Propagation Parts 1&2

An introduction to radiowave propagation

Course notes

What matters to us

Professionals

- Professionals are interested in Reliability
  - Most of their models are designed to assist in designing reliable radio links and in avoiding interference

Amateurs

- Amateurs tend to be interested in Unreliability
  - Working paths that are marginal and can't be relied on (DX)
  - Using effects that cause the professionals trouble, long range interference etc.
  - Sometimes, the more unreliable the better – to break a record
- Many amateurs are interested in reliable paths – but that's not so interesting and I won't be talking about them

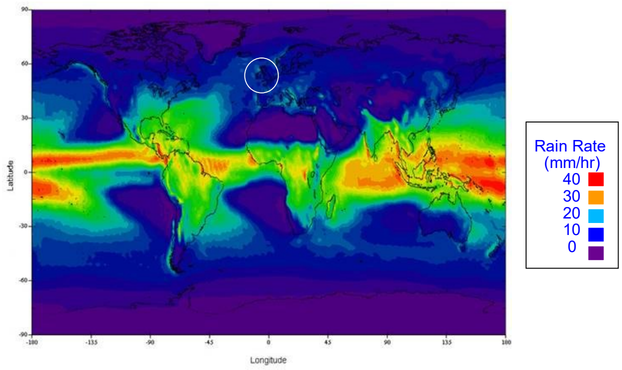
This talk will cover Anomalous propagation effects, rare events, why they happen and how often

Models and stuff

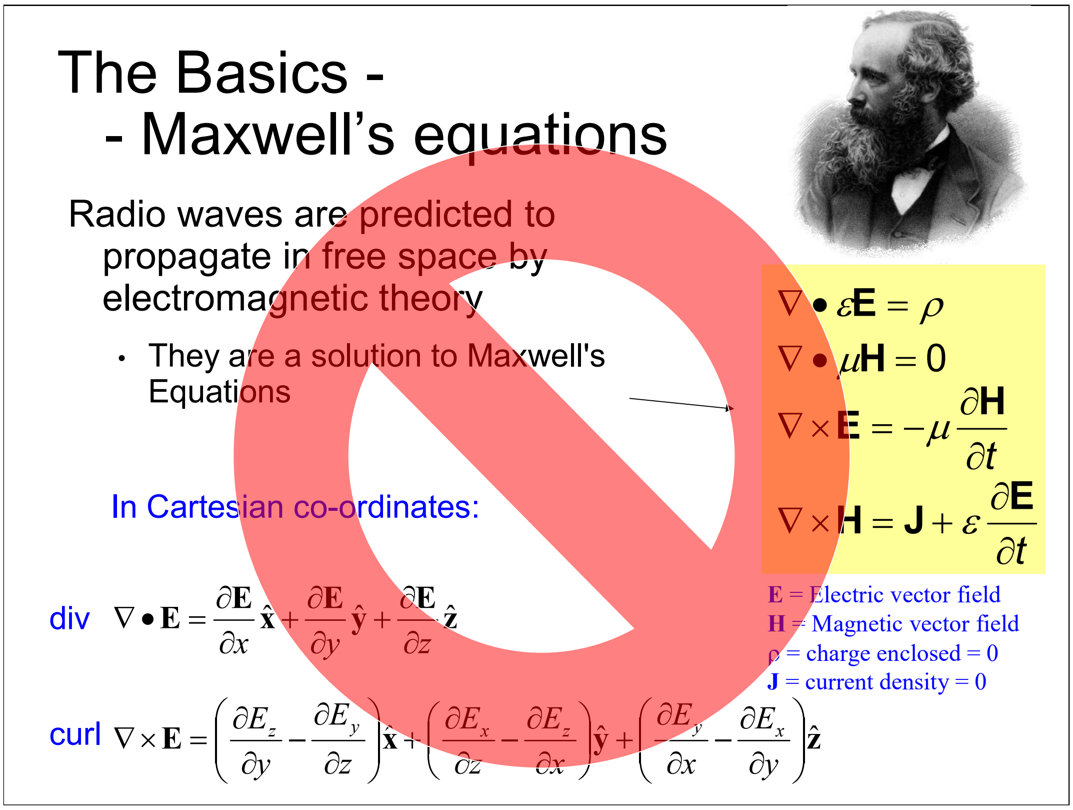
We are going to try to look beyond simply testing a path too see if it works to look into predicting what may happen

- Look at mechanisms
- Look at some models

(not too much maths)



0.01% Rain rate



These are really not that bad

The Divergence operator $\nabla \cdot \mathbf{E}$ $\nabla \cdot \mathbf{H}$

In physical terms, the divergence of a three dimensional vector field is the extent to which the vector field flow behaves like a source or a sink at a given point. Hence, the sourcing or sinking of an E field creates an H field. In Maxwell's equations, these represent Gauss law.

The Curl operator $\nabla \mathrm{x} \mathbf{E}$ $\nabla \mathrm{x} \mathbf{H}$

This is the tendency of the vector field to loop or rotate in space. The curl shows a vector field's rate of rotation: the direction of the axis of rotation and the magnitude of the rotation. Maxwell's equations show that looping E field with give rise to a change in the H field and a looping H field will give rise to a changing E field with a phase shift arising from the j term.

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

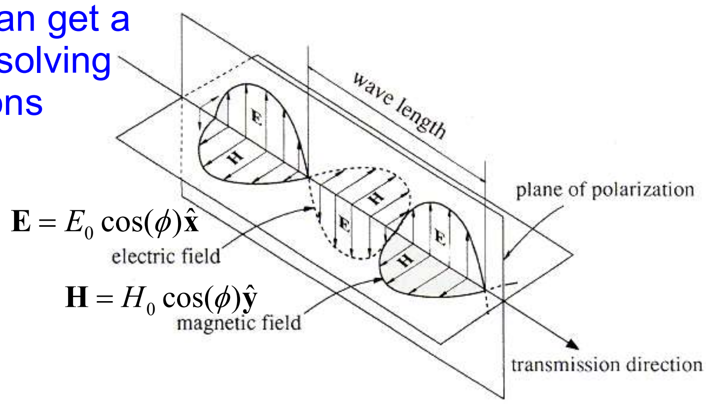
This is Faraday's Law
a magnetic field changing in time creates a proportional electromotive force

$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t}$$

This is Ampere's Law
relates the circulating magnetic field in a closed loop to the electric current passing through the loop

OK some maths – The plane wave

Fortunately, we can get a long way without solving Maxwell's equations



Just remember:

E and H are orthogonal

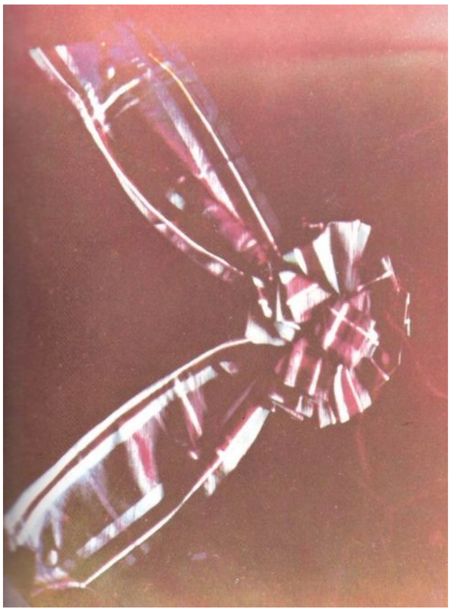
Sinusoidal variation in amplitude

Polarisation is defined by the E field

Wavelength is the distance travelled in one cycle of E and H.

James Clerke Maxwell (1831-1879) was an interesting character. His first paper to the Edinburgh Royal Society "On the Description of Oval Curves, and those having a plurality of Foci" was written when he was only 14 and had to be read out for him because he was too young. It was based on work he had done using twine, pins and a pencil.

Besides his famous work on Electromagnetic theory, he was a leading contributor to the kinetic theory in gases and to the theory of colour vision. He correctly discovered how we perceive colour and took the first colour photograph, an image of of a Tartan Ribbon in 1861 using 3 coloured filters, red, green and blue to capture and later project 3 copies of the image.



