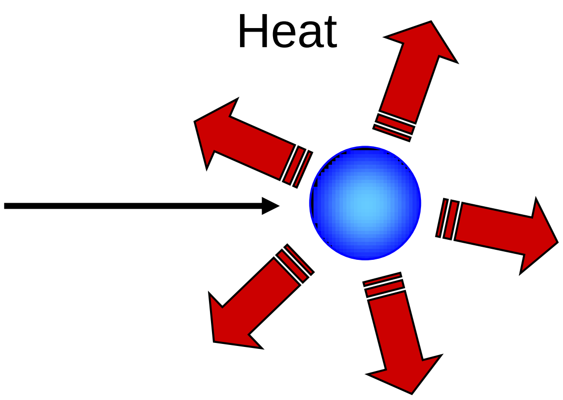
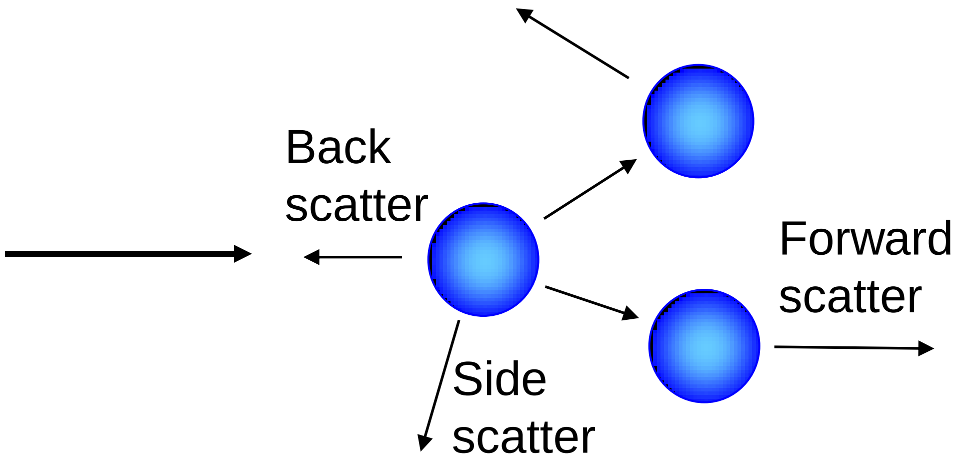
Chapter 7. Satellite fixed links (Note: Rain attenuation for any link)

- Absorption and scattering
- Precipitation (rain, snow, sleet)
- Atmospheric gases
- Path attenuation
- Statistical distribution
- Ionosphere electron density
- Faraday rotation
- Scintillation
- Other

Absorption and scattering



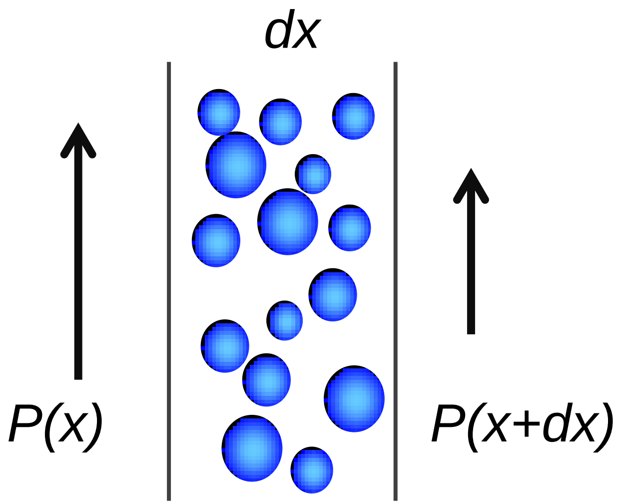
Absorption



Scattering

Total loss (in dB) : $\boldsymbol{L}_{\text{total}} = \boldsymbol{L}_{\text{absorption}} + \boldsymbol{L}_{\text{scattering}}$

Exponential attenuation



$$P(x+dx) - P(x) = -\alpha P(x)dx$$

$$dP(x) = P(x+dx) - P(x)$$

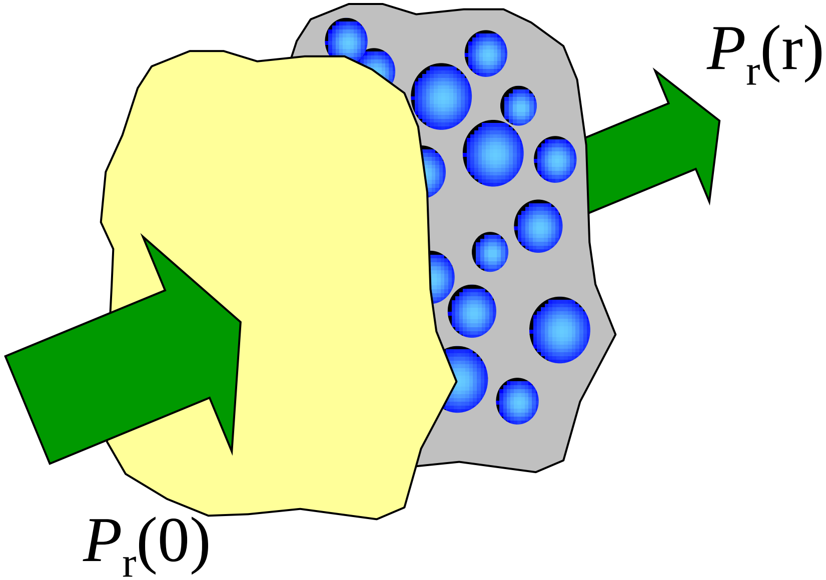
$$\frac{dP(x)}{P(x)} = -\alpha dx$$

$$d(\ln P(x)) = -\alpha dx$$

$$\ln P(x) = -\alpha x + const\alpha$$

$$\frac{P_d}{P_0} = e^{-\alpha d}$$

Rain attenuation



Received power P_r after distance r

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

where α is an attenuation factor.

Loss L in dB (noting P_t=$P_r(0)$)

$$L = 10 \ln \frac{P_t}{P_r} = \alpha r \cdot \log(e) = 4.343\alpha r$$

Usual to express specific attenuation γ (dB/km) $\quad \gamma = \frac{L}{r} = 4.343\alpha$

where α is given by $\quad \alpha = \int_{D=0}^{\infty} N(D)C(D)dD$

N is number of rain drops with diameter D and C is the attenuation cross section (dB/m) or extinction coefficient.

Rain attenuation over a path

Rain attenuation or loss *L* is found by integrating the specific attenuation over the whole path r_T

$$L = \int_0^{r_T} \gamma(r)\,dr \qquad \gamma = 4.343 \int_0^{\infty} N(D)C(D)\,dD$$

Given a drop size distribution *N* and attenuation cross section *C* from theory, *L* can be calculated.

There are several suggested drop size distributions, but often used the Marshall-Palmer distribution

$$N(D) = N_0 e^{-\frac{D}{D_m}}$$

$$N_0 = 8 \cdot 10^3 m^{-2} mm^{-1}$$

$$D_m = 0.122 R^{0.21}$$

The parameter D_m depends on the rainfall rate *R* in mm/h.

Drop size distribution (DSD)

Usually an exponential form $N(D)$, where N_0 and Λ (=1/D_m) are constants or functions.

$$N(D) = N_0 e^{-\Lambda D}$$

Early found that Λ had to be a function of R, rainfall rate

$$\Lambda = 4.1 R^{-0,21}$$

Given Λ also N_0 can be determined since the integral of $N(D)D^3V(D)$, where $V(D)$ is the terminal velocity, must equal R.

Typically is N_0 about 8000 med $mm^{-1}m^{-3}$. Actually, with this value the DSD is known as Marshall-Palmer.

The parameter Λ is also related to D_0 , the median, $\Lambda = 3.67/D_0$.

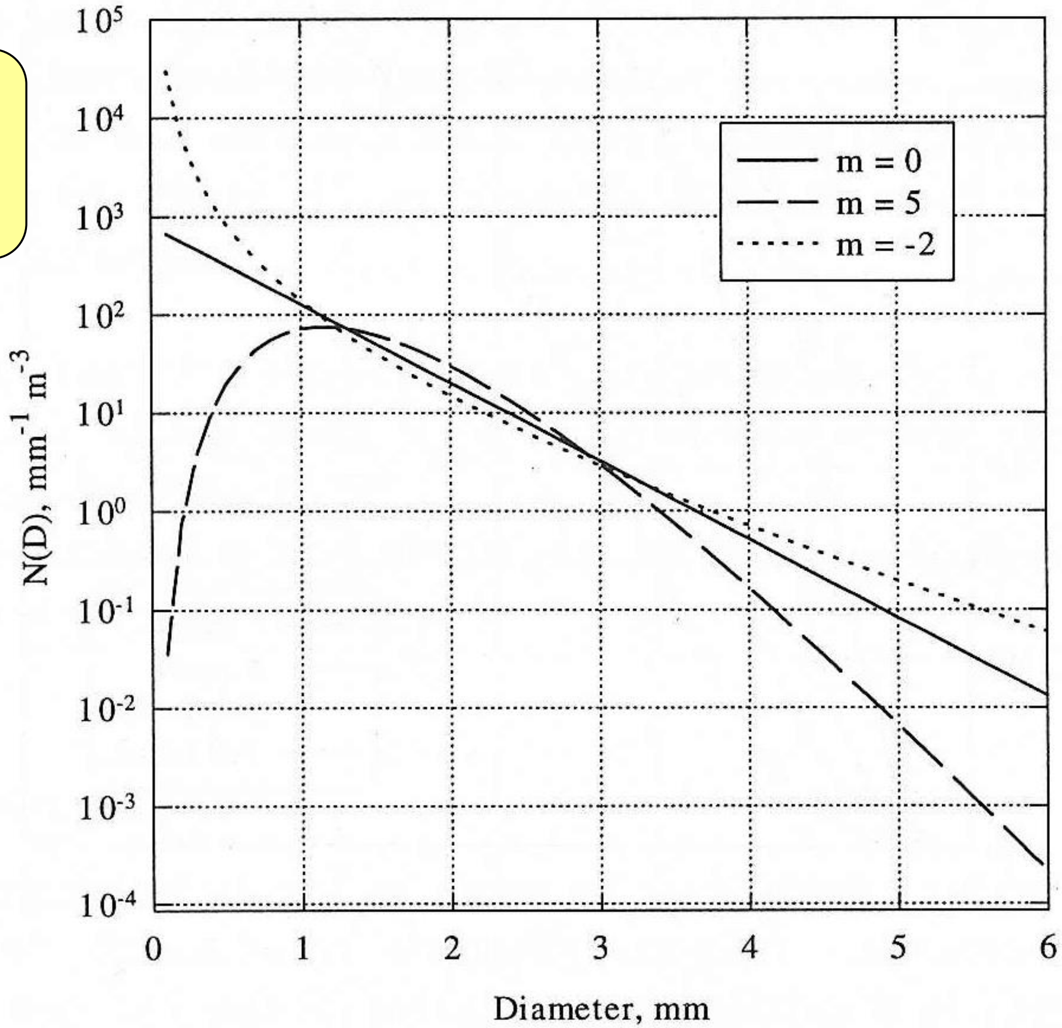
Example gamma drop size distribution (DSD)

Gamma distribution:

$$N(D) = N_0 D^m e^{-(3{,}67+m)D/D_0}$$

All DSDs shown in the figure result in the same rainfall rate R of 5 mm/h.

$D_0 = 1$ mm.



Source: Hall, Barclay, and Hewitt: Propagation of radiowaves

Specific attenuation formula

- In principle the outlined technique can be used for attenuation calculation
- But a simpler method is used in practise because the former require detailed input on the DSD
- The simple method is

$$\gamma = aR^b$$

where R is the rainfall rate in mm/h, and a and b are constants depending on frequency and polarisation

a and b for horizontal and vertical polarisation

f	a Hor	a Ver	b Hor	b Ver
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
4	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0335	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	0.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

