Microwave Propagation

Propagation you can’t rely on

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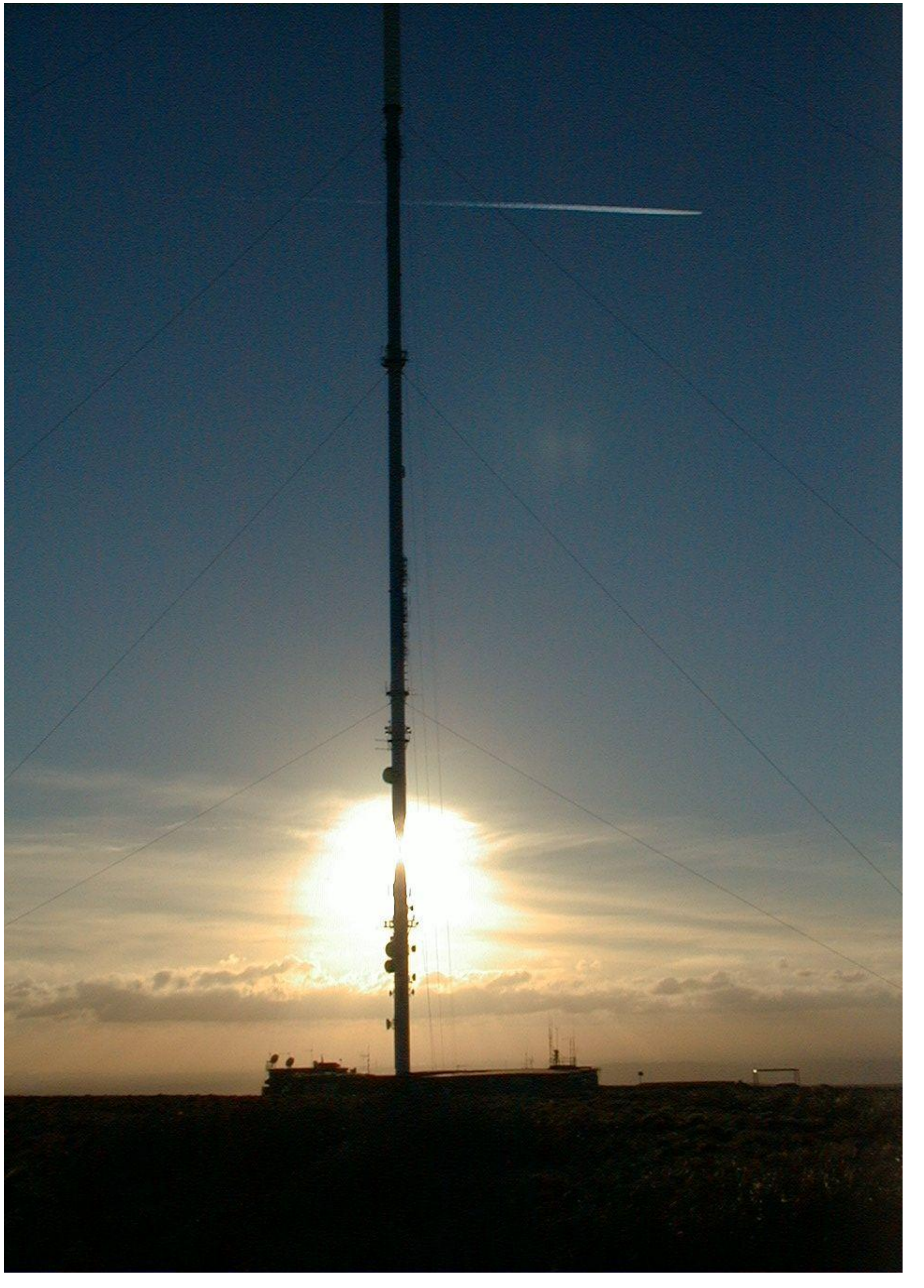


What matters to us

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
  - 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 I won’t be talking about them

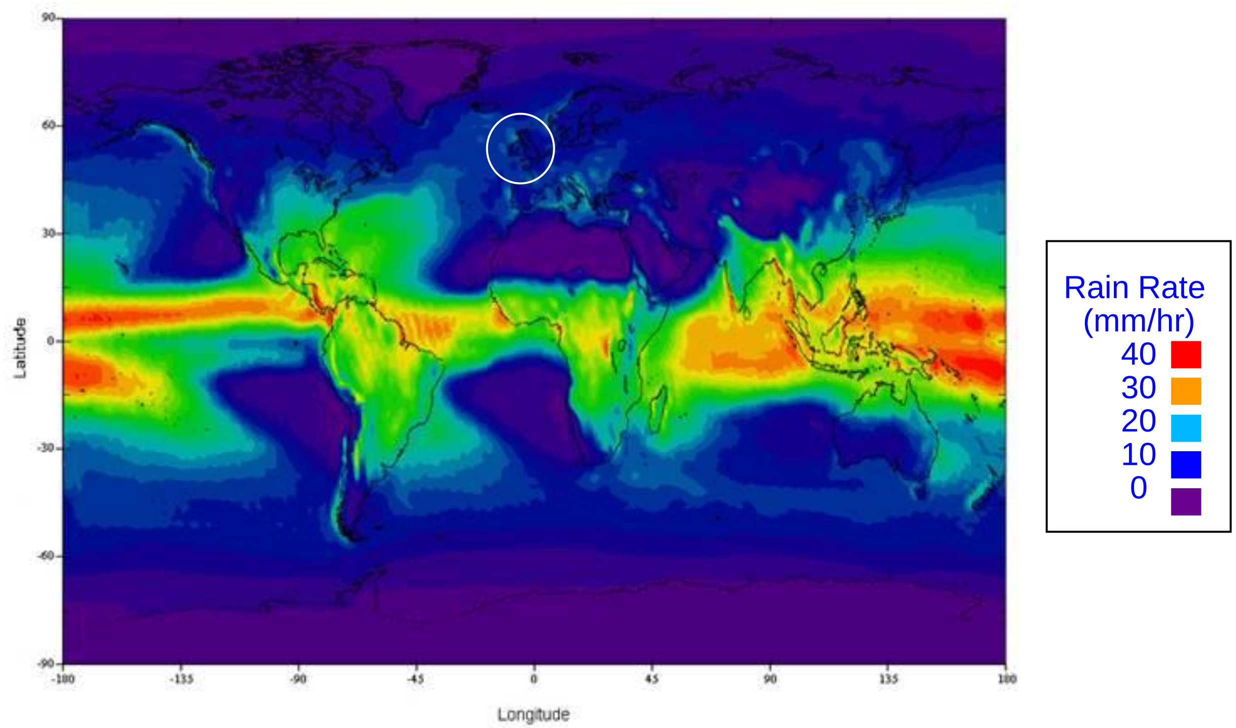
This talk will cover Anomalous propagation effects, rare events, why they happen and how often

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

The Basics -
- Maxwell's equations

Radio waves are predicted to propagate in free space by electromagnetic theory

- They are a solution to Maxwell's Equations

$$\nabla \bullet \varepsilon \mathbf{E} = \rho$$

$$\nabla \bullet \mu \mathbf{H} = 0$$

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

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

E = Electric vector field
H = Magnetic vector field
ρ = charge enclosed = 0
J = current density = 0

In Cartesian co-ordinates:

div $\nabla \bullet \mathbf{E} = \frac{\partial \mathbf{E}}{\partial x}\hat{\mathbf{x}} + \frac{\partial \mathbf{E}}{\partial y}\hat{\mathbf{y}} + \frac{\partial \mathbf{E}}{\partial z}\hat{\mathbf{z}}$

curl $\nabla \times \mathbf{E} = \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right)\hat{\mathbf{x}} + \left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right)\hat{\mathbf{y}} + \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right)\hat{\mathbf{z}}$

The plane wave solution

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

$$\mathbf{E} = E_0 \cos(\phi)\hat{\mathbf{x}}$$

$$\mathbf{H} = H_0 \cos(\phi)\hat{\mathbf{y}}$$

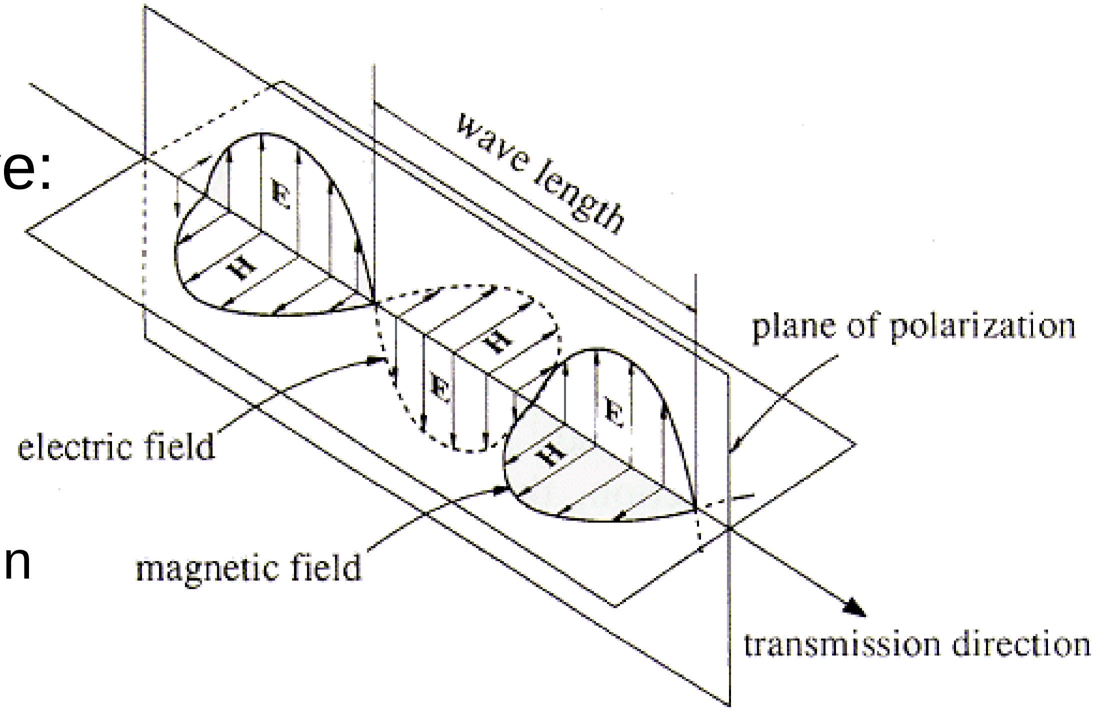
Just remember for a plane wave:

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.



Free space loss ?

We know that:

- A radio wave launched from a point in any given direction will propagate outwards from that point at the speed of light
- The wave will travel in a straight line, there is nothing to prevent it doing so
- The wave will do this forever.
  - Actually, this is not quite true, the energy is carries by photons that do eventually decay but as the half life of a photon is of the order of 6.5 Billion years, we don't need to worry about it often.

So how can we talk about a loss ?

Free space loss ?

We can't, but we do anyway…

– What it means is the ratio of the received power to the transmitted power, it's not really a loss at all, energy is conserved

$$\text{Free Space Loss} = \frac{P_r}{P_t}$$

– We can easily predict the free space loss:

– Free Space Loss = 92.45 + 20log(d) + 20log(f) dB
(where d is in km and f is in GHz)

- it is important to understand where this comes from

Field strength vs. distance

Power Flux Density

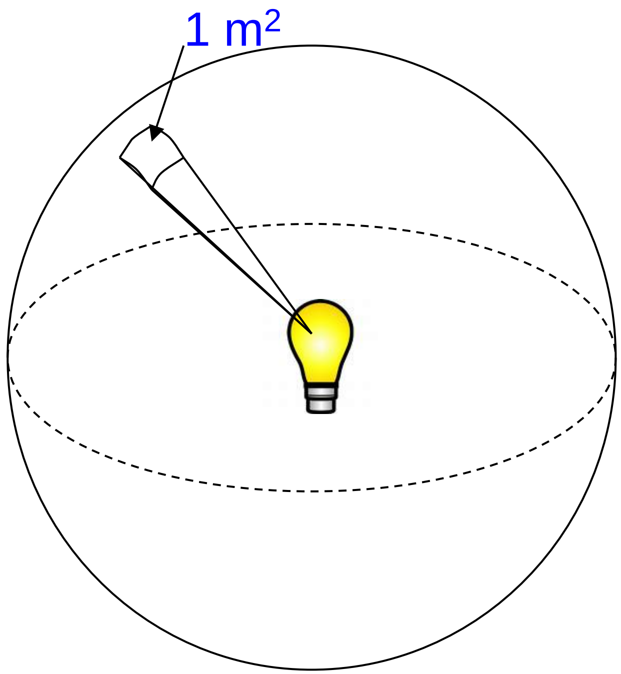
If have a point source energy spreads out over a sphere – the power per unit area is the power divided by the area of this sphere:

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

So:

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

This is the inverse square law



The FSL in dB/GHz/km

In useful units of GHz, km and dB:

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

$$\text{Free Space Loss(dB)} = 20\log\left(\frac{c}{4\pi \cdot 1\times10^3 \cdot 1\times10^9}\right) - 20\log(r) - 20\log(f)$$

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

We are not in free space

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

Gaseous Attenuation

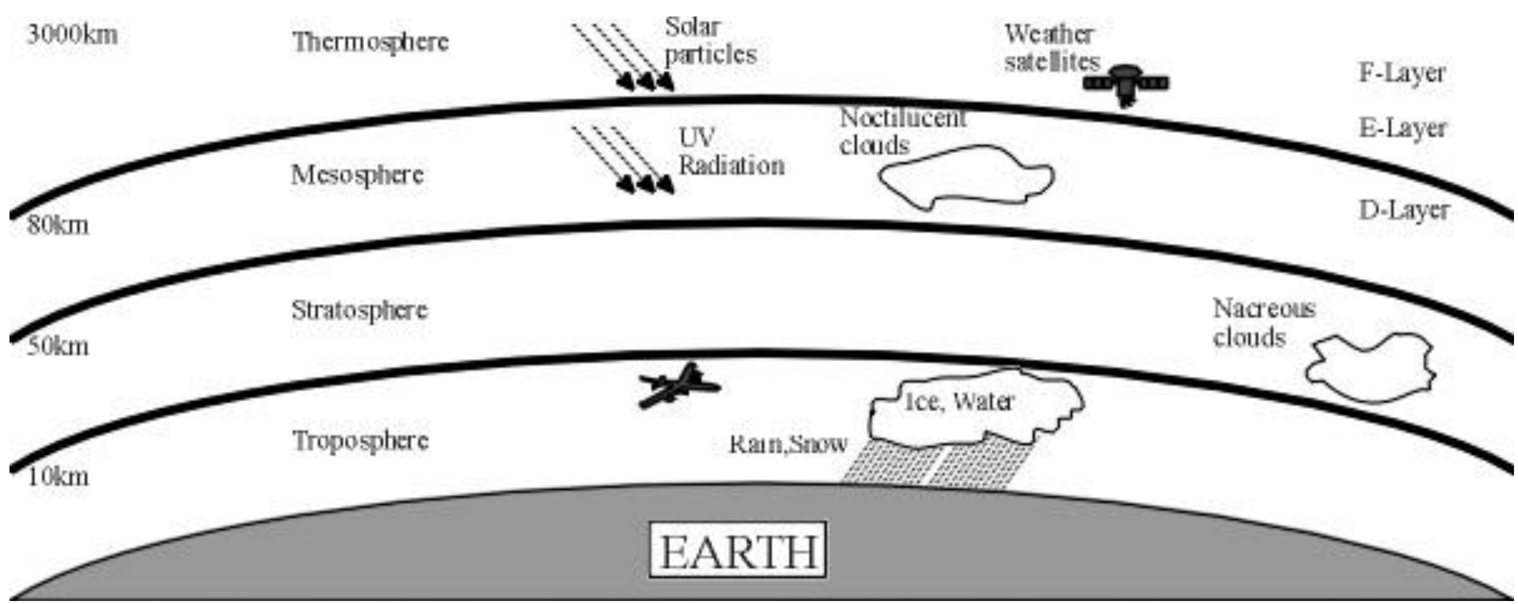
Diffraction

Refraction

Scattering

Propagation in the atmosphere

As microwave enthusiasts we are mainly concerned with the paths through the Troposphere, the lowest region of the atmosphere that extends upwards to about 10-20km.