First colour photo

Field strength vs. distance

Power Flux Density

If have a point source energy spreads out over a sphere – the power per unit area is the transmit power divided by the area of this sphere:

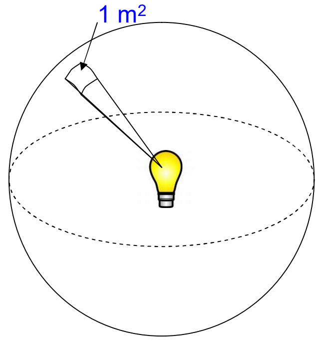
Area of a Sphere = $4\pi r^2$

So:

$P_{pfd} = P_t / 4\pi r^2$ w/m^2

This is the inverse square law

PFD – power flux density, the amount of power passing through 1 square metre



Free space loss (FSL)

There not really any loss but not all the energy is captured at the receiver

- it's only a loss in the sense that it the power has gone off to bother someone else
- We define the transmission loss as follows:

$$\text{Transmision Loss} = 10\log_{10}\left[\frac{P_{rx}}{P_{tx}}\right] \quad \text{dB}$$

Power received

Power transmitted

Finding the FSL in dB/GHz/km

In useful units of GHz, km and dB:

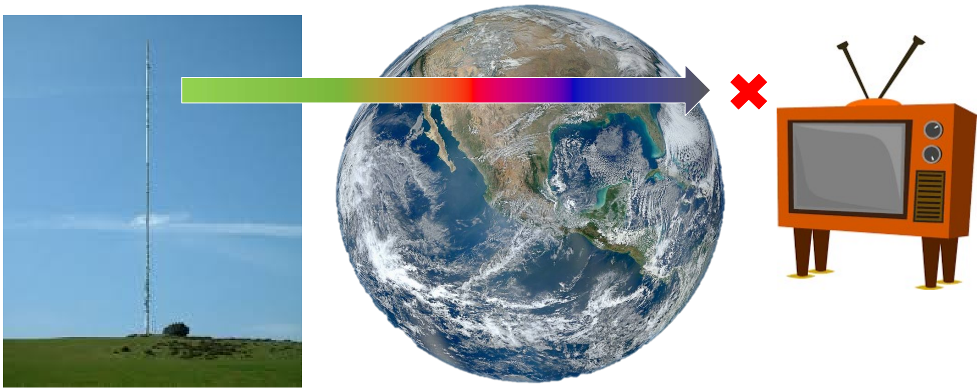
$$\text{Free Space Loss} = \left(\frac{\lambda}{4\pi r}\right)^2 = \left(\frac{c}{4\pi r f}\right)^2$$

$$\text{Free Space Loss (dB)} = 20\log\left(\frac{c}{4\pi \cdot 1\times 10^3 \cdot 1\times 10^9}\right) - 20\log(r) - 20\log(f)$$

$$\text{Free Space Loss} = -92.4 - 20\log(r) - 20\log(f) \qquad \text{dB}$$

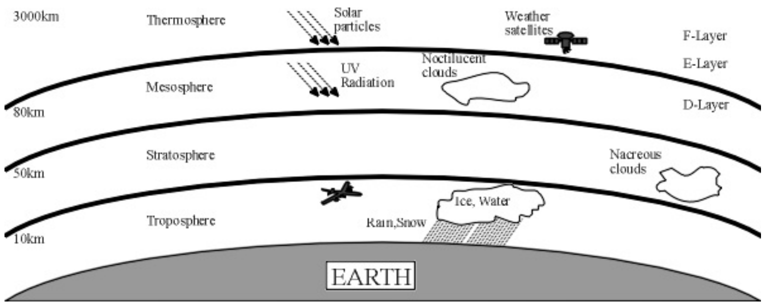
The main problem with this theory is we are not usually in free space

We want to communicate between points on the Earth – and the Earth gets in the way



Propagation in real life situations

At VHF and up we are mainly concerned with the paths through the Troposphere, the lowest region of the atmosphere that extends up to about 10-20km.



That is the effects of the terrain, air and the weather on radio paths – and especially the anomalous effects

Moving upwards from the ground the layers which are differentiated by the variation of temperature with height are:

Troposphere: From the ground continuing up to between 7 km at the poles and 17 km at the equator with some variation due to weather. It is the thinnest but most dense layer, with 72% of the total mass of the atmosphere is below 10 000m.

The troposphere is well mixed mixing due to solar heating at the surface. This heating warms air masses near the ground, which then rise as thermals. On average, temperature decreases with height.

Stratosphere: This extends from the top of the troposphere (7–17 km) up to around 50 km. In the stratosphere temperature increases with height.

Mesosphere: This extends from about 50 km to around 80-85 km. Temperature decreases with height.

Thermosphere: This extends from 80–85 km to in excess of 600km. The temperature increases with height. The Thermosphere is the boundary of the atmosphere, beyond the Thermosphere is the **Exosphere**, which extends into space.

The boundaries between the layers are the tropopause, the stratopause, the mesopause and the thermopause.

Gaseous attenuation

Long paths through the atmosphere are attenuated by gaseous absorption.

Air is made up of:

- Nitrogen (N_2) 78%
- Oxygen (O_2) 21%
- Argon (Ar) 0.9%
- Carbon dioxide (CO_2) 0.1% - (Varies with location, increasing…)
- Neon, Helium, Krypton 0.0001%
- Water vapour (H_20) which varies in concentration from 0-2%

(With Trace quantities of: Methane (CH_4), Sulphur dioxide (SO_2), Ozone (O_3), Nitrogen oxide (NO) Nitrogen Dioxide (NO_2). There are other gases too, as well as particulates and pollution)

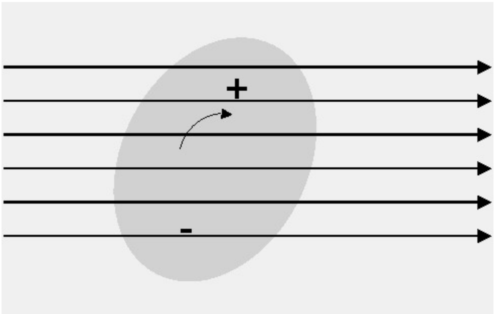
99% of the atmospheric mass is concentrated below 10km

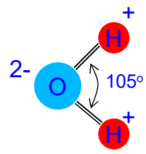
Why gasses attenuate radio signals

Gas molecules interact with the Electromagnetic field

This may cause energy loss

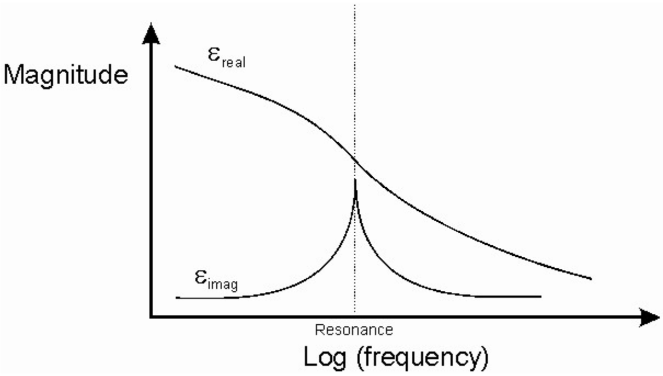
E.g. H_2O molecules are asymmetric and will try and align with the Electric field





There are other interactions too, magnetic field molecular oscillations etc.

Molecular resonance lines



Permittivity vs. Frequency

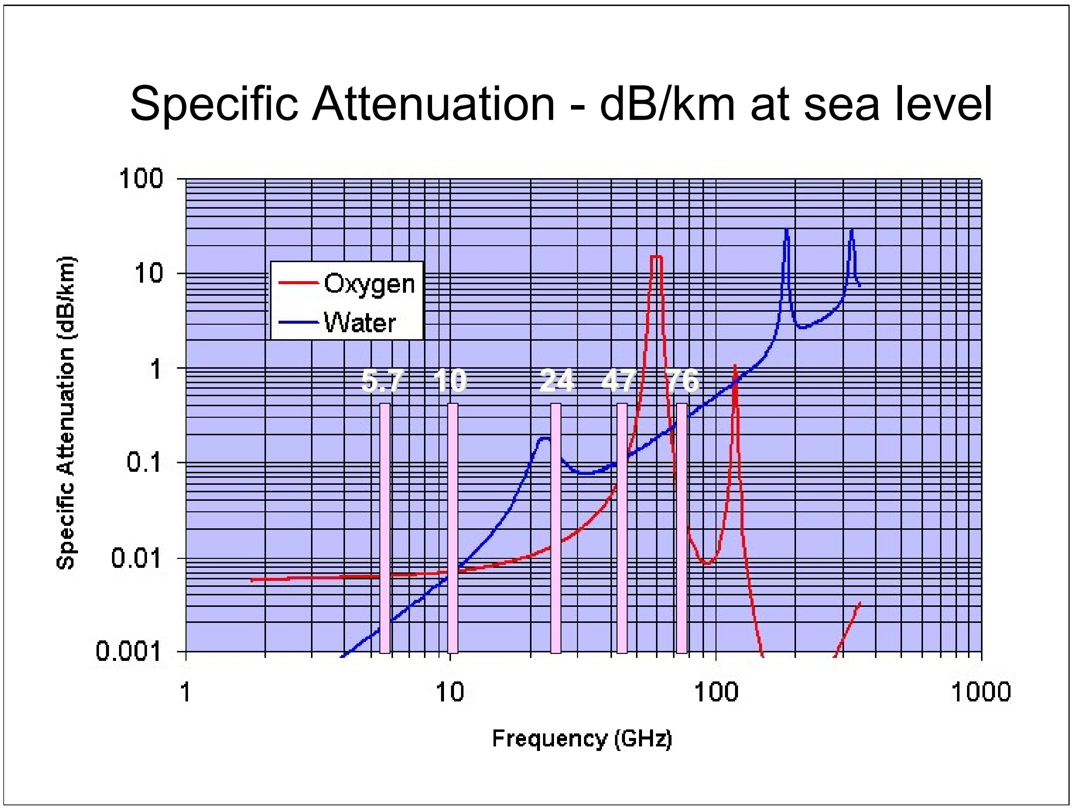
The imaginary part represents loss

Gaseous attenuation

This loss depends on:

- The resonant frequency - "absorption line" of the Gas molecules in question
- The concentration of that Gas in the atmosphere
- The length of the path through the gas

The most significant up to 300GHz are Water Vapour and Oxygen



Water vapour attenuation

Approximately, works up to ~ 350 GHz

$$A_{water} = \left\{ 0.050 + 0.0021\,\rho + \frac{3.6}{(f-22.2)^2 + 8.5} + \frac{10.6}{(f-183.3)^2 + 9.0} + \frac{8.9}{(f-325.4)^2 + 26.3} \right\} f^2 \rho\, 10^{-4} \quad \text{dB/km}$$

Where ρ is the water vapour concentration in g/m^3

f is the frequency in GHz

Oxygen attenuation

Approximately, works up to ~ 350 GHz

$$A_{O2} = \left(7.19\times10^{-3} + \frac{6.09}{f^2 + 0.277} + \frac{4.81}{(f-57)^2 + 1.5} \right) f^2 \times 10^{-3} \qquad f < 57\ \text{GHz}$$

$$A_{O2} = \left(3.79\times10^{-7} f + \frac{0.265}{(f-63)^2 + 1.59} + \frac{0.028}{(f-118)^2 + 1.47} \right) (f+198)^2 \times 10^{-3} \qquad f > 63\ \text{GHz}$$

Where: f is the frequency in GHz

For 57-63 GHz, an averaged value of 14.9 dB/km is used.

