Satellite signal attenuation due to atmospheric influences in northern Sweden
Adrian Stigsson

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Satellite signal attenuation due to atmospheric influences in northern Sweden.
Adrian Stigsson, adrian.stigsson@gmail.com

Supervisor: Sandra Nilsson  Arctic space technologies AB, Luleå.
Examiner: Maria Hamrin  Department of physics, Umeå University.

Master of Science Thesis in Engineering Physics, 30 ECTS
Department of Physics
Umeå University
SE-901 87 Umeå, Sweden

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Abstract

Earth-space traversing electromagnetic waves become attenuated as they propagate through the atmosphere. The sources of attenuation are weather phenomena in the Troposphere, and scintillation and absorption in the Ionosphere. On behalf of Arctic Space Technologies AB, an empirical model based on data from the last decade was built in Python, in order to estimate the level of attenuation and provide a better picture of the frequency environment at the site in Piteå. By utilizing recommendations from the International Telecommunication Union Radiocommunication Sector, and constraining the project to only consider the case where the satellite is at an $5^\circ$ apparent elevation in Piteå, and a range of weather phenomena a nuanced picture can be obtained. It was found that the attenuation from the Ionosphere in typical satellite frequency bands is not of significance, and therefore only the Tropospheric sources were considered. The results showed that the S-band is the most reliable band to utilize, since little to no changes were observed for a range of weather scenarios. For the X-band, larger changes in the level of attenuation were observed for higher levels of precipitation, yet not as severe as for the Ku- and Ka-bands. However, for the Ku- and Ka-bands, large fluctuations in the attenuation were observed for different cases. In conclusion, the attenuation at Arctic space’s site in Piteå for the S- and X-bands are the lowest and least effected by changes in weather. On the other hand, the Ku- and Ka-bands should be used predominantly under good weather circumstances.
Acknowledgements

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1 Introduction

Electromagnetic signals in the low Ghz frequency range are used when communicating with satellites in orbit. These signals lose their power (attenuation) as they traverse through a medium, which at high latitudes can come from both Tropospheric and Ionospheric conditions. Since both the Troposphere and Ionosphere are subject to rapid changes such as, rainfall rate, cloud coverage, space weather, etc, the attenuation needs to be statistically estimated.

Providing a statistical model and a program to estimate the level of attenuation is beneficial to both satellite operators, and to Arctic Space Technologies AB, a ground station operator. Arctic Space approached me with this thesis in order to gain a better understanding of the frequency environment at their ground station site in Piteå. The benefit of gaining an estimate of attenuation expected at their site is to ensure that the ground station infrastructure is up to standard and perform more accurate power budget calculations, as well as providing customers with insight to the frequency environment.

At the location in Piteå, the Ionospheric effects need to be investigated due to the proximity to the polar caps, and auroral oval, an area more subject to space weather. In this study, the relevance of such effects needs to be taken into consideration and ensured if they actually have any considerable effect on the attenuation.

In this thesis, we will answer questions regarding the level of attenuation at the site in Piteå. What sources of attenuation are there? What is the expected level of attenuation for a satellite at an $5^\circ$ apparent elevation? Based on the weather in the last decade, what is the expected best- and worst-case attenuation?
2 Theory

The most established way of predicting tropospheric attenuation is provided as recommendations from the International Telecommunication Union Radiocommunication Sector (ITU-R). These recommendations take both a statistical approach and provide some tools [1]. The recommendations are based on an average year for, e.g., precipitation. Plimon noted that it is hard to define an average year due to environmental changes, leading to excessive precipitation or droughts [2].

ITU-R does not cite any sources, instead they claim that the recommendations have been produced by study groups of experts in the field [3]. Due to the absent sources and ever-changing environment, caution may need to be taken when utilising these recommendations.

The lower GHz frequency range of interest are the S-, X-, Ka- and Ku-bands. In Table 1 we see that the bands of interest cover frequencies from 2.025-31 GHz, excluding the ranges 3.4-7.25 and 8.5-10.7 GHz.

