IMPLEMENTATION OF RAIN AND GASEOUS ATTENUATION MODELS FOR 26-30 GHz KA-BAND COMMUNICATION

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ABSTRACT

Analyses have shown that there is an increasing interest on Ka-Band usage for satellite missions. In addition to the usage of Ka-Band for a geostationary relay satellite there are already plans to install a Ka-Band terminal on the European module (Columbus) of ISS. An own Ka-Band antenna at Weilheim Ground Station of DLR (German Aerospace Center) assures a direct access to satellites using Ka-band and offers an opportunity to co-operate with international partners in a worldwide Ka-Band antenna network.

One of the responsibilities of DLR is to provide continuous and reliable high data rate links to/from spacecrafts and the ISS. Since the high data rate communication link is one of the initial requirements of future space missions, the Ka-band was decided to be used in near future for communications to a potential geostationary relay satellite. In addition to the geostationary mission it is envisaged to analyse the Ka-band usage for potential moon missions. This paper covers a study of Ka-band attenuation due to rain and atmospheric gases and implements the ITU model in Matlab code for Weilheim Ground Station.

KEY WORDS

Ka-band, ITU, rain and gaseous attenuation model

1. INTRODUCTION

Ka-band microwave propagation becomes very important issue due to increasing demand of new satellite-to-ground and ground-to-satellite links operating in this band. Ka-band frequencies have significant link advantage over widely used X-band because the higher frequency allows the spacecraft to focus the transmitted RF energy in a smaller beam. For the same spacecraft antenna size and transmitter output power, the potential link performance gain is equal to the frequency ratio squared, or about 12 dB. This advantage can translate to a higher data rate, smaller antenna size, lower mass, lower power consumptions on board, or a combination of these [1]. For this reason, two of these frequencies, namely 26 and 30

GHz, can be used for future lunar missions as well as future national and joint European missions, e.g. Small GEO, DEOS, Heinrich Herz. Ka-band was also selected for NASA's lunar mission and also being used for Deep Space Missions and planned for Earth Observation Missions.

However, high frequency signals have shorter wavelengths and are easily degraded by rain, clouds and other atmospheric effects. Many experiments have been carried out worldwide to study these effects and many papers have been written to deal with this problem. Unfortunately, for historical reasons, German Aerospace Center was not very active in Ka-band research before and never applied existing models in practice. Therefore, this study is undertaken in order to show the importance of such analysis for Ka-band link design. In this work, the ITU attenuation models have been studied, applied and implemented in order to support upcoming Ka-band missions of DLR, providing good results and Matlab codes.

2. OVERVIEW AND FUTURE UPGRADES OF WEILHEIM GROUND STATION AT DLR

Weilheim ground station was established by the German Aerospace Center (DLR) in 1968 at Weilheim. The station is a part of the German Space Operations Center (GSOC) ground infrastructure supporting German and international space missions.
The station illustrated on Fig. 2.1 is the heart for communication between Earth and satellites, which allows controlling spacecrafts and downloading the data during their passes.

The Weilheim Ground Station Complex consists of several spacecraft tracking stations (antennas) which provide support for space missions mainly in the S-band and Ku-band frequency ranges.

Presently there are no Ka-band antennas available at Weilheim ground station. But, there is a plan to build one in the near future. It is clear that Ka-band has many

advantages and this band will be one of the major means of satellite communications for the next 5-20 years.
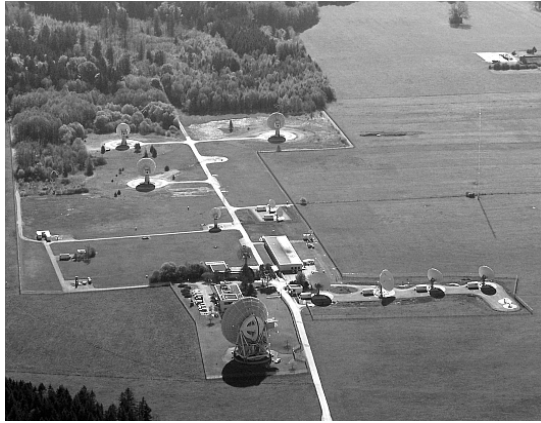

Figure 2.1 Weilheim Ground Station Complex [2]

Presently, this band is mostly unused and the majority of communication satellites operate in lower frequency bands (C- and Ku- bands). For future satellite communications, however, Ka-band is more desirable because its higher frequency allows wide bandwidth applications, smaller ground station and spacecraft components, and stronger signal strength. Typical bandwidth values for different frequencies are illustrated on the Fig. 2.2. Ka-band is the first frequency with enough bandwidth available to carry simultaneous services ranging from multiple voice communications, high data rate computer connections and teleconferencing.