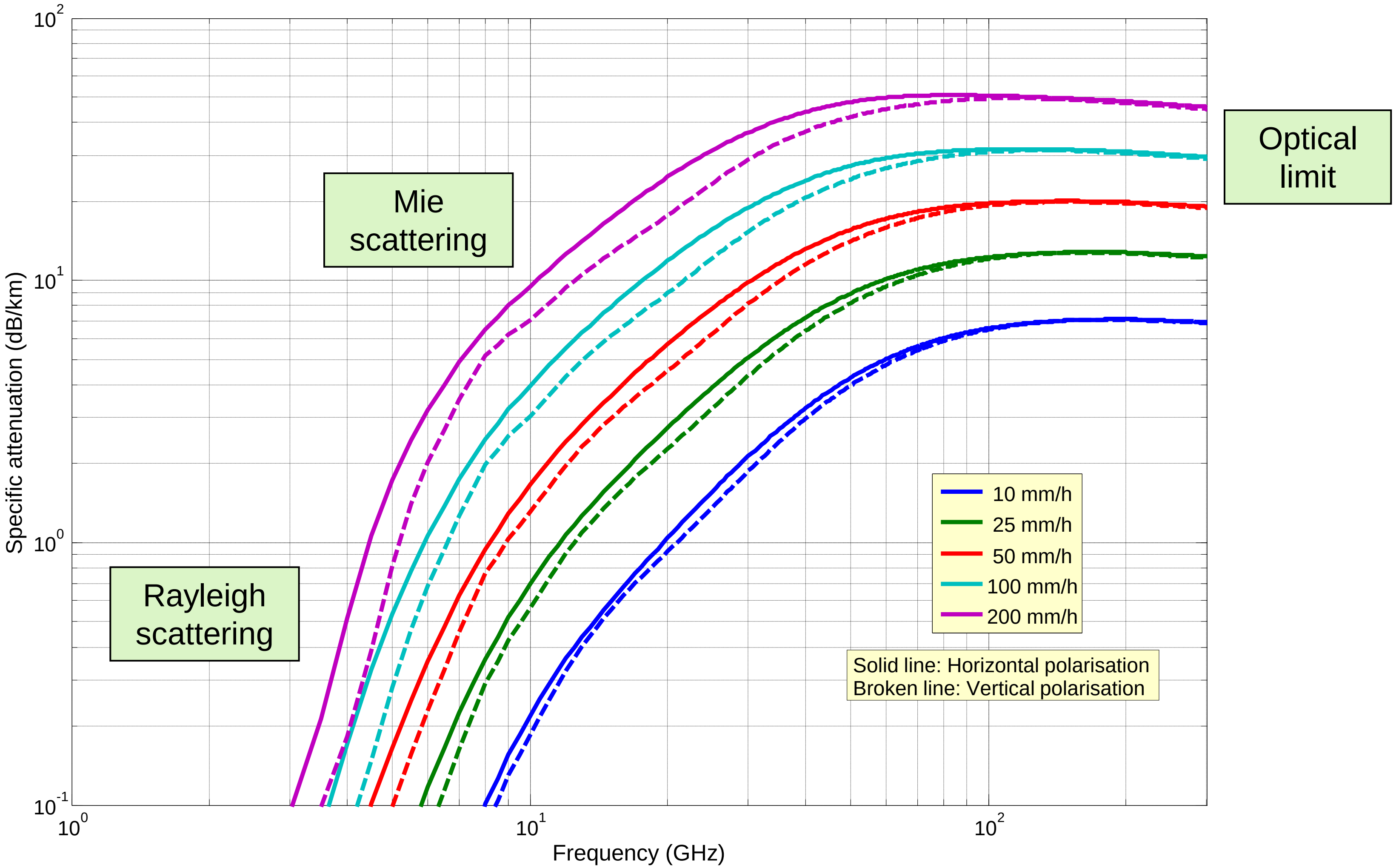
$$\gamma = aR^b$$

$$a = [a_H + a_V + (a_H - a_V)\cos^2\theta\cos 2\tau]/2$$

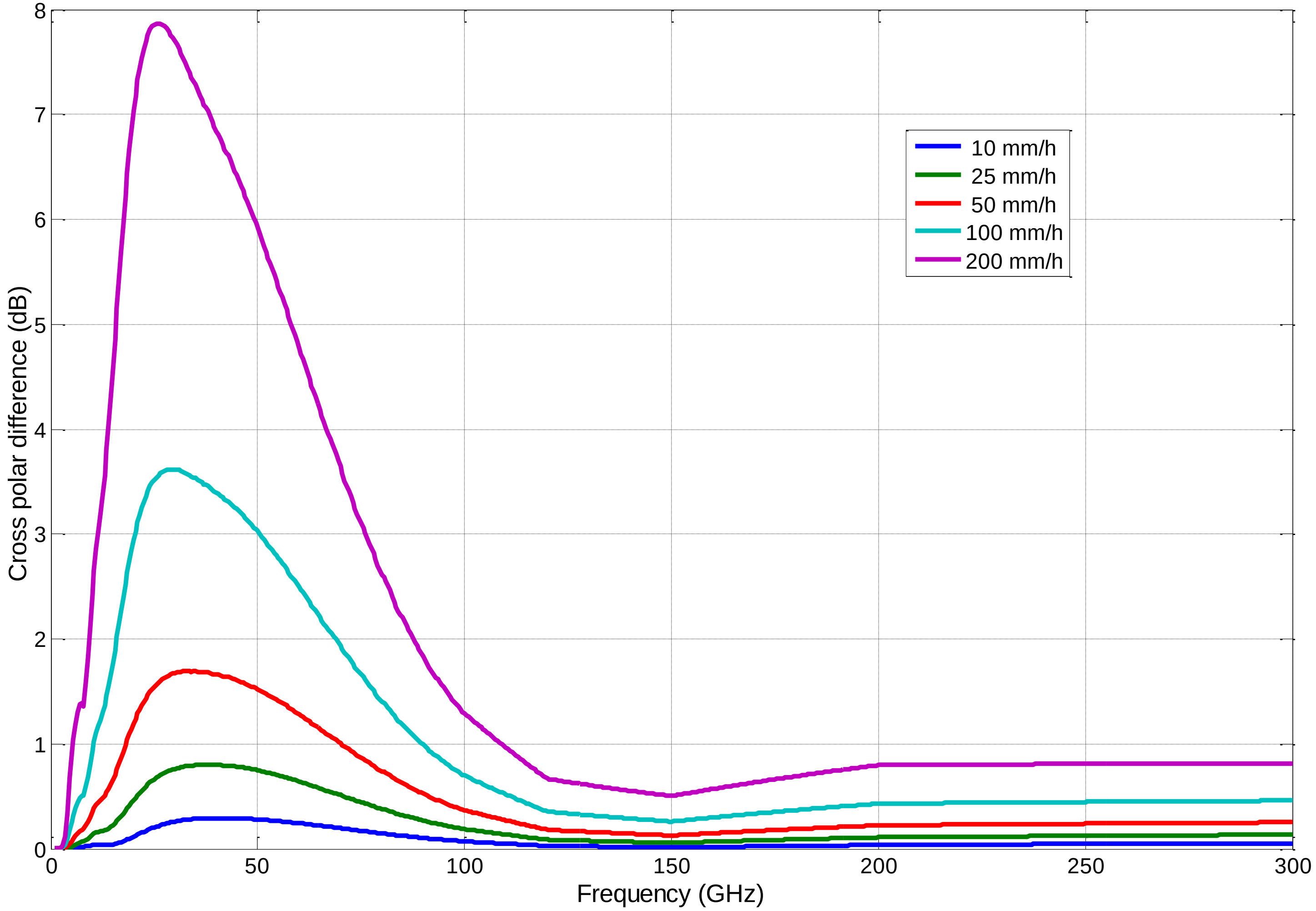
$$b = [a_H b_H + a_V b_V + (a_H b_H - a_V b_V)\cos^2\theta\cos 2\tau]/2a$$

where θ is the path elevation angle and τ the polarisation tilt angle relative to horizontal. Use $\tau = 45^o$ for circular polarisation.

Specific rain attenuation

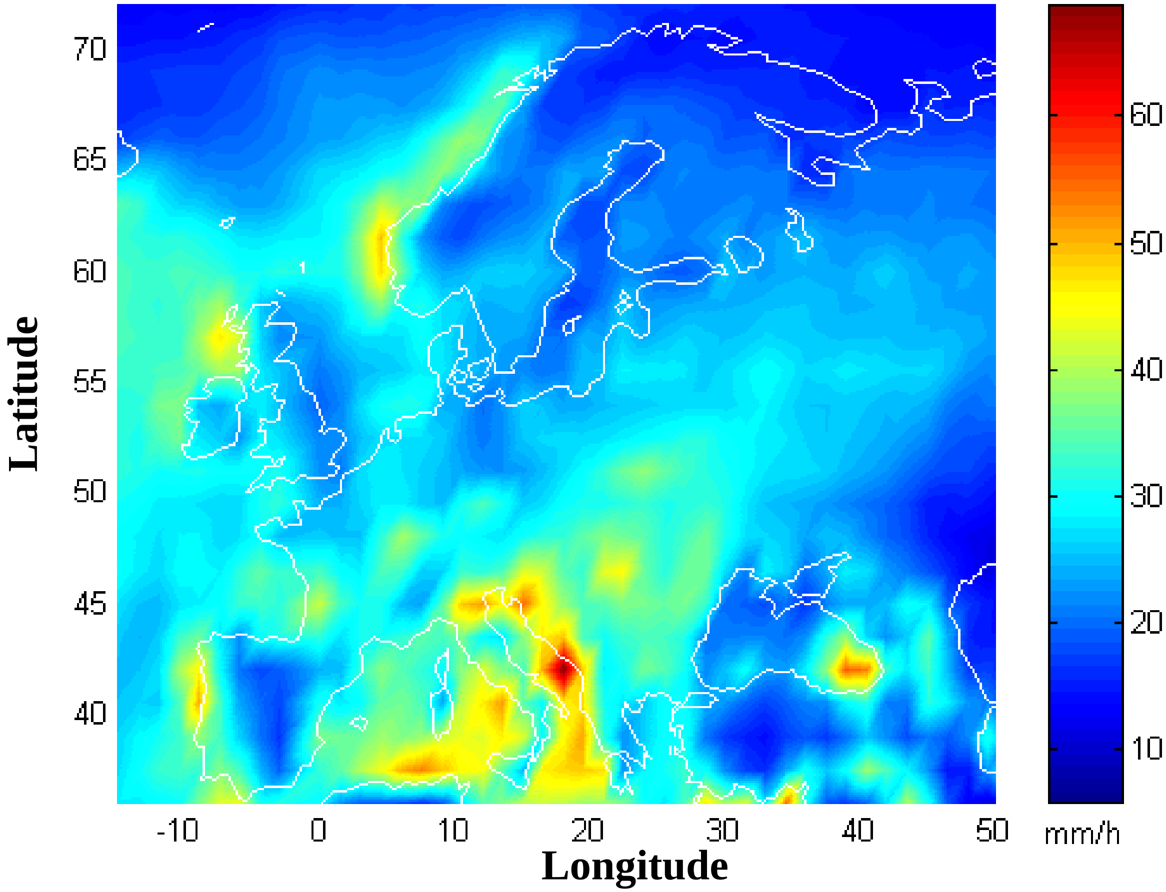


Cross polar difference in specific rain attenuation



Prediction Steps 1 and 2

1: Rainfall rates not exceeded (mm/h) at 0.01% of a year

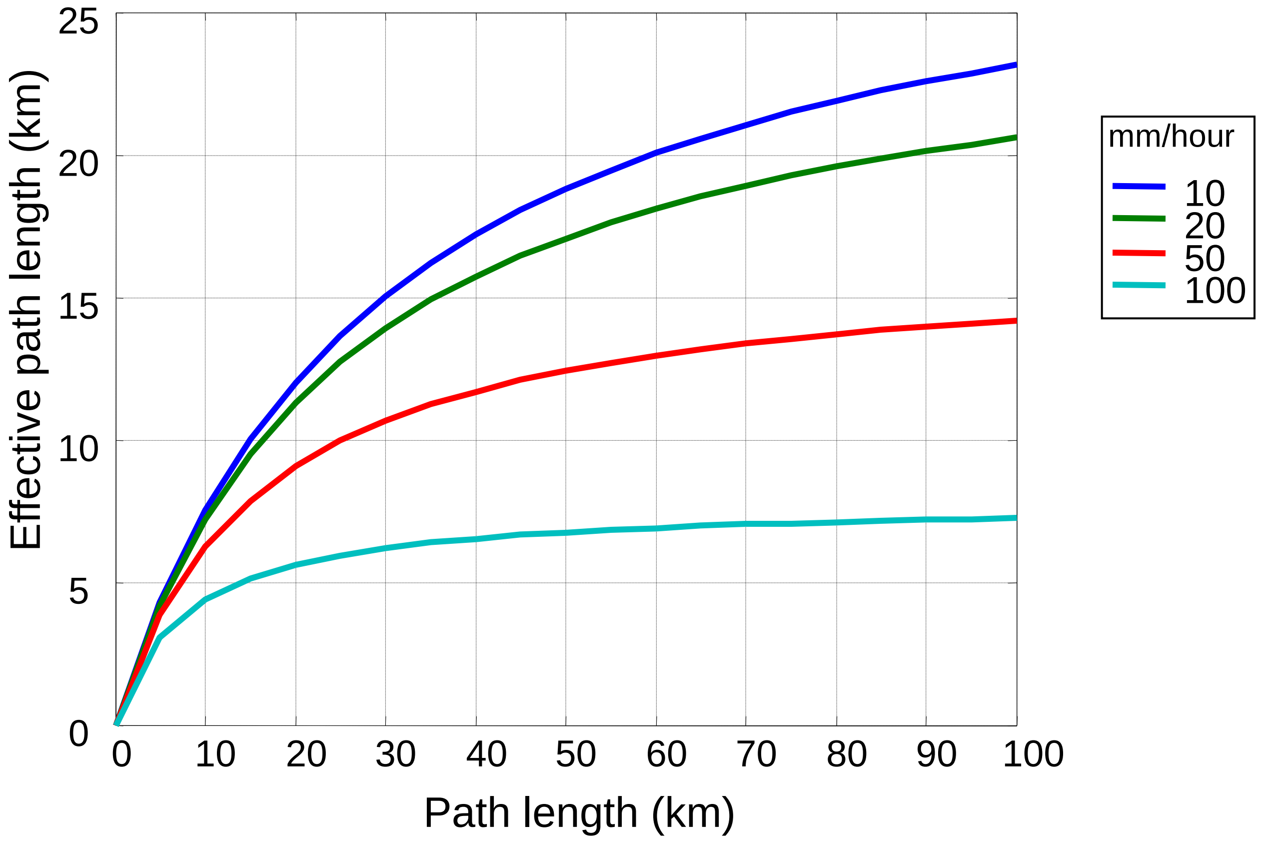


2: Find *a* and *b* for the frequency and polarisation in question

Prediction Step 3

3: Horizontal path reduction factor (non-uniform rain)