We are interested in the effects of the air and the weather on radio paths – and especially the anomalous effects

Gaseous attenuation

Long paths through the atmosphere are attenuated by gaseous absorption.

Air is:

- 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)

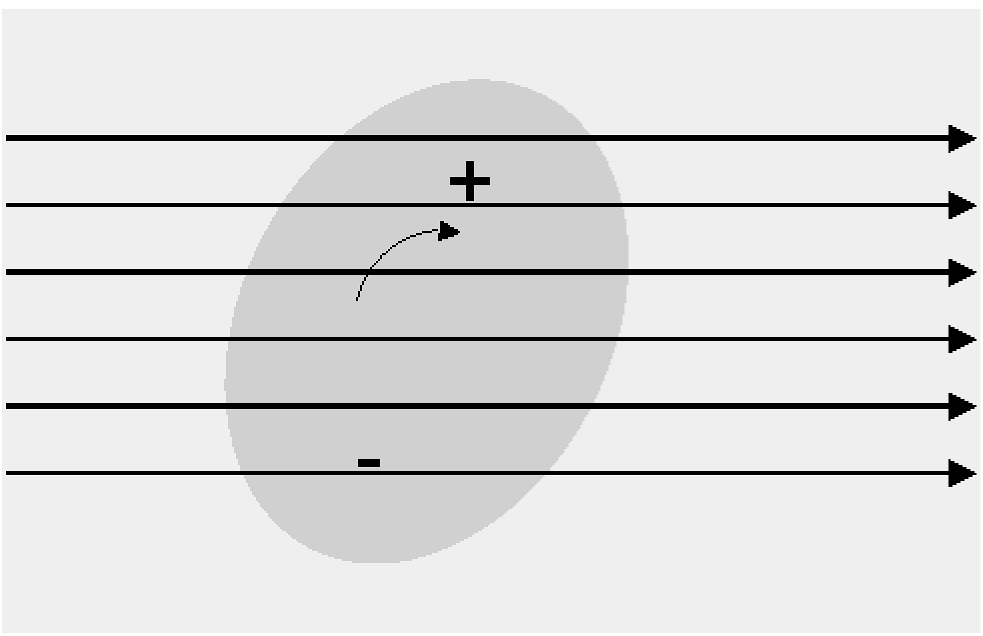
99% of the atmospheric mass is concentrated below 10km

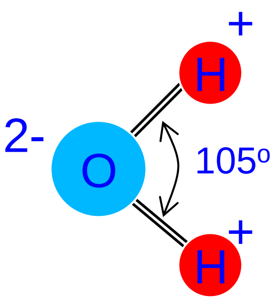
Gaseous attenuation

Gas molecules interact with the Electromagnetic field

This may cause energy loss

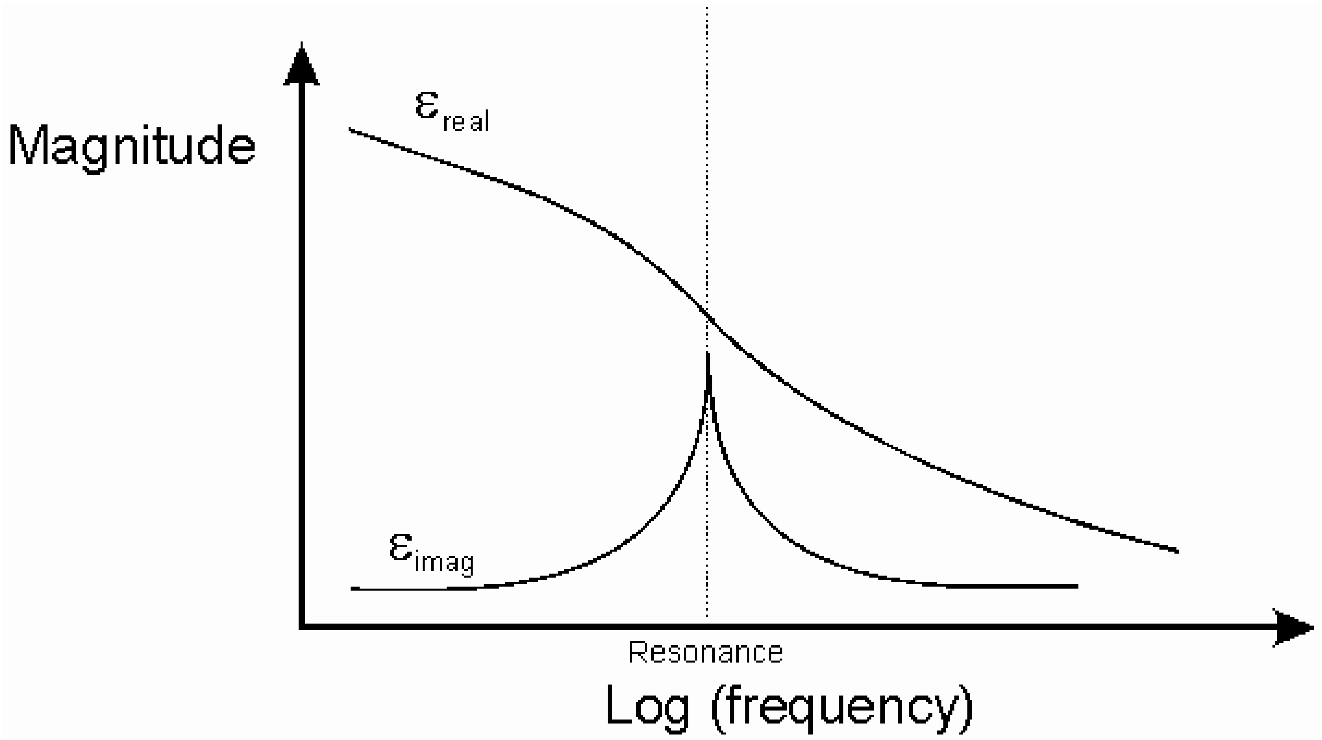
E.g. H_2O molecules are asymmetric and will try and align with the Electric field





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

Resonance lines



Permitivity vs. Frequency

Gaseous attenuation

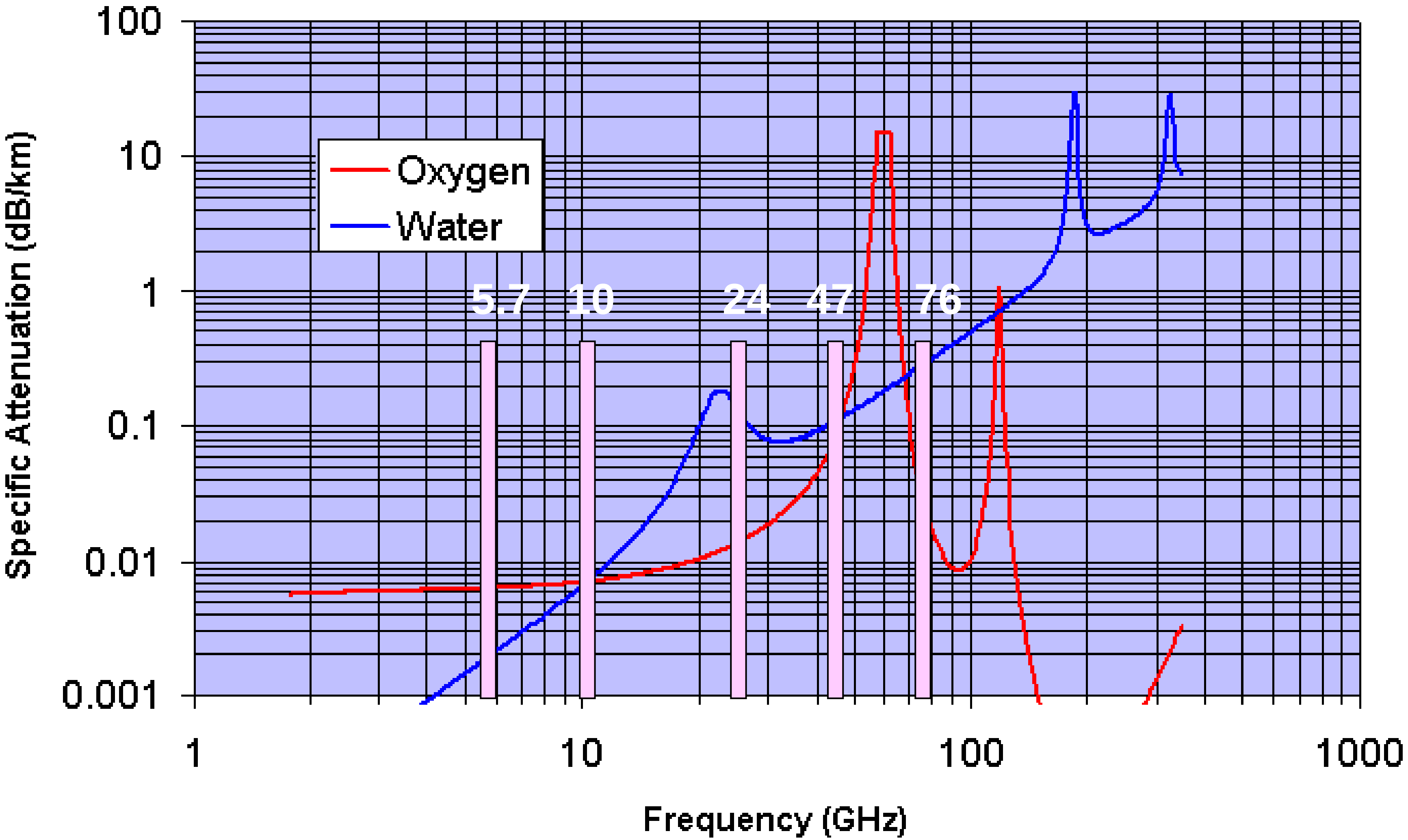
The loss depends on:

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

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

Gaseous attenuation

Specific Attenuation - dB/km as sea level



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

In Duct gas loss per 100km

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

Band	Total (dB/100km)	Oxygen (dB/100km)	Water (dB/100km)
13cms	0.6	0.6	0.01
9cms	0.6	0.6	0.02
6cms	0.6	0.6	0.06
3cms	0.9	0.6	0.2
24GHz	7.9	1.2	6.7
47GHz	14	11	4
76GHz	15	6.8	8.6

These values are closer to those you would get inside a duct

The ground

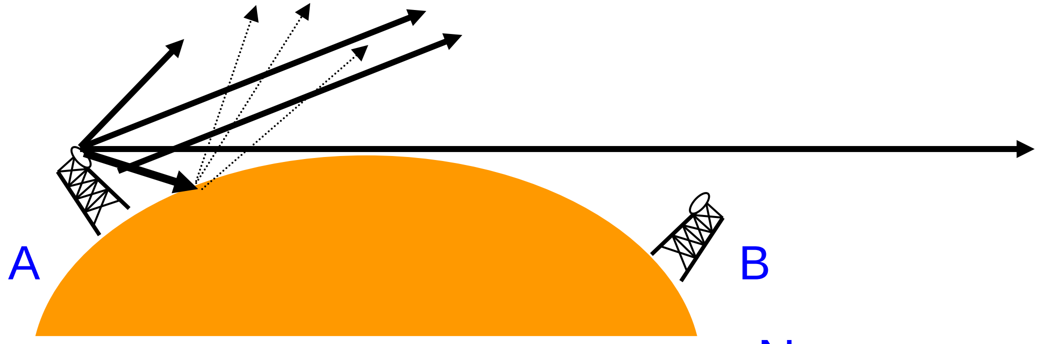
(Terrain getting in the way)

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

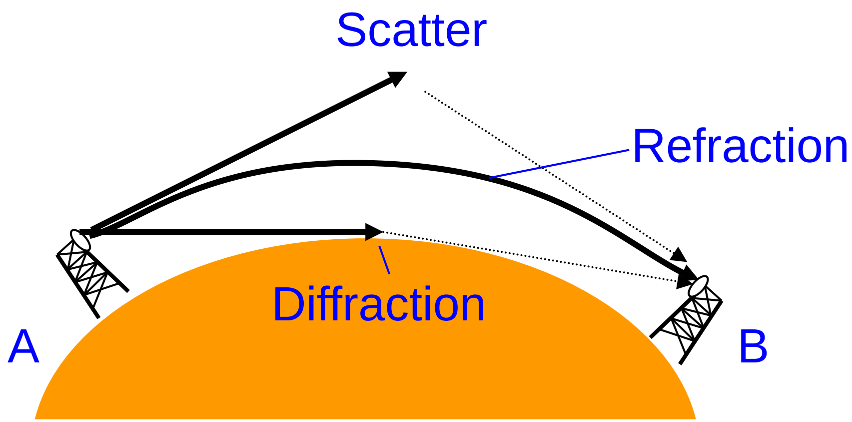
We know signals do propagate beyond the horizon