With the same antenna size and power, and the same tracking time, a Ka-band mission can return four times more data than a comparable X-band mission.
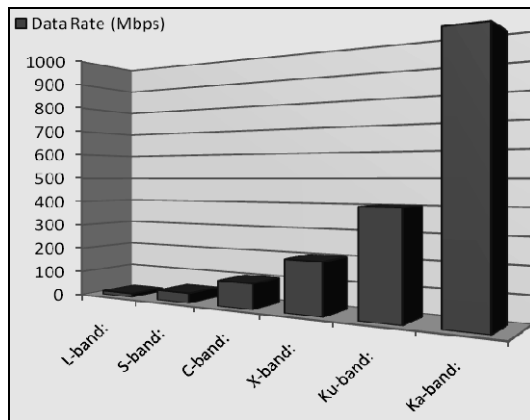

Figure 2.2 Typical values of data rate vs. bandwidth

3. RADIO WAVE PROPAGATION AT 26-30 GHZ

High frequency signals also mean short wavelengths. The millimeter wavelength Ka-band signals are easily degraded by rain, a problem known as rain attenuation. These high frequencies are affected by number of factors,

which in the end reduce the availability and reliability of the link.

3.1 Propagation theory and Friis equation

The well known Friis Equation is used to estimate distance related to free space loss:

$$P_r = \frac{P_t G_t A_r}{4\pi d^2} = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 = \frac{P_t G_t G_r}{L_{FS}} \qquad (1)$$

Where:

P_r, P_t - received and transmitted power respectively

G_r, G_t - Rx and Tx antenna gain respectively

A_r - effective area of receiving antenna $(\lambda^2 G_r / 4\pi)$

L_{FS} - free space loss $(4\pi d / \lambda)^2$

λ - wavelength of radio wave

d - distance between receiver and transmitter

The same equation can be represented in decibels (dB) as follows:

$$P_r = P_t + G_t + G_r - L_{SF} \qquad (2)$$

and

$$L_{SF} = 92.42 + 20\log f + 20\log d \qquad (3)$$

where:

f − frequency in GHz and d - distance in kilometers

Carrying out the analysis for Ka-band propagation, we have to consider atmospheric losses which occur due to signal attenuation in these frequencies. As [3] suggests, it is necessary to introduce a modification into the Friis equation.

The modified Friis equation is given as follows:

$$P_r = \frac{P_t G_t A_r}{4\pi d L_a} = \frac{P_t G_t G}{L_a} {}_r \left(\frac{\lambda}{4\pi d}\right)^2 = \frac{P_t G_t G_r}{L_{FS} L_a} \qquad (4)$$

Or, again in decibels (dB) representation:

$$P_r = P_t + G_t + G_r - (L_{FS} + L_a) \qquad (5)$$

where L_a is a complicated loss term due to atmospheric gas absorption, rain, fog/cloud, scintillation/multipath, and other atmospheric effects. This term is usually negligible at lower frequency bands, but is not neglected at higher frequency bands. The term is dependent on weather condition (percentage of time) and radio wave frequencies (increases with increasing frequency). Since the Weilheim ground station complex was never operated

in these frequency bands, this research will be dedicated to study this term, which includes all contributions from atmospheric absorption, clouds, fog, precipitation and scintillation.

