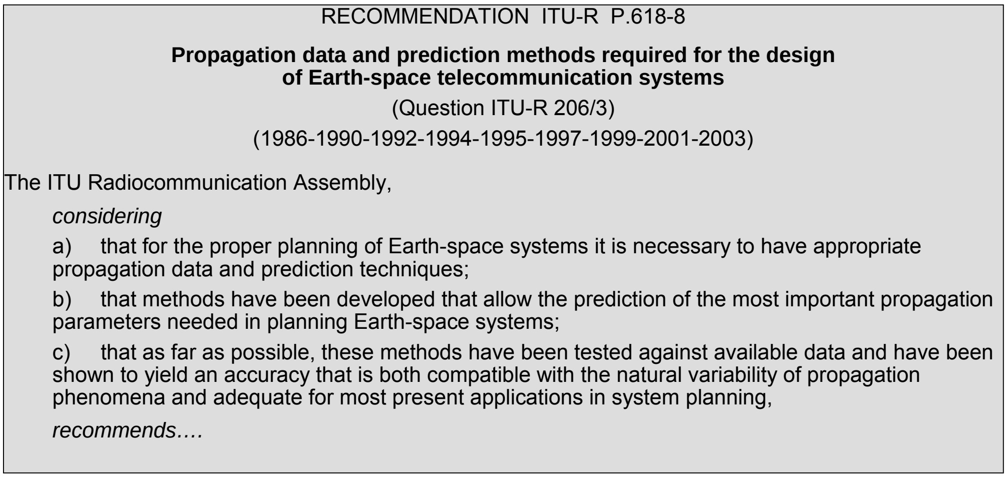
1 - T. Maseng and P. Bakken, “A stochastic dynamic model of rain attenuation,” IEEE Trans. Comm., vol. 29, pp. 660 – 669, 1988.

Fixed satellite

Satellite communications
Satellite broadcasting

ITU-R satellite propagation model

ITU-R Recommendation P.618 is the one to use



RECOMMENDATION ITU-R P.618-8

Propagation data and prediction methods required for the design of Earth-space telecommunication systems

(Question ITU-R 206/3)

(1986-1990-1992-1994-1995-1997-1999-2001-2003)

The ITU Radiocommunication Assembly,

considering

a) that for the proper planning of Earth-space systems it is necessary to have appropriate propagation data and prediction techniques;

b) that methods have been developed that allow the prediction of the most important propagation parameters needed in planning Earth-space systems;

c) that as far as possible, these methods have been tested against available data and have been shown to yield an accuracy that is both compatible with the natural variability of propagation phenomena and adequate for most present applications in system planning,

recommends….

We will look at some of the models in this recommendation once we have covered the principles

These are the main effects to consider

a) absorption in atmospheric gases; absorption, scattering and depolarization by hydrometeors (water and ice droplets in precipitation, clouds, etc.); and emission noise from absorbing media; all of which are especially important at frequencies above about 10 GHz;

b) loss of signal due to beam-divergence of the earth-station antenna, due to the normal refraction in the atmosphere;

c) a decrease in effective antenna gain, due to phase decorrelation across the antenna aperture, caused by irregularities in the refractive-index structure;

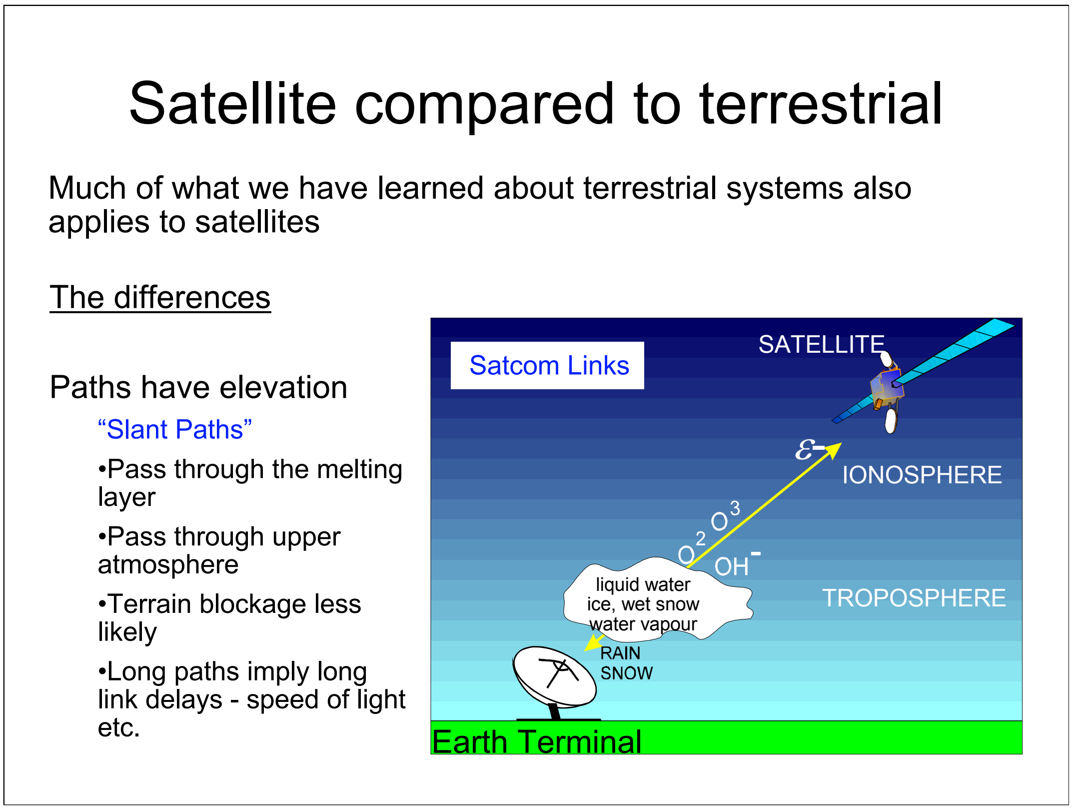
d) relatively slow fading due to beam-bending caused by large-scale changes in refractive index; more rapid fading (scintillation) and variations in angle of arrival, due to small-scale variations in refractive index;