$d_{eff} = rd$, where $r = 1/(1+d/d_0)$ and $d_0 = 35e^{-0.015R(0.01\%)}$



Prediction Step 4

4: Attenuation

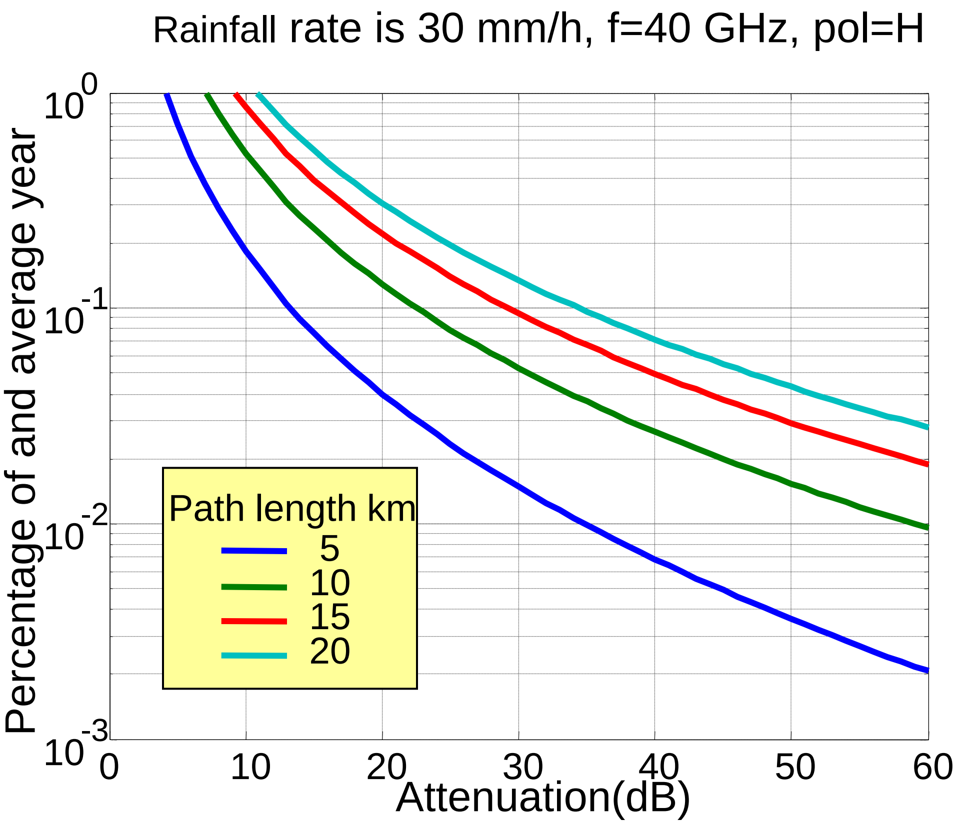
For 0.01% of an average year

$A_{0.01} = \gamma d_{eff}$

and for *p* %

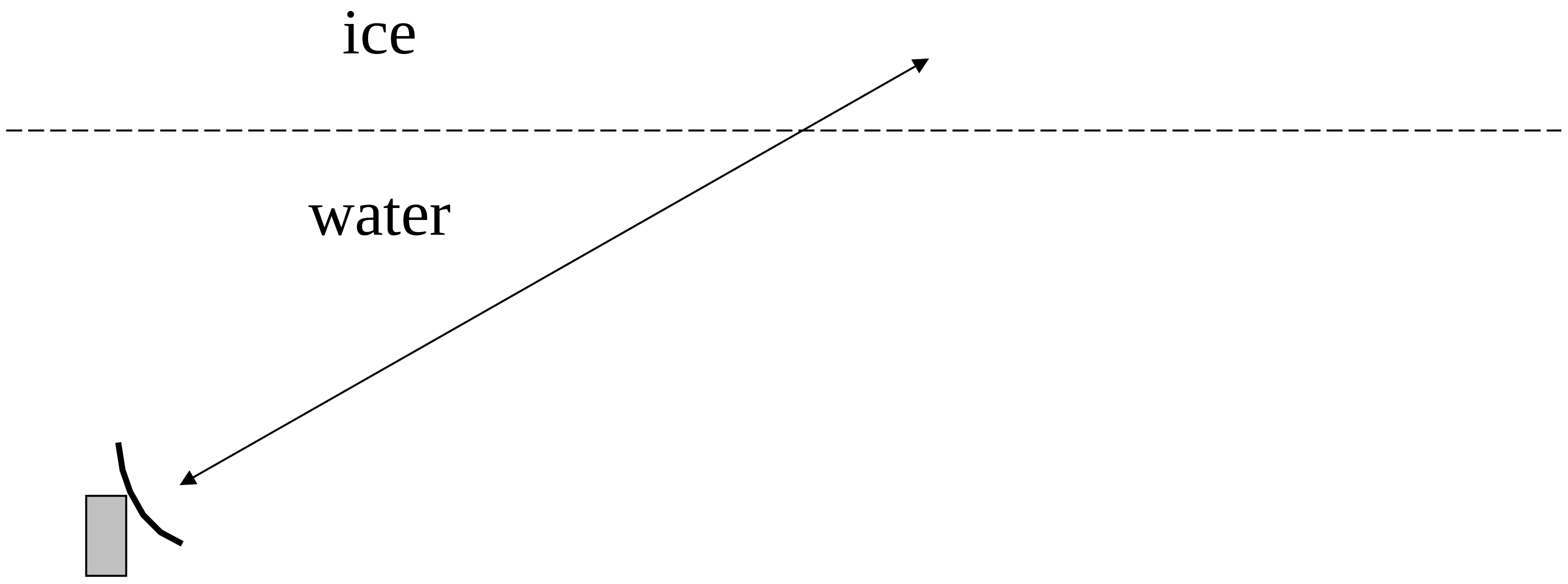
$A_p = A_{0.01} 0.12 p^{-(0.546+0.043 \log p)}$

where $0.001\% \leq p \leq 1\%$



Satellite link

Almost as for a terrestrial path but have to take the elevation angle into account.

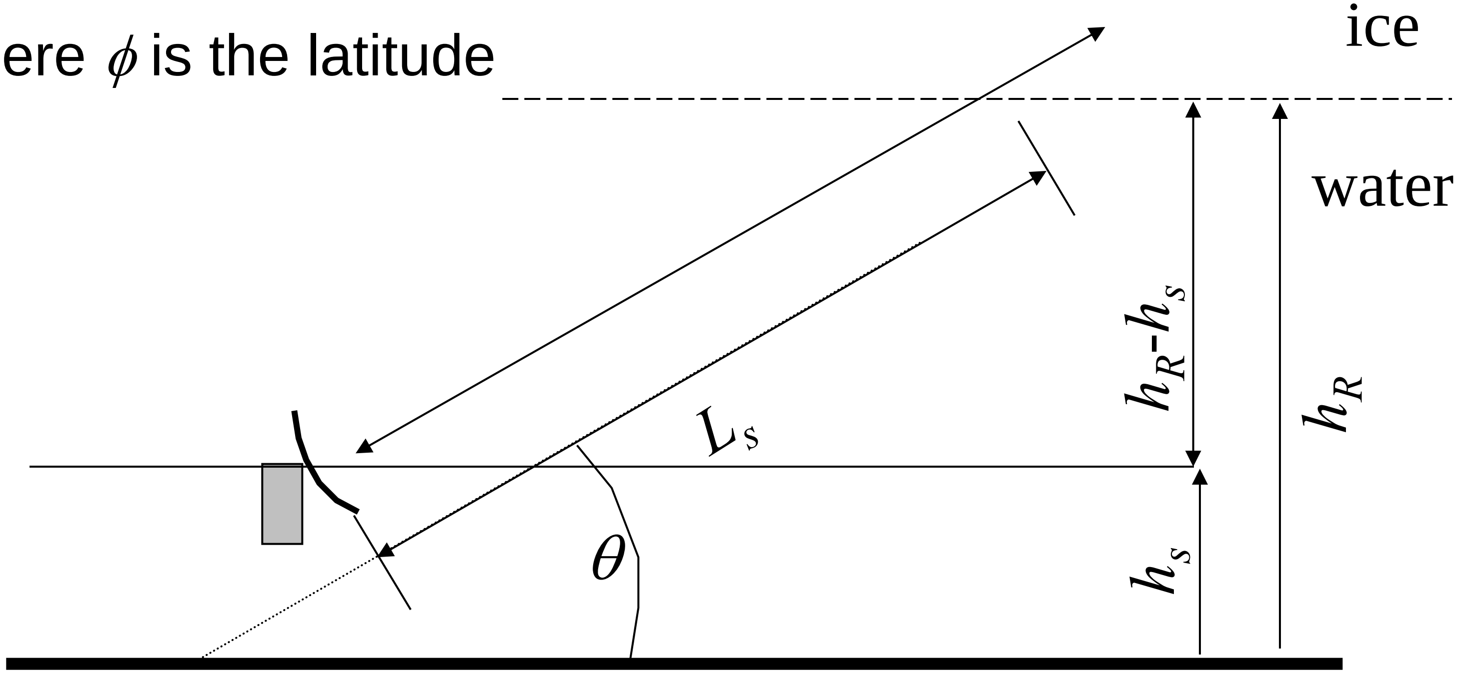


Prediction Step 1

1: Effective rain height

$$h_R = \begin{cases} 3.0 + 0.028\phi & 0 \le \phi < 36^o \\ 4.0 - 0.075(\phi - 36) & \phi \ge 36^o \end{cases}$$

where ϕ is the latitude



Predictions Steps 2 and 3

2: Length through rain

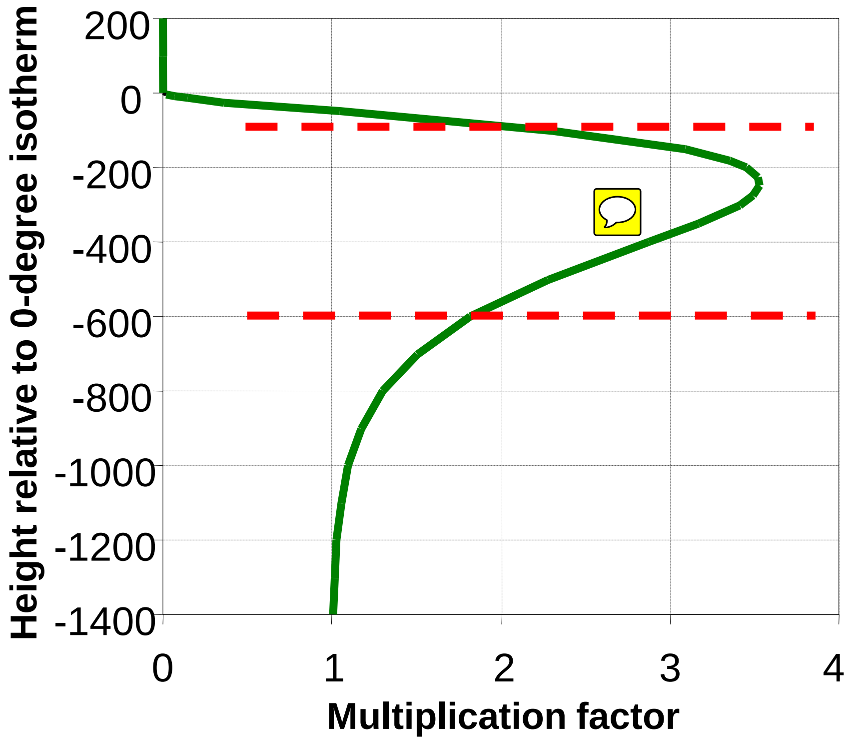
$$L_S = \begin{cases} \dfrac{(h_R - h_S)}{\sin\theta} & \theta \geq 5^o \\ \dfrac{2(h_R - h_S)}{\left(\sin^2\theta + \dfrac{2(h_R - h_S)}{R_e}\right)^{0,5}} & \theta < 5^o \end{cases}$$

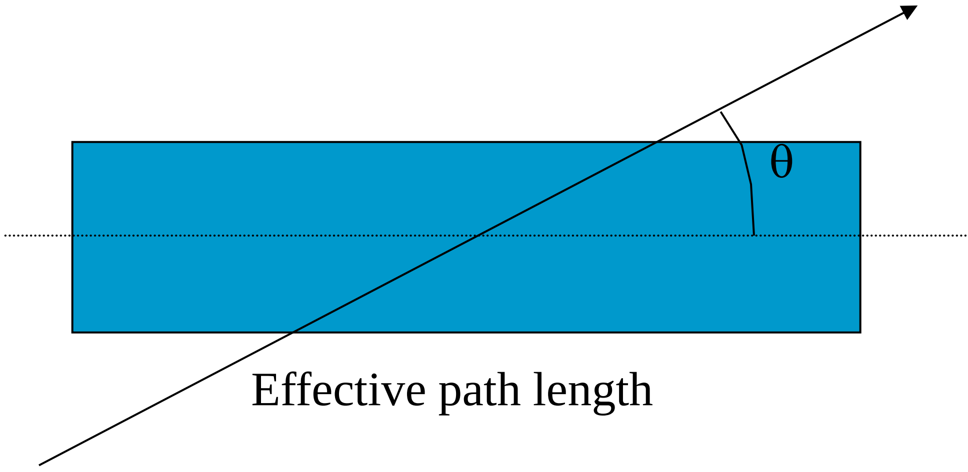
3: Horizontal length

$L_G = L_S \cos\theta$

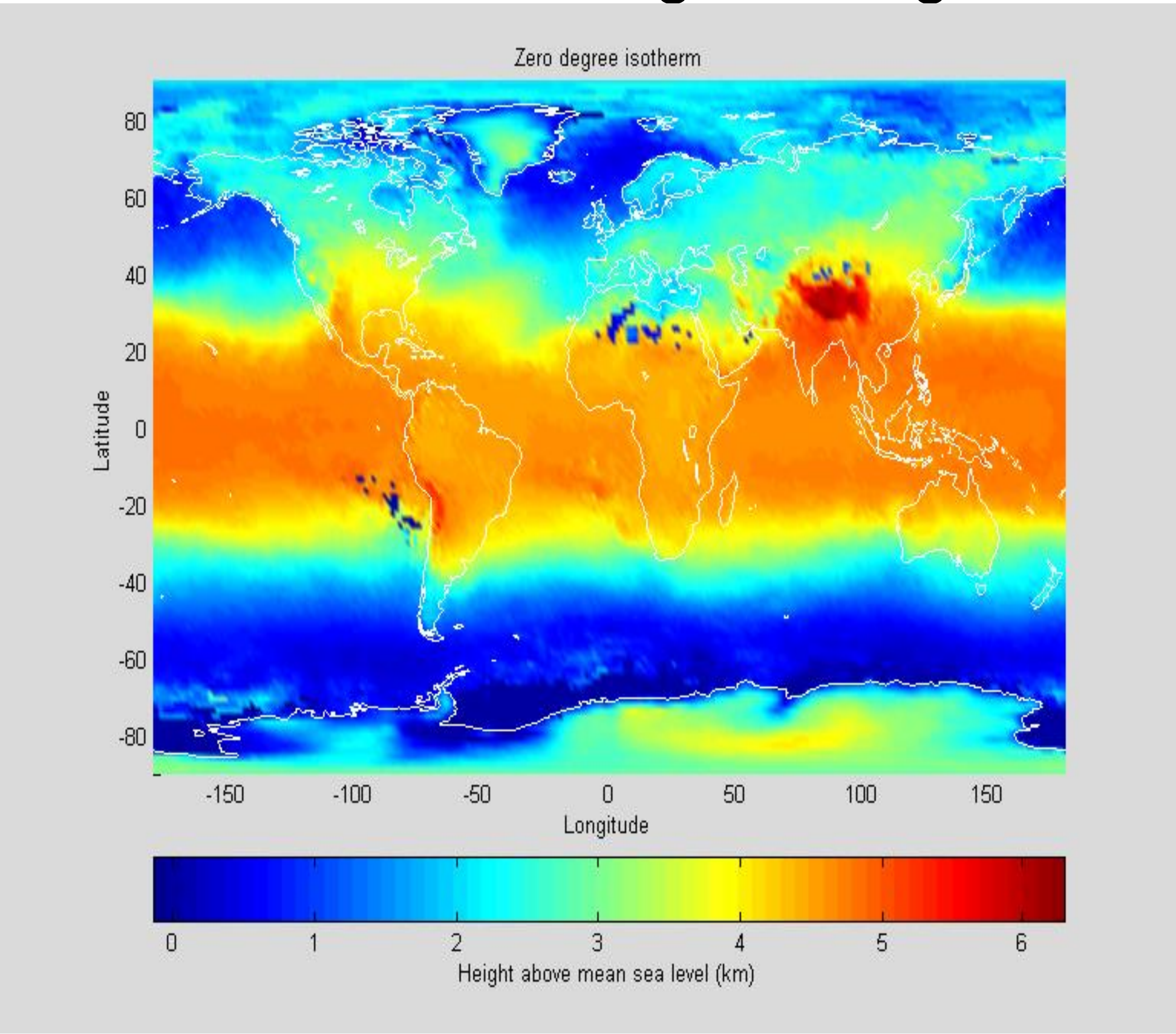
is used as the effective path length.
The rest is now as for terrestrial path where L_G is used in place of *d*.
Now also a vertical correction (ITU-R P.618).