The major mechanisms are

Refraction - bending of signals towards ground

Scattering - from air, from rain

Diffraction - diffraction from terrain

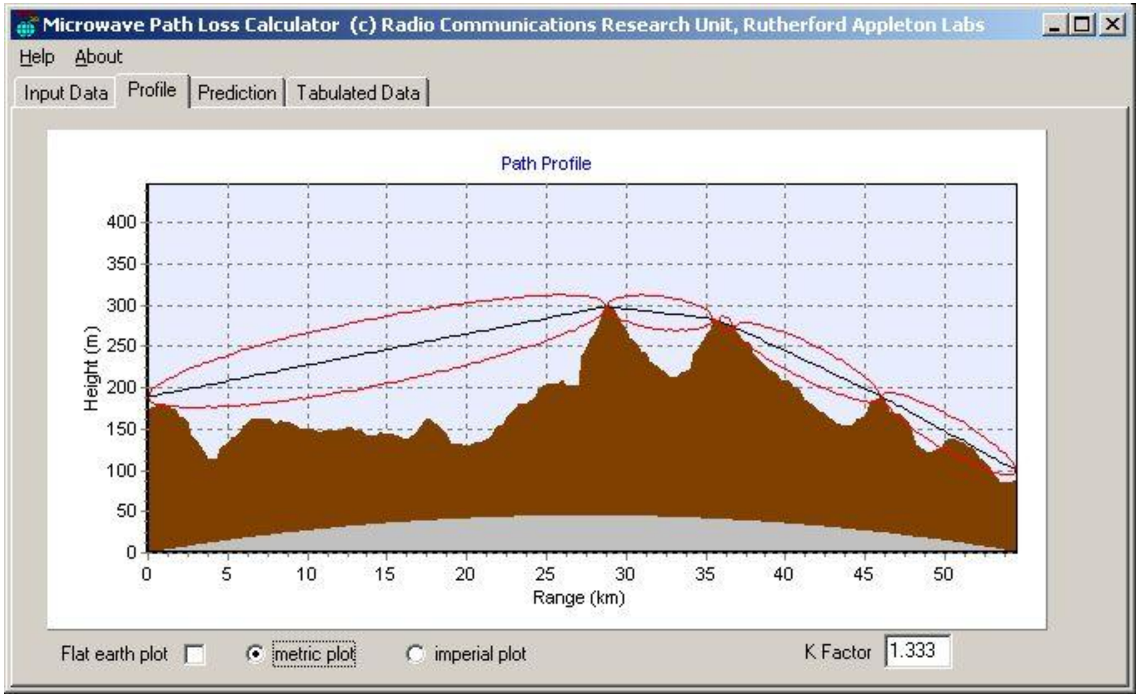


Long range paths are dominated by troposcatter for most of the time. These are Normal “flat band” conditions. Amateur DXers are interested in abnormal conditions – generally refraction and rain scatter

Diffraction

In view of time, we are not covering diffraction

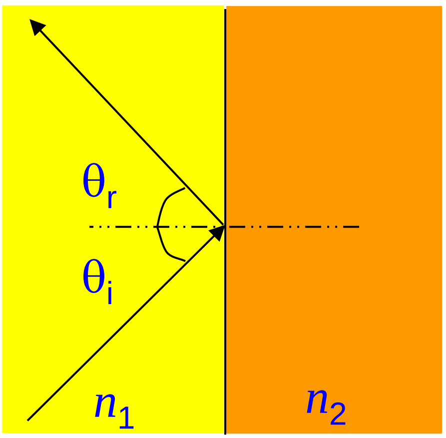
- It is a mode of propagation that is always present but far beyond line of sight the losses are very high
- This is because the loss at each obstacle rapidly adds up



Well – almost. Some special cases do occur, diffraction over a sharp mountain peak

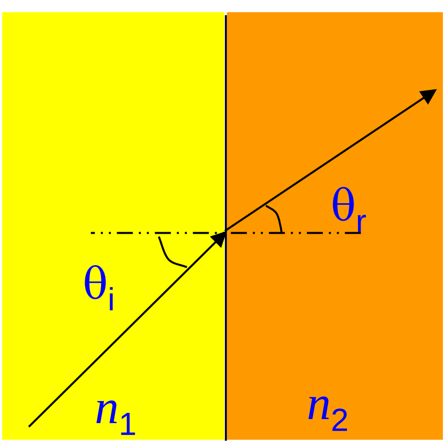
Refraction

Remember Snell's laws



Reflection

Angle of incidence = angle of reflection



Refraction

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

This is what is important

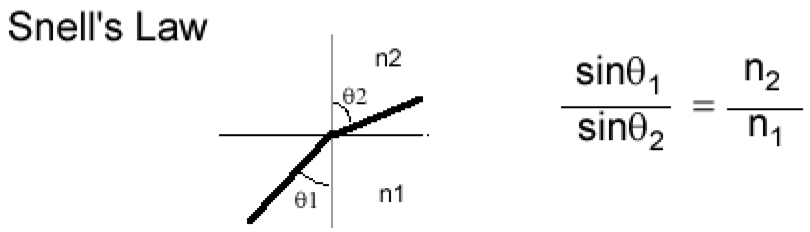
If $n_2 < n_1$ $\theta_r < \theta_i$

The ray is bent downwards

The atmosphere vs. height

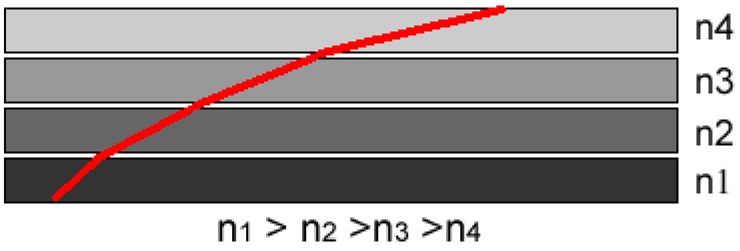
Higher altitudes

- Lower pressure
- Lower temperatures

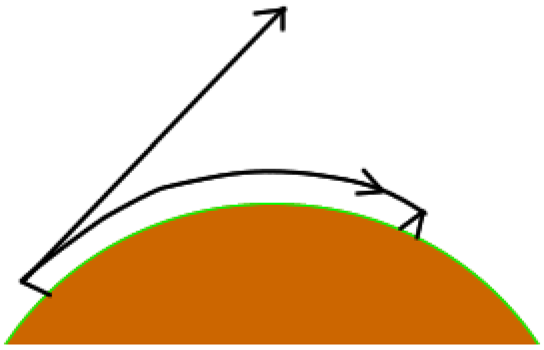


Refractive index falls with height

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



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



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 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 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

The refractive index of air

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

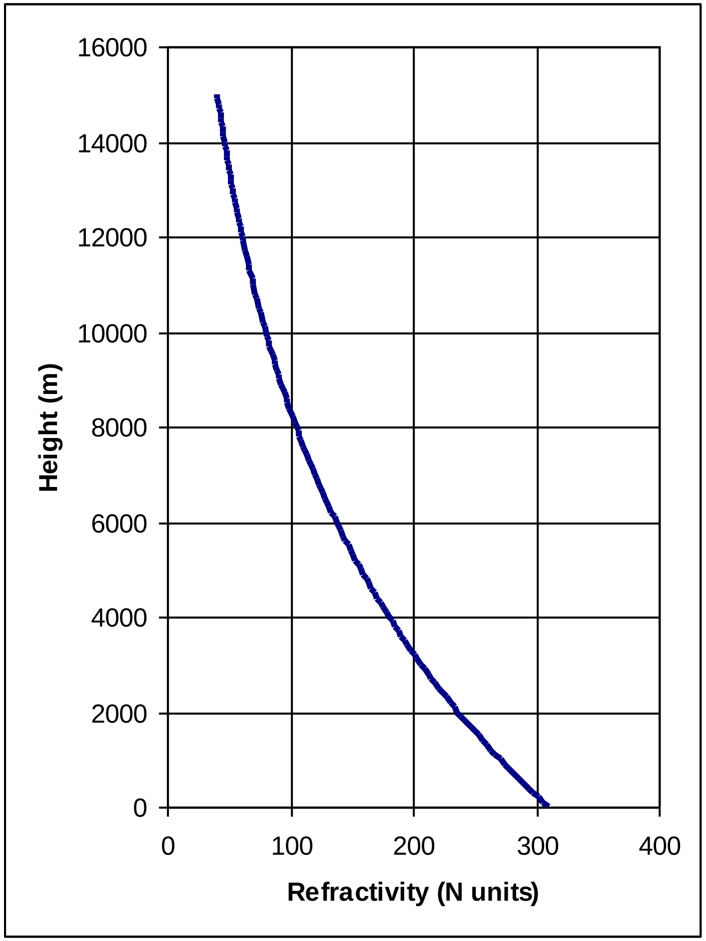
The scale height is ~7.4km

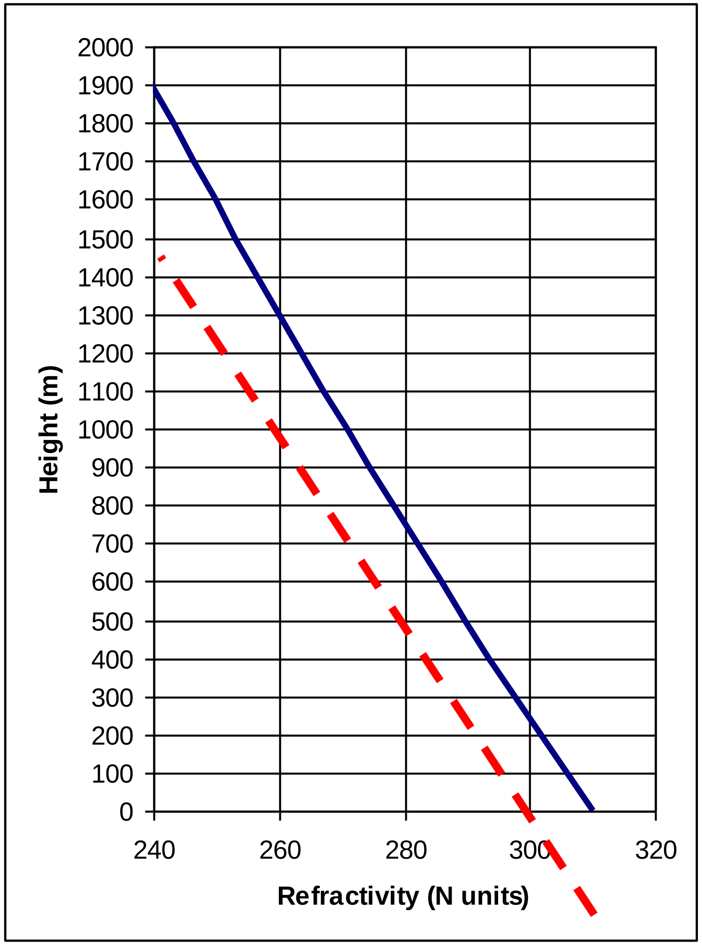
In the first 1000m we can approximate this as a straight line

Slope ~ -40 N/km

We write this as:

$$dN/dh = -40$$





But we want to know abnormal conditions giving dx

The radius of curvature

Say we wanted a signal to follow the Earth curvature and give us tropo DX

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 $\sin\theta \sim \tan\theta \sim \theta$)

The Earth radius ~ 6371 km

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

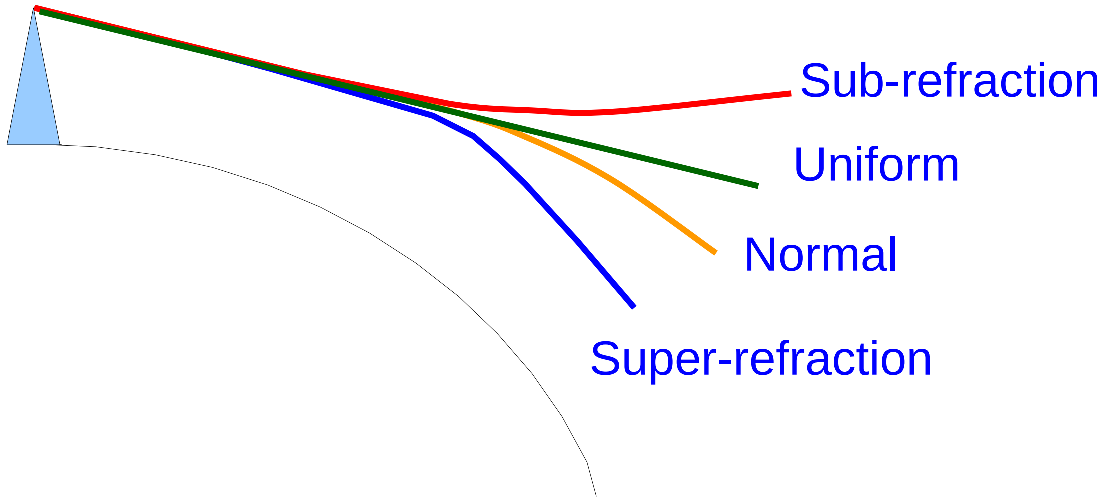
To follow Earth curvature, $d\theta/dh = -1.57\times10^{-4}$ radians/km

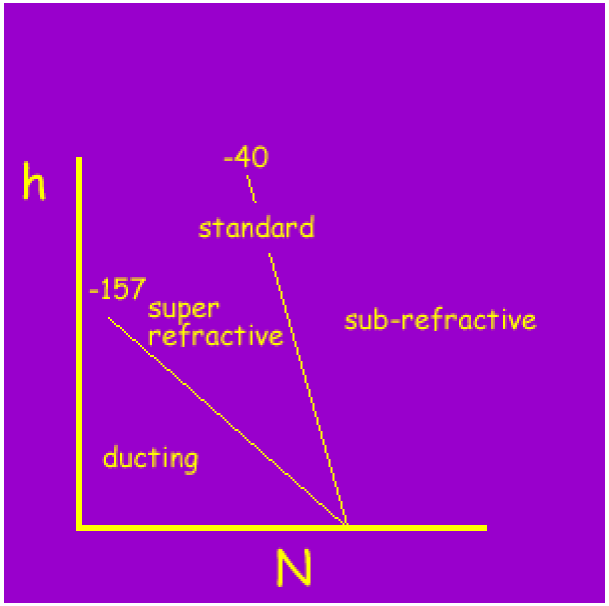
So dN/dh = -157 N units/km to follow the Earth's curve

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

Super-refraction

If dN/dh exceeds -157 N units, signals will be refracted by more than the curvature of the Earth and be trapped





When does this happen ?