e) possible limitations in bandwidth due to multiple scattering or multipath effects, especially in high-capacity digital systems;

f) attenuation by the local environment of the ground terminal (buildings, trees, etc.);

g) short-term variations of the ratio of attenuations at the up- and down-link frequencies, which may affect the accuracy of adaptive fade countermeasures;

h) for non-geostationary satellite (non-GSO) systems, the effect of varying elevation angle to the satellite



Satellite compared to terrestrial

Much of what we have learned about terrestrial systems also applies to satellites

The differences

Paths have elevation

“Slant Paths”

- Pass through the melting layer
- Pass through upper atmosphere
- Terrain blockage less likely
- Long paths imply long link delays - speed of light etc.

Ionospheric effects may be important, particularly at frequencies below 1 GHz. For convenience these have been quantified for frequencies of 0.1; 0.25; 0.5; 1; 3 and 10 GHz in Table 1 for a high value of total electron content (TEC).

The effects include:

j) Faraday rotation: a linearly polarized wave propagating through the ionosphere undergoes a progressive rotation of the plane of polarization;

k) dispersion, which results in a differential time delay across the bandwidth of the transmitted signal;

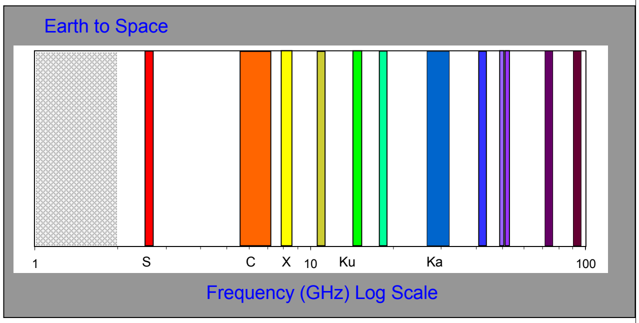
l) excess time delay;

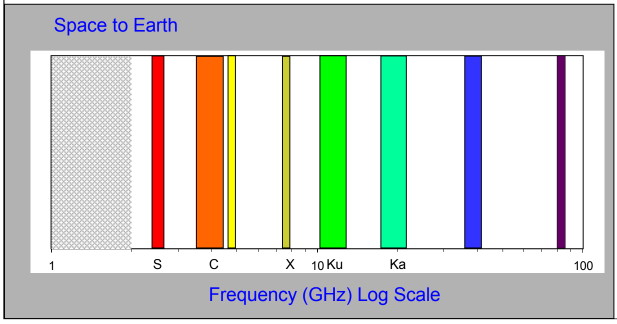
m) ionospheric scintillation: inhomogeneities of electron density in the ionosphere cause refractive focusing or defocusing of radio waves and lead to amplitude fluctuations termed scintillations. Ionospheric scintillation is maximum near the geomagnetic equator and smallest in the mid-latitude regions. The auroral zones are also regions of large scintillation.

Satcom frequency bands 2-100 GHz (Fixed services)

There are many bands allocated for satellite systems

Around 1-2 GHz are mobile bands


Earth to Space


Space to Earth

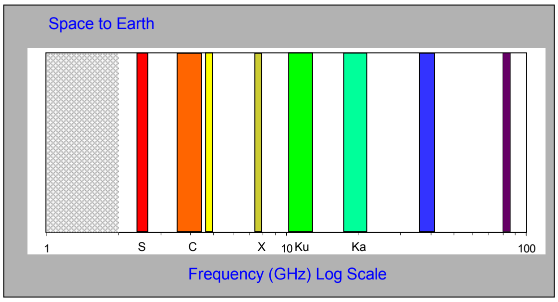
In particular, there is a large amount of bandwidth above 20 GHz which is not used much at the moment

Space - Earth	Earth-Space
2.5-2.69	2.655-2.69
3.4-4.2	5.725-7.075
4.5-4.8	7.9-8.4
7.25-7.75	12.75-13.25
10.7-12.7	14-14.8
17.7-21.2	17.3-18.1
37.5-40.5	27-31
81-84	42.5-43.5
102-105	47.2-50.2
149-164	50.4-51.4
231-241	71-75.5
	92-95
	202-217
	265-275