Gas loss per 100km

1013 mB, 15C, Water vapour concentration 7.5g/m^3

Band	Total (dB/100km)	Oxygen (dB/100km)	Water (dB/100km)
13cms	0.7	0.7	0.03
9cms	0.8	0.7	0.07
6cms	0.9	0.7	0.2
3cms	1.5	0.8	0.7
24GHz	18	1.4	16.5
47GHz	24	13	11
76GHz	36	9	27

Needs to be dry for mm-waves

The ground

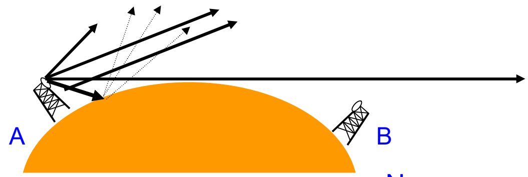
(Terrain getting in the way)

Atmospheric propagation

You might imagine waves travel along straight lines for ever, or until they hit something

For a transmitter on the ground

- Power radiated above the horizon will go into space
- Horizontal signals will travel to the horizon and then be absorbed
- Signals below horizontal will be absorbed or scatter into space



No energy gets from A to B ?
(we know it does)

Rule of thumb – distance to radio horizon (km) versus transmitter height (m)

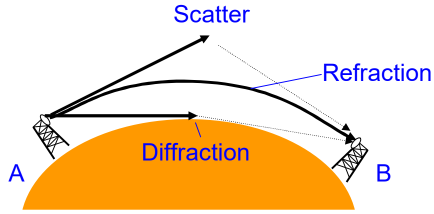
$$d = 4.12\sqrt{h}$$

Atmospheric propagation

We know signals do propagate beyond the horizon

The major mechanisms are

- Refraction - bending of signals towards ground
- Scattering - from air, from rain
- Diffraction - diffraction from terrain

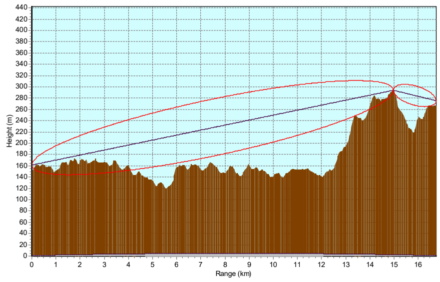


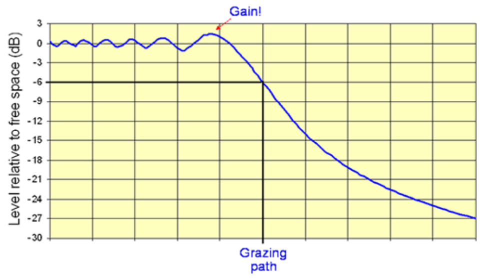
Long range paths are dominated by troposcatter for most of the time. These are Normal “flat band” conditions. Amateur DXers are interested in abnormal conditions – generally refraction and rain scatter

Diffraction

In view of the maths and time, I am not covering diffraction

- It is a mode of propagation that is always present but far beyond line of sight the losses become very high
- This is because the loss at each obstacle rapidly adds up

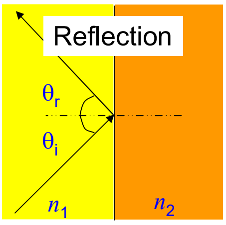




Some special cases do occur, paths with only one sharp obstacle e.g. diffraction over a sharp mountain peak – DX, unreliable but useful.

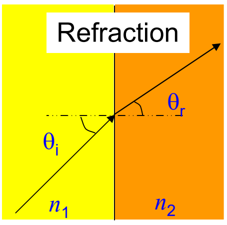
Refraction

Remember Snell's laws



For reflection

Angle of incidence = angle of reflection



For refraction

$$\frac{\sin(\theta i)}{\sin(\theta r)} = \frac{n_2}{n_1}$$

Where n is the refractive index

If $n_2 < n_1$ $\theta_r < \theta_i$ <u>the ray is bent downwards</u>

Willebrord Snel van Royen (1580–1626) was a Dutch astronomer and mathematician and is most famous for his law of refraction now known as Snell's law.

In 1617 he reported on an experiment to measure the distance between Alkmaar and Bergen op Zoom which are separated by one degree with the aim of determining the radius of the Earth.

He measured one degree to be equal to 107.4 km. which was only 3km out. He also developed new method for calculating π. He discovered his law of refraction in 1621.

Willebrord Snel van Royen

The atmosphere vs. height

Higher altitudes

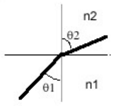
- Lower pressure
- Lower temperatures

Refractive index falls with height

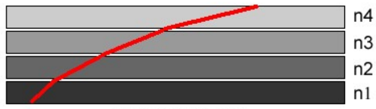
- waves get “bent” downwards
- they propagate beyond the geometric horizon! DX!

To find out by how much we need to know about the refractive index of air with height

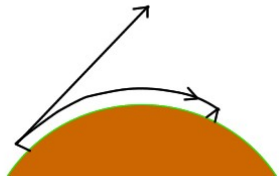
Snell's Law



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



$n_1 > n_2 > n_3 > n_4$



The N unit

The refractive index of air is very close to 1

Typically n = 1.0003 at sea level

This is most tedious - lots of decimals to type – hard sums

We define a new unit, the N unit – “Refractivity”

$$N = (n - 1) \times 1\,000\,000$$

Refractive index

The refractivity of air

The value of N is:

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

dry term wet term

P = dry pressure, ~1000mb
T = temperature, ~300k
e = water vapour partial pressure ~40mb

The parameters vary with time and space

- the dry term depends only on pressure and temperature
- the wet term also depends on the water vapour concentration

N = 310 typical at sea level in the UK

Refractive index vs. height

$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{e}{T^{2}}$$

Pressure falls exponentially with height

- The scale height is around 8km

Temperature normally falls by about 1°C per 100m of altitude

Water partial pressure is much more complex

- it is strongly governed by the weather
- is limited to the saturated vapour pressure (the water the air can hold)
- The saturated water vapour pressure is around 40 mbar at 300K (a warm day) and 6mbar at 273K (freezing).
  - So the amount of water vapour above the zero degree isotherm is negligible.
  - The zero degree isotherm is typically a few km, near the cloud base.

There is practically no water vapour above 3km in the UK

So if you want to break the 24GHz UK DX record, start with a pair of sites 3000m ASL…

The scale height is the height where the pressure is 1/eth of the ground value. (This value of e is not the water vapour pressure, it is the constant e from natural logs and has the value 2.718). Scale heights are used frequently in describing functions that decrease exponentially.

Because the water vapour pressure is governed by the amount of moisture the air can hold, once the temperature drops below 0C the water vapour condenses out as clouds. Practically, we can say the amount of water vapour above 2-3km is negligible.

Get on with it

The result of all this is that the refractive index falls exponentially with height in a "standard" atmosphere

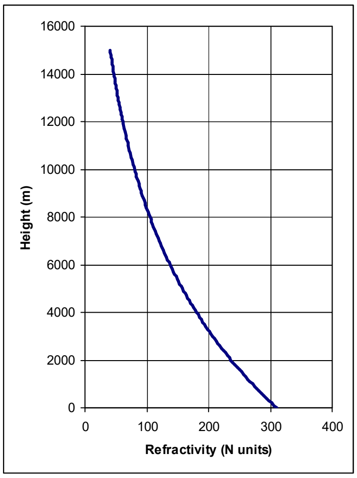
The scale height is ~7.4km

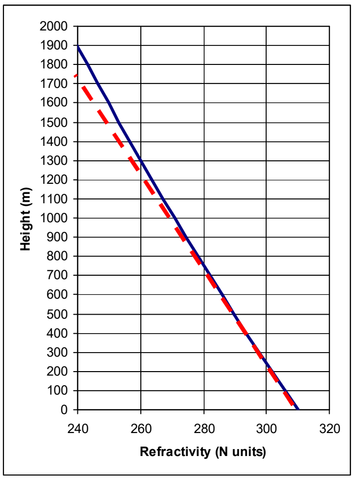
In the first 1000m we can approximate this as a straight line

Slope ~ -40 N/km

We write this as:

$$dN/dh = -40$$

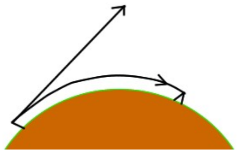




This is normal - but we want to know abnormal conditions - Tropo

Representing an exponential function as a straight line is cheating, but it is a good enough approximation up to 1000m or so. Beware of this when planning systems on top of mountains.