Ducting and inversions

Non-standard atmospheres 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:

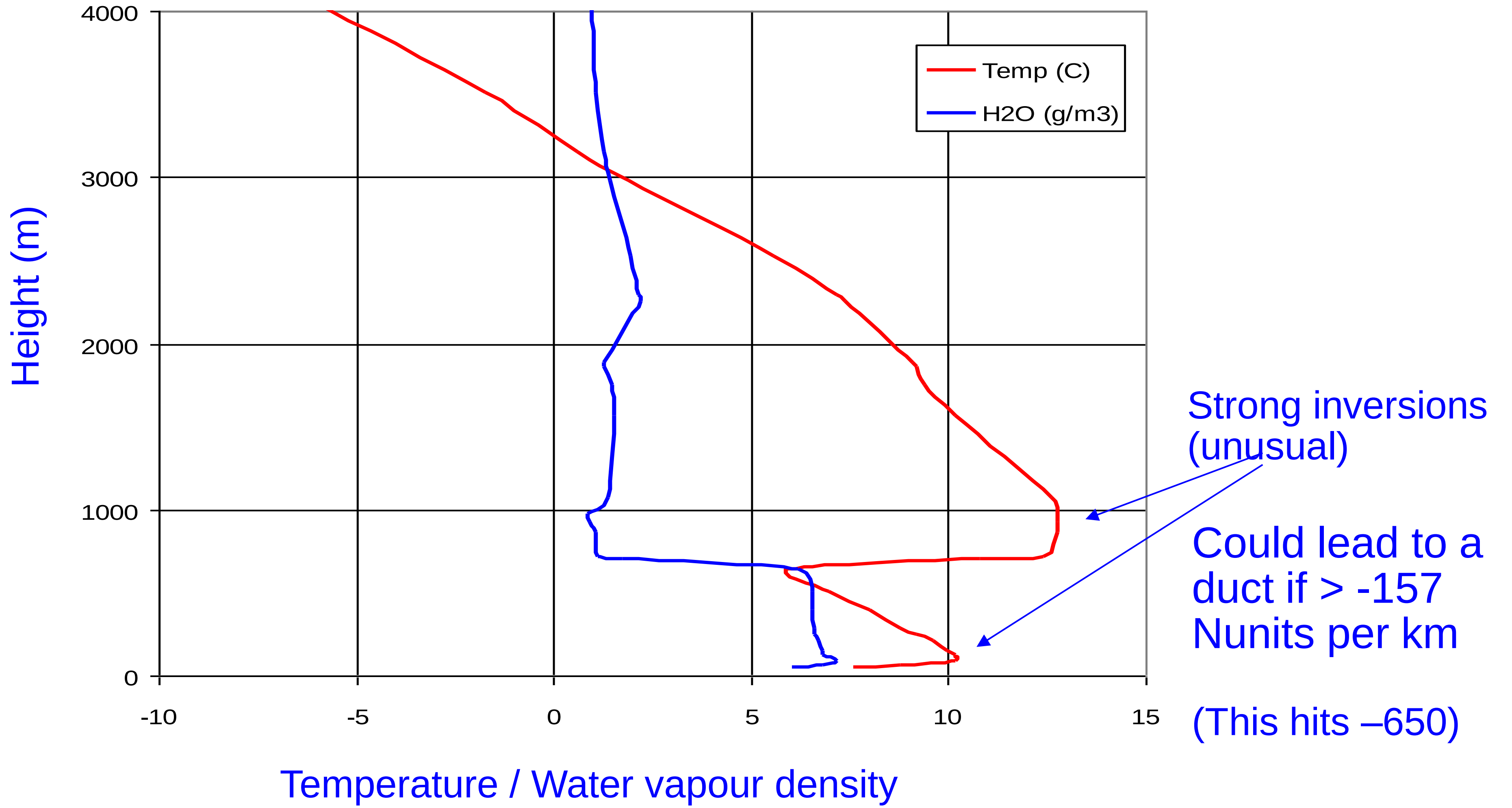
- Water vapour density
- Temperature

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

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

Ducting and inversions

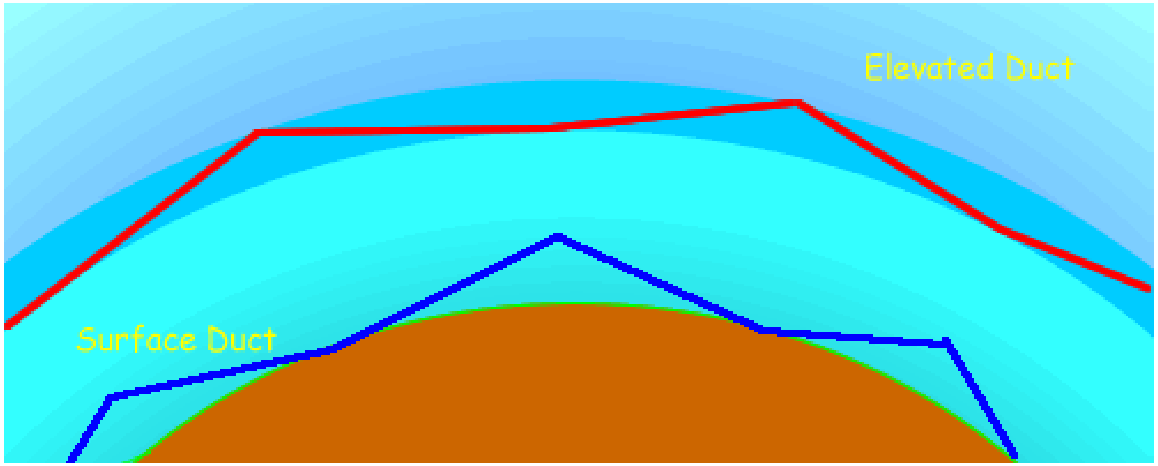
An example of the temperature inversion on 7th November 2006



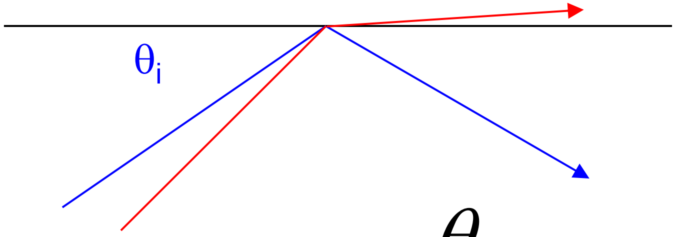
Ducts

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°



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

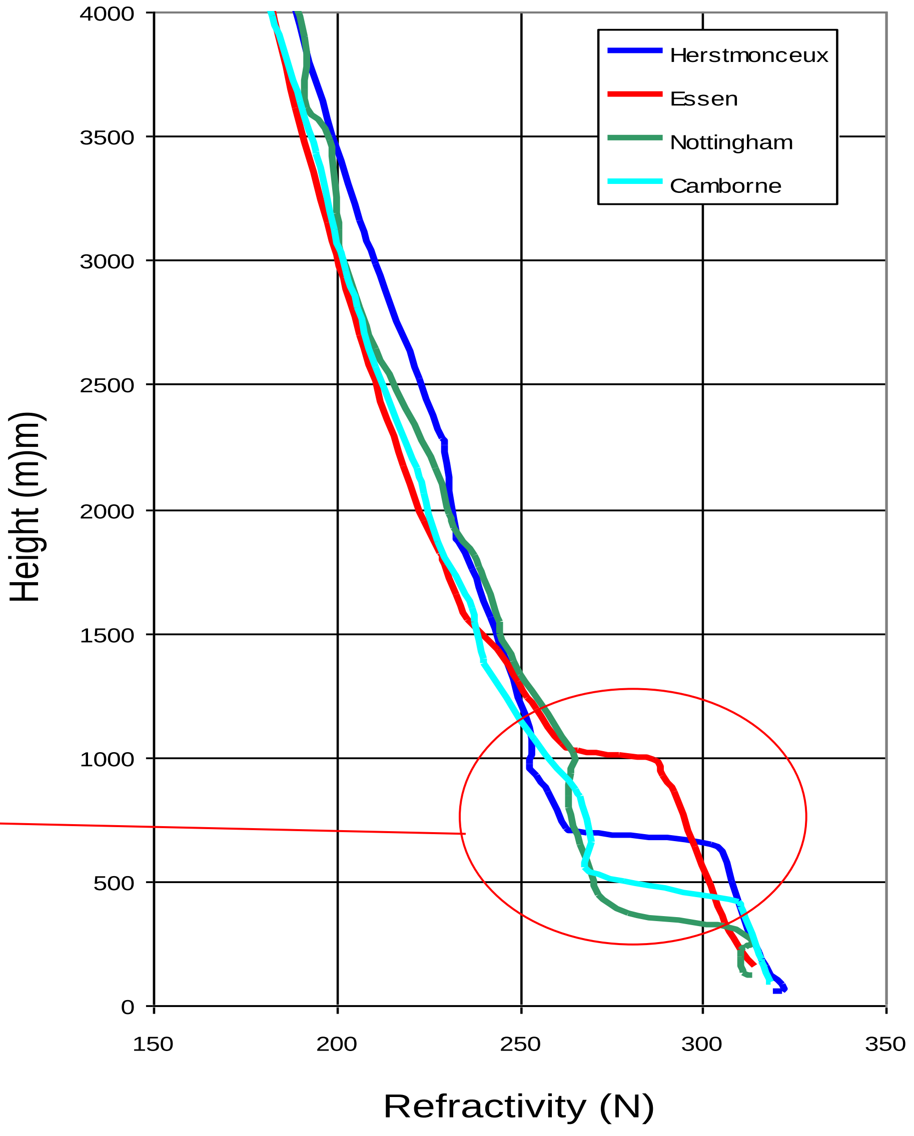
Measured ducts

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)

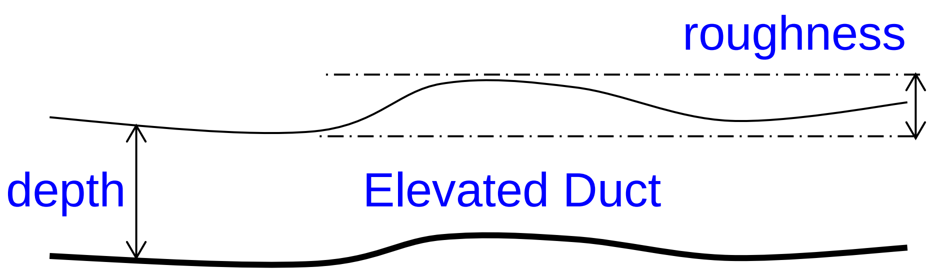


00:00Z 7th November 2006

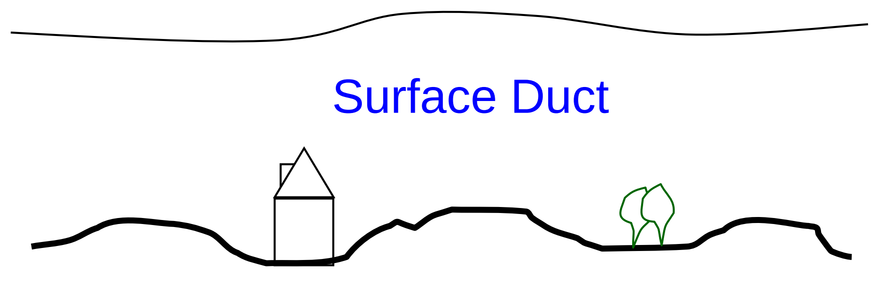
Data acquired from http://weather.uwyo.edu/upperair/sounding.html

Will a duct support microwave Dx?

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

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

- 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

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

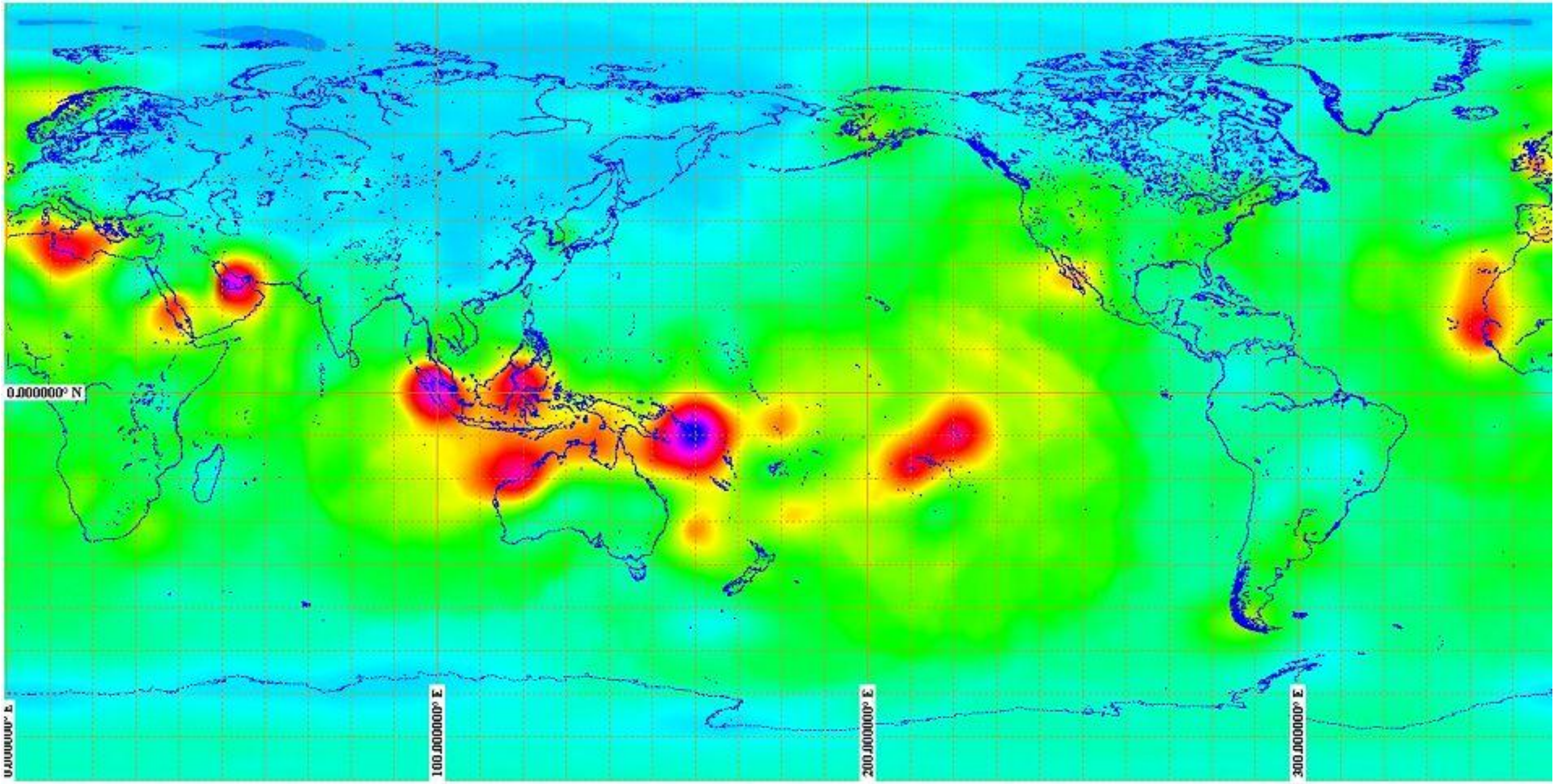
Advection

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

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

UK incidence of ducting

UK probability of ducting

(Or why you really need to be on the East coast)

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

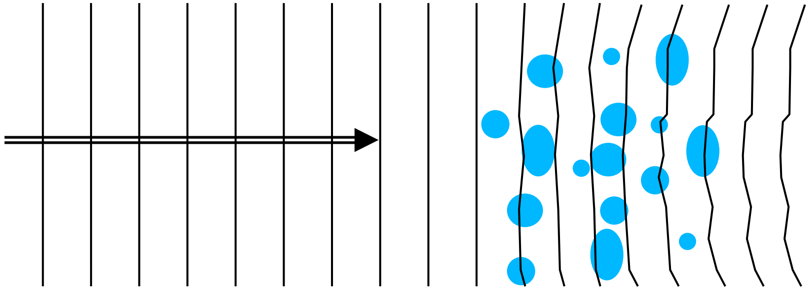
Warning – to make this easier I have made several gratuitous simplifications
Do not expect exact results