Slant path approximation



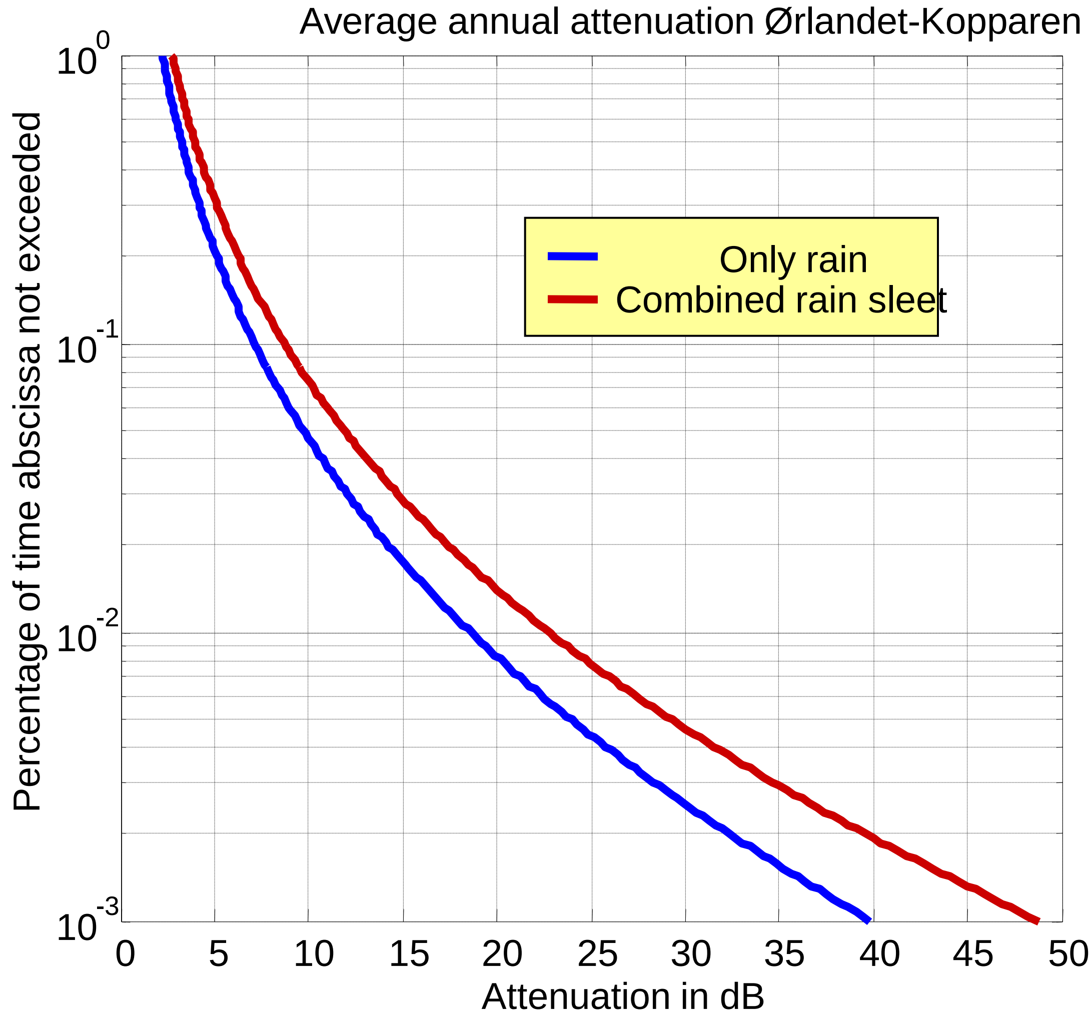


Median zero-degree height



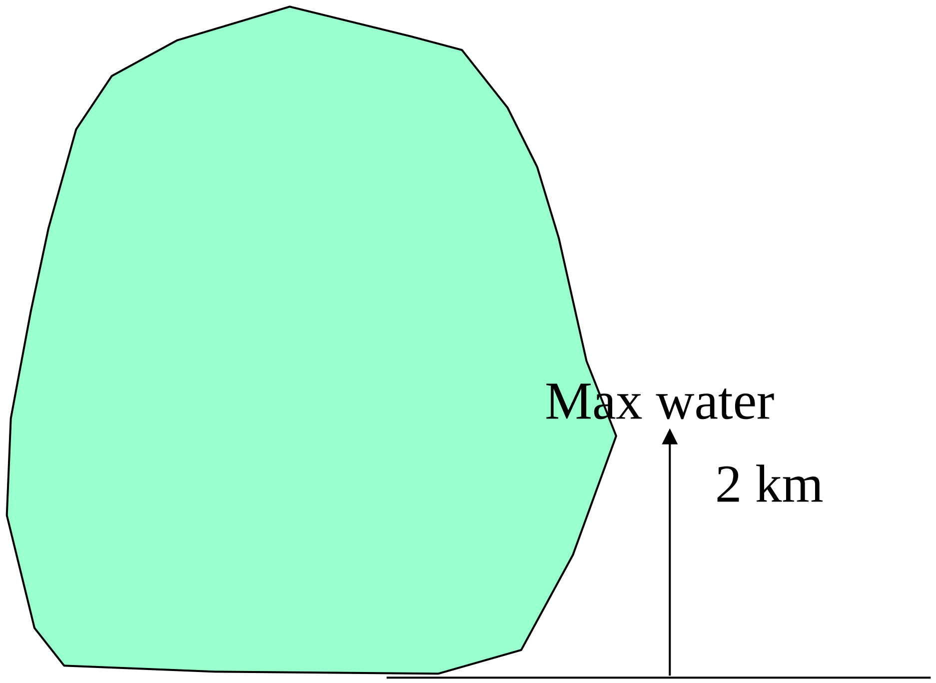
Combined rain sleet example

18 GHz, 15.6 km, vertical polarisation



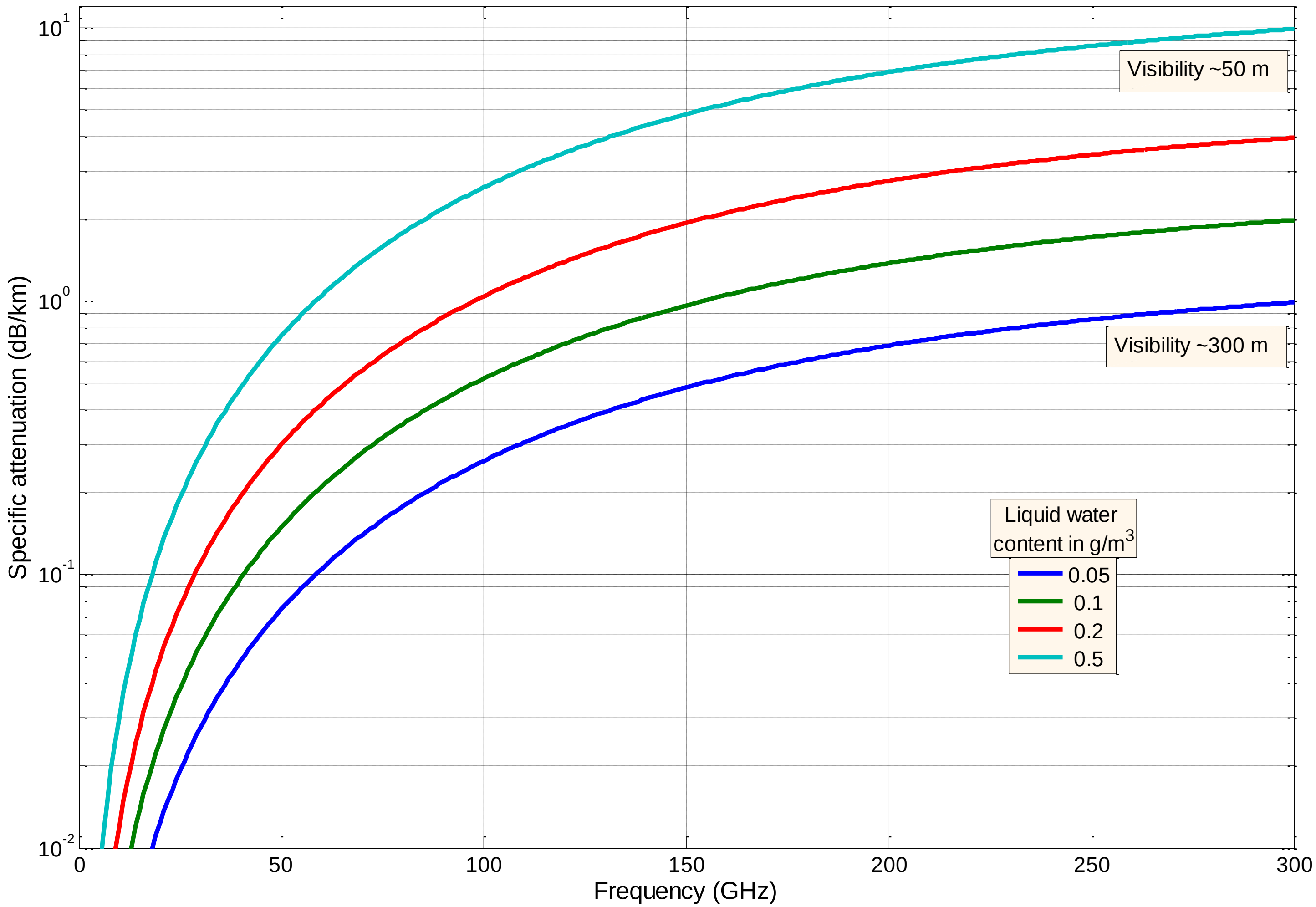
Fog and clouds

Non-precipitating clouds contain water as well. Below 100 GHz little influence. Too little water for absorption and too small particles for scattering.