<table>
<thead>
<tr>
<th>Band</th>
<th>Uplink (GHz)</th>
<th>Downlink (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>2.20-2.29</td>
<td>2.025-2.11</td>
</tr>
<tr>
<td>X</td>
<td>7.25-7.75</td>
<td>7.9-8.4</td>
</tr>
<tr>
<td></td>
<td>8.4-8.5</td>
<td>7.145-7.235</td>
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<tr>
<td>Ku</td>
<td>10.7-12.75</td>
<td>13.75-14.5</td>
</tr>
<tr>
<td>Ka</td>
<td>17.7-21.2</td>
<td>27.5-31</td>
</tr>
<tr>
<td></td>
<td>25.5-27.5</td>
<td></td>
</tr>
</tbody>
</table>

2.1 Tropospheric attenuation

Sources of attenuation in the Troposphere come from weather phenomena. These sources are precipitation, absorption from gases, clouds (including fog) and heterogeneous index of refraction (scintillation).

In the following theory of the Tropospheric attenuation, it is important to understand what the variable \( p \) represents. \( p \) represents a percentage of one year in the range 0–100, and is used to indicate what fraction of one year we can accept loss of data. For example, if one can accept that the attenuation is too high (in total or from a specific source), such that the attenuation makes the signal undetectable for \( p \)% of a year. Then what the equations in sections 2.1.1–2.1.5 will return is how weak the signals have become in dB, which the infrastructure needs to be able to compensate for, in order to ensure connectivity. This can be done either from the satellite but more commonly at the ground station.

2.1.1 Rain

The attenuation due to rain, \( A_R \), can be calculated using the following equation from [4]:

\[
A_R(p) = A_{0.01} \left( \frac{p}{0.01} \right)^{-(0.655+0.033b(p)-0.045b(A_{0.01})-\beta(1-p)\sin \theta)} [dB]
\]

(2.1)

The variable, \( p \), is the fraction of one year that the attenuation is exceeded of an average year in the range 0.001-5%. In our specific case, for time percentages of a year different to that of 0.01%, \( \beta = 0 \) since the latitude of interest is greater than \( |\varphi| > 36^\circ \). The angle between the
horizon and apparent elevation of the satellite is given by $\theta$.

$A_{0.01}$ is the predicted attenuation exceeded for 0.01% of an average year, calculated as:

$$A_{0.01} = \gamma_R L_E \quad [dB]$$

and $\gamma_R$ is the specific attenuation and $L_E$ the effective path length.

Note that equation [2.1] for a set $A_{0.01}$ value and increasing $p$ will fall off exponentially. This is such that when designing the power budget or infrastructure that if a high unavailability time percentage is acceptable, a lower level of compensation for the attenuation can be considered.

### 2.1.2 Scintillation

The attenuation of satellite signals due to scintillation, $A_S$, affect the signals as well. The cumulative tropospheric attenuation for a given $p$ is given in [4]:

$$A_S(p) = a(p) \sigma \quad [dB] \quad (2.2)$$

Where $a(p)$ is the time percentage factor for, $0.01 \leq p \leq 50$, and $\sigma$ is the standard deviation of the signal for the propagation path over the considered period.

### 2.1.3 Gaseous attenuation

Atoms and molecules absorb electromagnetic signals, due to this the signals become attenuated. If the local temperature, dry air pressure, and water vapour partial pressure profile as a function of the height, $h$, is known, the attenuation due to atmospheric gasses, $A_G$, can be calculated using equation 11 in [5], integrating from the ground station, $h_1$, to the edge of the atmosphere, $h_2$:

$$A_G = \int_{h_1}^{h_2} \frac{\gamma(h)}{\sqrt{1 - \cos^2(\varphi(h))}} dh \quad [dB] \quad (2.3)$$

where

$$\cos(\varphi(h)) = \frac{(R_E + h_1)n(h_1)}{(R_E + h)n(h)} \cos(\varphi_1)$$

here $n$ is the refractive index, $R_E$ is the average radius of Earth (6 371 km), $\varphi$ is the apparent elevation of the satellite and $\gamma$ is the specific attenuation as a function of the height above ground.

If either the water vapour pressure profile, temperature, or dry air pressure is unknown then we need to utilise:

$$A_G = \sum_{i=1}^{i_{max}} a_i \gamma_i \quad [dB] \quad (2.4)$$

where $a_i$ and $\gamma_i$ is the path length and specific attenuation in the i:th layer respectively. The layers of the atmosphere are then modelled as an exponentially increasing layer thickness.