Hydrometeors

Hydrometeors simply means water in the atmosphere

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

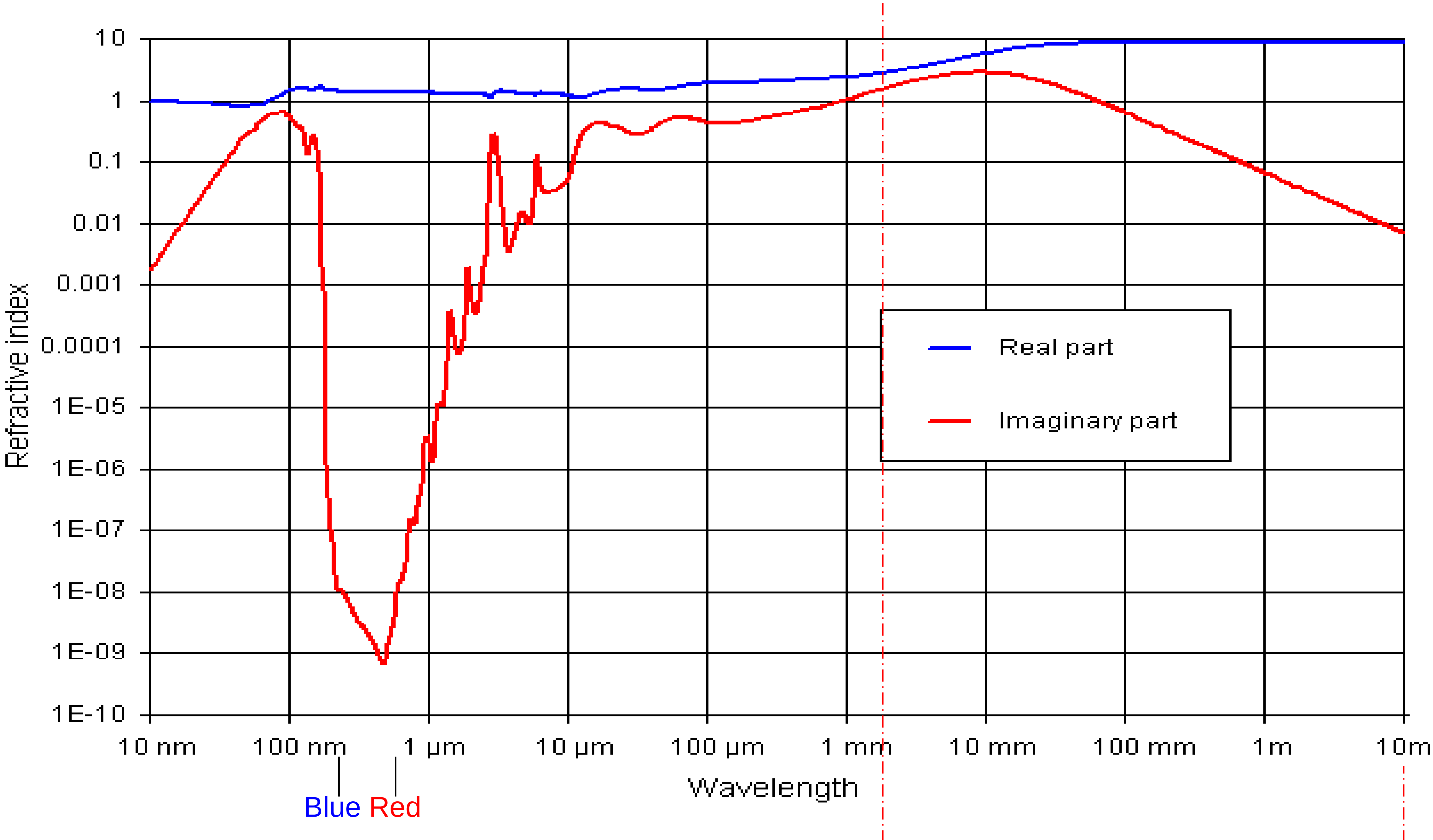
- As far as the radio wave is concerned, they are bits of lossy dielectric suspended in air



The distortion of the wavefront means there will be scattering

There may also be dielectric losses

Refractive index of water



Optical window
(400-700nm - low loss)

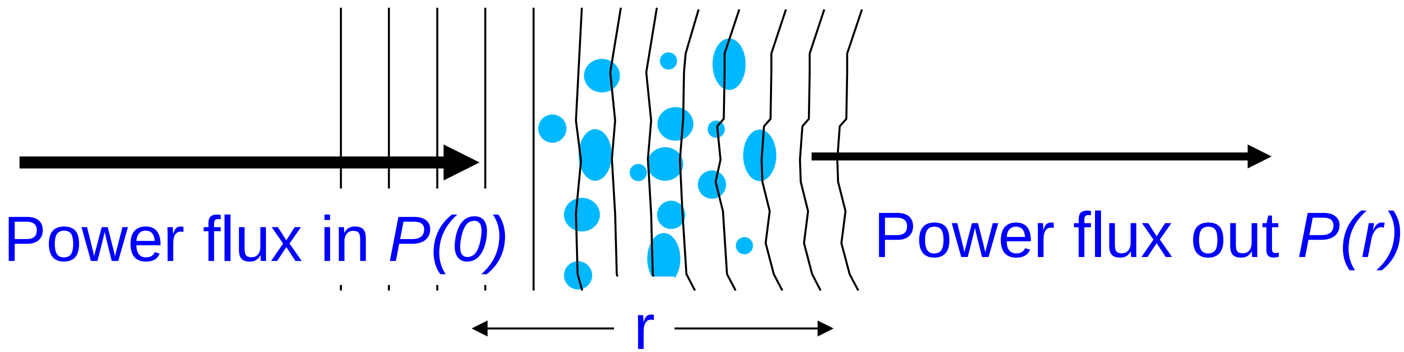
100GHz

30MHz

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

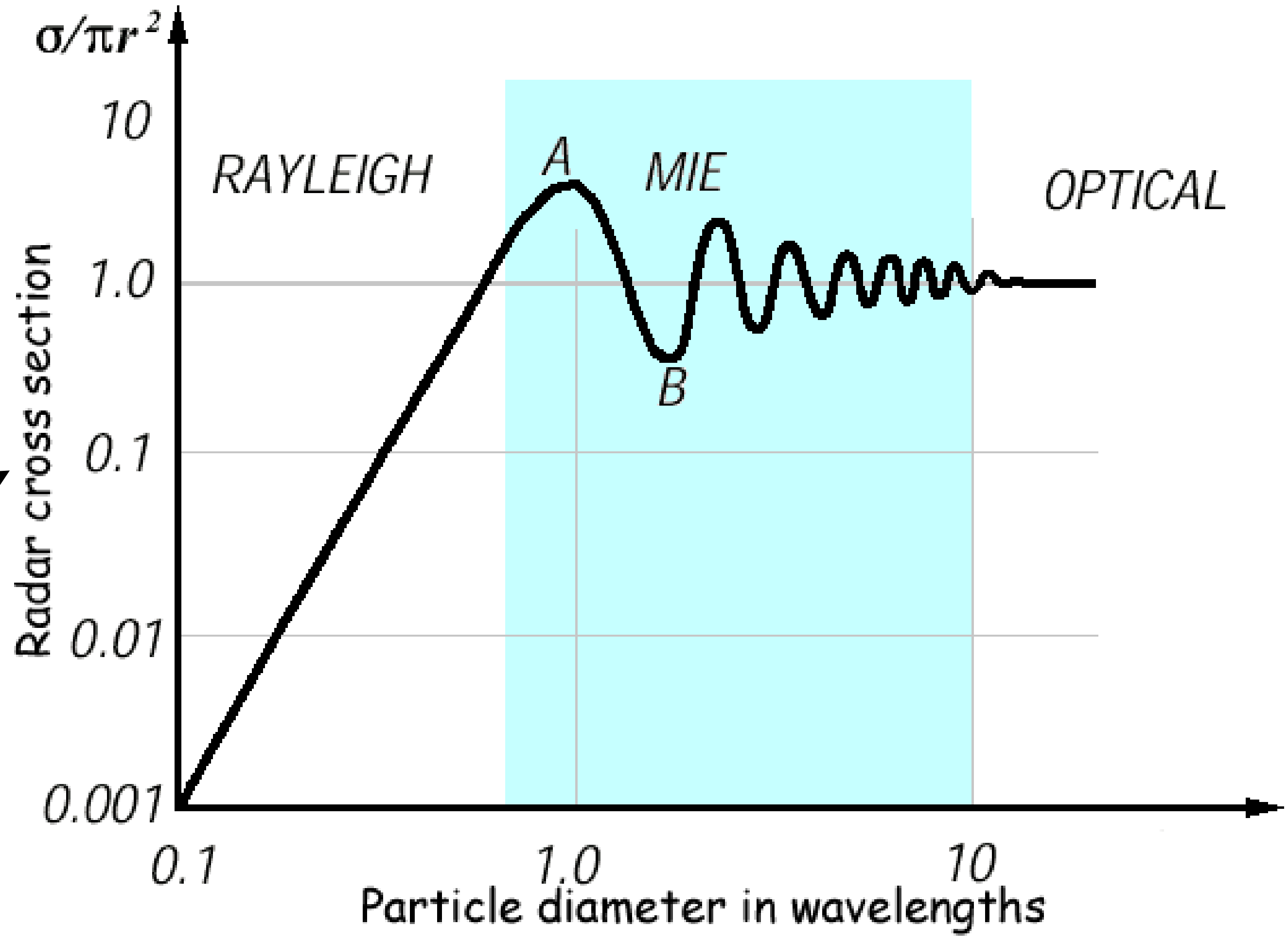
– The distribution depends on the climate and the rainfall rate R
– For rain, there tend to be more small drops than large ones
– In convective rain (thunderstorms) we get more large drops

This is where it gets interesting as big drops scatter well

Scattering regions

The scattering depends on wavelength compared to drop size

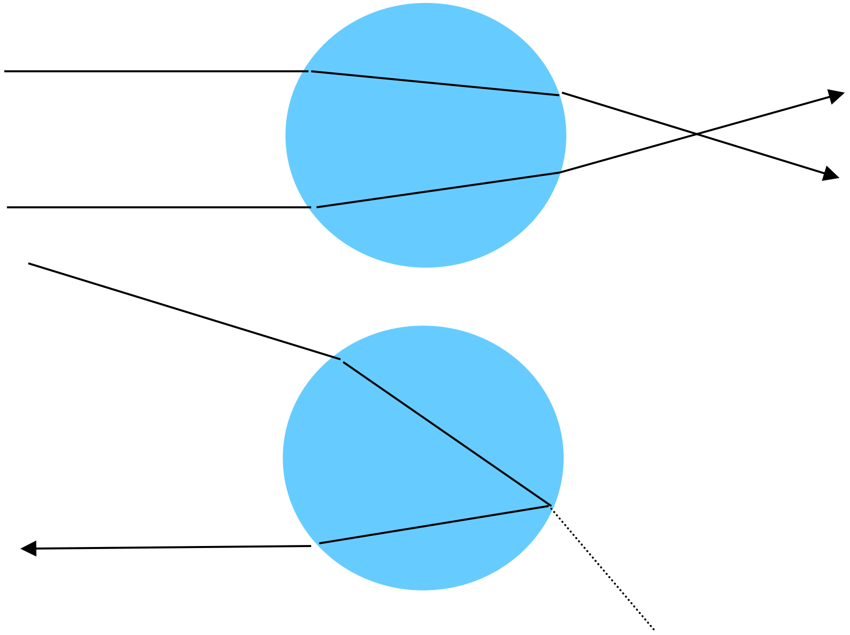
A measure of the amount of scatter



Optical scattering

When the particle is much larger than the wavelength

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

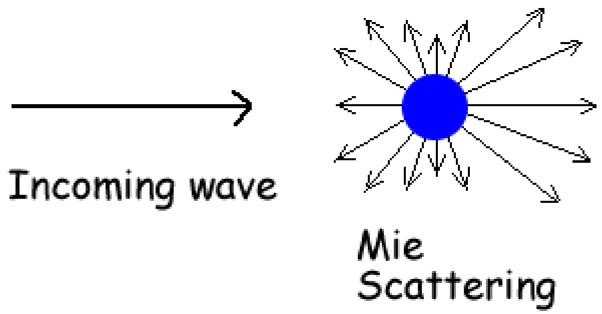


Important 1 THz and above when $\lambda < 300\mu m$ E.g. IR links

Mie scattering

When the particle is similar is size to the wavelength

- Mie scattering occurs
- Mie scattering has a stronger forward radiation lobe
- It is a model for approximating the effects



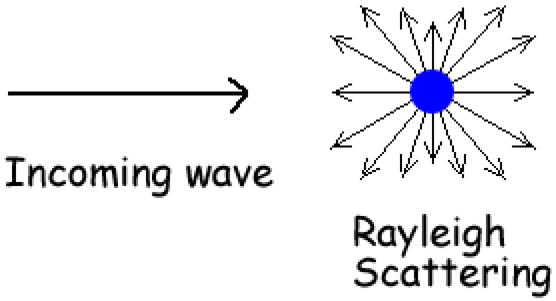
With Mie scattering, there is a stronger forward lobe

More complicated to model (resonance)

Rayleigh scattering

When the wavelength is larger than the particle

- The forward scatter by Hydrometeors is via a mechanism called Rayleigh scattering.
- Rayleigh wrote a paper about it in 1871, hence the name
- Occurs when the particle is small compared to the wavelength



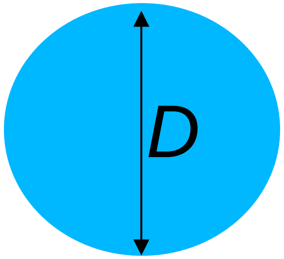
Energy is scattered with a pattern like that of a dipole antenna

Energy is proportional to D^3/λ

This is the scattering we see for microwave links

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:

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

S accounts for non-Rayleigh scatter

R (mm/hr) is the rain rate

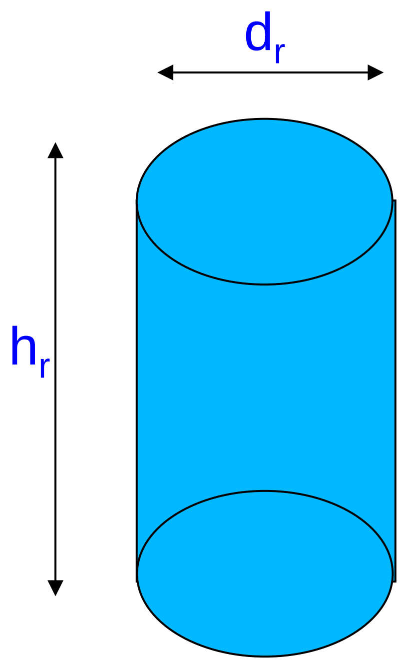
V (km^3) is the common volume

S is a correction for non Rayleigh effects above 10 GHz

Rain rate and common volume

Finding V

Assume the rain is at the mid point of a long great circle path where $d \gg d_r$ 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 $V = \pi d_r^2 h_r / 4$

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

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)