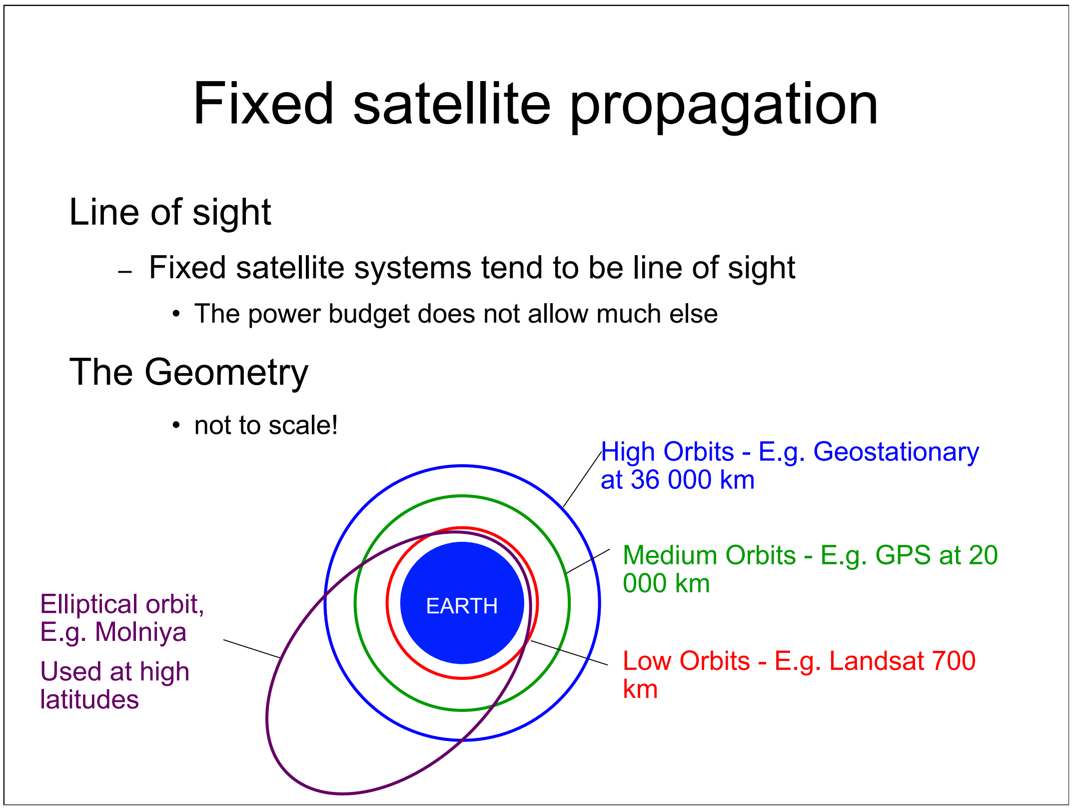
Satcom Frequency bands 2-100 GHz

Space to Earth links tend to be power limited and the higher bands suffer significant rain attenuation

But higher bands allow more directive antennas to be made smaller, so there is a trade off in the link budget



We will now look at the most significant propagation effects along slant paths in the fixed satellite service



Fixed satellite propagation

Line of sight

- Fixed satellite systems tend to be line of sight
  - The power budget does not allow much else

The Geometry

- not to scale!

High Orbits - E.g. Geostationary at 36 000 km

Medium Orbits - E.g. GPS at 20 000 km

EARTH

Low Orbits - E.g. Landsat 700 km

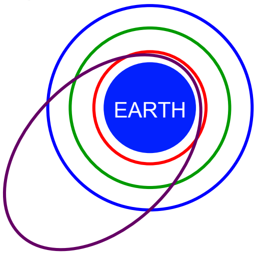
Elliptical orbit, E.g. Molniya

Used at high latitudes

There are an infinite number of potential orbits, but those we are going to consider most are the Geostationary Orbit for fixed services, and low orbits for mobile services.

It is important to remember the propagation delay - the speed of light is finite and a signal sent via a Geostationary satellite will take a quarter of a second or so to make the 72 000km trip.

Line of sight slant paths



Line of sight

- Elevation angles can vary from 0° to 90°
  - For all but Geostationary systems, azimuth and elevation change with time
- At low elevation angles
  - We have longer paths through the atmosphere
    - Increased Rain loss, Gas Loss
  - The layering effects of the Troposphere become more significant
    - More scintillation etc.
    - Angle of arrival differences that require tracking of large antennas
  - We have to worry about multipath from terrain

Ionospheric effects

Ionospheric effects

- Ionospheric Scintillation
  - Caused by variations in electron density
    - Most important at VHF and near the magnetic poles
- Faraday Rotation
  - Caused by electrons along the path combined with the effect of the Earth's magnetic field
    - The group and phase velocity in the medium depends on the polarisation
    - Again most important at VHF
    - Inversely proportional to the square of the frequency

Scintillation can be a problem at C-band, for example, scintillation of up to 5 dB peak to peak have been recorded on links to Hong-Kong for 0.01% of the time. However, it is mainly a problem in the lower bands.

Faraday rotation by the ionosphere can reach as much as 1° at 10 GHz. The planes of rotate in the same direction on the up- and down-links. So it is impossible to compensate for Faraday rotation by rotating the polarisation of the antenna when the same antenna is used both uplink and downlink.

Ionospheric effects

Group Delay

- Free electrons cause a reduction in the group velocity, i.e. the waves slow down so the transit time increases.
  - There is a frequency dependence $1/f^2$.
- The electron density is not constant but varies with time, location and solar activity.
- For example GPS needs to know the excess delay for determining position, low elevation satellites will have more delay than high elevation ones leading to positioning errors if correctly not compensated
- Conversely, GPS can be used for measuring the total electron content along the path and broadcasting corrections