Since the specific attenuation is dependent on the surface water vapour density, we calculate this from observational data using the Clausius–Clapeyron equation to calculate the water vapour pressure as a function of relative humidity, $H_r$, and temperature, $T$, given in °C:

$$P_w = 6.112 H_r e^{17.67 \frac{T}{T+257.15}} \quad [Nm^{-2}] \quad (2.5)$$
Equation 2.5 is then used to calculate the water vapour density, \( \rho_w \), from the ideal gas law as given in equation 2.6:

\[
\rho_w = \frac{P_w 10^3}{R_w (T + 273.15)} \quad [gm^{-3}] 
\]

(2.6)

Where the specific gas constant of water vapour \( R_w = 461.52 \ [Jkg^{-1}K^{-1}] \), and \( 10^3 \) is only there to convert to gm\(^{-3}\) [6].

### 2.1.4 Cloud attenuation

When considering the effect of clouds, fog is also taken into consideration. If local data is available and the slant path angle is given between \( 5^\circ \leq \varphi \leq 90^\circ \) then the cloud attenuation, \( A_C \), along the path can be calculated as:

\[
A_C = \frac{L K^\prime_l (f, 237.15)}{\sin(\varphi)} \quad [dB] 
\]

(2.7)

where \( L \) is the total columnar water content of liquid water and the cloud liquid specific attenuation coefficient, \( K^\prime_l \), as a function of frequency, \( f \), and \( T \) (fixed for liquid temperature at 273.15 K) can be found by calculating:

\[
K^\prime_l = \frac{0.819(1.9479 \times 10^{-4} f^{2.308} + 2.9424 f^{0.7436} - 4.9451)}{\varepsilon''(1 + \eta^2)}
\]

Where \( \varepsilon'' \) is the complex dielectric permittivity of water and \( \eta \) is the specific attenuation due to cloud particles. However, if local data is unavailable one need to approximate the total columnar water content by replacing \( L \) with an approximation, \( L_{RED} \). Which can be approximated using a global grid of needed values. If there is no point close enough to the desired location, one must in that case perform bi-linear spatial interpolations, all available in the ITU-R recommendations.

### 2.1.5 Total tropospheric attenuation

As stated in [4], the total signal attenuation is a combination of factors, primarily due to rain, clouds, gaseous attenuation due to water vapour and oxygen as well as tropospheric scintillation. The general method of calculating the total attenuation, \( A_T(p) \), due to all these factors combined, is given in [4]. By combining equations 2.1, 2.2, 2.3 or 2.4 (dependent on situation) and 2.7 we obtain the total attenuation as:

\[
A_T(p) = A_G(p) + \sqrt{(A_R(p) + A_C(p))^2 + A_S^2(p)} \quad [dB] 
\]

(2.8)

This is however only valid for \( p \) in the range 0.001-5\%, in order to account for \( p \) in the range 5-50\% the total attenuation is calculated without the rain attenuation:

\[
A_T(p) = A_G(p) + \sqrt{A_C^2(p) + A_S^2(p)} \quad [dB] 
\]

(2.9)

This is due to two reasons, the percentage of time and \( A_{0.01} \). The probability that there is continuous rain for 5\% of a year is low. Looking at the equation 2.1 using \( p = 5 \) and, e.g., letting \( A_{0.01} \) vary, we see that in order for \( A_R(5) = 1 \), the value of \( A_{0.01} \approx 31 \text{ mm/h} \), which is unlikely to occur. Due to this and the probability of continuous rain for more than 5\% of a year, the attenuation from rain can be neglected above this.
2.2 Ionospheric attenuation

The Ionosphere become transparent for higher frequencies[7], therefore we do not expect much/any attenuation from absorption. Scintillation in the Ionosphere can however have somewhat more of an impact.

Ionospheric effects are negligible above 10 GHz [4], therefore we will not be implementing any calculations of the attenuation for the Ku- and Ka-bands, even if the Ku-Band is close to the 10 GHz cut-off line. We will focus on Ionospheric attenuation will be implemented to the S- and X-bands instead, since these frequencies might be more significantly attenuated due to Ionospheric sources.