3.2 The atmosphere as a propagation environment

The transmission of a satellite signal occurs almost in a free space conditions (more than 97% of a slant path in case of geostationary satellite and 99.9% in case of Earth-Moon communication). The problem of receiving a radio frequency signal, between two antennas separated by atmosphere, is in principle simple, but in practice is complicated. The frequency band and the weather conditions play the important role in such communication networks. [4]

If we had only a free space environment, then the radio wave would only obey Friis equation according to which the signal will decrease in intensity with the inverse square of distance. The power detected by the receiver will depend on the gains of the two antennas, the transmitted power level, and the transmitter to receiver distance. Provided that there is no powerful radio source, such as the sun, within the main-lobe of the receiver's antenna, the signal to noise ratio, and thus achievable throughput per bandwidth, will depend only on the Friis equation and the noise performance of the receiver hardware. The data rate achieved across such a link will thus depend on the distance, antenna specifications, power output and quality of the receiver system. However, the "free space" model of radio propagation is very much a "best case scenario" and one which is not frequently encountered in daily operation, with the exception of trivial cases like microwave links between adjacent buildings.

In real life, satellite link design is a complicated engineering task, which introduces a number of interesting, often difficult to solve, obstacles in this process. These are the effects of refraction, scattering, and absorption in the natural environment. Propagation impairments produced by the troposphere are a limiting factor for the effective use of the 20/30 GHz frequency band.

The problems become acute for systems operating in the bands above 10 GHz, where radio links can be adversely affected by atmospheric gases (primarily oxygen and water vapor), rain, clouds, fog and scintillation. These conditions, when present alone or in combination on the Earth-space radio link, can cause uncontrolled variations in signal amplitude, phase, polarization, and angle of arrival which results in reduction in the quality of analog transmissions and an increase in the error rate of digital transmission.

There are two basic types of atmospheric losses in the atmosphere. There is an energy absorption by atmospheric gases which are always present in the atmosphere and weather-related gaseous losses. To distinguish between these two, the weather-related losses are referred as atmospheric attenuation (line A, Fig. 3.1) and the absorption losses (line B, Fig. 3.1), simply, as atmospheric absorption [5]. The value of atmospheric loss is strongly depended on operating frequency – this is shown on the Figure 3.1.

In the case of near 30 GHz frequencies, there are several losses that can be neglected. For example, the regular decrease of refractive index with height causes ray-bending and hence a defocusing effect at low angles of elevation.
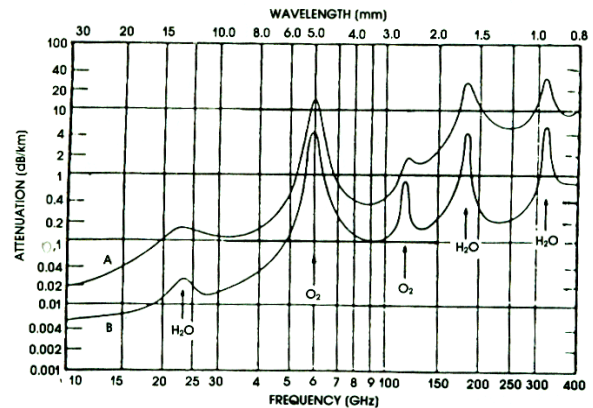

Figure 3.1 Frequency dependent attenuation of electromagnetic radiation in standard atmosphere (Dantor, 2006)

Since Weilheim ground station is based on 47.8º N and the future Ka-band station is planned to be operated on elevation angles above 5º, according to ITU recommendation, this effect can be neglected. The attenuation due to dust-storms can also be neglected at frequencies below 30 GHz [6]. At the frequencies below 60 GHz, the attenuation caused by frozen particles such as snow or ice crystals is very small and may be neglected as well [7]. The refraction is also small on elevation angles above 5º. Therefore, most of the tropospheric refractive effects can be neglected in this analysis. In the next paragraphs will discuss the losses which noticeably affect the proposed Ka-band link and therefore cannot be easily neglected – they include rain, gases, clouds and fog attenuations.

3.3 Implementation of ITU rain attenuation model

Since the ITU's rain attenuation model is widely used in satellite communication system design, it makes sense to implement the model for calculating rain attenuation at frequencies 11 to 100 GHz. For the simplicity of programming, the Matlab was chosen as a tool for model implementation. As described in the earlier paragraphs, the following parameters are used as inputs for the model:

- operating frequency (11-100), in GHz
- latitude of the Earth station, in degrees
- antenna elevation angle, in degrees
- rainfall rate, in mm/h
- ground station height above see level, in meters
- polarization of the transmitted/received signal

Other parameters are derived from the input, using different mathematical formulations as well as several databases (e.g. frequency and regression coefficients).