	Small clouds	**Large clouds**
g/m^3	0.5	2
D μm	3-30	10-15

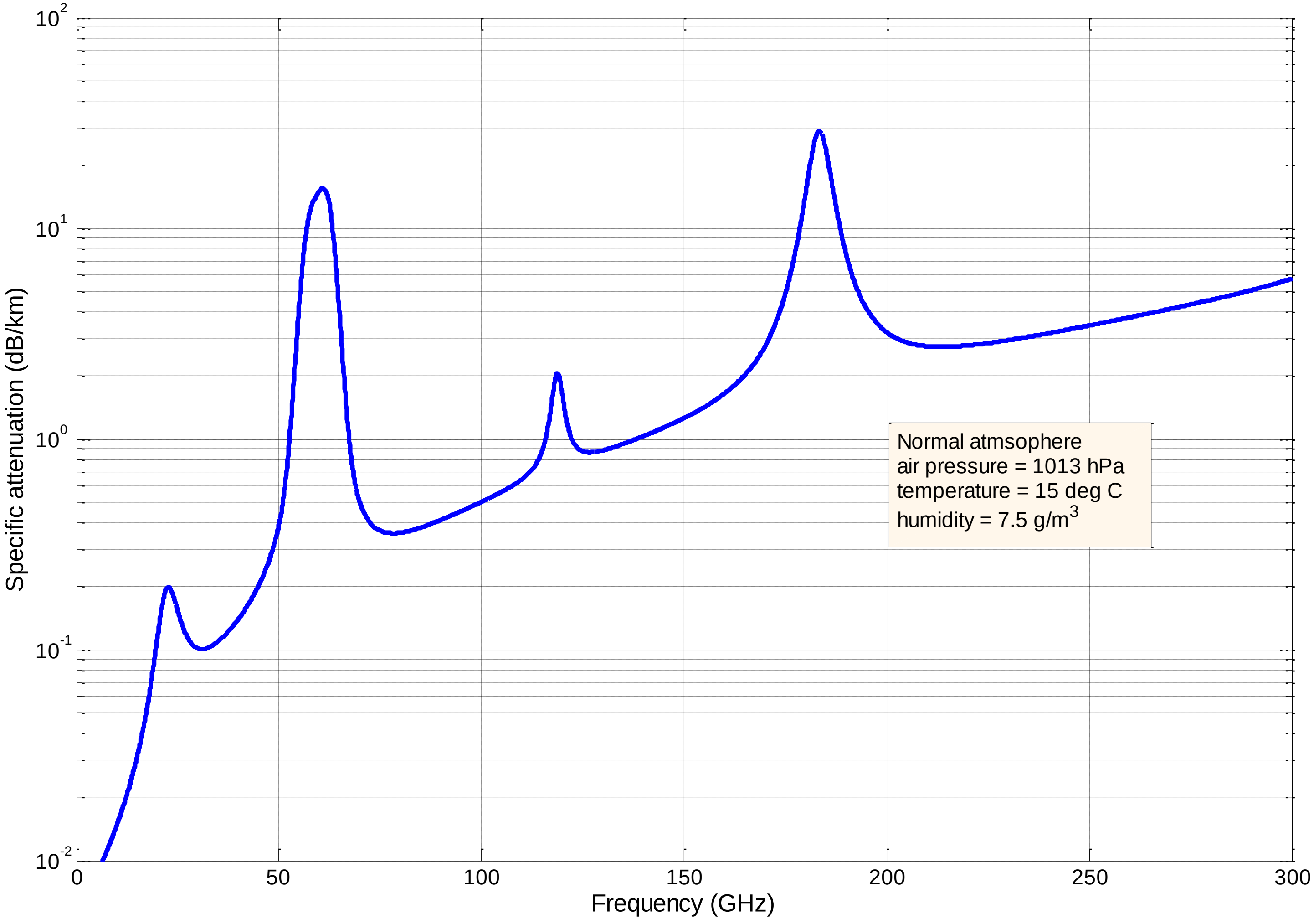
Attenuation due to clouds and fog



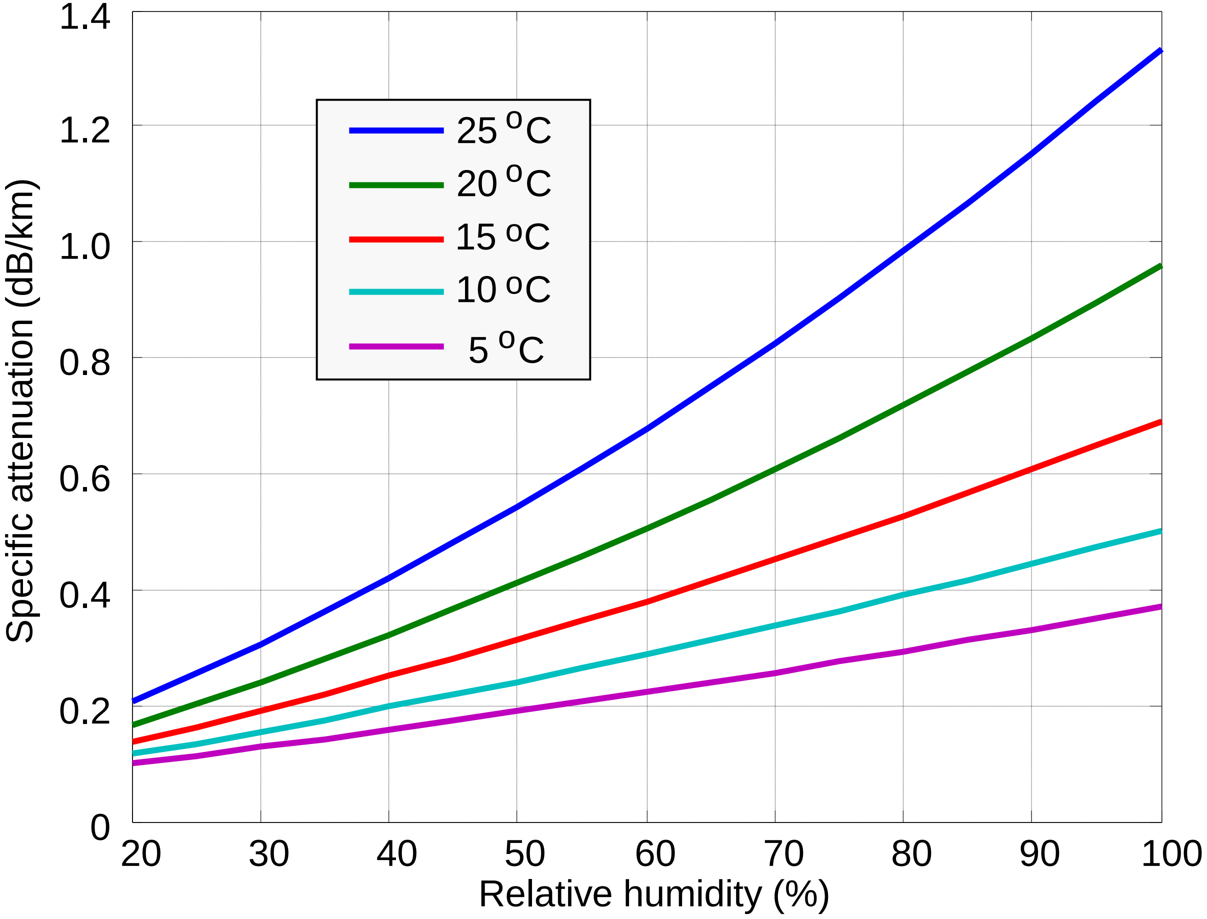
Gaseous absorption

- Oxygen
  Oxygen has permanent magnetic dipole moment caused by electron spin (electrons in pairs).
  A change of the electron spin orientation related to rotational angle moment give a number of absorption lines near
  60 GHz and a single line at 119 GHz
- Water vapour
  The water vapour molecule has a permanent electric dipole moment and a rotation of the molecule under the exposure of an electric field give absorption lines at 22, 183 and 325 GHz.

Specific gaseous absorption, 0-300 GHz

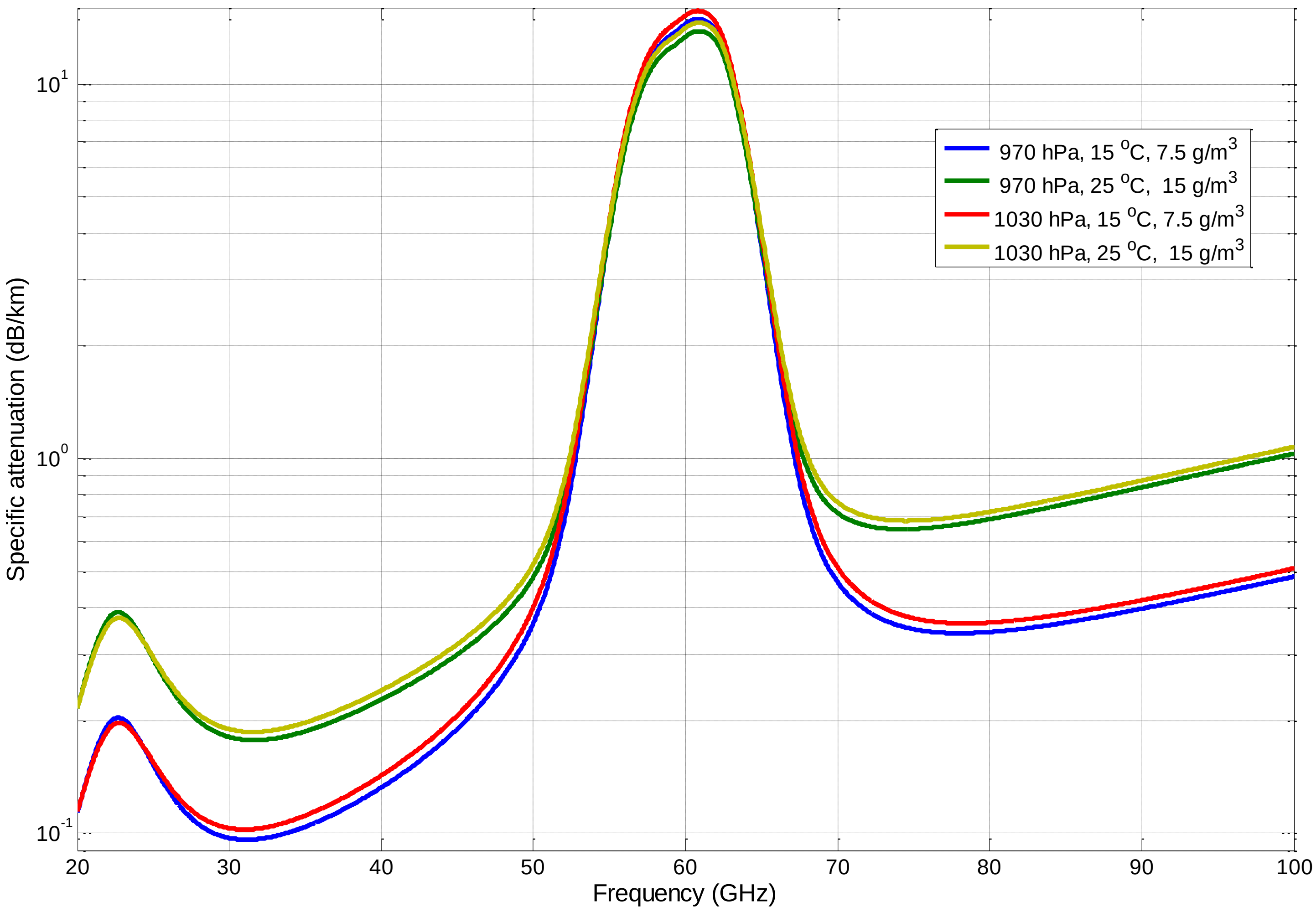


Specific gaseous attenuation at 83.5 GHz

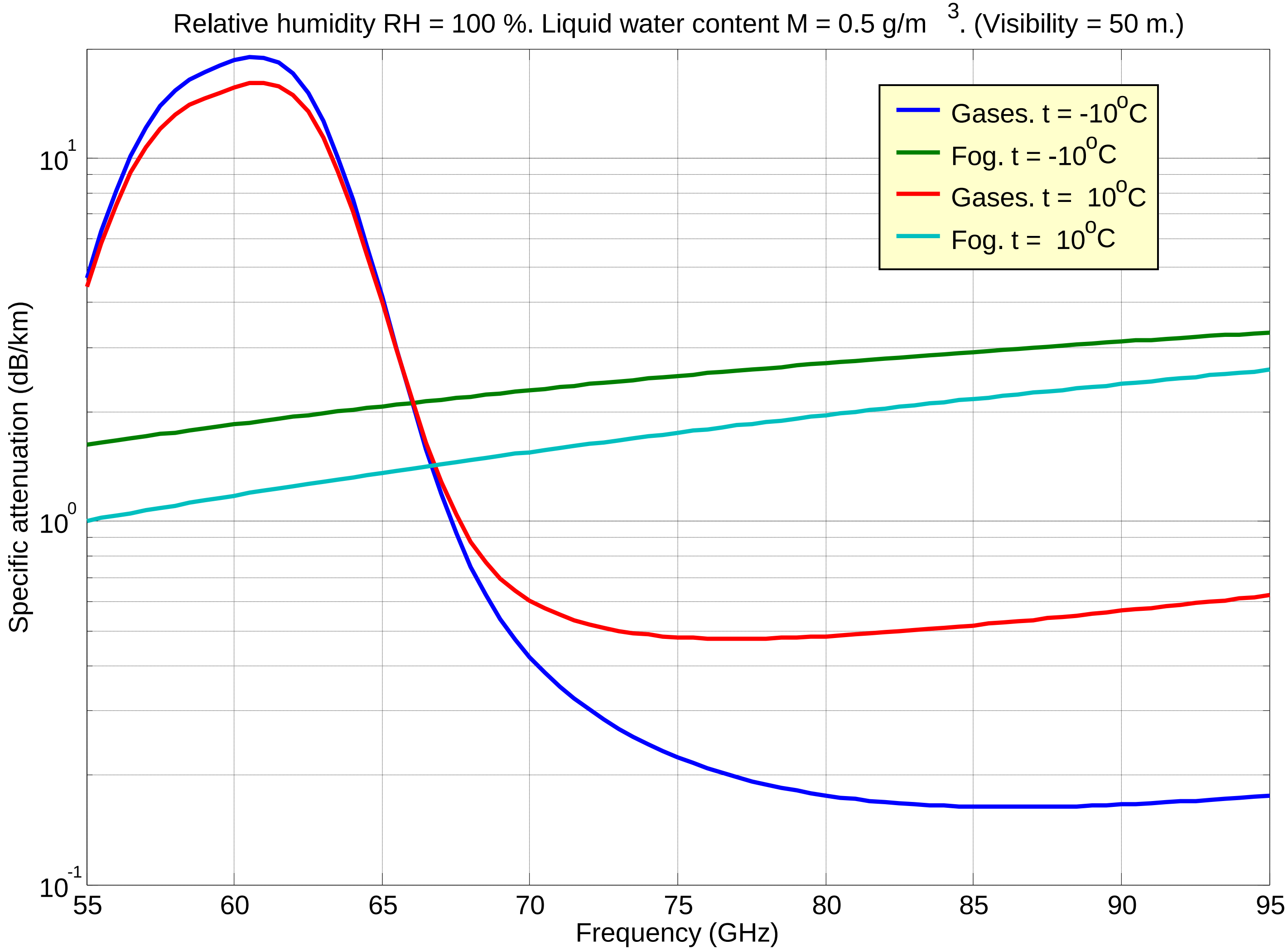


p = 1013 hPa
f = 83.5 GHz.