Ionospheric effects

A typical 30^0 elevation path

Effect	**Frequency dependence**	**0.1 GHz**	**0.25 GHz**	**0.5 GHz**	**1 GHz**	**3 GHz**	**10 GHz**
Faraday rotation	$1/f^2$	30 rotations	4.8 rotations	1.2 rotations	108°	12°	1.1°
Propagation delay	$1/f^2$	25 μs	4 μs	1 μs	0.25 μs	0.028 μs	0.0025 μs
Refraction	$1/f^2$	$<1^0$	< 0.16°	$<0.04^0$	$<0.01^0$	$<0.001^0$	$<0.0001^0$
Variation in the direction of arrival (r.m.s.)	$1/f^2$	0.3^0	0.05^0	0.01^0	0.003^0	0.0004^0	0.00003^0
Absorption (auroral and/or polar cap)	$\sim 1/f^2$	5 dB	0.8 dB	0.2 dB	0.05 dB	6×10^{-3} dB	5×10^{-4} dB
Absorption (mid-latitude)	$1/f^2$	< 1 dB	< 0.16 dB	< 0.04 dB	< 0.01 dB	< 0.001 dB	$< 1 \times 10^{-4}$ dB
Dispersion	$1/f^3$	0.4 ps/Hz	0.026 ps/Hz	0.0032 ps/Hz	0.0004 ps/Hz	1.5×10^{-5} ps/Hz	4×10^{-7} ps/Hz
Scintillation$^{(1)}$	See Rec. ITU-R P.531	See Rec. ITU-R P.531	See Rec. ITU-R P.531	See Rec. ITU-R P.531	> 20 dB peak-to-peak	~ 10 dB peak-to-peak	~ 4 dB peak-to-peak

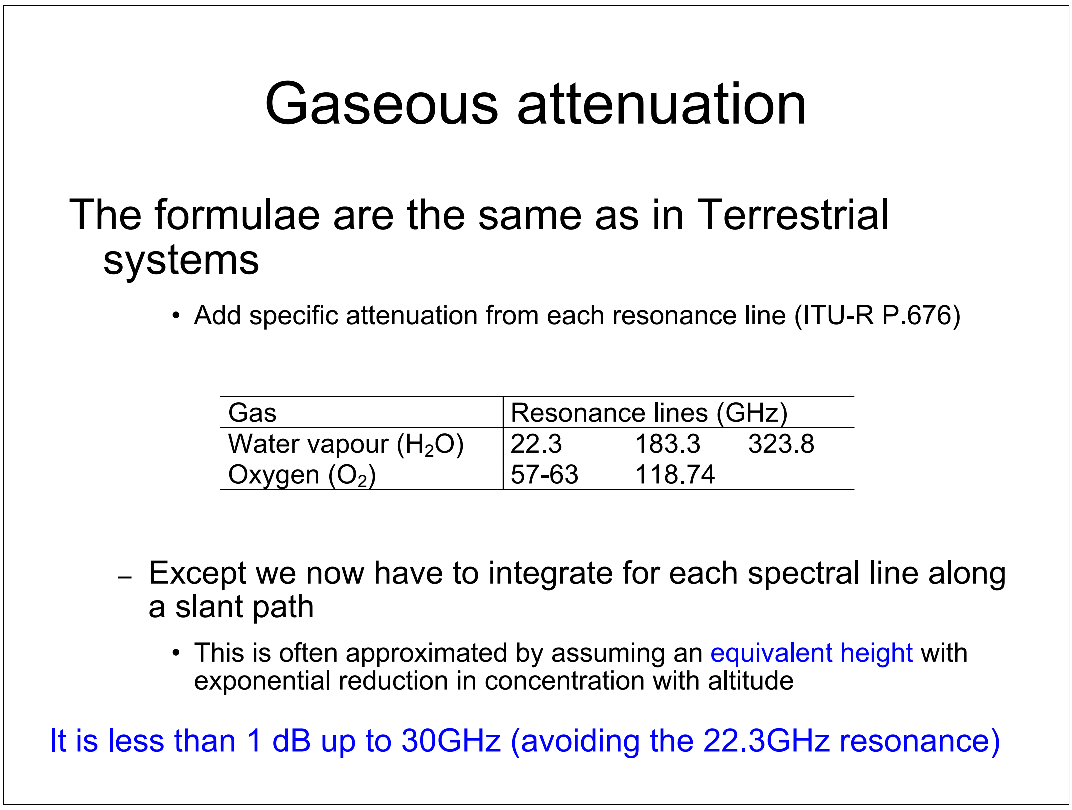
* This estimate is based on a TEC of 10^{18} electrons/m^2, which is a high value of TEC encountered at low latitudes in daytime with high solar activity

** Ionospheric effects above 10 GHz are negligible.

(1) Values observed near the geomagnetic equator during the early night-time hours (local time) at equinox under conditions of high sunspot number.

Note - GPS ~1.5 GHz, An error of 0.1uS = 30 meters

Tropospheric effects on slant paths



Gaseous attenuation

The formulae are the same as in Terrestrial systems

- Add specific attenuation from each resonance line (ITU-R P.676)

Gas	Resonance lines (GHz)		
Water vapour (H_2O)	22.3	183.3	323.8
Oxygen (O_2)	57-63	118.74	

- Except we now have to integrate for each spectral line along a slant path
  - This is often approximated by assuming an equivalent height with exponential reduction in concentration with altitude

It is less than 1 dB up to 30GHz (avoiding the 22.3GHz resonance)

Here is a simple method to work out slant path gaseous losses

Step 1: Calculate the specific attenuations at the surface for dry air γ_o, and water vapour, γ_w, for the frequency, f, and the water vapour density, ρ_w, as specified in Recommendation ITU-R P.676.

Step 2: Compute the equivalent heights for dry air h_o, and water vapour, h_w, as specified in Recommendation ITU-R P.676.

Step 3: Calculate the total slant path gaseous attenuation, A_g, through the atmosphere.