The radius of curvature



Normally N falls by 40 units per km. This leads to the standard 4/3 radio horizon

To get the signal to follow the curvature of the Earth the refractivity needs to fall by 157 N units per km

Proof:

The rate of change of angle $d\theta/dh \sim dn/dh \sim dN/dh \times 10^6$

(From Snell's law and applying the small angle approximation $\sin\theta \sim \tan\theta \sim \theta$)

$$\frac{\sin(\theta_i)}{\sin(\theta_r)} \approx \frac{\theta_i}{\theta_r} = \frac{n_2}{n_1}$$

The Earth radius ~ 6371 km

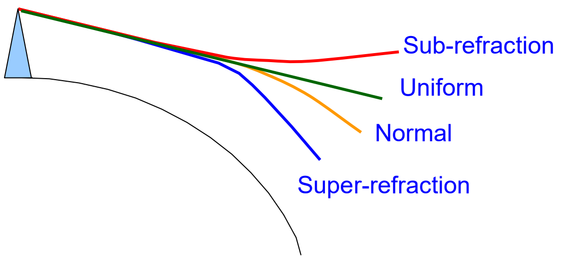
To follow Earth curvature, $d\theta/dh = -1.57\times10^{-4}$ radians/km

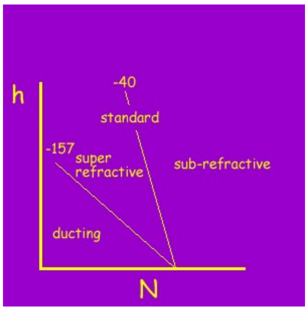
So dN/dh = -157 N units/km to follow the Earth's curve

(This is the threshold of ducting, Normally dN/dh = -40)

Super-refraction

If refractivity falls by more than 157 N units per km, signals will be refracted by more than the curvature of the Earth and be trapped





When does this happen ?

Ducting and inversions

Non-standard atmospheric conditions lead to anomalous propagation

Pressure is not a factor – it tends to be quickly restored to equilibrium by winds

Most important are the variations in:

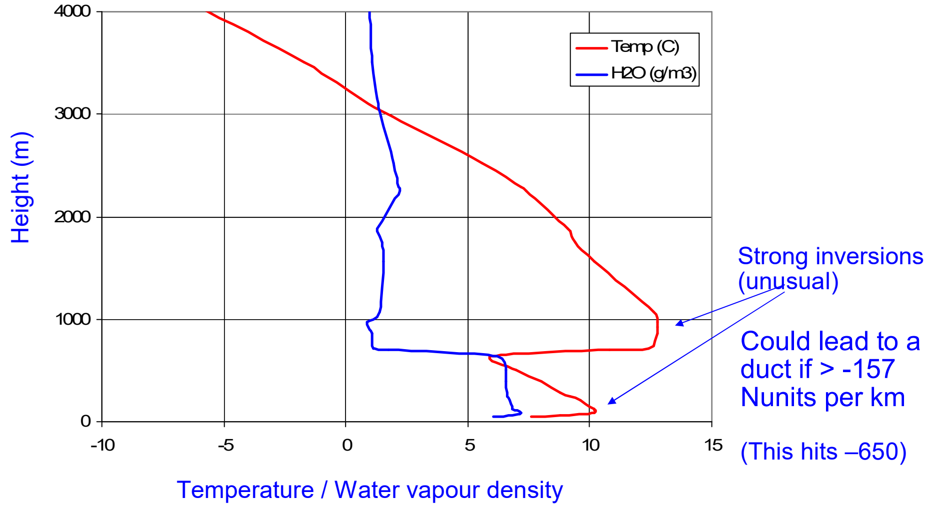
- Water vapour density
- Temperature

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

Ducts form when either T is increasing or water vapour is decreasing <u>unusually</u> rapidly with height

Ducting and inversions

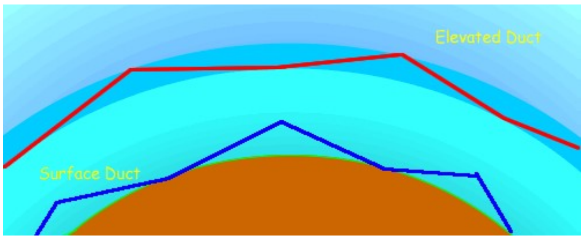
An example of the temperature inversion on 7th November 2006 (I wrote this a while back)



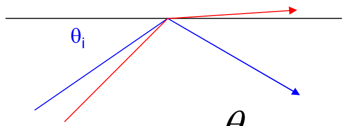
Ducts

- Ducts can be at ground level or elevated

- Depending on the terminal height the signal may or may not couple into the duct



To couple into and remain in a duct the angle of incidence must be small, typically less than 1°

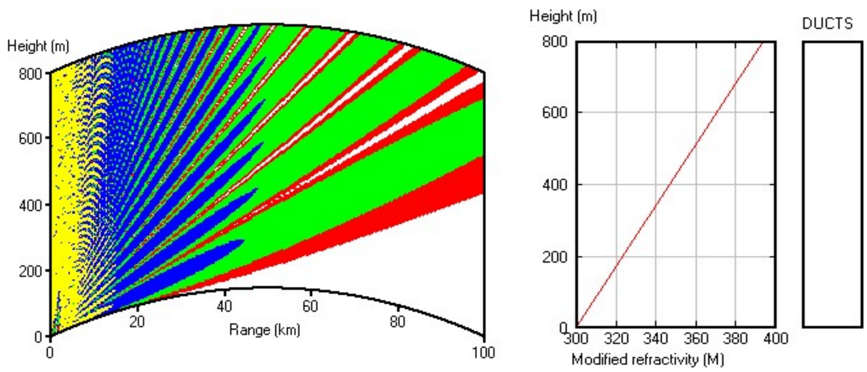


$$\theta_{maximum} \approx \sqrt{\frac{2}{|\Delta N|}}$$

The significance of elevated ducts is that they can allow signals to propagate for very long distances over the horizon. It is possible for intermediate terminals to be below the elevated duct and not able to couple into it – resulting in non-monotonic path loss with range.