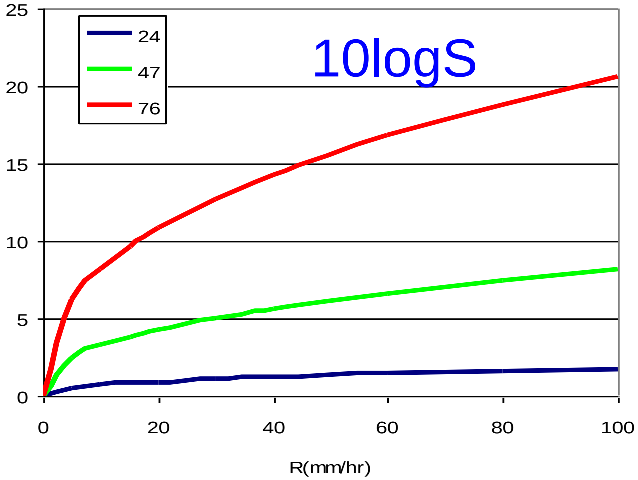
$$10\log(P_r^{scat} / P_r^{fs}) = 10\log\sigma - 20\log d - 59$$

So

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

Rain scatter example

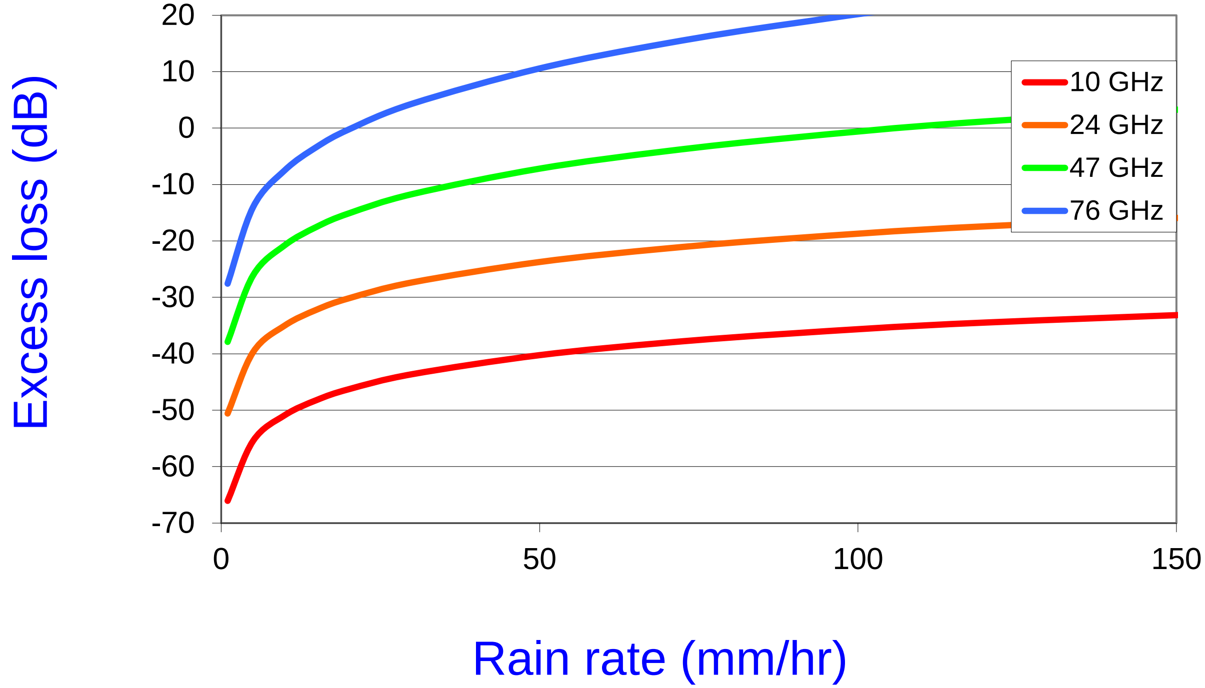
Some examples for a 100km path:



Scattering function

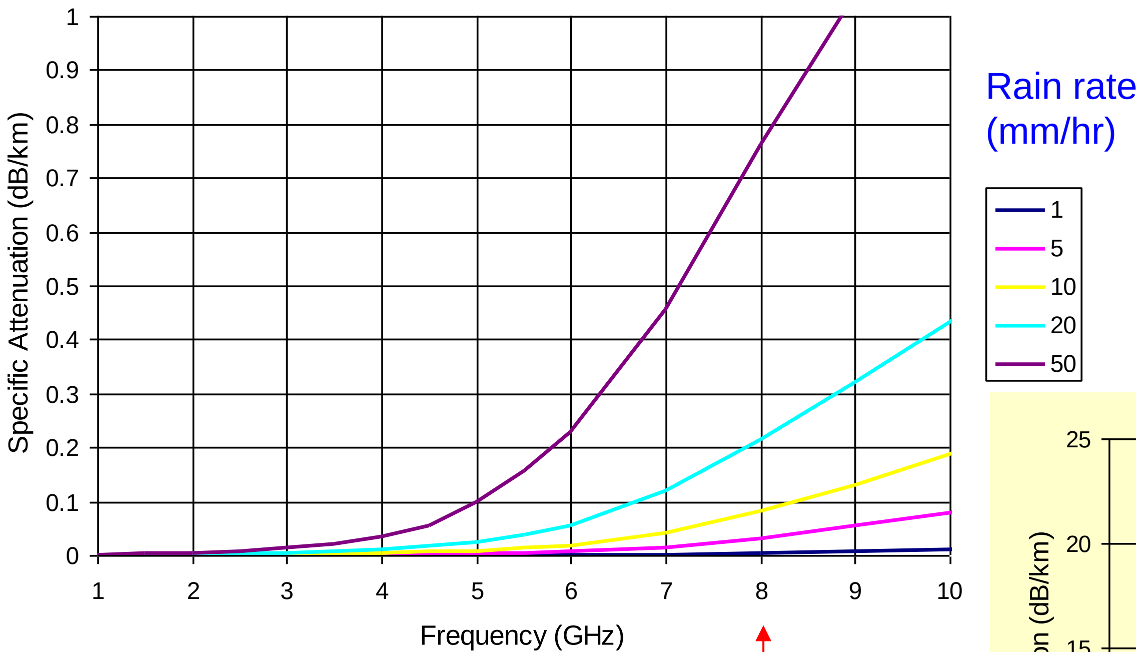
Not realistic – remember rain fading?

Excess path loss
(ignoring rain fading and gaseous loss)

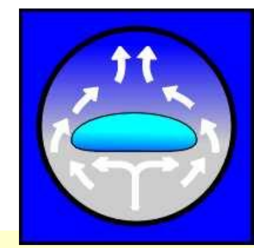


Specific attenuation of microwaves

Specific attenuation for horizontal polarisation

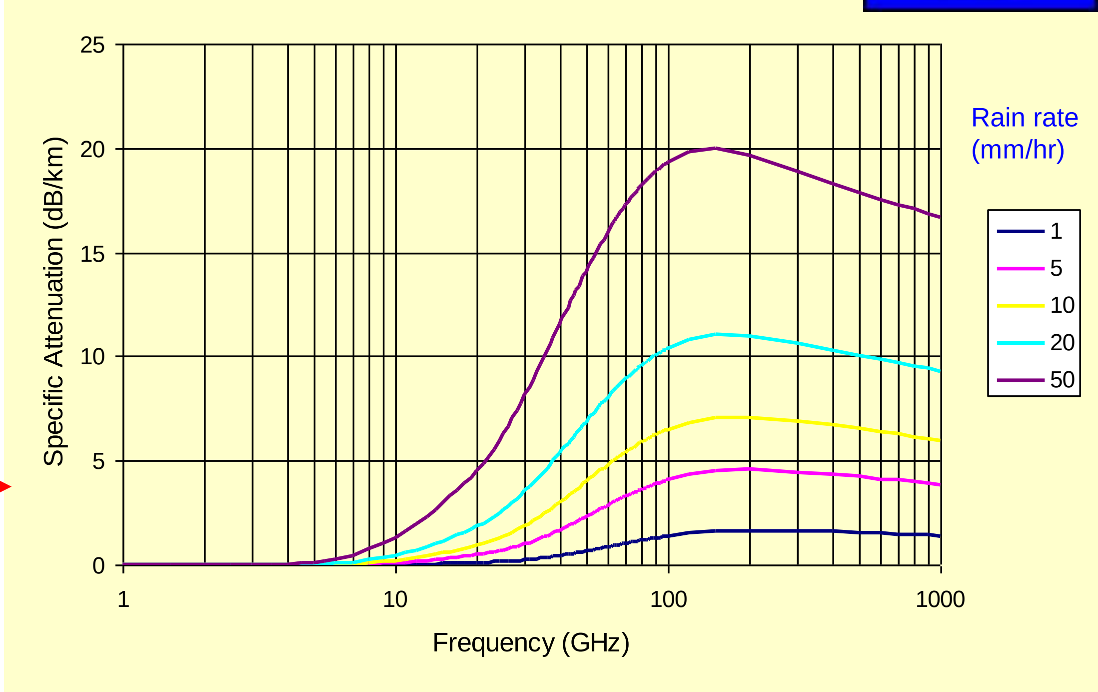


Horizontal attenuation tends to be a little higher than vertical because of the shape of falling raindrops



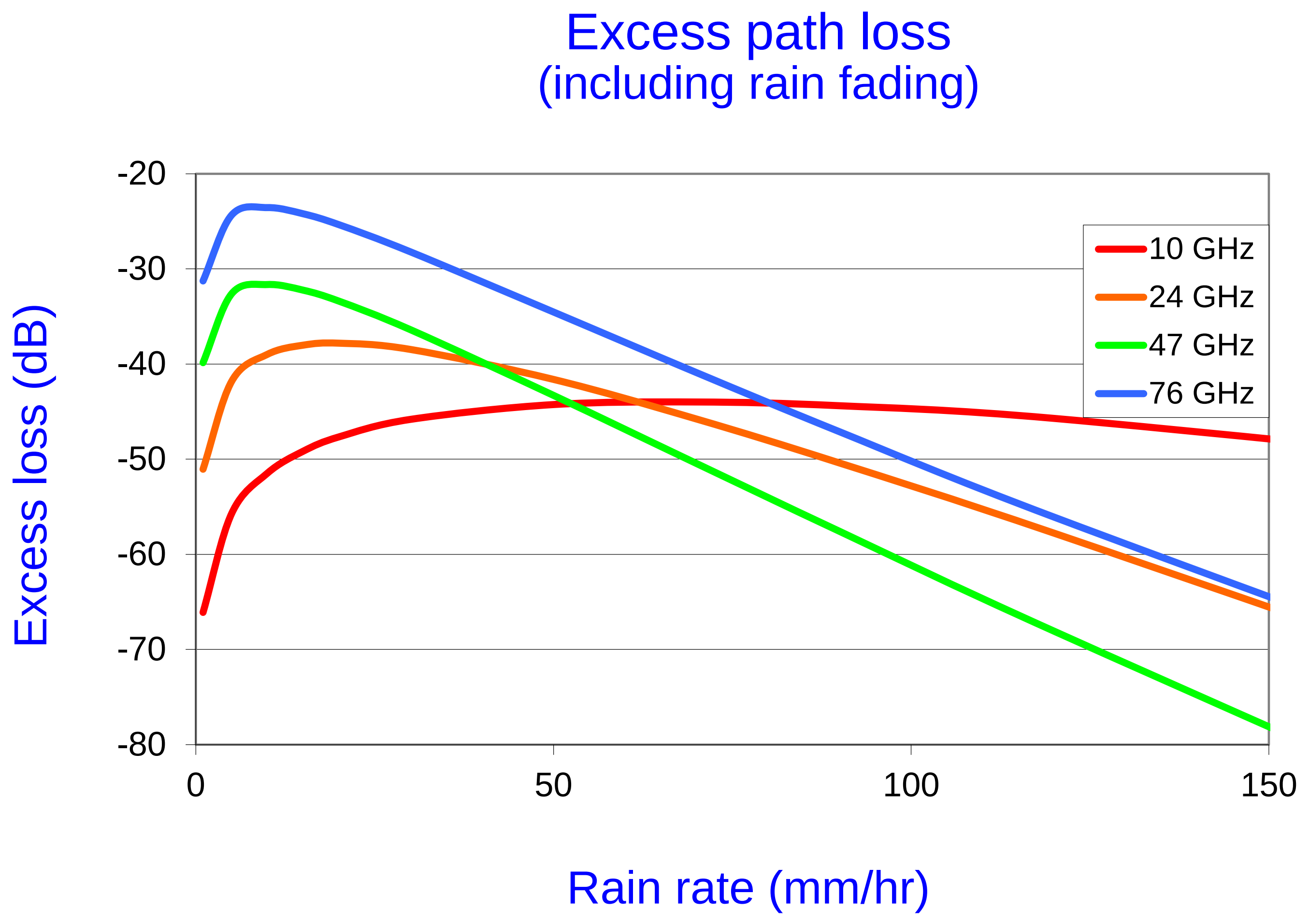
The attenuation is low below 10 GHz

Increases rapidly above 10 GHz



Rain scatter example

Now with the rain attenuation from the cell:

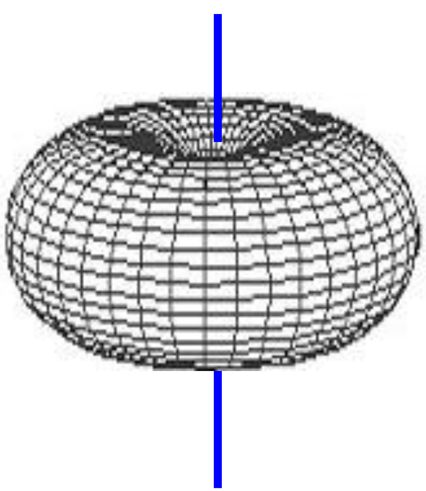


Horizontal versus Vertical

Vertical polarisation has a slightly lower rain loss

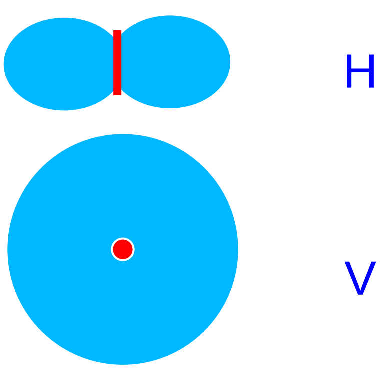
- Non spherical drop, scatters H more than V 

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

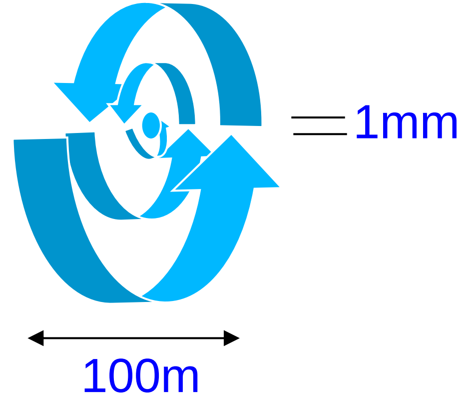
This is what gives us anytime dx for a few 100km on non line of sight paths (explains why talkback so difficult)