Gaseous absorption for varying atmosphere



Gaseous and fog/cloud attenuation: two cases for the same air pressure and humidity



Refraction and absorption

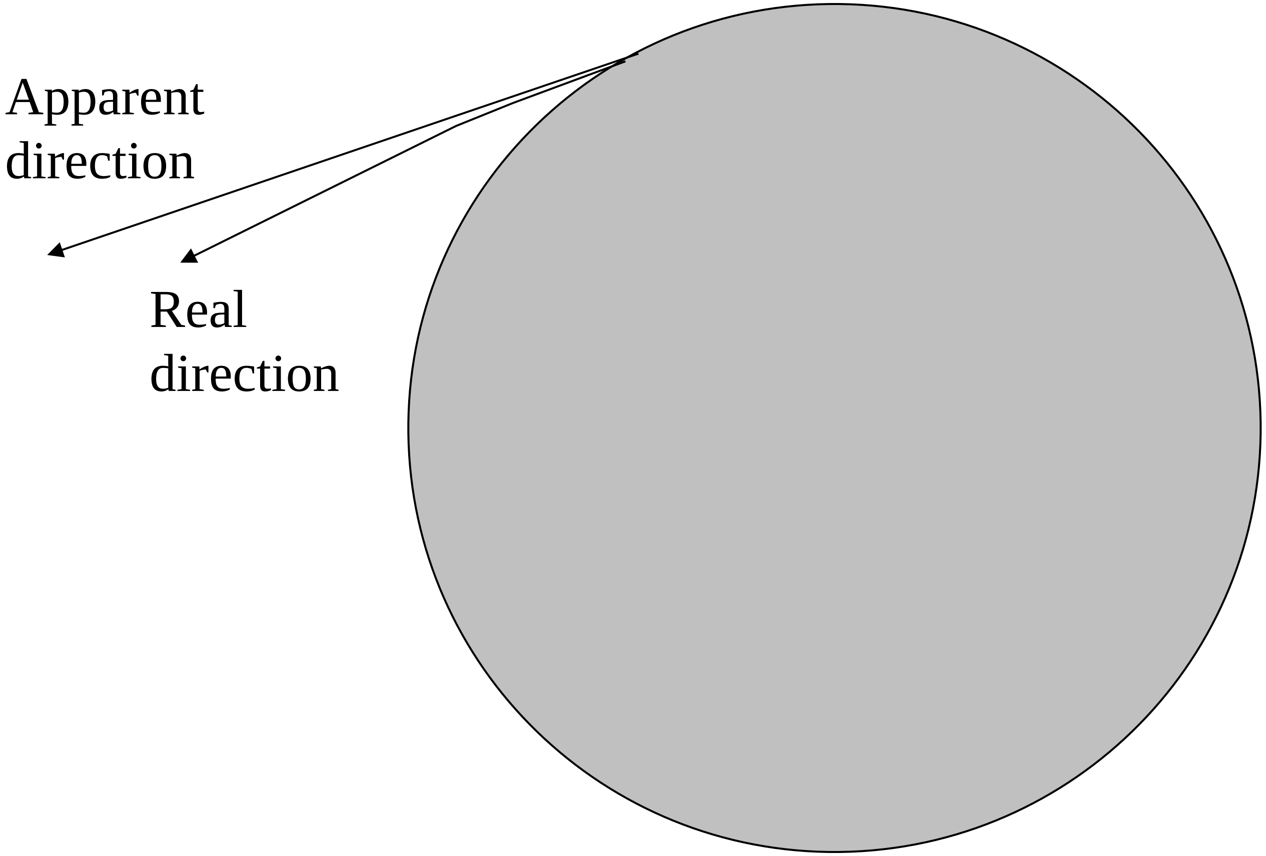
Unified view using complex refractive index:

$$n(\mathbf{r}) = \mathrm{Re}(n(\mathbf{r})) + j\,\mathrm{Im}(n(\mathbf{r}))$$

$$\mathbf{E}(\mathbf{r},t) = E_0 e^{j[\mathrm{Re}(n(\mathbf{r}))\mathbf{k}_0\cdot\mathbf{r}-\omega t]} e^{-\mathrm{Im}(n(\mathbf{r}))\mathbf{k}_0\cdot\mathbf{r}}$$

Result in reduction of *E*
exponentially with distance r

Tropospheric refraction

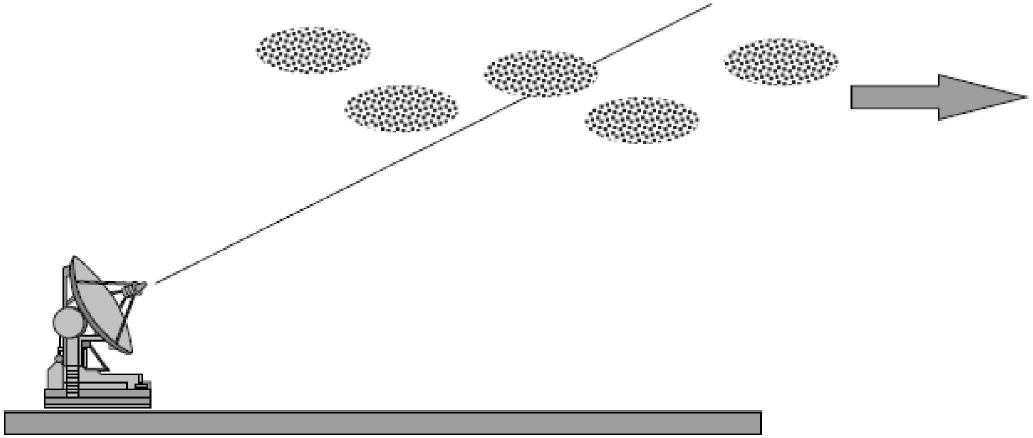


Turbulence

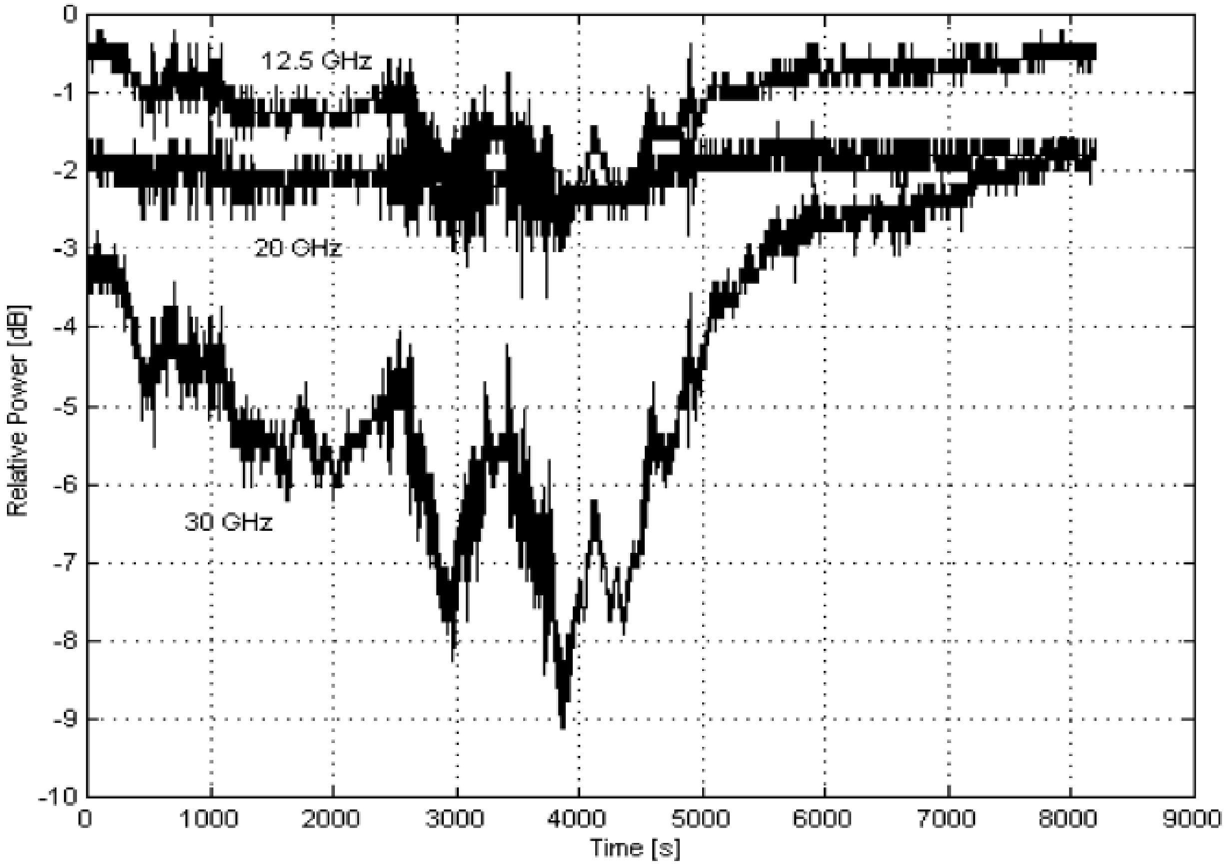
- Small scale non-regular air areas.
- Such areas start with forces between to different moving air layers of about 100 m in size. These produce smaller and smaller areas down to mm size.
- Influence radio waves:
  - Scintillation, rapid signal variations
  - Scattering such that part of the signal is spread to all directions (Creates the possibility of communication far beyond the horizon)

Propagation through turbulence

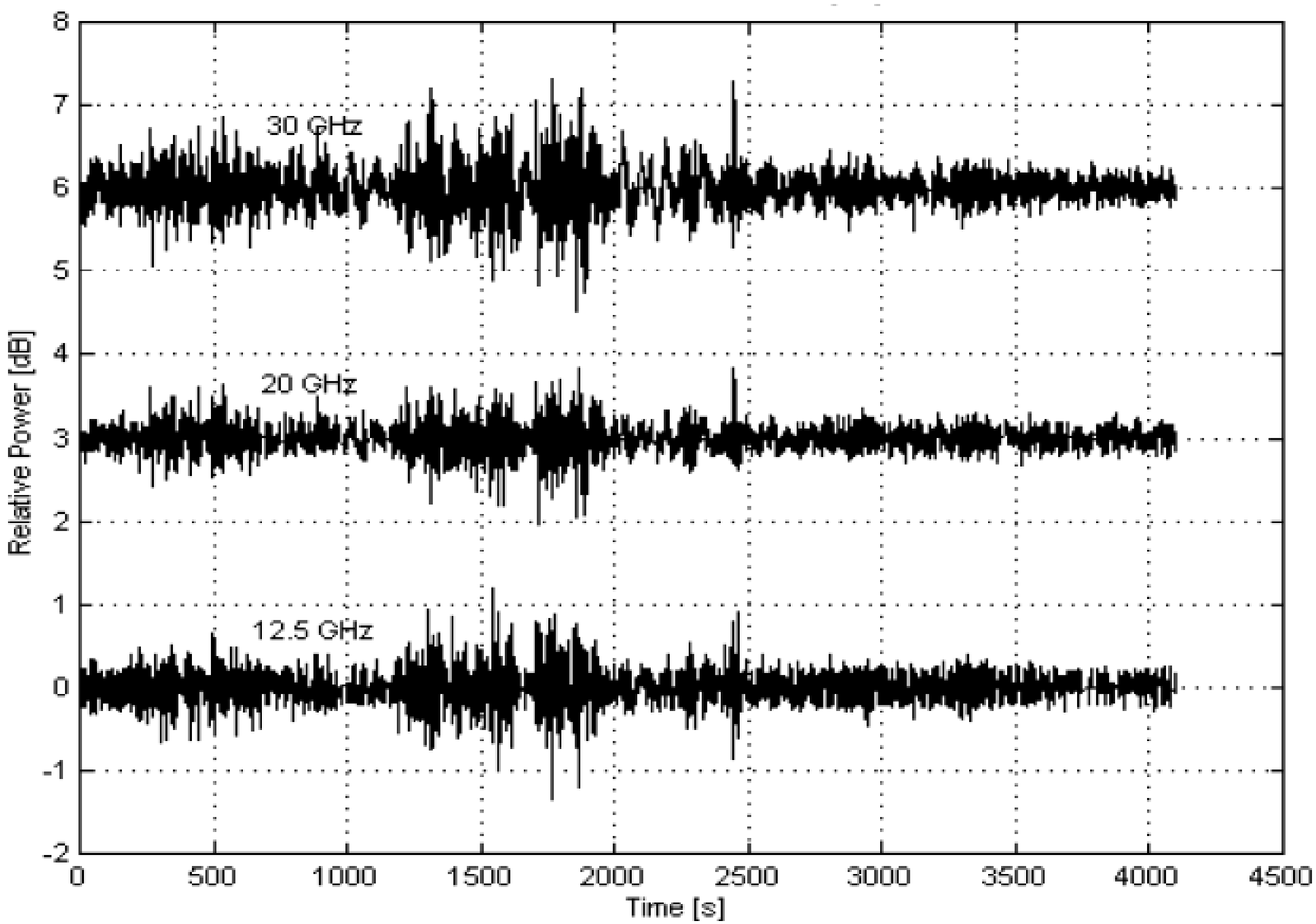
Small scale variability of refractive index in the air