Using the implemented model, for a given system it is possible to predict attenuations for different availabilities. Rain availability is essentially the percentage of time that the available rain fade margin is not exceeded [7], or simply (100-Ap). For the planners of new system, the 99.9% availability performance is not of interest, since in our climate the attenuation can easily achieve the values of more than 15 dB at 99.9% which leads to huge and unpractical antenna designs. Figure 3.3 illustrates the results of rain attenuation prediction for different rain availabilities at 30 GHz at Weilheim region. As can be seen from the Fig. 3.2, rain attenuation is quite important figure to keep in mind when designing the link. For the availability of 97% there is 3 dB rain attenuation, which is still high for practical purposes. Considering that the downlink frequency is lower, the attenuation due to rain will also be lower than 3 dB.
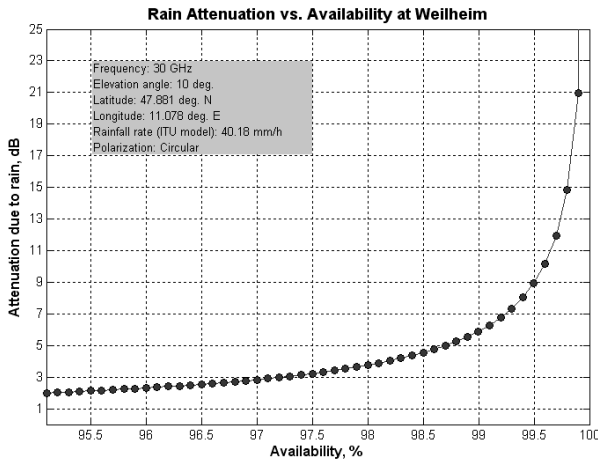

Figure 3.2 Rain attenuation vs. availability at Weilheim Ground Station at frequency 30 GHz and circular polarization.

The initial requirement for the link availability was 90%. However, for historical reasons, the ITU model [6] allows the analysis of the availabilities only up to 95%. In Figure 3.2, one can see the distribution of rain attenuation for different values of availability. During the analysis, it was also noticed that the polarization can affect the rain attenuation significantly. For example, vertically polarized waves are less affected by rain attenuation due to vertically elongated shape of most raindrops. This is shown as a comparison between vertical, horizontal and circular polarization on the Fig. 3.3. From the calculations and the zoomed image, it is clear that at 99.5%

availability, the difference between the attenuations of horizontally and vertically polarized waves is more than 1.5 dB. Since dependence of availability on rain attenuation is an exponential, the more significant difference is observed on higher rain availabilities.

On lower availabilities, the difference is not of much significance and is of about 0.5 dB and less. This is illustrated on Fig. 3.3. However, considering other additional attenuations due to gases, fog or clouds, the overall attenuation and the difference can reach significant values.
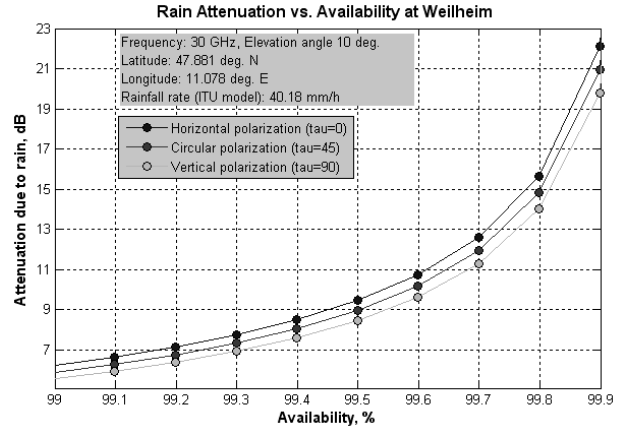

Figure 3.3 Zoomed signal polarization dependence of rain attenuation at Weilheim Ground Station Complex at frequency 30 GHz.

According to internal DLR documentation, the most projects have been done using circular polarization. In that case the difference becomes insignificant and can be omitted.

From the Fig. 3.4 we see 1.95 dB rain attenuation at 95% of availability. For the Small GEO mission, the elevation angle is fixed and is 35º.