Duct classifications

Standard atmosphere

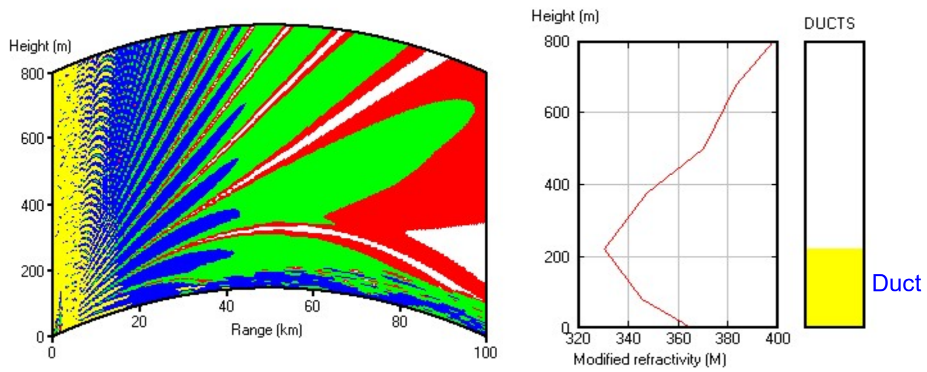


None

Simulations of a duct at 3 GHz from a 20m high antenna

Duct classifications

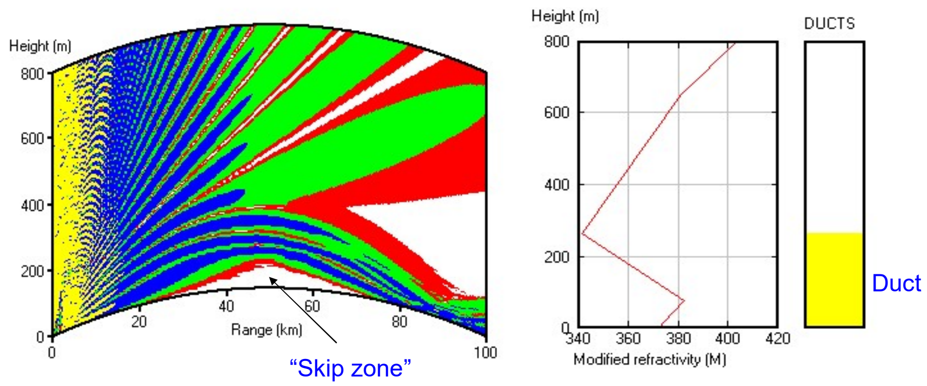
Surface layer, surface duct



Simulations of a duct at 3 GHz from a 20m high antenna

Duct classifications

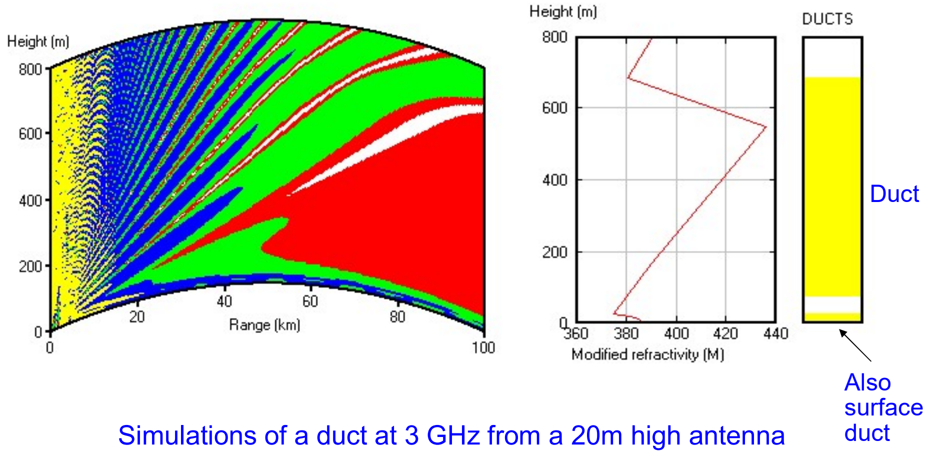
Elevated layer, surface duct



Simulations of a duct at 3 GHz from a 20m high antenna

Duct classifications

Elevated layer, elevated duct



Simulations of a duct at 3 GHz from a 20m high antenna

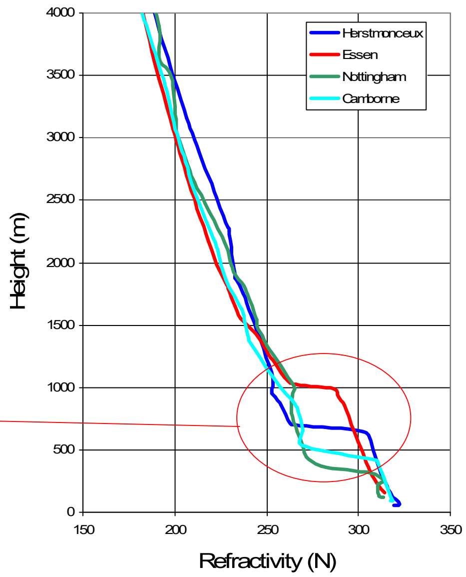
Measured ducts

Non-standard refractivity vs. height

Can get layering, limited in height but extensive in area

Here is an example:

This sharp decrease in N with height gives strong super-refraction (big lift that night)

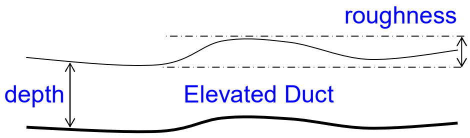


00:00Z 7th November 2006

Data acquired from
http://weather.uwyo.edu/upperair/sounding.html

Will a duct support a signal?

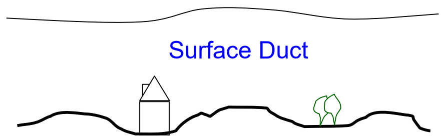
The depth and "roughness" are important



If the duct depth is small compared to the wavelength, energy will not be trapped

If the roughness is large compared to the wavelength, energy will be scattered out of the duct

Surface ducts have the ground as a boundary and energy will be lost to the terrain, vegetation etc.



Why we get ducts

Causes:

- The weather alters temperature pressure and humidity
  - regions of air are moved about, mixed up, elevated and depressed by cyclones and anti-cyclones
- radiation from the land raises the air temperature near the ground
- The ground cools quickly on clear nights
- evaporation from areas of water can cause local high humidity gradients

Evaporation ducts and Temperature Inversion

Evaporation Ducts

- Generally over a large body of water, the humidity gradient is very high in the first few metres

Temperature Inversions

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

- Cold ground at night cools local air and temperature rises with height, this is an inversion
  - If it is dry, the P/T term dominates δN, which rises and leads to super-refraction
  - If it is humid, fog condenses out, this reduces the water vapour density near the cold ground, δN falls and sub-refraction occurs

Evaporation Ducts

There is usually a region for a few metres above the surface of the sea where the water vapour pressure is high due to evaporation. This also occurs over large bodies of water, for example the great lakes. The thickness of the duct varies with temperature of the location, typically 5m in the North sea, 10-15m in the Mediterranean and often much more over warm seas as in the Caribbean and Gulf. Naturally, these ducts have a significant effect on Shipping and have been extensively researched. It is the reason that VHF/UHF propagation over sea can extend to great distances causing all sorts of international frequency co-ordination problems.

Temperature Inversions

Usually, temperature falls with height by about 1K per 100m. On clear nights the ground cools quickly and this can result in a temperature inversion, where the air temperature rises with height. If it is dry, the temperature term is dominant in Equation 5 and super refraction and ducting can occur. This is particularly common in desert regions.

If there is significant water vapour the relative humidity can quickly rise to 100% and vapour condenses out as fog. This condensation reduces the water vapour density near the ground leading to cold dry air near the ground, warmer moister air above and results in sub-refraction. This can lead to multipath on otherwise apparently perfectly good line of sight links.

Subsidence

Subsidence

- Descending cold air is forced downwards by an anticyclone
  - The air that is forced down is compressed
  - compressed air heats up
  - this air becomes warmer than the air nearer the ground
  - leads to an elevated temperature inversion, at 1-2km, too high for most stations to couple into
- As the anticyclone evolves the air at the edges subsides and this brings the inversion layer closer to the ground
- Anticyclones and subsequent inversions often exist over large continents for long periods

Subsidence

This is a mechanism that can lead to elevated ducts and is associated with high pressure weather systems - anticyclones. Descending cold air forced downwards by the anticyclone heats up as it is compressed and becomes warmer than the air nearer the ground leading to an elevated temperature inversion. (Atmospheric pressure always increases closer to the ground). This all happens around 1-2km above the ground far too high to cause ducting except for very highly elevated stations as the coupling angle into the duct is too great for a ground based station. As the anticyclone evolves the air at the edges subsides and this brings the inversion layer closer to the ground. A similar descending effect happens at night. In general, the inversion layer is lowest close to the edge of the anticyclone and highest in the middle. Anticyclones and subsequent inversions often exist over large continents for long periods.

Advection

Advection

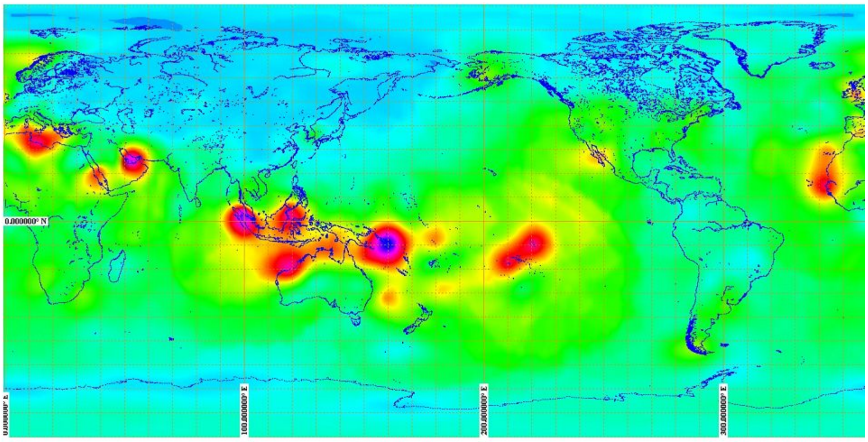
- This is the movement of air masses (winds)
- air from a warm land surface advects over the cooler sea
  - The warm air mixes with the cooler air which is relatively moist through being close to the sea
  - This extends the height of the evaporation duct and causes a temperature inversion
  - Which forms a surface duct within the first few 100m above the sea
  - These ducts do not persist over land and are a coastal effect

Advection

This is the movement of air masses, typically occurring in Early evenings in the summer with air from a warm land surface advecting over the cooler sea. This warm air mixes with the cooler air which is relatively moist through being close to the surface of the sea. This leads extending the height of the evaporation duct and to high humidity gradients and a temperature inversion forming a surface duct within the first few 100m above the sea. These ducts do not persist over land and are a coastal effect. Typically in the UK they are associated with warm anticyclonic weather over the continent of Europe and advection out over the north sea. They tend to be weaker than subsidence ducts but do occur relatively often over the North Sea and can persist for many days. For example, it is relatively common for UHF signals to propagate well beyond line of sight from the East coast of England across the North Sea to the low countries.

The incidence of ducting

Global probability of ducting



Some areas, E.g. The Gulf states have a very high probability of ducting
With ducts present for more than 50% of the time

This map is from the latest ITU-R recommendations. It replaces an earlier model that only used Latitude.

$$\beta_{ud} = \begin{cases} 10^{-0.015|\varphi|+1.67} & \text{for } |\varphi| \le 70° \\ 4.17 & \text{for } |\varphi| > 70° \end{cases}$$

This really does still need to be tested some more as it may be more of a reflection of Matlab plotting routines for sparse data than actual reality. Use with care.