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

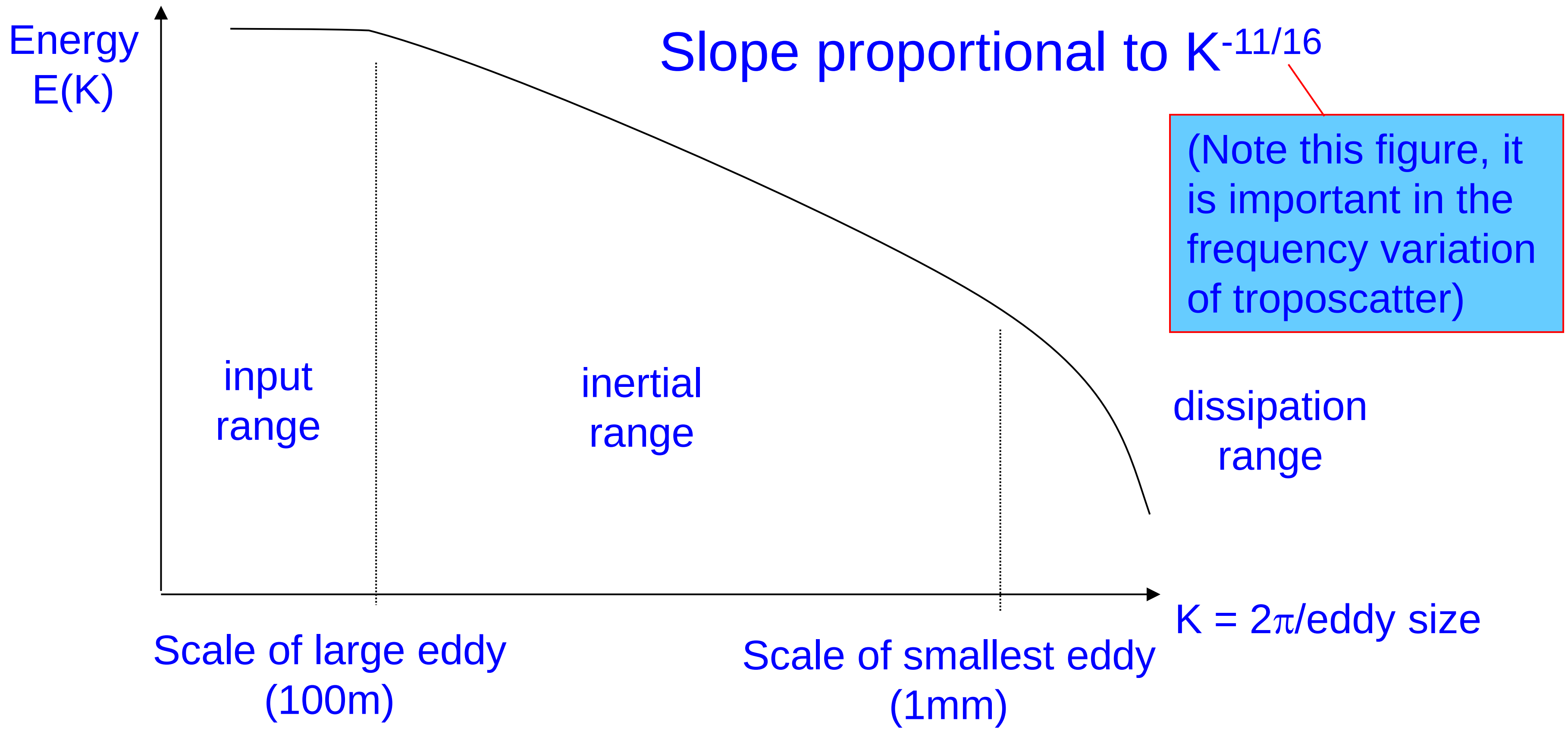
From these, smaller eddies are shed

This process continues until the length scale is small enough for viscous action to become important and dissipation to occur.

Turbulence spectrum

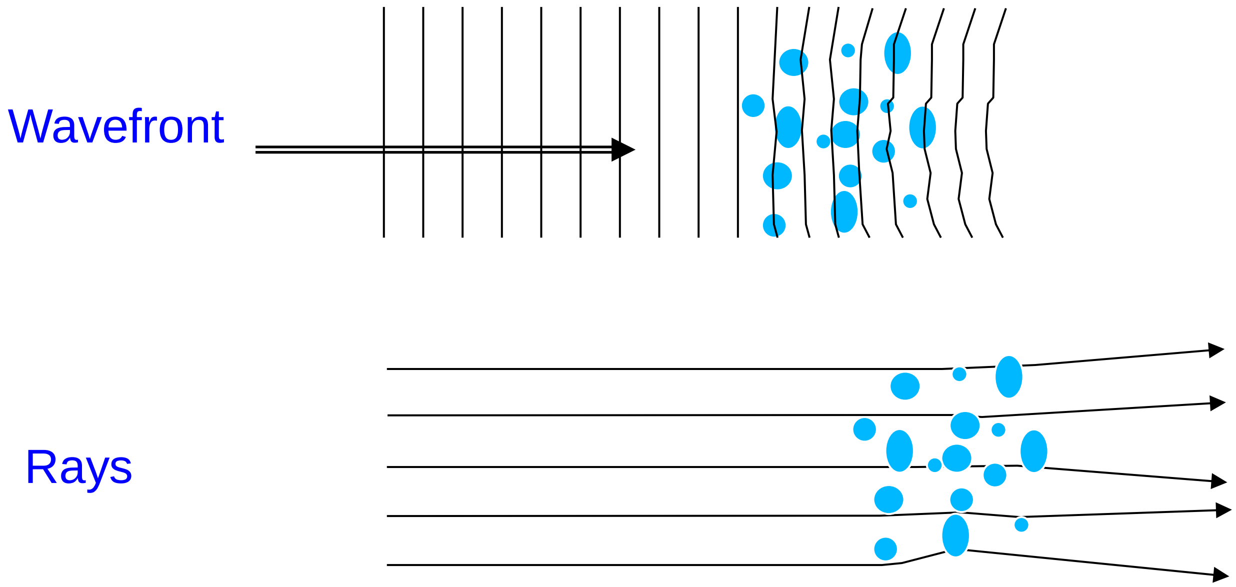
The variations have a spectrum

The Kolmogorov spectrum



Effect of irregularities on wavefront

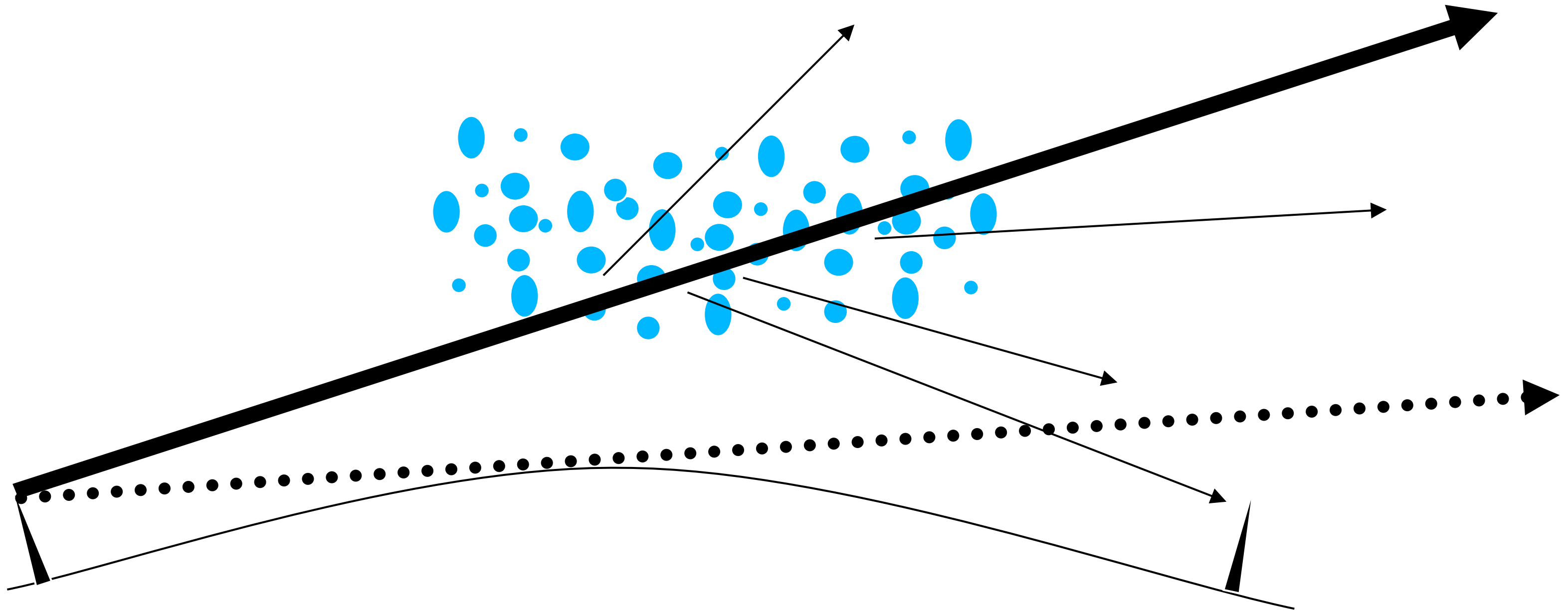
The wavefront is scattered and defocused



Energy is scattered by small angles, which over long paths leads to Troposcatter

Troposcatter

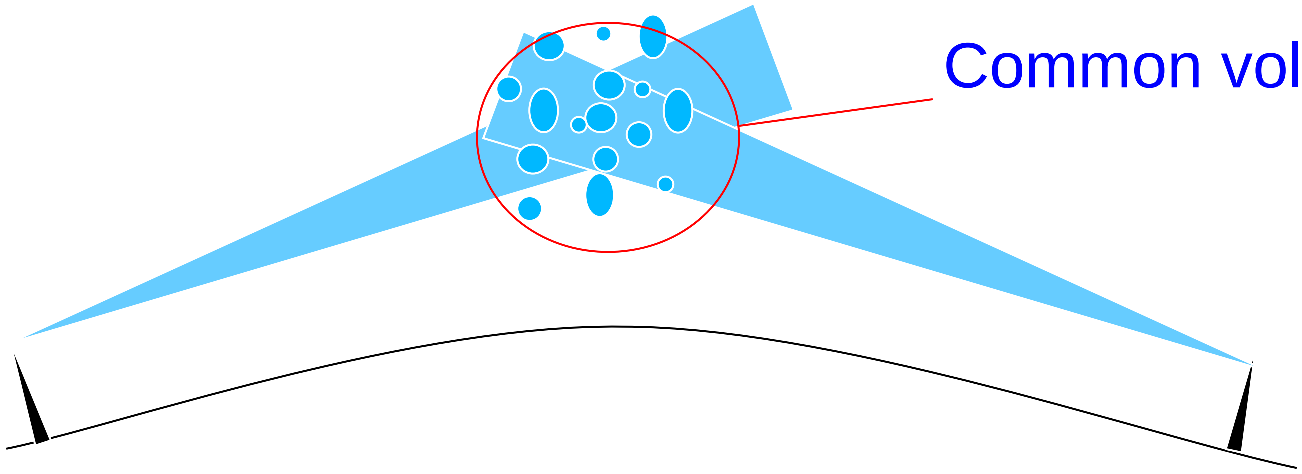
Signals are scattered to a receiver beyond the horizon



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 ~80dB, including antenna gain, but very few terrestrial paths this long are line of sight

Troposcatter is 65 dB below line of sight in this case

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:

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

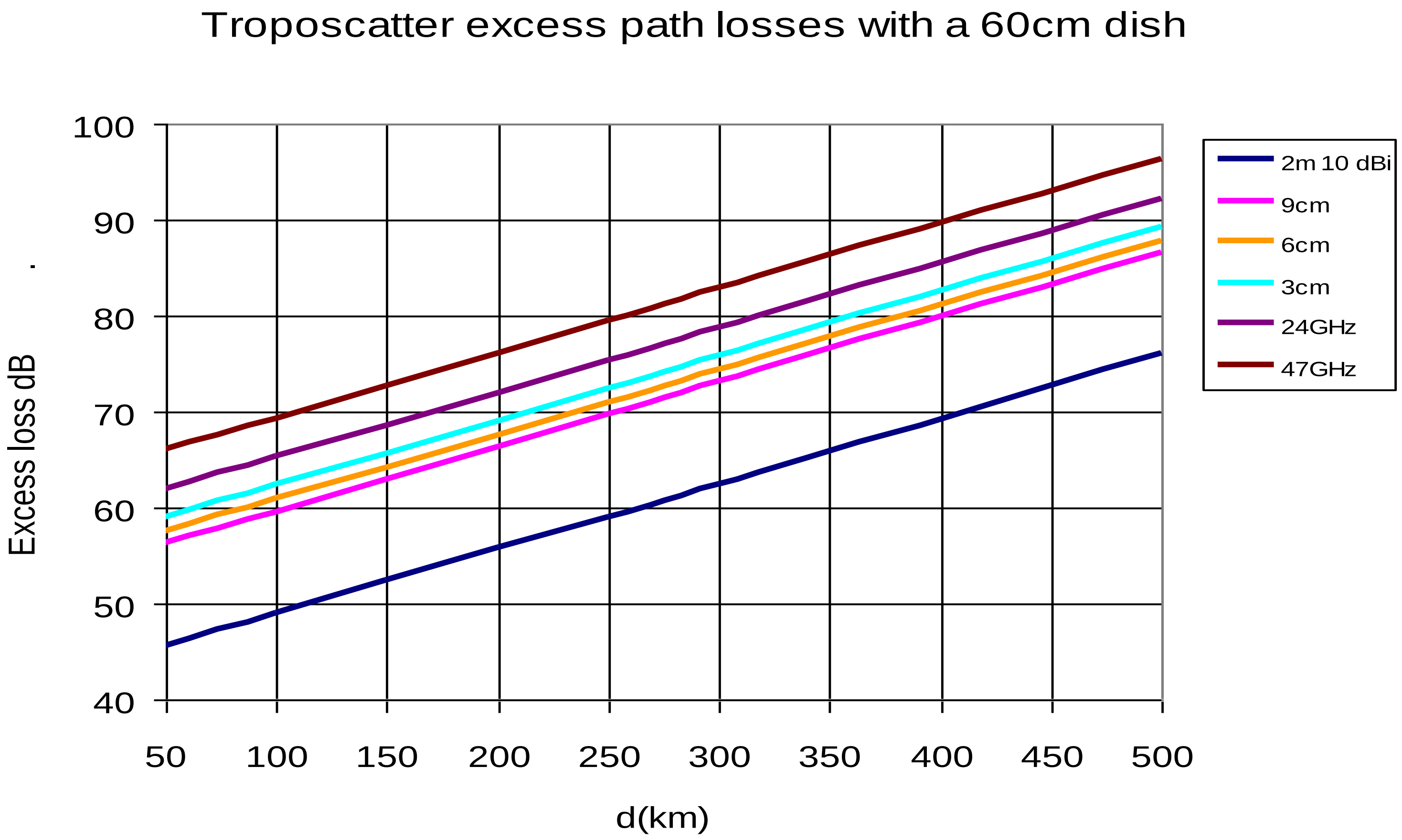
Where G_t, G_r are the gains of the antennas