2.2.1 Scintillation

The Ionospheric scintillation is calculated by an approximation of the peak to peak fluctuations, $P_{fluc}$, as a function of the scintillation index, $S_4$, by equation (6) from [8]:

$$P_{fluc} = 27.5 S_4^{1.26}, \text{ if } 0.0 \leq S_4 \leq 1.0$$

where the $S_4$ is calculated from equation (5):

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

where $I$ is the intensity of the signal, which is proportional to the amplitude of the electric field squared. The peak-peak loss, $L_p$, can then be calculated as in step 4 in section 5.8 from [8], using the equation for $S_4$ in $P_{fluc}$:

$$L_p = P_{fluc} / \sqrt{2} \quad [dB]$$

On page 156 in [9], we find a rule of thumb for the upper limit of scintillation:

$$f = \frac{u}{\sqrt{2AD}} \quad [Hz] \quad (2.10)$$

where $u$ is the velocity the irregularities move at. D is the distance to the Ionosphere, which acts as a phase screen, and $\lambda$ is the wave length. This states that for a frequency, $f$, larger than equation 2.10 the signal is not affected by scintillation.

Note, that the Ionosphere is a turbulent region which is highly dependent on the solar activity, and can therefore only be approximated, unless one were to simulate the Ionosphere in its entirety for different scenarios, and calculate the scintillation for each scenario.

2.2.2 Absorption

We do not expect any large attenuation due to absorption from auroras or polar caps. This can be seen when calculating the total absorption, A, of electromagnetic waves in the Ionosphere, using equation (3.95) section 3.4.4 in [9]:

$$A = \frac{1.168 \times 10^{-18}}{f^2} \int N\nu dl \quad [dB]$$

Where $f$ is given in MHz, $N$ are the number of electrons per cubic meter, $\nu$ is the velocity of the electrons and $dl$ is the length element as we integrate from the satellite to the bottom of
the Ionosphere. This holds if the gyro frequency of the electrons is much smaller than the radio frequency of consideration, which is the case for frequencies above 30 MHz.

Since the frequencies of interest are in the order of $10^3$ MHz, it is easy to see that the attenuation from absorption will be negligible. Therefore, this will not be included when developing the tool, nor in the statistical analysis.
3 Method

In this chapter, I will go over the methodology used and explain what was done in order to produce the results seen in section 4.

All programming performed during the project was performed in the Python language, using the Spyder environment. Spyder is a free and open-source scientific environment written in Python, for Python, and designed by and for engineers. Libraries used are Numpy (to handle NaN-values and vectors), Pandas (to structure the data), ITUR-Py (for easy implementation of the theory described in section 2.1), and Matplotlib (for visualizing the results).

3.1 Data

The data required as seen in section 2.1 is, ambient surface temperature \( ^\circ \text{C} \), point rainfall rate for 0.01% of an average year, \( R_{0.01} \text{[mm/h]} \), water vapour density \([\text{g/m}^3]\), relative humidity [%] and pressure [hPa]. Trafikverket operates a weather station along the E4 road in Bärtnäs, station number 2510, which is the closest to the site (approximately 3 km away), and collects data on temperature, humidity, and precipitation (snow, rain, and a mix of snow and rain).

Station 2510 has a temporal resolution of approximately one measurement per 30 minutes. This resolution does not meet the model’s required resolution of one measurement per minute. However, the station is the closest to the site, that provides in situ measurements with a temporal resolution lower than one hour. Therefore, I chose to rely on this data.

In order to develop the empirical model for Piteå, the temperature, humidity, and precipitation data from the last decade will be used. That is, from the first of January 2012, until the 31:st of December 2022. Since no pressure data was obtainable in the area, this was instead approximated using the built-in bilinear approximation in the ITUR-Py library.

3.2 Pre-processing and analysis

The data came in the form of an Excel sheet where the columns contain the surface temperature, air temperature, humidity, the amount of snow, rain, and a mixture of both that have fallen in the last 30 minutes. One additional column contains strings, indicating what type of precipitation was recorded, if present, as well as a column with time stamps indicating year, month, day, hour, and minute, called a DateTime column.