UK incidence of ducting

UK probability of ducting

- Evaporation ducts - happen all the time
  - Widespread duct forms over the sea,
    e.g. North Sea - UK - Low countries
- Surface ducts - 6% of time
  - Tend to be up to 300m in height and cover ~100km
- Elevated ducts 7% of time
  - Up to 3km altitude, and cover ~100km

Rain scatter

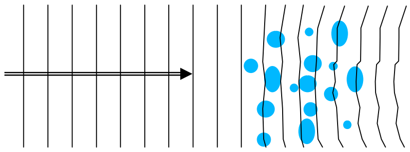
Warning – to make this easier I have made several gratuitous simplifications

Hydrometeors

Hydrometeors are water in the atmosphere

- Forms include
  - Rain, Snow, Hail,
  - Fog, Mist, Clouds (Ice crystals)

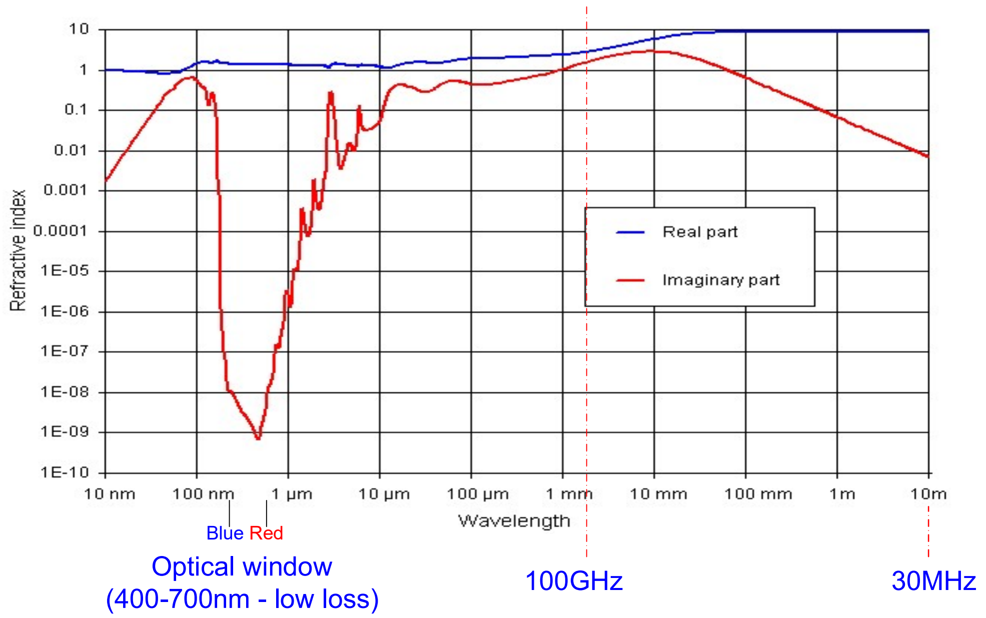
- As far as the radio wave is concerned, they are bits of lossy dielectric suspended in air



The distortion of the wavefront means there will be scattering

There may also be dielectric losses

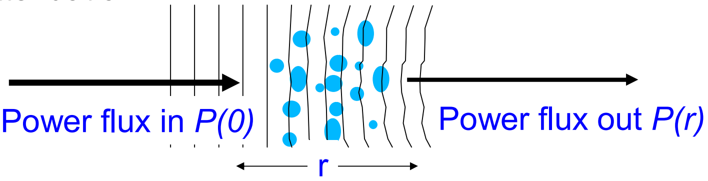
Refractive index of water



Rain attenuation

Rain attenuates by a combination of absorption and scattering

Specific attenuation:



$$P(r) = P(0) \cdot e^{-\alpha r}$$

Where α is the reciprocal of the range where P drops by 1/e

In dB

$$\text{Loss} = 10 \log\left[\frac{P(0)}{P(r)}\right] = 4.434\,\alpha r \quad \text{dB}$$

The value 4.343α is called the specific attenuation, γ

γ is usually expressed in dB/km

Specific attenuation

We can calculate specific attenuation from theory:

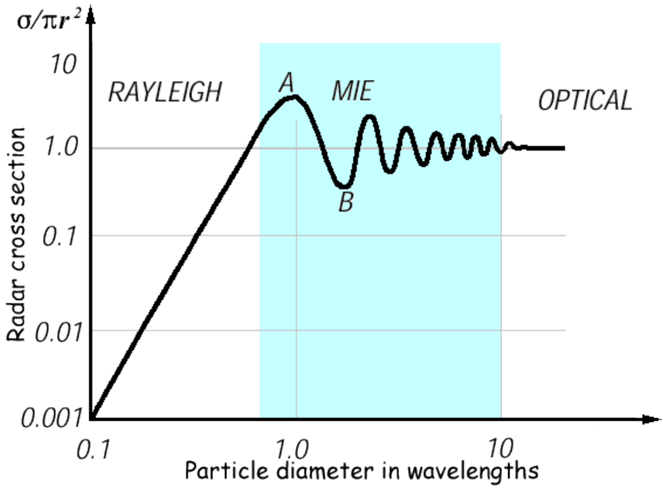
It depends on the number of drops per unit volume and the distribution of drop sizes

- The distribution depends on climate and the rainfall rate *R*
- For rain, there tend to be more small drops than large ones
- In convective rain (thunderstorms) we get more large drops

This is where it gets interesting as big drops scatter well

Scattering regions

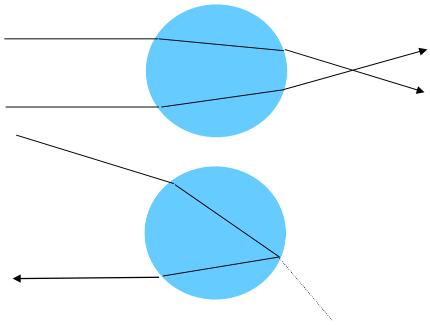
The scattering depends on wavelength vs. drop size



Optical scattering

When the particle is much larger than the wavelength

- Refraction
  - de-focussing
- Internal reflection
  - E.g. Rainbow

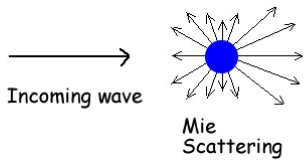


Important 1 THz and above when $\lambda < 300\mu m$
E.g. IR links

Mie scattering

When the particle is similar is size to the wavelength

- Mie scattering occurs
- Mie scattering has a stronger forward radiation lobe

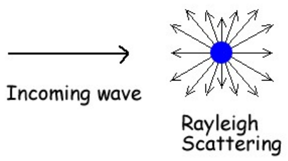


Complicated to model
(resonance effects)

Rayleigh scattering

When the wavelength is larger than the particle

- Forward scatter via a mechanism called Rayleigh scattering.
- Rayleigh wrote a paper about it in 1871, hence the name



Energy is scattered with a pattern like that of a dipole antenna

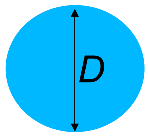
Energy is proportional to D^3/λ

This is the scattering we see for microwave links

Signals are not coherent – its not a lot of use for DATV

When is it Rayleigh

The Rayleigh criterion for scattering



Electrically small:

$\pi D/\lambda \ll 1$ where D is the diameter of the particle

Small phase shift:

$\pi nD/\lambda \ll 1$ where n is the refractive index

If both true which is the case up to 50GHz, we can use a Rayleigh approximation

Bistatic scattering

The power received by scatter from rain located at a distance *dr* from the receiver is related to the power transmitted *Pt* at a distance *dt* from the rain by:

$$P_r^{scat} = P_t \frac{G_t G_r \lambda^2}{(4\pi)^3 d_t^2 d_r^2}\sigma$$

← Scatter function

The bistatic radar equation

For rain:

$$10\log\sigma = -22 + 40\log f + 16\log R + 10\log V + 10\log S$$

is a useful approximation where:

$$10\log S = \begin{cases} R^{0.4}\cdot 4\times 10^{-3}(f-10)^{1.6} & \text{for } f > 10\text{ GHz} \\ 0 & \text{for } f \le 10\text{ GHz} \end{cases}$$

S accounts for non-Rayleigh scatter
R (mm/hr) is the rain rate
V (km^3) is the common volume
S is a correction for non Rayleigh effects above 10 GHz

To do it properly we need to integrate the rain contribution over all space – this has to be done numerically – hence the approximations to follow

$$P_r = P_t \frac{\lambda^2}{(4\pi)^3} \iiint_{\text{all space}} \frac{G_t G_r \eta A}{r_t^2 r_r^2} \mathrm{d}V$$

In dB

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

Gas loss

S is a correction for non Rayleigh scattering above 10GHz

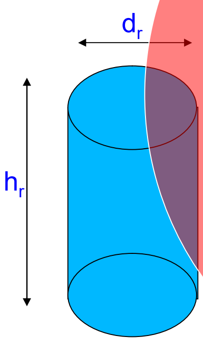
Where

$$Z_R = \text{Reflectivity} = 400R^{1.4} \quad C = \int_0^{h_{max}} \int_0^{2\pi} \int_0^{\frac{d_r}{2}} \frac{G_1 G_2}{r_1^2 r_2^2} Ar\, \mathrm{d}r\, \mathrm{d}\varphi\, \mathrm{d}h$$

Rain rate and common volume

Finding V

Assume the rain is at the mid point of a long great circle path where $d >> d_r$ and the rain storm is fully illuminated by the antennas



Approximate the rain is a cylinder of uniform rain rate extending from the cloud base to the ground.