– For $\theta > 10°$:

$$A_g = \frac{\gamma_o h_o \ e^{-h_s/h_o} + \gamma_w h_w}{\sin\theta} \qquad \text{dB}$$

– For $\theta \leq 10°$:

$$A_g = \frac{\gamma_o h_o \ e^{-h_s/h_o}}{g(h_o)} + \frac{\gamma_w h_w}{g(h_w)} \qquad \text{dB}$$

with:

$$g(h) = 0.661\, x + 0.339 \sqrt{x^2 + 5.5\,(h/R_e)}$$

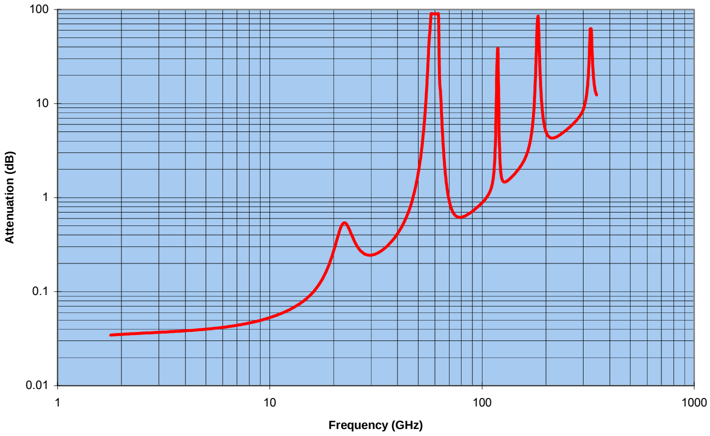
$$x = \sqrt{\sin^2\theta + 2(h_s/R_e)}$$

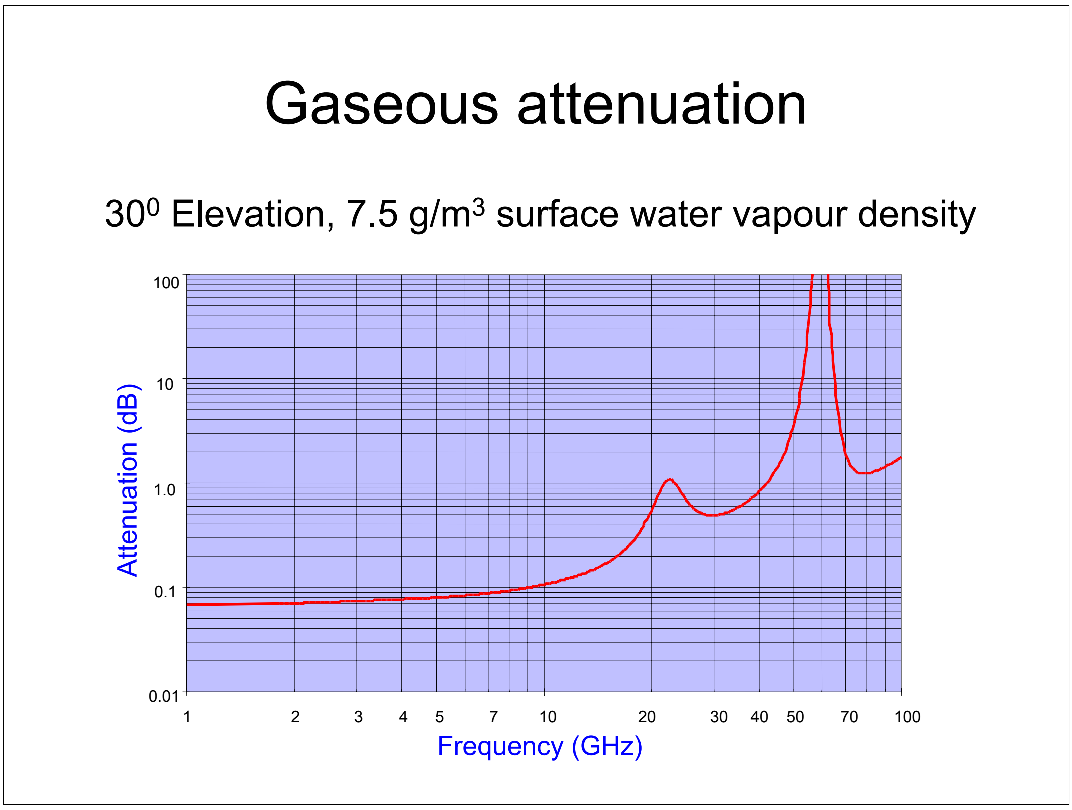
where h is to be replaced by h_o or h_w as appropriate.

Gaseous attenuation

Zenith Attenuation

- This is the total attenuation vertically upwards
- We scale this to the required elevation angle





Gaseous attenuation

30^0 Elevation, 7.5 g/m^3 surface water vapour density

This graph was generated using a simple approximation for the elevation angle.

Depolarisation

Caused by rain and especially ice.

- It occurs where the characteristics of the medium are different for different polarisation planes.
  - For example, needle shaped ice crystals or non spherical raindrops.
- Power is randomly coupled from one polarisation plane to another
- It is significant when re-using spectrum
- for rain, use a similar model as for terrestrial links
- in clouds, ice can cause significant depolarisation above 20GHz

The ice model is long which is why it is not given here.

Frequency reuse through orthogonal polarization is often used to increase the capacity in telecommunication systems. The cross-polar isolation is an important factor in determining the interference into each orthogonal channel from the other. Rain depolarisation limits the isolation.