Therefore the attenuation is about 0.9 dB. Once we got the rain attenuation value for the uplink (30 GHz), since the geometry of the system does not change, we are able to employ a frequency scaling method, to find the rain attenuation at downlink frequency (26 GHz) using [6]:

$$A_2 = A_1(\varphi_2 / \varphi_1)^{1-H} \qquad (6)$$

where:

$$\varphi(f) = \frac{f^2}{1 + 10^{-4} \cdot f^2} \qquad (7)$$

$$H(\varphi_1, \varphi_2, A_1) = 1.12 \cdot 10^{-3} (\varphi_2 / \varphi_1)^{0.5} (\varphi_1 A_1)^{0.55} \qquad (8)$$

The frequency scaling model from ITU [6] gives a quite good approximation of the attenuation for the 26 GHz downlink. As can be seen on the Figure 3.5, the lower frequency is less affected by rain attenuation and is

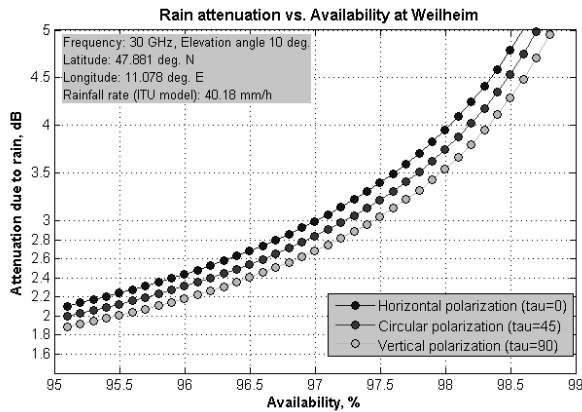approximately 1.4 dB at our downlink frequency at availability of 95%.

Figure 3.4 Signal polarization dependence of rain attenuation at Weilheim Ground Station Complex at frequency 30 GHz.

Finally, the ITU-R.P.618-8 model has been implemented in Matlab and the results were compared with the hand-based calculations, as well as with the calculations of other telecommunication experts of DLR. From the above figures the final attenuations for 30 and 26 GHz links can be observed.
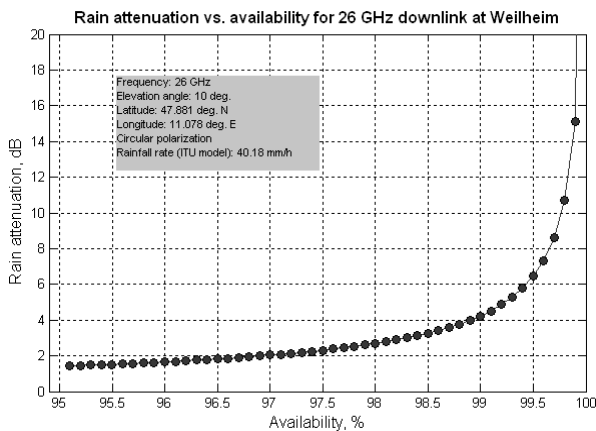

Figure 3.5 Rain attenuation at Weilheim Ground Station Complex obtained by frequency scaling model for 30 GHz.

These results will be one of the important inputs during the link budget calculations for different Ka-band missions.

3.3.1 Attenuation due to atmospheric gases

Attenuation by atmospheric gases depends on frequency, elevation angle, altitude above sea level and water vapor content. It is relatively small compared to rain attenuation. Below 10 GHz, attenuation due to atmospheric gases is less then 0.01 dB/km, while above 10 GHz, the attenuation starts to increase severely, especially for low elevation angles. Water vapor and oxygen are the main contributors to gaseous attenuation in the frequency range

below 30GHz with a maximum occurring at 22.5GHz. The attenuation due to oxygen absorption exhibits an almost constant behavior for different climatic conditions, whereas the attenuation due to water vapor varies with temperature and absolute humidity. [8]

The principal interaction mechanism between radio waves and gaseous constituents is molecular absorption from molecules. Accurate predictions of atmospheric attenuation can be determined using quantum physics and its absorption laws. Absorption attenuation of radio waves results from a quantum level change in the rotational energy of molecules. Spectral line absorption occurs when a quantized system, such as a molecule, interacts with an electromagnetic radiation field and makes a transition between two quantum states of the system. [9]