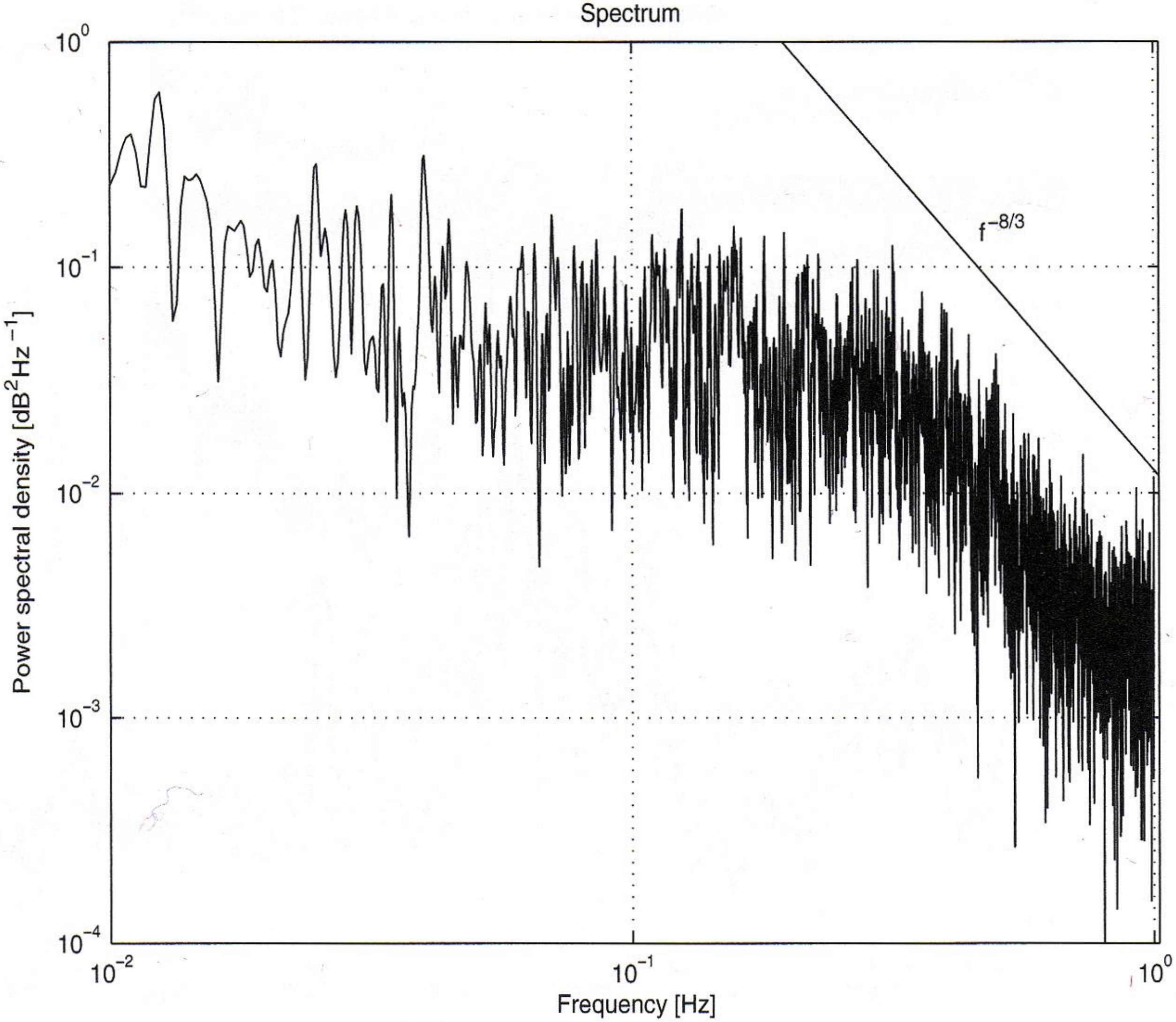
Scintillation, measured data



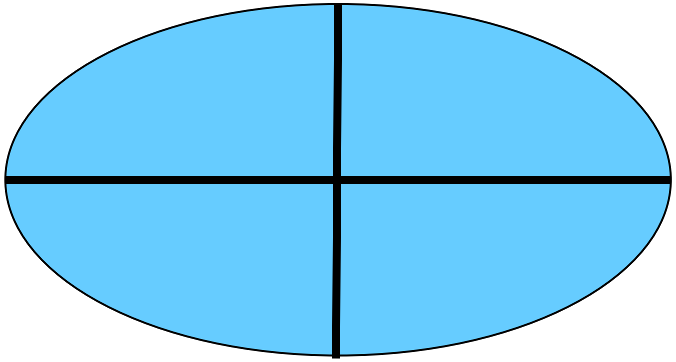
Scintillation, high pass filter



Power spectral density, example at 20 GHz



Depolarisation under rainfall

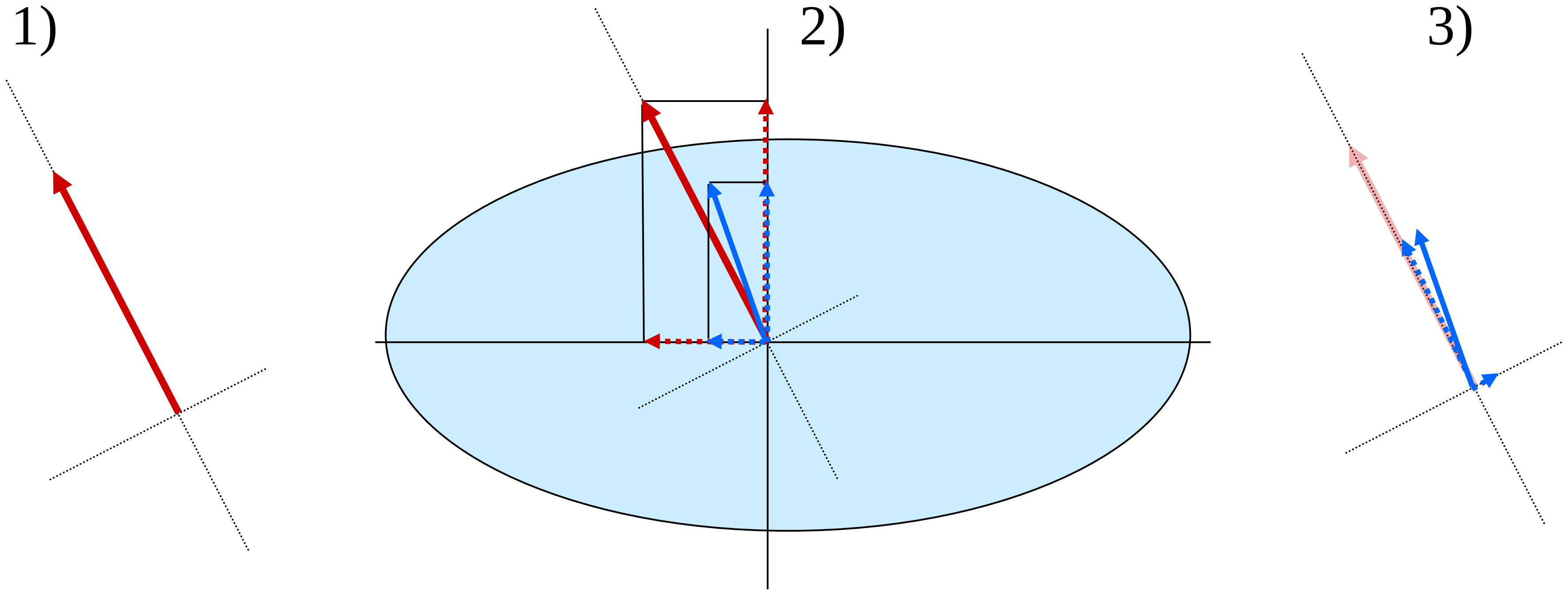


Raindrops become flat with size.

Drop diameter mm	small/large axis
2	0.92
4	0.82
6	0.65

Depolarisation mechanism

Rain drops attenuate
the wave differently:

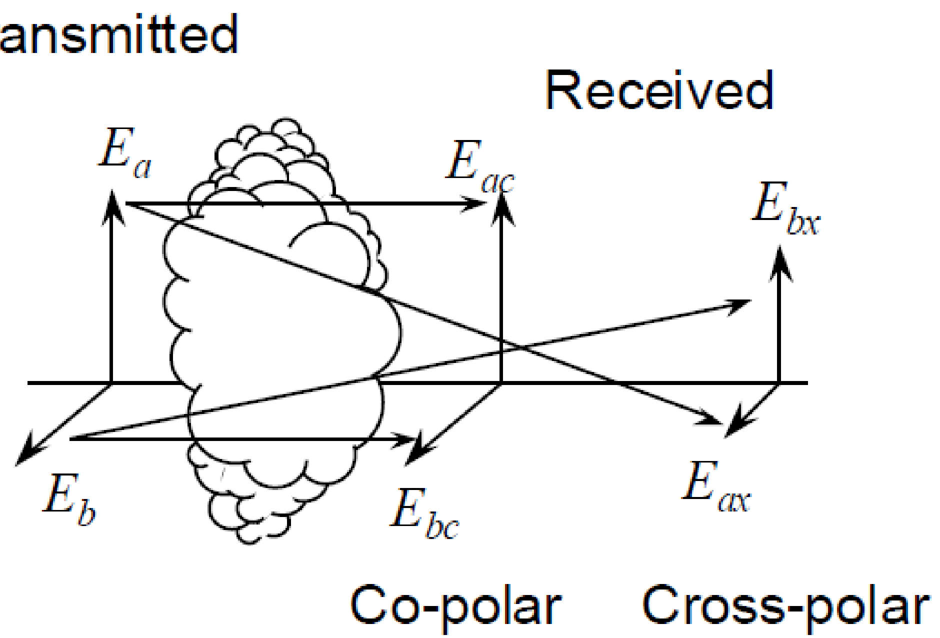


Cross polar discrimination (XPD) and cross polar isolation (XPI)