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

Troposcatter

Example troposcatter path loss, for inland UK :

(145MHz 10 dBi antennas, otherwise 60cm dishes, 70% efficient)

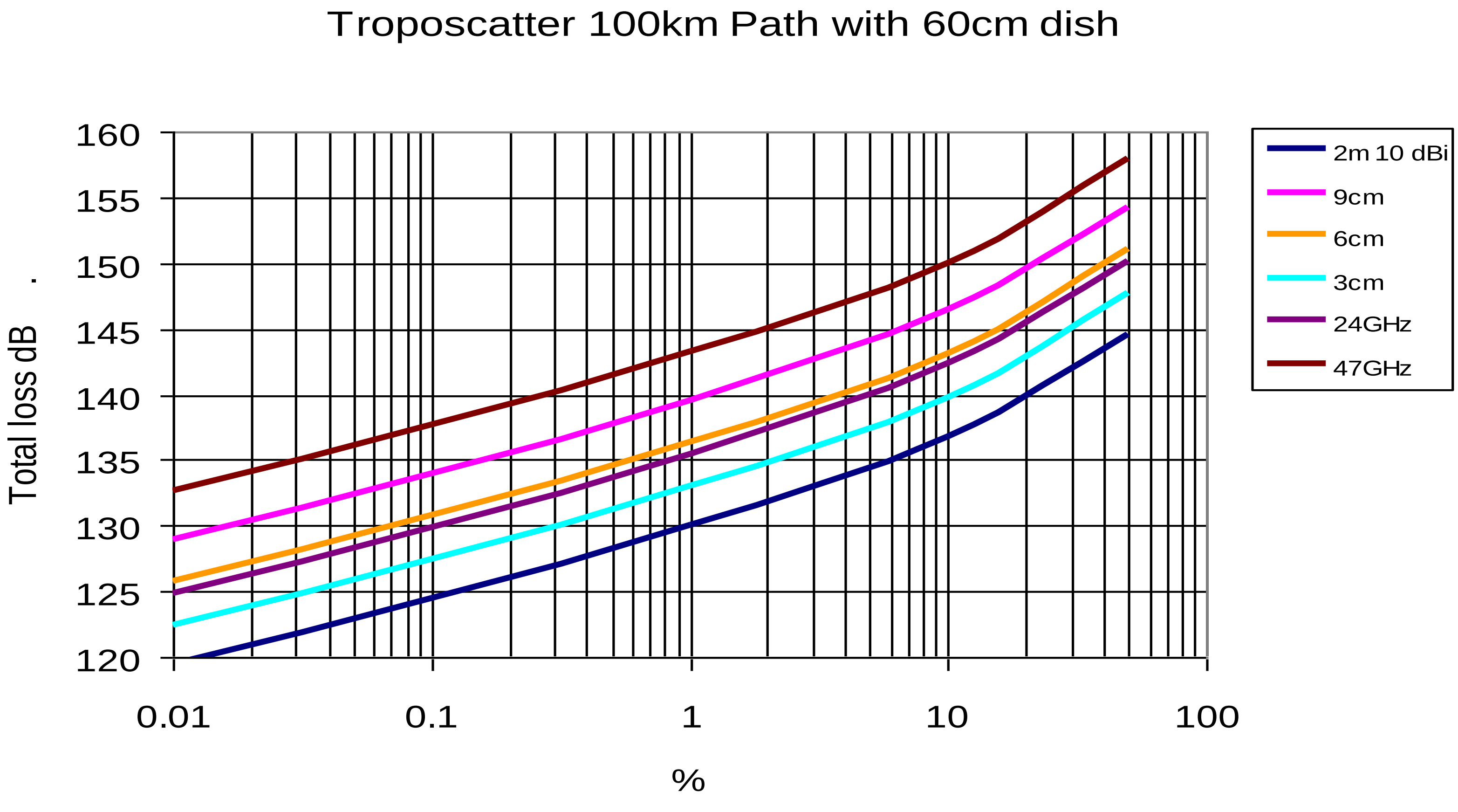


Note – excess versus the equivalent length line of sight path and $\theta_{t,r} = 0$

Troposcatter

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

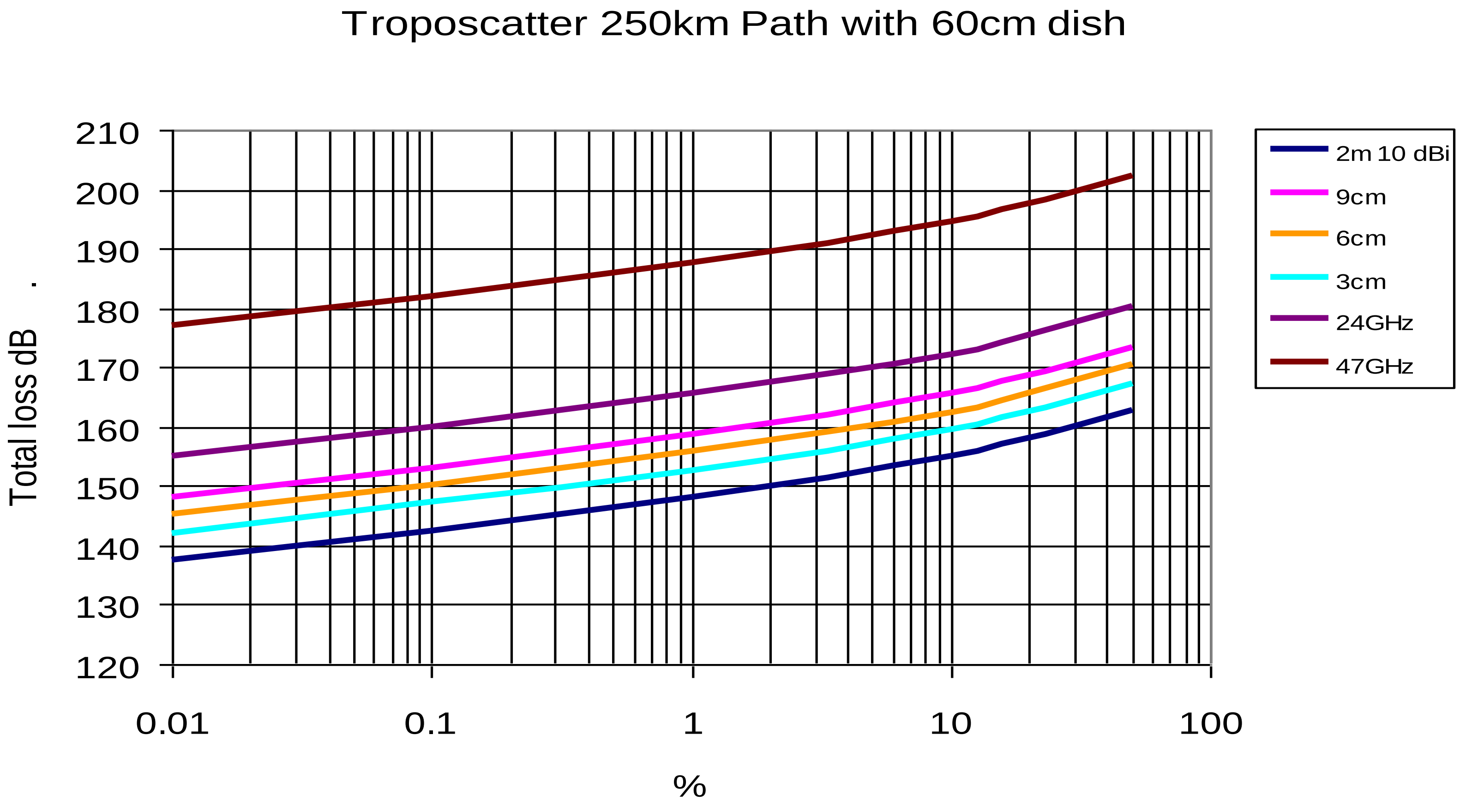
(Again 145MHz 10 dBi antennas, otherwise 60cm dish, 70% efficient)



Troposcatter

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

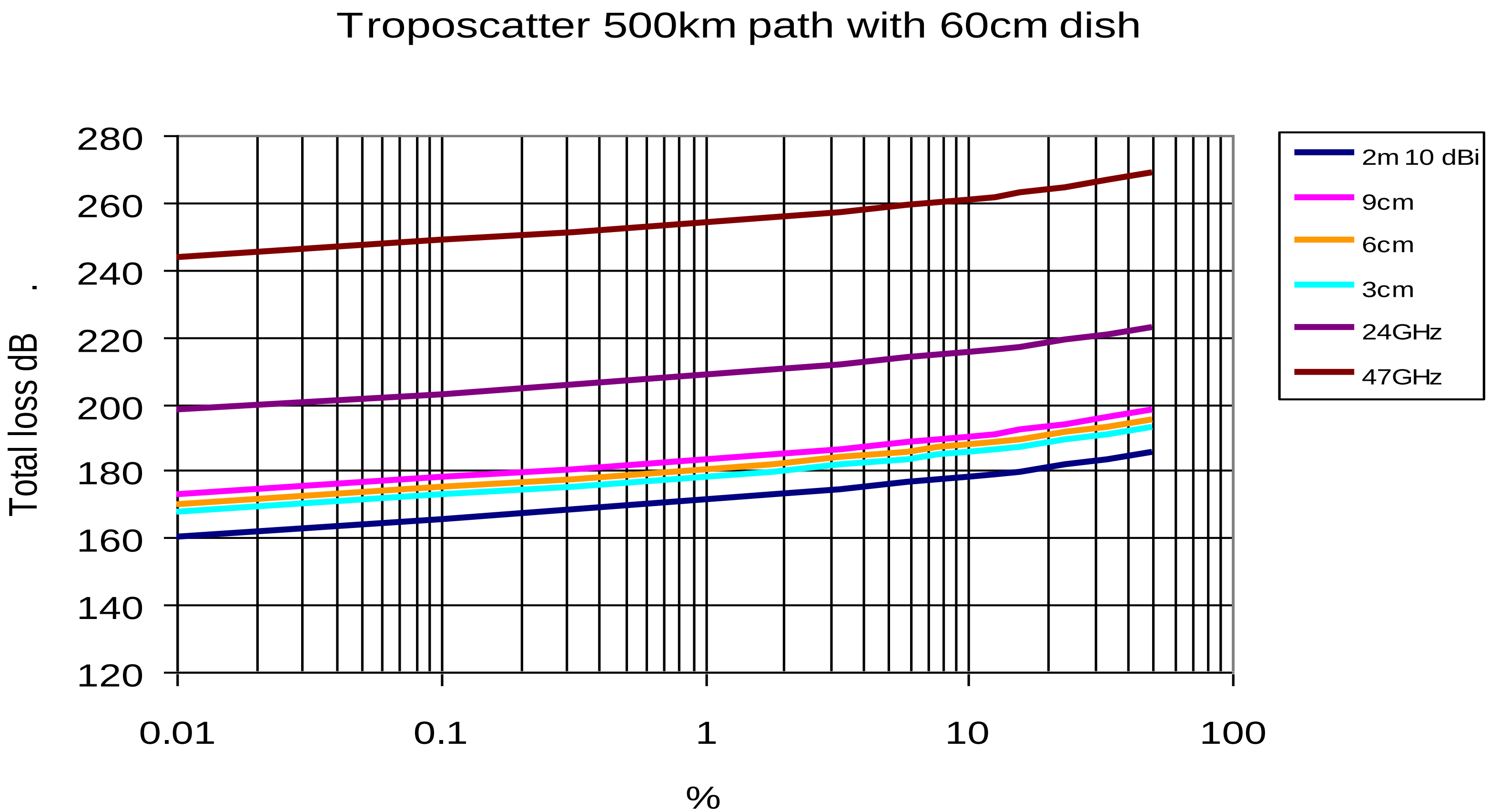
(Again 145MHz 10 dBi antennas, otherwise 60cm dish, 70% efficient)



Troposcatter

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

(Again 145MHz 10 dBi antennas, otherwise 60cm dish, 70% efficient)



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.

Data availability

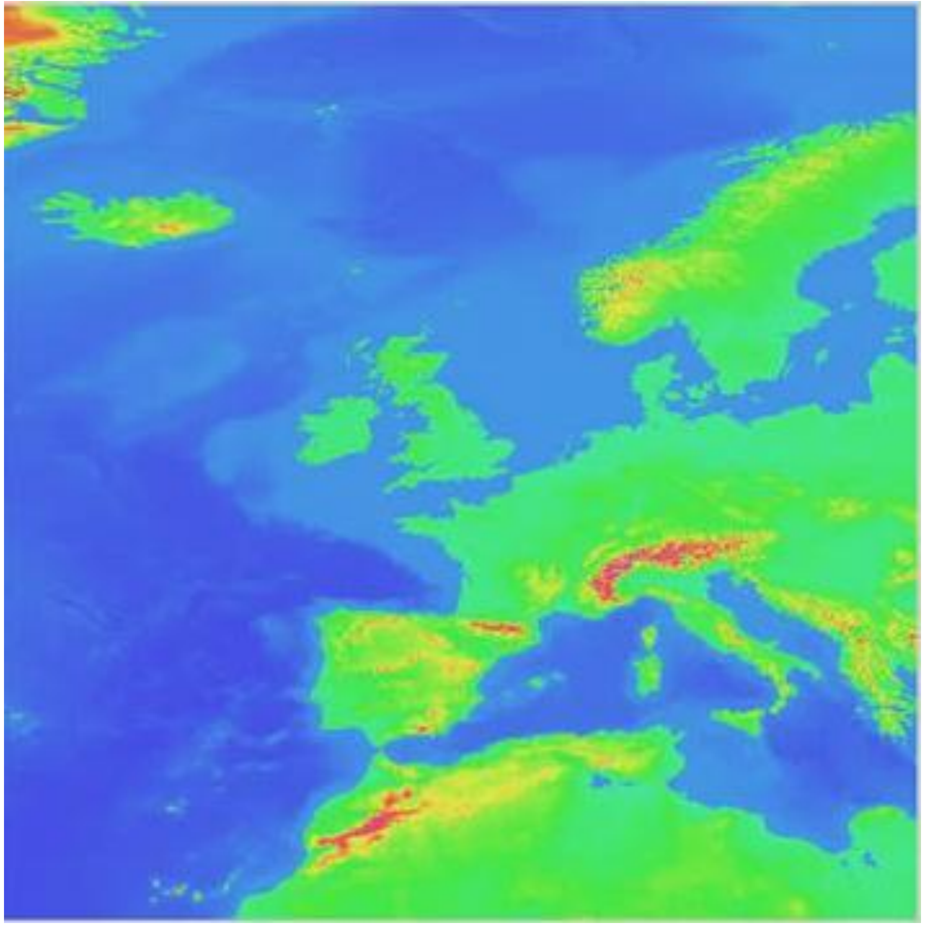
Propagation is greatly influenced by terrain and the weather

- 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 (or OSGB if you are rich enough)
  - 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 via GTOPO30 from USGS
  - 30 arc second samples Approx 900m resolution
- For +-60 degrees by SRTM from NASA
  - 3 arc second samples, Approx 90m resolution



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All this will be on my website

http://www.mike-willis.com