Noise

The noise temperature of space is generally very low

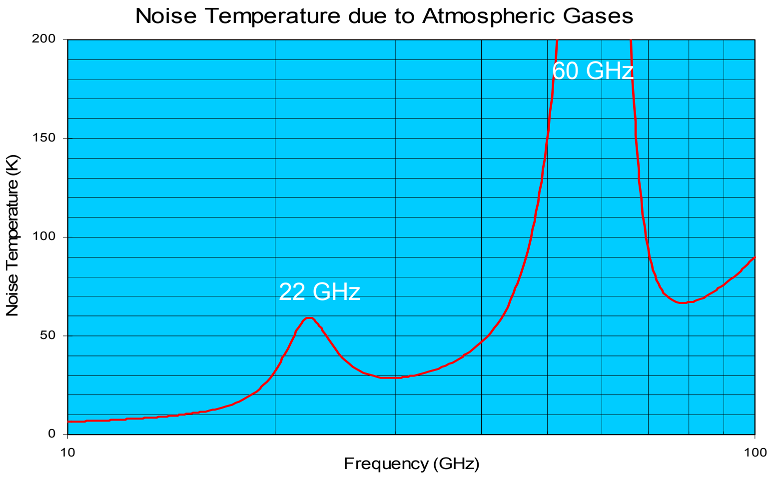
- There are some cosmic noise sources, for example the sun, crab nebula etc.
  - But most of the noise received at an earth station comes from terrestrial and atmospheric sources
- Clear sky noise arises from the thermal noise emitted by atmospheric gasses.
  - Where there is significant absorption, there is also significant noise emission
  - Rain can be a major noise source in proportion to the rain attenuation
  - To calculate it, use the equations we covered for lossy media:

$T_{sky} = T_{medium}(1 - 10^{-A/10})$ where T_{medium} = 260K for rain
A = attenuation in dB T_{medium} = 28

Noise example

This is what you might expect at 30^0 elevation

(looks just like the attenuation plot)



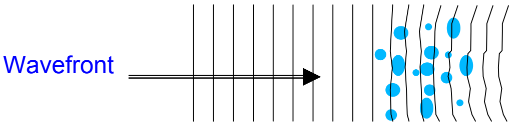
Angle of arrival variations

The troposphere is not stationary, especially in terms of relative humidity

- Signals will experience a different refractive index over time. Refraction processes will therefore vary, causing the angle of arrival to change
- The effects are usually small and only noticeable with a large (in terms of wavelengths) antenna
  - Compensation can be made by re-pointing the antenna

Beam spreading

Same as terrestrial systems except the effect is magnified because of the long paths through the atmosphere



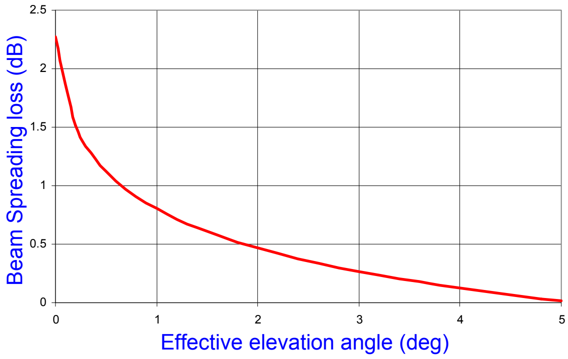
- Different radiowave paths will experience different refractive indices and different velocities causing a de-correlation in amplitude and phase
- The beam spreads out - leading to a loss
- With large antennas the phase of the wavefront across the aperture becomes non-coherent, resulting in an apparent reduction in gain, though this is generally less than the spreading loss

Beam spreading loss

It is negligible for elevations above 5^0. Below 5^0

Spreading Loss = $2.27 - 1.16\log(1 + \theta_n)$ dB

where θ_0 is the apparent elevation angle (mrad) taking into account the effects of refraction. The loss is constrained be > 0



Coherence bandwidth ?

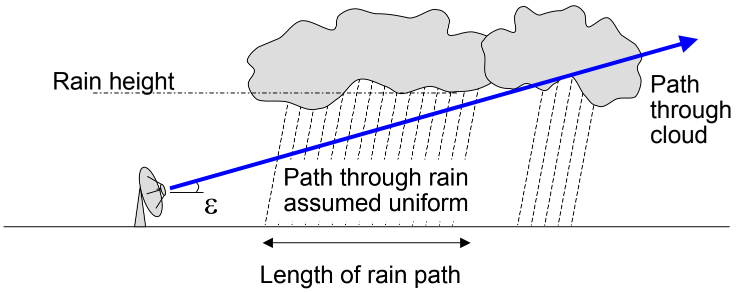
Dispersion through the atmosphere limits the coherence bandwidth

- The degree of dispersion increases with hydrometeor scatter along the path
- Not generally a problem as the coherence bandwidth is much greater than the frequency allocations available
- With enough rain to cause significant dispersion, the attenuation is already severe

Rain attenuation model

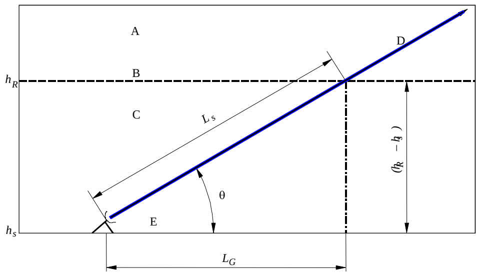
The rain attenuation model is based on the same principles as for terrestrial services

- We model rain rate up to the rain height and calculate the path length through it



Rain attenuation model

Diagrammatically



A: Frozen precipitation (ice)
B: Rain Height
C: Liquid precipitation (rain)
D: Earth space Path
E: Ground height

Rain Height
$$h_R(\text{km}) = \begin{cases} 5 - 0.075(\varphi - 23) & \text{for} \quad \varphi > 23° \quad \text{Northern Hemisphere} \\ 5 & \text{for} \quad 0° \le \varphi \le 23° \quad \text{Northern Hemisphere} \\ 5 & \text{for} \quad 0° \ge \varphi \ge -21° \quad \text{Southern Hemisphere} \\ 5 + 0.1(\varphi + 21) & \text{for} \quad -71° \le \varphi < -21° \quad \text{Southern Hemisphere} \\ 0 & \text{for} \quad \varphi < -71° \quad \text{Southern Hemisphere} \end{cases}$$

UK = 3km

Note - This rain height model is basic and does not account for season.