Two sources are available to provide predictions of attenuation due to gaseous absorption. They are the Liebe Complex Refractivity Model, and procedures developed by the ITU-R (ITU-R P.676-3, 1997). The ITU-R presents a detailed line-by-line summation of the spectral lines of water vapor and oxygen, which is similar to the Liebe method. An approximation to the line-by-line method is also provided by the ITU-R. Both the Liebe Complex Refractivity and the ITU-R models compute specific attenuation, in dB/km. Both models assume a stratified atmosphere and divide it into small layers, for which a description of the moisture (or humidity) content, temperature and barometric pressure is imposed on these layers. The specific attenuation is computed at these layers, and the total path attenuation is obtained by integrating the specific attenuation from the surface of the earth to a zenith height of 30 km typically. This integral gives the total path attenuation vertically, 90° perpendicular to the earth's surface, and is called the zenith attenuation. To obtain the gaseous absorption along the satellite path the zenith attenuation is scaled as a function of the elevation angle, measured relative to the local horizontal. The scaling is the cosecant of the elevation angle for angles between 10° and 90°. The barometric pressure, air temperature and humidity at various levels in the atmosphere are needed to compute specific attenuation [10].

The Liebe's Complex Refractivity Model is very accurate, but it is computationally expensive. Even the numerical algorithm (ITU's Line-by-line calculation) is computationally intensive and requires many efforts.

To provide a reasonably accurate estimate without the computational intensity, the ITU-R has a model to approximate the line-by-line calculation. The approximation model is provided in Recommendation ITU-R P.676-6 (2005).

This model provides predictions for frequencies from 1 to 350 GHz. The approximation introduces some departure from the line-by-line calculation. The agreement is to

within approximately ± 15 % on average at frequencies away from the centers of major absorption lines.

The input parameters required for the calculation are:
- frequency, f (GHz)
- pressure, p (hPa)
- air temperature, T (degrees ºC)
- water vapor density, ρ (g/m3).

First we calculate the specific attenuation for dry air (oxygen) and water vapor (H2O).

For dry air (oxygen) the specific attenuation γ_O (dB/km), for f ≤ 57 GHz, is given by:

$$\gamma_O = \left[\frac{7.27 r_t}{f^2 + 0.351 r_p^2 r_t^2} + \frac{7.5}{(f-5.7)^2 + 2.44 r_p^2 r_t^5} \right] \times$$

$$f^2 r_p^2 r_t^2 \cdot 10^{-3} \qquad (9)$$

The contribution of water vapor is given by γ_w (dB/km) which is:

$$\gamma_w = \left[\begin{array}{l} 3.27\times10^{-2} r_t + 1.67\times10^{-3}\frac{\rho r_t^7}{r_p} + 7.7\times10^{-4} f^{0.5} + \frac{3.79}{(f-22.235)^2 + 9.81 r_p^2 r_t} + \cdots \\ \frac{11.173 r_t}{(f-183.31)^2 + 11.85 r_p^2 r_t} + \frac{4.01 r_t}{(f-325.153)^2 + 10.44 r_p^2 r_t} \end{array} \right] f^2 \rho r_p r_t \times 10^{-4} \qquad (10)$$

where:

rp = p/1013
rt = 288/(273 + T)

Before proceeding further, some additional remarks about the input weather parameters are necessary. The parameters P, T and ρ are assumed to be referenced to the ground station. This is obtained using the recommendation ITU-R P.835-4 [11]. A small program has been written in Matlab which uses the formulation of this recommendation to calculate standard atmospheric conditions. For high latitudes (above 45º N), which is true for Weilheim station, the conditions are summarized in the Table 1. As [5] suggests, we will use the equivalent height (h$_0$ for oxygen, and h$_w$ for water vapour) instead of z. Equivalent height is based on an exponential atmosphere assumption specified by a scale height to describe the decay in density with altitude.