$$XPD = 20\log\frac{E_{ac}}{E_{ax}}$$

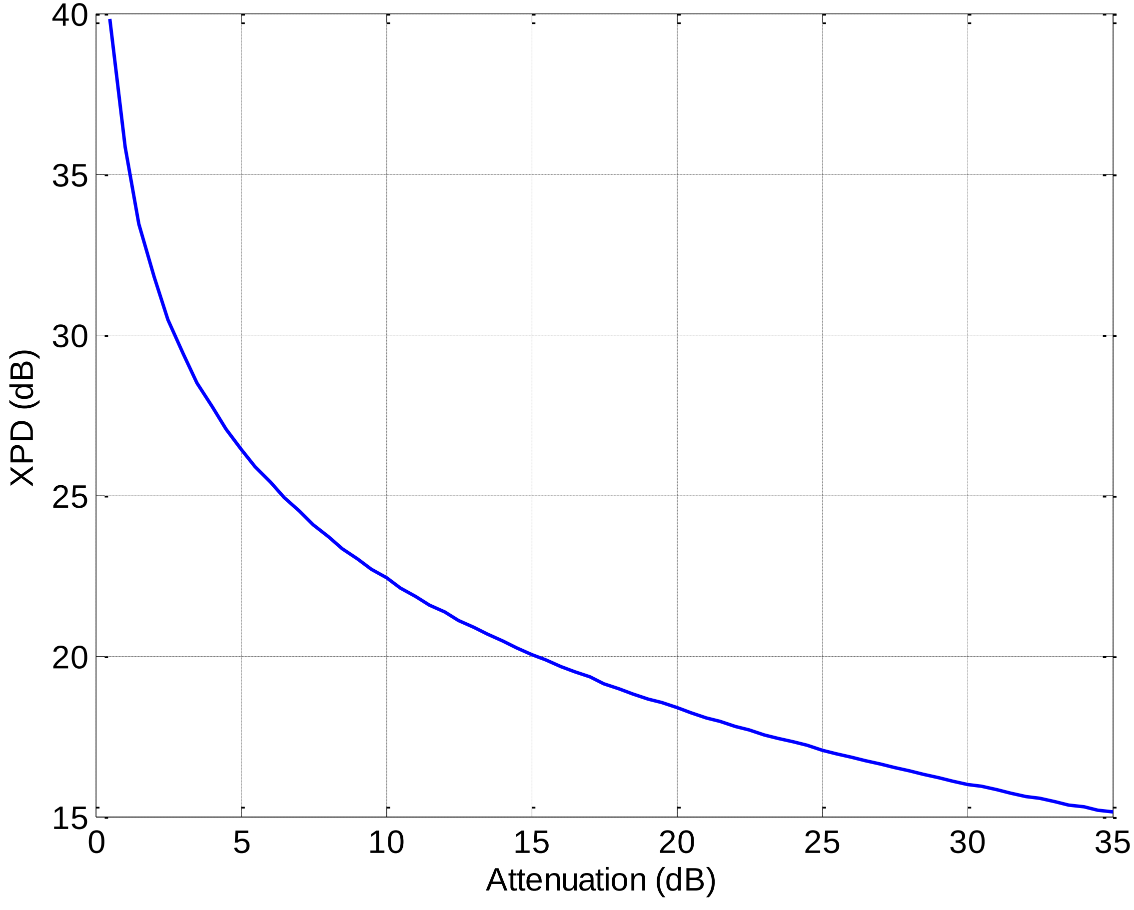
$$XPI = 20\log\frac{E_{ac}}{E_{bx}}$$

where E is given



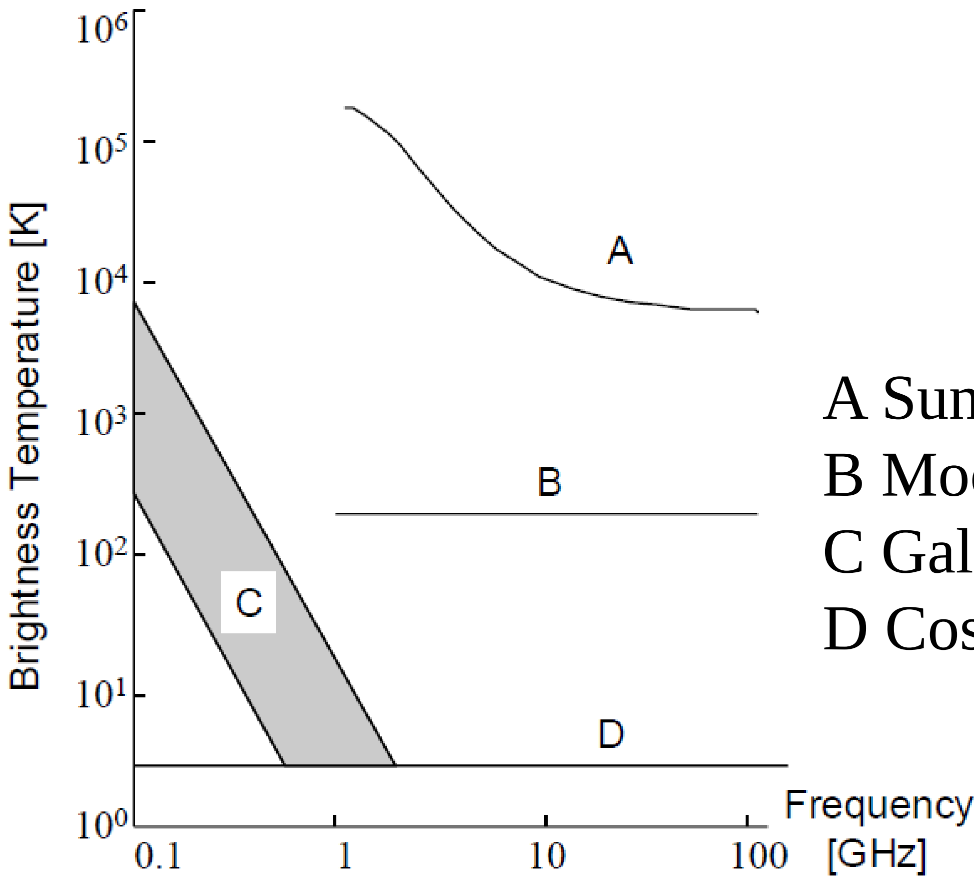
Cross polar discrimination model

The loss is L (dB), then $XPD = a - b\log L$ dB



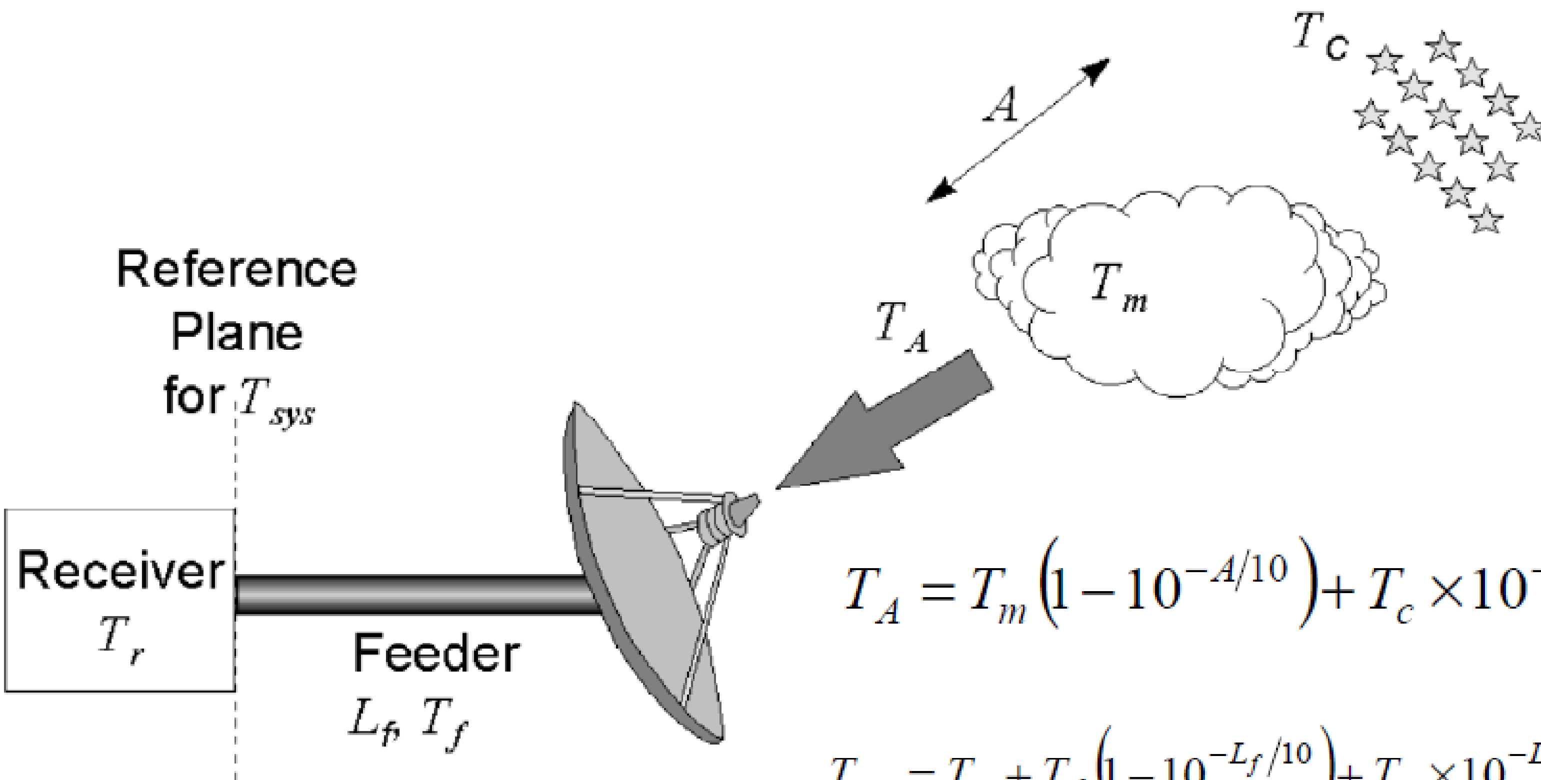
a=35.8
b=13.4
NASA ref. for
10 GHz

Extraterrestrial noise sources



A Sun
B Moon
C Galactic
D Cosmic

Combining noise sources

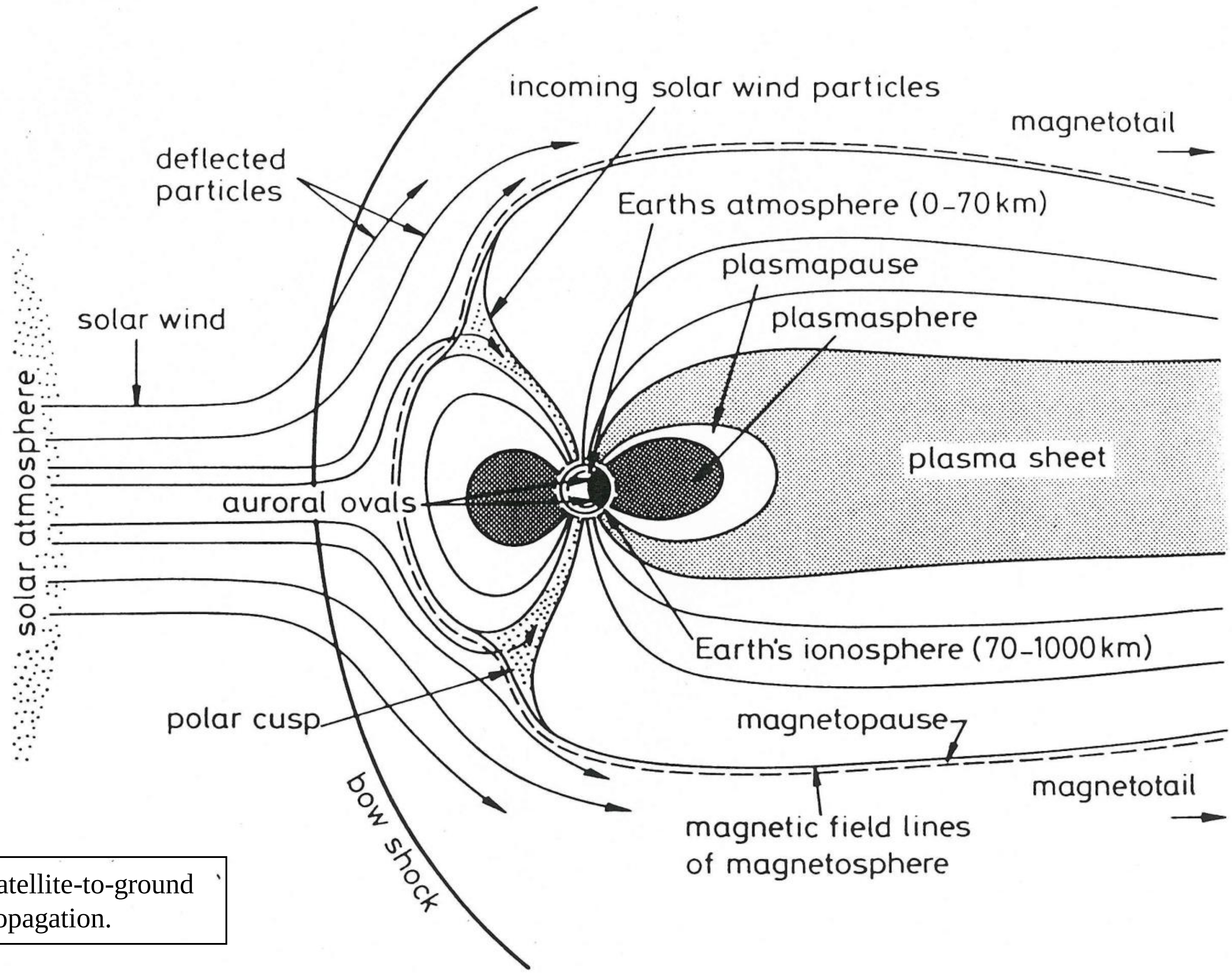


$$T_A = T_m\left(1 - 10^{-A/10}\right) + T_c \times 10^{-A/10}$$

$$T_{sys} = T_R + T_f\left(1 - 10^{-L_f/10}\right) + T_A \times 10^{-L_f/10}$$


(c) Dennis C. Anderson

Ionosphere

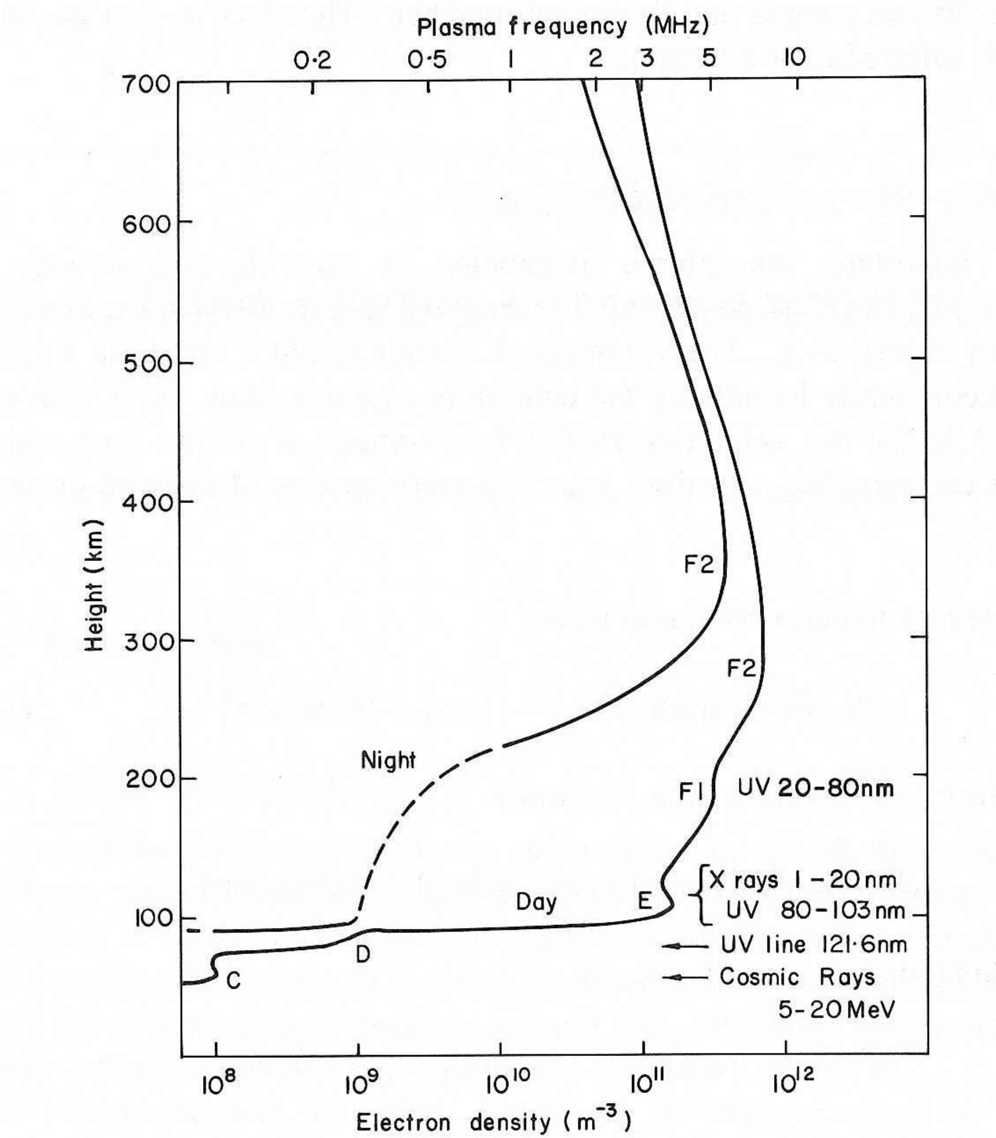


J E Allnutt. Satellite-to-ground radiowave propagation.

Characteristic of the ionosphere characteristic

- The ionosphere is a medium where the electrons and ions are free,
  i.e., a plasma
- Production of free electrons due to
  - UV and x-ray
  - Particles from the sun
  - Meteors
- Electrons interact with radiowaves
- Ionosphere named in layers: D, E, F (F1 og F2)
  First talked about a electron layer – an E-layer, but then obtained more information. However, it is more continuous and not separated layers.
  D: 55-95 km, only at day-time 10^9 electron/m^3
  E: 95-150 km, $\sim 10^{11}$ electron/m^3 (day), $\sim 3{,}5 \cdot 10^{10}$ electron/m^3 (night)
  F: > 150 km, 10^{12} electron/m3 (day), $\sim 5 \cdot 10^{10}$ electron/m^3 (night)

Typical electron density as a function of height



Source: Hall, Barclay, and Hewitt: Propagation of radiowaves

Transmission through the ionosphere, Faraday rotation

Faraday rotation is the rotation of a linear polarised wave. Perhaps helpful: Different propagation time for decomposed circular orthogonal polarisations give change of polarisation plan or angle for a linear polarised signal. For frequencies above 10 GHz the angle is small.

$$\phi = \frac{2.36 \cdot 10^{20}}{f^2} B_{av} N_T$$

$$N_T = \int_0^{r_T} N(r) dr \quad \text{electrons/m}^2$$

$B_{av} = \mu H_{av}$, is the average magnetic field of the Earth in Weber per m^{-2}, typical $7 \cdot 10^{-21}$ Wbm^{-2}, f the frequency in Hz

N_T is total electron content (TEC) per m^2 (total number of electrons in a vertical column with 1m^2 cross section), varies from 10^{16} to 10^{19} electrons/m^2.

Reason for circular polarisation often used.

Transmission through the ionosphere, group delay

Propagation time (e.g., extra propagation length Δr) where f is in Hz and N_T is the total electron content. The integral is called total electron content (TEC), about $30 \cdot 10^{18}$ electrons. Bandwidth is reduced for small f. Delay t in s.

$$\Delta r = \frac{40.3}{f^2} N_T$$

$$t = \frac{40.3}{cf^2} N_T$$

Variation in apparent path length has an impact on accuracy of satellite positioning systems. Can be compensated measuring it at several frequencies.

Transmission through the ionosphere, dispersion

The group delay is frequency dependent, dispersive.

$$\frac{dt}{df} = -\frac{80.6}{cf^3} N_T$$

$$\Delta t = -\frac{80.6}{cf^2} \Delta f N_T$$

Ionospheric scintillation

Usually small, but can become large in particular at geomagnetic equator and polar areas (northern light). The cause is the varying number of electrons along the path.

Conclusions tropospheric and ionospheric effects

- Troposphere
  - Precipitation attenuation (water, sleet, snow)
  - Scattering, depolarisation, refraction
  - Gaseous absorption
  - Scintillation
- Ionosphere
  - Total electronic content
  - Faraday rotation
  - Scintillation
  - Refraction