Correction factors:

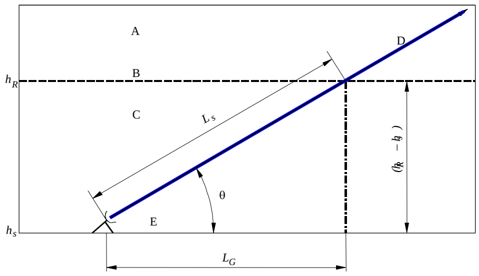
Convective Regions (e.g. Mountainous Terrain) + 300m

Maritime Regions (- 500m)

Seasonal corrections

Month	Correction (m)
January	-990
February	-985
March	-750
April	-575
May	+85
June	+770
July	+1150
August	+1165
September	+835
October	+340
November	-375
December	-750

Rain attenuation model



Procedure involves finding a horizontal and vertical scaling factor

Use $R_{0.01}$ to find

specific attenuation $\gamma_R = kR^{\alpha}$

Rain slant path length $L_s = \dfrac{h_r - h_s}{\sin\theta}$ Valid for $\theta > 5^o$

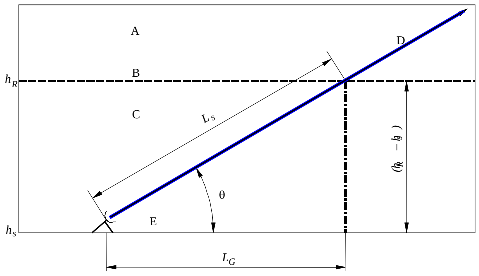
Horizontal projection $L_G = L_s \cos\theta$

Horizontal reduction factor $r_{0.01} = \dfrac{1}{1 + 0.78\sqrt{\dfrac{L_G\,\gamma_R}{f}} - 0.38\left(1 - e^{-2L_G}\right)}$

(f in GHz)

Rain attenuation model

Vertical adjustment factor



Find angle $\phi = \tan^{-1}\left(\frac{h_R - h_s}{L_G\ r_{0.01}}\right)$ degrees

If $\phi > \theta$ $\quad L_R = \frac{L_G\ r_{0.01}}{\cos\theta}$ km

otherwise $\quad L_R = \frac{(h_R - h_s)}{\sin\theta}$ km

There is a Latitude dependence

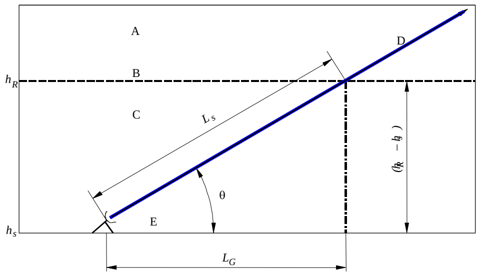
If | Latitude | < 36°, χ = 36 - | Latitude |

otherwise χ = 0

Vertical adjustment factor $v_{0.01} = \dfrac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-(\theta/(1+\chi))}\right)\dfrac{\sqrt{L_R\ \gamma_R}}{f^2} - 0.45\right)}$

Rain attenuation model

Effective path length



$$L_{Eff} = L_R \, v_{0.01}$$

Finally:

$$\text{Attenuation } A_{0.01} = \gamma_R \, L_E \quad \text{dB}$$

There is a percentage of time scaling factor as in the terrestrial case

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}))} \quad \text{dB}$$

For latitudes > 36^0

Other time percentages

There is a percentage of time scaling factor as in the terrestrial case

P.618 recommends

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}))} \text{ dB}$$

For latitudes > 36^0

An older approximation is:

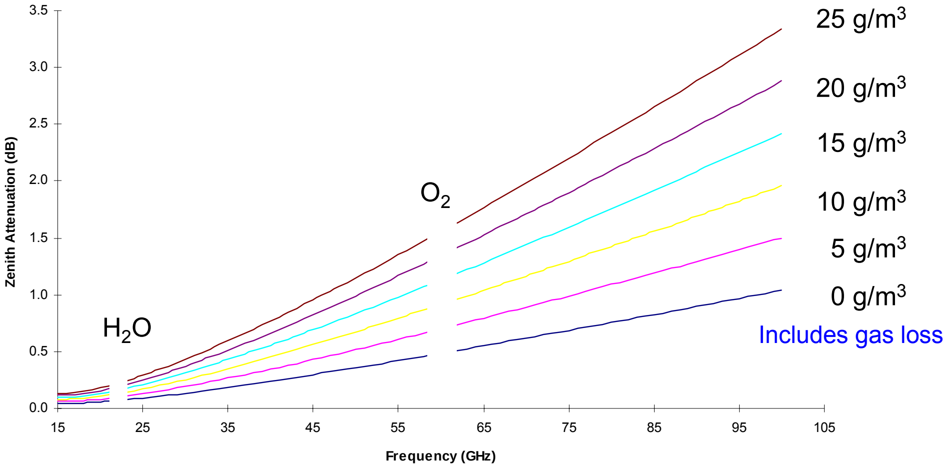
$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-0.33} \quad \text{for } 0.001 \le p \le 0.01$$