Table 1: Atmospheric conditions in Weilheim		
	Summer	Winter
Pressure, (hPa)	937.9	935.3
Temperature, (K)	283.7	258.3
Water vapor concentration, (g/m3)	7.13	1.24

It is a function of temperature, pressure and density. With the above clarification, we can now introduce the formula for the total zenith attenuation due to atmospheric gases:

$$A_{zen} = \gamma_0 h_0 + \gamma_w h_w \qquad (11)$$

For the dry air, the equivalent height (in kilometers) is given by:

$$h_0 = 6 \quad , \text{for } f < 50 \text{ GHz} \qquad (12)$$

The water vapour equivalent height for f ≤ 350 GHz is given as:

$$h_w = h_{w0}\left(1 + \frac{3}{(f-22.2)^2+5} + \frac{5}{(f-183.3)^2+6} + \frac{2.5}{(f-325.4)^2+4}\right) \qquad (13)$$

where:

$$h_{w0} = 1.6 + 0.001 \cdot (T-15) \cdot 1.6 \quad , \text{ km in clear weather}$$
$$h_{w0} = 2.1 + 0.01 \cdot (T-15) \cdot 2.1 \quad , \text{ km in rain}$$

Then, for space-to-ground or ground-to-space communication, the elevation angle dependence is also taken into account to find the total attenuation at elevation angle 10 ≤ θ ≤ 90 degrees:

$$A_{slant} = \frac{h_o \gamma_o + h_w \gamma_w}{\sin \theta} \quad \text{dB} \qquad (14)$$

3.3.2 Implementation of the gaseous attenuation model

The gaseous attenuation model was implemented in Matlab and the results are presented below.

For the Weilheim ground station with elevation angle of θ=10º, the Fig 3.6 shows the total gaseous attenuation for winter and summer seasons. As can be seen from the figure, there is a strong attenuation band centered around 22.5 GHz, which is due to absorption of the energy in this frequency by water vapor. Since, our system operates on 26 and 30 GHz, this jump is still affects the propagation of the signal.
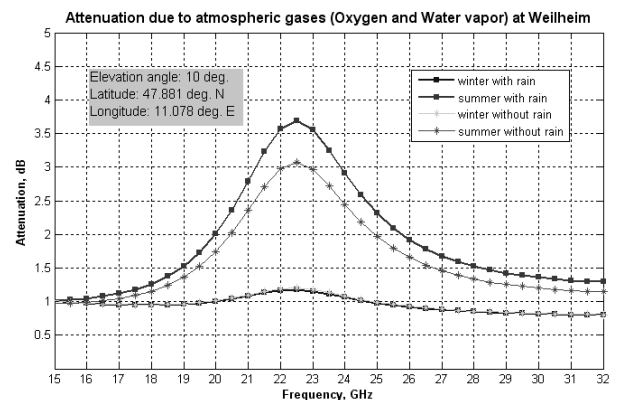

Figure 3.6 Season dependent gaseous attenuation at Weilheim Ground Station Complex

Here we can observe the big difference between the attenuations in different seasons and different weather conditions, which is mainly due to significant difference of water vapor content and temperatures.

For our analysis, the worst case has to be considered. Therefore we use the gaseous attenuation during the summer rain time. Its value is 1.92 dB at 26 GHz and 1.35 dB at 30 GHz.

3.3.3 Attenuation due to clouds and fog

Clouds (and fog) may be categorized generically as hydrosols - suspended droplets of liquid water, which are typically less than 0.1 mm in diameter. The attenuation caused by hydrosols becomes significant for systems operating above 20 GHz. This significance becomes more prominent with increasing frequency and decreasing elevation angle. Portion of clouds and fog that are frozen do not cause significant attenuation, but can cause a depolarization of the radio wave. There are two models which provide calculation of cloud attenuation which do not differentiate between clouds and fog though the inputs of typical values for each may be slightly different. The ITU recommendation provides model [12] to calculate the cloud and fog attenuation for a given probability value. In our case this value is 5%. It is valid for liquid water only and is applicable for systems operating at up to 200 GHz. Only three inputs are required:

- frequency (GHz),
- elevation angle (°),
- total columnar liquid water content of the cloud/fog (kg/m2).