Its volume $V = \pi d_r^2/4\ h_r$

Typically h_r ~3km $\qquad d_r \approx 3.3R^{-0.08}$

E.g. for Heavy rain, R = 50mm/hr or more, d_r = 2.4km

V = 23km^3

Bistatic scattering

We substitute the free space loss into the bistatic radar equation to give us a relative loss:

The rain scattered power in dB below below free space is:

$$P_r^{fs} = P_t \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

(free space loss)

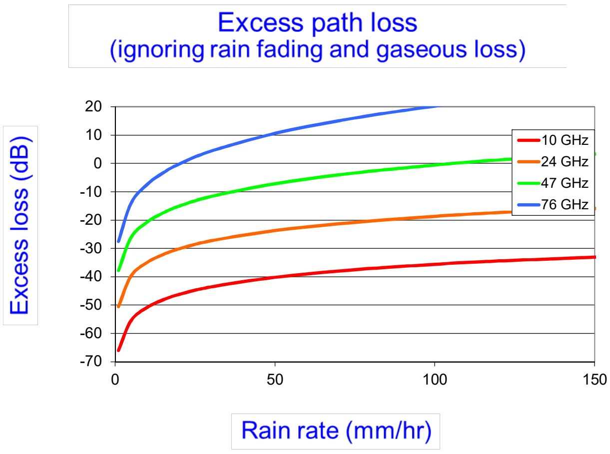
$$10\log(P_r^{scat} / P_r^{fs}) = 10\log\sigma - 20\log d - 59$$

So

$$10\log\left(P_r^{scat} / P_r^{fs}\right) = 40\log f + 16\log R + 10\log V + 10\log S - 20\log d - 81 \quad \text{dB}$$

Rain scatter example

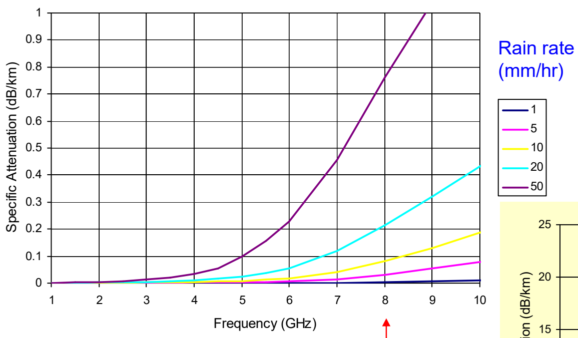
Some examples for a 100km path:



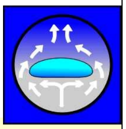
Not realistic – chances are there is also rain attenuation when there is rain scatter

Rain attenuation

Specific attenuation (dBs / km)

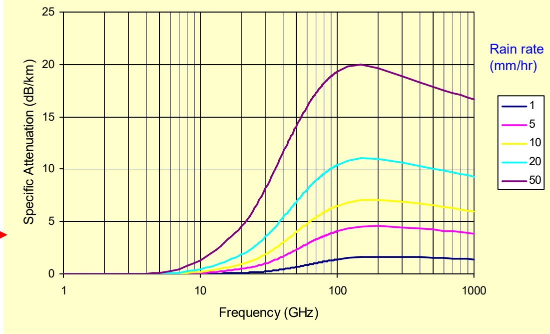


Horizontal polarisation attenuation tends to be a little higher than vertical because of the shape of falling raindrops



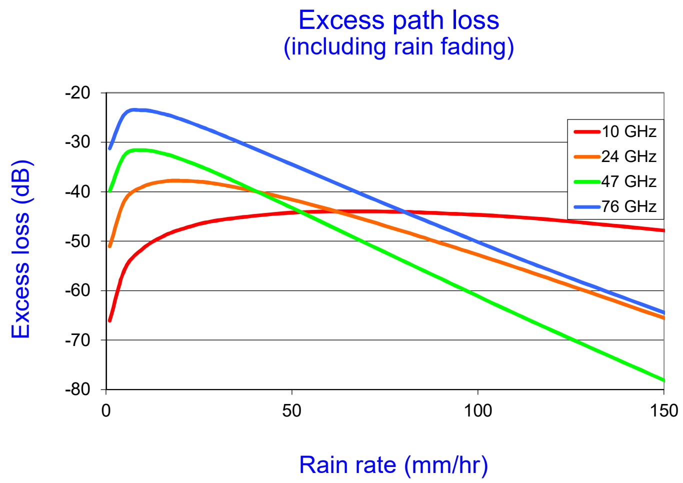
The attenuation is low below 10 GHz

Increases rapidly above 10 GHz



Rain scatter model

With rain attenuation included:

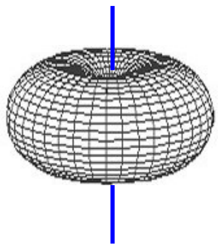


Horizontal versus Vertical?

Vertical polarisation has a slightly lower rain loss

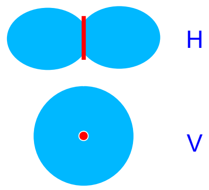
– Non spherical drop, scatters H more than V 

But remember the scatter is radiated with the pattern of a dipole



So we would expect vertical polarisation to give us a better off axis scatter signal

Patterns Looking down from above



Normal propagation

Tropospheric scatter

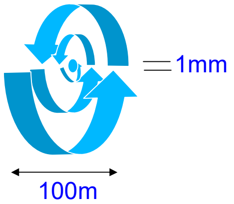
This is what gives us anytime dx for a few 100km on non line of sight paths

Cause - air is not uniform

Eddies, thermals, turbulence etc exist where air has slightly different pressure

Eddies have

- outer scales ~100m
- inner scales of ~ 1mm



Energy fed into a turbulent system goes primarily into the larger eddies

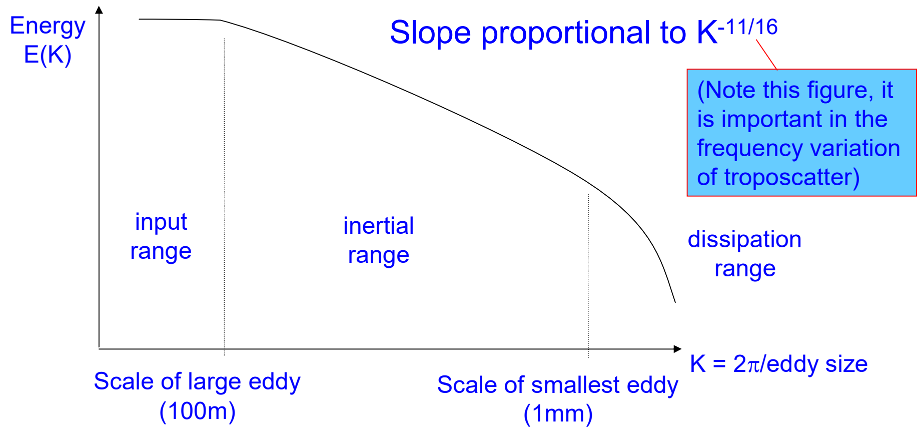
From these, smaller eddies are shed

This process continues until the length scale is small enough for viscous action to become important and dissipation to occur. I.e. the little ones don't last long

Turbulence spectrum

The variations have a spectrum

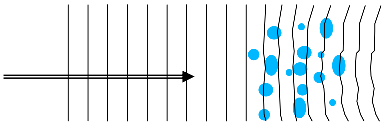
The Kolmogorov spectrum



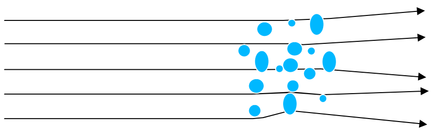
Effect of irregularities on wavefront

The wavefront is scattered and defocused

Wavefront



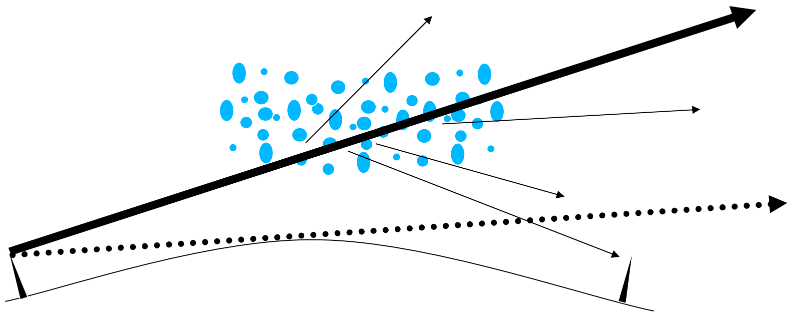
Rays



Energy is scattered by small angles

Troposcatter

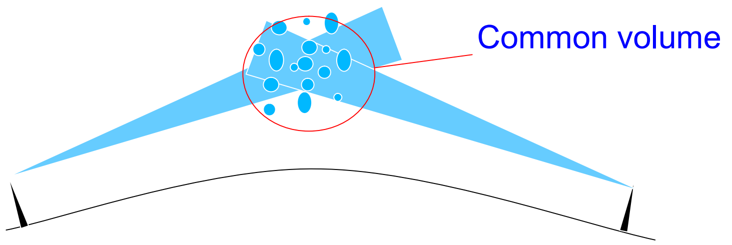
A small amount of the energy is usefully scattered beyond the horizon



Dominant (most common) mode for long range VHF/UHF propagation

Troposcatter

Much like rain scatter the common volume formed by the intersection of the antenna patterns is important



A typical value for the loss by this mode, for a 250km 145MHz path with 10 dBi antennas is ~145dB - THIS INCLUDES ANTENNA GAIN

The line of sight loss would be only 80dB, including antenna gain, but very few terrestrial paths this long are line of sight

Troposcatter signals will be 65 dB below line of sight in this case – so exploitation needs high radiated power and sensitive receivers

Troposcatter model

The troposcatter loss is given (for p < 50%) by:

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

L_f is a frequency dependant loss:

$$L_f = 25 \log f - 2.5\,[\log(f/2)]^2$$

N_0 is surface refractivity, 320 in UK

θ is the radial distance angle (milliradians)

$$\theta = \frac{10^3\,d}{a_e} + \theta_t + \theta_r$$

Note - The loss increases dramatically with $\theta_{t,r}$

L_c is the aperture-medium coupling loss:

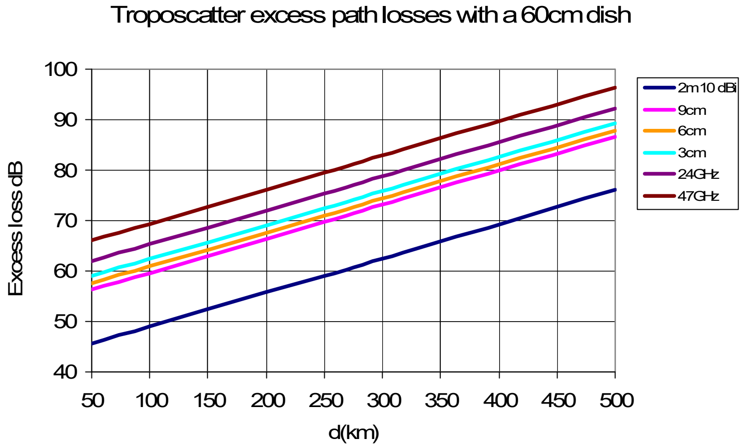
$$L_c = 0.051 \cdot e^{0.055(G_t + G_r)}$$