The data was first placed in separate data frames for easier manipulation, and access to specific data along with the DateTime column replacing the index column in the data frames. If data were missing this was indicated by a '-', this was replaced with a numpy.NaN for easy data handling. A resampling of the data was performed in such a way that if two DateTime indices have the same year, month, day, and hour value, but different minute value, a resampling will be performed. For the precipitation data frames, if both considered values are not NaN, then the values will be summed together, form a mm/h value, and be pared with the indicated DateTime index. If there are one or two NaN values in the same DateTime index the resampled value is set to NaN. When the temperature or humidity is considered, the average of the two values with the same DateTime index is calculated and set to be the hourly average value.

By using equation 2.5 in equation 2.6 and the humidity and temperature data from the sta-
tion, I calculated the water vapour density as an hourly average just as for the temperature and humidity and placed it in a separate array.

Snow is not relevant to the rain attenuation due to rain absorbing the signals while the crystalline structure of snow scatter the electromagnetic waves, and therefore different approaches to calculating their respective attenuations are needed. Under the assumption that the rain acts as an attenuation when the precipitation consists of a mixture of rain and snow. A quick look at the data revealed that the measured precipitation did not include what fraction was snow or rain. Due to this missing information, no compensation was possible in order to obtain how much it rained for these measurements, and data were lost.

Since there are data points missing, we will need to investigate what data to include and exclude, in order to determine what data can be used. By counting the number of NaNs and dividing by the total number of data points on both a yearly and monthly basis, we can exclude years or months that are missing a large fraction of data. Along with the exclusion of years when the number of data points are insufficient, we may also gain a deeper insight into what must be done moving forward in order for the model to be more representative of the site in Piteå. The analysis of the missing data can be found in appendix A.1.

3.3 Program

Utilizing the Python function library on GitHub (ITUR-Py) [11], which is built on the theory in section 2.1 I wrote a program. This program needs to be able to compute the attenuation of electromagnetic waves, for the S-, X-, Ku- and Ka-bands as seen in Table 1. Performing a sweep over the whole frequency range for all sources, we gain a deeper understanding of what source induces the most attenuation at what part of the spectrum, along with sweeps over each respective bands for the total attenuation.

By using the function “atmospheric_attenuation_slanth_path()” (from ITUR-Py) which implements equations 2.8 and 2.9 that need latitude, longitude, frequency, elevation, probability, dish diameter, and a boolean operator indicating if only the total should be returned, as minimum input parameters, I calculated an estimation of the predicted attenuation from tropospheric sources. This was done by implementing the ITUR-Py function and plotting in functions with frequency sweeps over the entire range, as well as the specific bands. The general pseudocode is presented in appendix A.2. Except from temperature, humidity, and rain precipitation data obtained and used, set parameters are elevation, el = 5°, physical dish diameter, D = 7.3 m, latitude (65.33°), longitude (21.42°), height of ground station above sea level, hs = 0.006 km, polarisation angle, θ = 45°, antenna efficiency, η = 0.5 and p = 0.01.

3.4 Statistics

In order to determine the level of attenuation, I considered four cases along with their occurrence in the past. These cases were, no precipitation, average precipitation per hour from the most average year ± 0.1 mm/h, the precipitation corresponding to a yellow warning as defined by the Swedish Meteorological and Hydrological Institute (SMHI) [13], with a rainfall rate of 2.9 ± 0.1 mm/h and the maximum measured precipitation in one hour. The choice of taking the average and yellow warning values ± 0.1 mm/h is in order to account for measurement errors, as well as ensuring that if each specific value is not observed then the range accounts for encapsulating the value of interest.

By taking these four scenarios and retrieving the average humidity, average temperature, and
calculating the average water vapour density at the time these scenarios were observed. We can build a more realistic picture of what level of attenuation is expected.

The fraction of time these scenarios considered have occurred in the past is also of interest. The results of each scenario occurring, including and excluding NaNs, can be found in appendix A.3.

Seasonal variations are important to consider both for the attenuation and from a ground station design point of view. Therefore, by dividing the data into monthly partitions and obtaining the mean temperature, humidity, and precipitation for each month we gain a deeper insight in what atmospheric conditions we can expect in each month. These results can be found in appendix A.4.
4 Results

Here I present the results of the attenuation calculations, the remaining results considering average precipitation per month, fraction of missing data points, etc, can be found in the appendix, see section 8 or contents, where each specific part can be found.