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-0.91} \quad \text{for } 0.01 < p \le 0.1$$

$$A_p = 1.3A_{0.01}\left(\frac{p}{0.01}\right)^{-0.5} \quad \text{for } 0.1 < p \le 1$$

Clouds

We introduced the attenuation due to clouds in the introduction



Attenuation at Zenith (looking straight up) for cloudy sky

Cloud data

Typical cloud characteristics

Cloud Type	Drops (m^{-3})	Liquid water (g/m^3)	Average radius (μm)
Cumulus	3.0×10^8	0.15	4.9
Stratocumulus	3.5×10^8	0.16	4.8
Stratus	4.6×10^8	0.27	5.2
Cumulonimbus	7.2×10^7	0.98	14.8

This data is of course highly variable

Cloud attenuation model

Altzhuler and Marr model

- Assumes the Rayleigh approximation
- Based on measurements at 15 GHz and 35 GHz
- A liquid water temperature of 10°C is assumed
- Cloud and Fog produce the same attenuation versus frequency characteristics
- Also includes Gases - but not the absorption peaks

Model (valid for 15 GHz - 100 GHz):

$$A_{Zenith}(\lambda,\rho)=\left(-0.0242+0.00075\lambda+\frac{0.403}{\lambda^{1.15}}\right)(11.3+\rho) \quad \text{dB}$$

Where λ is in mm, and ρ is in g/m^3.

This simple model is not pat of the ITU-R recommendation. That model is much more refined. However, this does give an indicative value to use in preliminary planning.

Cloud attenuation model

For slant paths, we approximate the attenuation (in dB) for elevation angle ε by:

$$A_{Slant} = \frac{A_{Zenith}}{\sin\varepsilon}$$ for ε >10°

$$A_{Slant} = A_{Zenith}\left[(r_e + h_e)^2 - r_e \cos^2\varepsilon\right]^{\frac{1}{2}} - r_e \sin\varepsilon$$ for ε <10°

Where r_e is the effective earth radius 8497km and h_e is the height of the cloud/fog and can be estimated from:

$$h_e = 6.35 - 0.302\rho$$

This is a very simple model, which does not work at the absorption peaks, there are much more complex ones, which do.

1/sin ε really is cheating - but it is good enough for many purposes.

Tropospheric scintillation

Tropospheric scintillation magnitude

- increases with frequency f $^{7/12}$ and with path length
- decreases as antenna size increases because of aperture averaging
- Monthly-averaged r.m.s. fluctuations are well-correlated with the wet term of the radio refractivity

$$N = \underbrace{77.6\frac{P}{T}}_{\text{Dry term}} + \underbrace{3.73 \times 10^5 \frac{e}{T^2}}_{\text{Wet term}}$$

- At very low elevation angles $<5^0$ the scintillation is combined with a the same processes seen on terrestrial links

ITU-R P.618 gives a detailed model for estimating scintillation on satellite paths.

Tropospheric scintillation

Clear Sky Model

Standard deviation $\sigma = \dfrac{1}{\sin(\varepsilon)^{0.85}} \sqrt{G(r)} \cdot f^{7/12} \cdot 2.5 \times 10^{-2}$ dB

Where *G(r)* = aperture averaging factor, ε = elevation angle, *f* = frequency in GHz

$$G(r) = 1 - 1.4\left(\frac{R}{\sqrt{\lambda L}}\right) \text{ for } 0 \le \frac{R}{\sqrt{\lambda L}} \le 0.5$$

$$G(r) = 0.5 - 0.4\left(\frac{R}{\sqrt{\lambda L}}\right) \text{ for } 0.5 < \frac{R}{\sqrt{\lambda L}} \le 1.0$$

$$G(r) = 0.1 \text{ for } 1 > \frac{R}{\sqrt{\lambda L}}$$

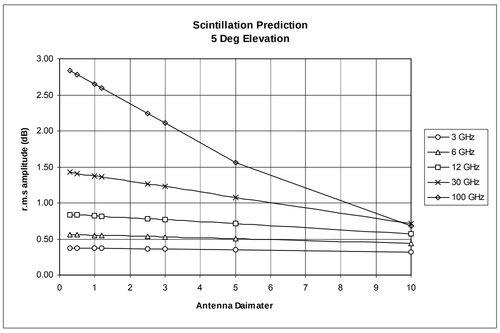
$$R = \sqrt{\eta}\,\frac{D}{2}$$

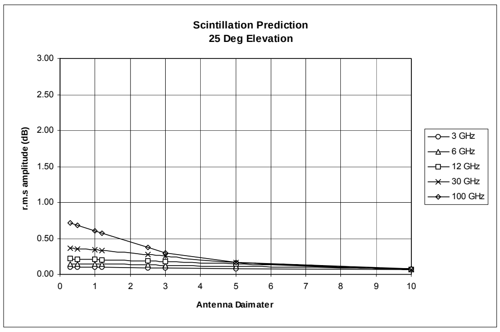
$$L = \frac{2h}{\sqrt{\sin^2(\varepsilon) + \frac{2h}{R_e}} + \sin(\varepsilon)}$$

D = antenna diameter
η = antenna efficiency
h = height of turbulence, 1000m
R_e = effective earth radius 8500km

Tropospheric scintillation

Scintillation Model Examples





Tropospheric scintillation

Scintillation Spectra

- Measurements have indicated a low pass characteristic
  - Corner frequency of 0.1 Hz
  - Slope of -8/3

Statistical Characteristics

- Over a few minutes
  - Variance is constant
  - Amplitude PDF is approximately Gaussian
- For longer periods
  - Amplitude distribution expressed in dB is Gaussian
  - The standard deviation of this amplitude is a random variable with a normal distribution .