Where G_t , G_r are the gains of the antennas

A_g is the gas loss assuming $\rho = 3$ g/m^3

Troposcatter example

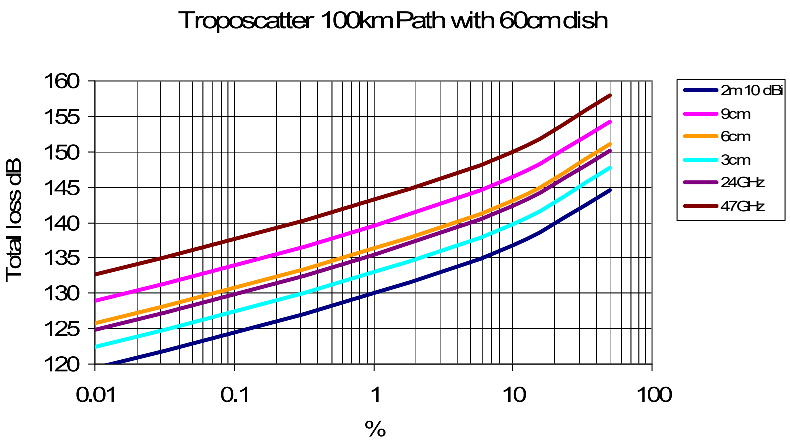
Typical for inland UK



Note – excess is comparted to the equivalent length line of sight path and $\theta_{t,r} = 0$

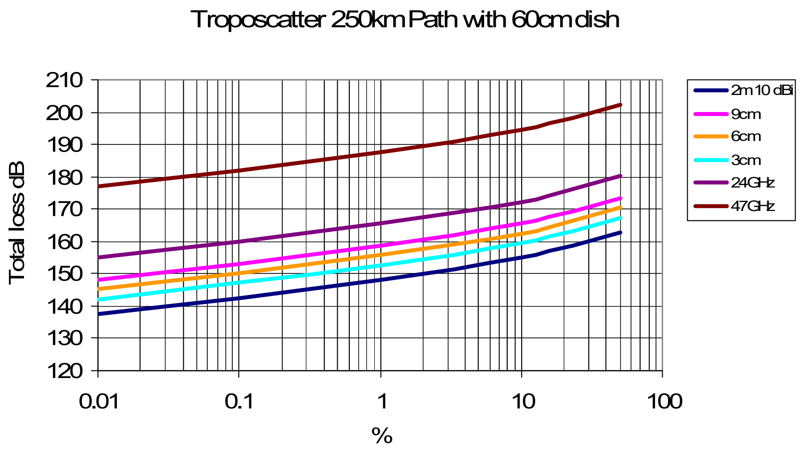
Troposcatter

Another example, total loss for a 100km troposcatter path:



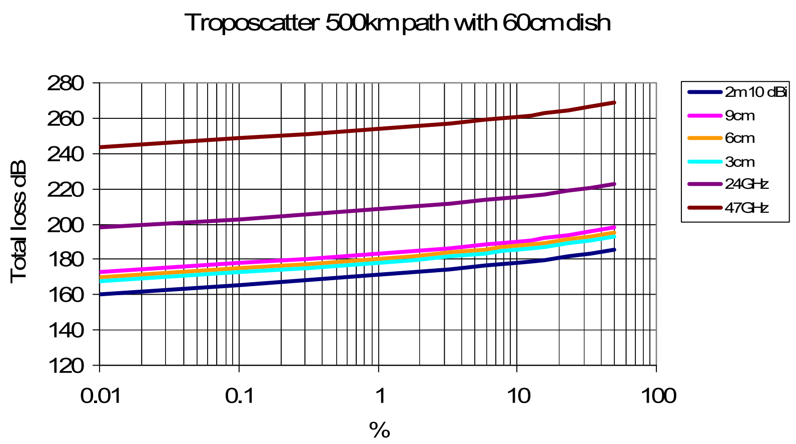
Troposcatter

Another example, total loss for a 250km troposcatter path:



Troposcatter

Another example, total loss for a 500km troposcatter path:



Molecular scattering

Rayleigh Scattering

When wavelengths are comparable to the the size of gas molecules
Increases with the fourth power of the frequency which is why the sky is blue (very small particles in upper atmosphere)

Raman scattering

EM waves to excite resonance in gas molecules
Energy is transferred
particular importance to optical systems.

The excited molecule may not transition back to the original state and can emit EM energy at a different frequency.

Remember that the energy in a radiowave is quantified into discrete packets of energy called photons - wave/partial duality etc. The energy of the photon is related to the frequency of oscillation $e = hf$, where h is Plank's constant. When considering the scattering of high frequency radiowaves, it is often more convenient to think in terms of photons.

Rayleigh Scattering: When photons are of wavelengths comparable to the the size of gas molecules, scattering occurs. The most common mode of scattering is elastic scattering where energy is not transferred from the photon to the molecule. This type of scattering is called Rayleigh scattering. This scattering increases with the fourth power of the frequency, which incidentally is why the sky is blue.

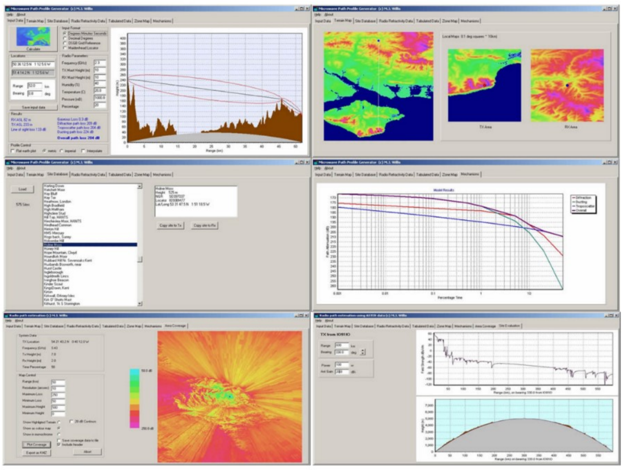
Raman scattering: It is also possible for photons to interact with gas molecules in an inelastic manner so that energy is transferred between the photon and the molecule. This is called Raman scattering and this is of particular importance to optical communications systems.

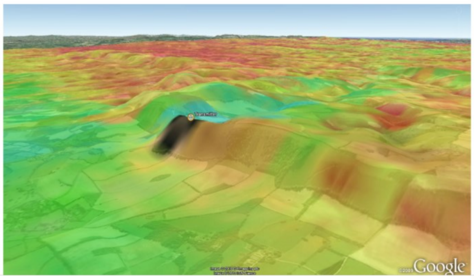
At higher photon energies incident photons can excite vibrational modes polarised molecules. This is an energy transfer process with the resultant emission of a scattered photon of lower energy (i.e. lower frequency/higher wavelength) and leaving the molecule in a higher energy vibrational mode. Only certain vibrational mode energies are allowed and by inference, only discrete frequency/wavelength differences can occur. The spectra of the resultant scattered photons forms a set of spectral lines at discrete offsets from the original frequency/wavelength called "Stokes lines". It is also possible for a molecule to give up some of its energy to an incident photon and thereby increase the photon energy. Again, this forms a discrete set of lines, the "anti-Stokes lines".

Prediction software

No need to do the maths, software is available from many sources

Here is mine:





Getting more data

Propagation is greatly influenced by terrain and the weather

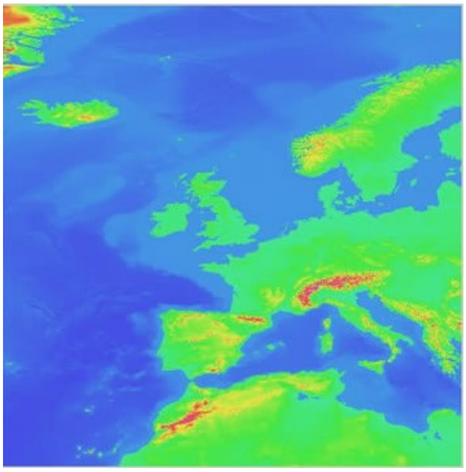
- Data has been collected over many years
  - Statistics are available from ITU
    - Rainfall rates, Refractivity gradients, Clouds, Wind speed, Solar activity, etc. etc.
  - Terrain maps available from USGS
  - Refractivity data can be acquired from http://weather.uwyo.edu/upperair/sounding.html

Topographic data

High resolution terrain height data is needed for planning radio links

- Now available for the world from USGS
  - ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)
  - SRTM (Shuttle radar)
  - 1 & 3 arc second samples Approx 30-90m resolution

Don’t ask where, just google



These datasets are large – They come on multiple DVDs.

The best free data can be obtaind from the Shuttle Radar Topography Mission (SRTM) webpag, http://srtm.usgs.gov/ . The SRTM was a joint project between the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA).

The data was collected over a 1 arc second grid for all land areas between 60° north and 56° south latitude. For various reasons, mostly to do with “defense” global data is only available at 3 arc second resolution – but this is available for free. This is very different to OSGB data which, although better resolution is expensive and subject to strict licensing conditions.

Questions?