The total attenuation within a cloud or fog (in dB) can be written as:

$$A_c = \frac{L_{5\%} \cdot K_l}{\sin \theta} \qquad (15)$$
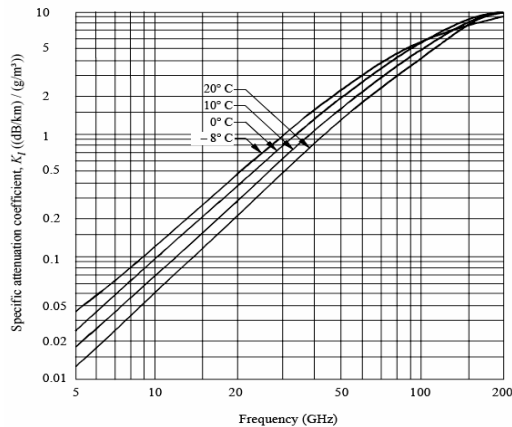
where:

Figure 3.7 Specific attenuation by water droplets at various temperatures as a function of frequency (ITU-R-P.840-3).

K_l : specific attenuation coefficient ((dB/km)/(g/m3))

$L_{5\%}$: total columnar liquid water content of the cloud/fog (kg/m2) exceeded for 5% of the year, given as 0.2 kg/m2 for Weilheim [12].

The specific attenuation coefficients for winter (-8ºC) and summer (10ºC) seasons at each frequency are given in the Fig. 3.7.

Substituting the values of specific attenuation coefficients and total columnar liquid water content of the cloud/fog into equation (3.31) yields the total attenuation due to clouds which is summarized in Table 2 below:

Table 2: Attenuation due to clouds and fog at Weilheim ground station for elevation angle 10º and probability of 5% (availability 95%)		
	Summer	Winter
Cloud attenuation at 26 GHz, dB	0.5	0.8
Cloud attenuation at 30 GHz, dB	0.7	1.1

As clearly seen from the results, the winter exhibits more extreme attenuation values due to lower temperature, and therefore this particular value has to be accounted during the link margin calculation as a worst case. Since, the calculations are not difficult, no model was implemented for this case.

3.3.4 Total attenuation due to atmospheric effects at Weilheim

In the previous paragraphs we considered several atmospheric effects, which have a strong influence at Ka-band communications. In particular, the calculations have been done for frequencies 26 GHz and 30 GHz, taking into account the weather conditions in Weilheim ground station or its surroundings. The model was also implemented. Using this model, any engineer can calculate attenuations due to atmospheric effects at Ka-band frequencies if the need arises. Of course, the results may differ from the real attenuation behavior due to the lack of exact onsite data and the approximate manner of the methods used in the analysis. However, these results must be sufficient for approximation of link margin in satellite communication networks operating at Ka-band.

The results of the total attenuation due to atmospheric effects for frequencies 26/30 GHz and elevation angle 10º are summarized for availability 95% in the Table 3 below:

Table 3: Total attenuation due to atmospheric effects at Weilheim		
Atmospheric effect	@26 GHz	@30 GHz
Attenuation due to rain	1.4 dB	1.95 dB
Attenuation due to atm. Gases	1.92 dB	1.35 dB
Attenuation due to clouds/fog	0.8 dB	1.1 dB
TOTAL attenuation	4.12 dB	4.4 dB

From the results, we see that even though, in general, attenuation is a function of frequency, e.g. the higher the frequency, the higher the attenuation, this principle does not work for gaseous attenuation. Since the gaseous attenuation is defined by peaks of absorption lines of water vapor and oxygen, it behaves differently from attenuations due to rain or clouds. Here the gaseous attenuation has a peak at 22.5 GHz which slowly reduces, but its slope is still not zero on the frequencies we did analyze.

In general, the above presented results comply quite well with the results of other groups (e.g. EADS) within 0.5 dB.

4. Conclusion

The ITU attenuation model has been implemented for Weilheim city in Germany. After the implementation, the results have been used for the link planning of German Moon mission and SmallGEO satellite. The advantage of this implementation is that DLR can use this code for planning any Earth-to-space and space-to-Earth communication links at frequencies 26-30 GHz. Due to the different weather and geographical conditions, this implementation is valid only for Weilheim ground station. It is not recommended to use this tool for calibration and ranging, since the precision of ITU model may not be sufficient. However one can use this tool for Ka-band link planning. Our future work will be based on experimental data and will also include radiometer and satellite beacon measurements. This will allow more precise link planning and calibration in the future.

Acknowledgements

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