Note in figures 1, 3, 5 and 7 there is a bump in the approximate frequency range 20-25Ghz. As mentioned in table 1, this range is not part of a frequency range reserved for satellite communication and can therefore be ignored.

For the average precipitation, we see the attenuation as a function of the frequency in figure 1.

![Figure 1: Total attenuation as a function of frequency. The precipitation is taken to be 0.7 mm/h with the average temperature 10.5°C and humidity of 98.7% and an average water vapour density calculated to be 8.8 g/m³.](image)

To compute the attenuation as a function of frequency the following parameters were used: a rainfall rate of 0.7 mm/h, the average temperature as this rainfall rate was observed to be, 10.5°C, the average humidity was 98.7%, and the calculated average water vapour density was 8.8 g/m³. This produced a minimum total attenuation of 1.95 dB and a maximum of approximately 19 dB.
In figure 2 we see a more detailed picture of the total attenuation for each respective bands.

As we can see, the average precipitation yields the highest attenuation in the Ka-band of approximately 19 dB at 31 GHz.
In the case of no precipitation, the values drop to lower levels than with precipitation, as seen in figure 3.

Figure 3: Attenuation as a function of frequency. The precipitation is taken to be 0 mm/h with the average temperature 4.3° C and humidity 79.3% and the average calculated water vapour density was calculated to be 5.3 g/m³ at the time when there is no rain measured.

It can further be seen that the cloud attenuation is the dominant source of attenuation at higher frequencies, and the scintillation is still the dominant source of attenuation at lower frequencies. During the time that a precipitation of 0 mm/h was observed, an average temperature of 4.3° C and humidity of 79.3% was observed and the average calculated water vapour density of 5.3 g/m³ was used.
In order to obtain a more detailed picture of the total attenuation for each respective bands, we see in figure 4 a more detailed picture.

Figure 4: Total attenuation as a function of frequency for each respective band. The precipitation is set to 0 mm/h, with the average temperature 4.3° C, humidity 79.3% and the average calculated water vapour density was calculated to be 5.3 g/m³ at the time when there is no rain measured.

As we can see in figure 4d it is clear that the highest level of attenuation we can expect in the Ka-band at 31 GHz at approximately 12.5 dB.
When studying the extreme case of precipitation in the range of $2.9 \pm 0.1$ mm/h, we see in figure 5 that the attenuation can reach as high as approximately 30 dB in the Ka-band at 31 GHz:

![Figure 5: Attenuation as a function of the frequency. The precipitation is taken to be at the yellow limit for a weather warning from SMHI which is $2.9 \pm 0.1$ mm/h. Along with the average measured temperature, 10.6°C and humidity 97.8% and an average water vapour density of 9.1 g/m³ was calculated as the measured rainfall rate occurred.](image)

During the time that a rainfall rate of 2.9 mm/h, defined as a yellow warning by SMHI, the average temperature observed was 10.6°C, an average humidity of 97.8%, and an average water vapour density of 9.1 g/m³ was calculated. Under these conditions, the attenuation from rain is the most dominant factor for higher frequencies.
The fraction of data that indicates a precipitation from 2.9 mm/h and above is small, however it is necessary to know what the maximum obtained attenuation can be. Therefore, this is presented in figure 6:

(a) Total attenuation in the S-band, yellow SMHI limit.

(b) Total attenuation in the X-band, yellow SMHI limit.

(c) Total attenuation in the Ku-band, yellow SMHI limit.

(d) Total attenuation in the Ka-band, yellow SMHI limit.

Figure 6: Total attenuation for each respective band, with a rainfall rate corresponding to a yellow warning from SMHI of 2.9 mm/h ± 0.1 mm/h. Along with the average measured temperature, 10.6°C and humidity 97.8% and an average water vapour density of 9.1 g/m³ was calculated as the measured rainfall rate occurred.

Figure 6d shows that at this point the attenuation is starting to increase more and more for higher frequencies and the highest level of attenuation is in the Ka-Band at 31 GHz around 30 dB.
In figure 7 we see the attenuation over the whole frequency range for the worst case attenuation where the rainfall rate was measured to be 13 mm/h. During this time, the average temperature observed was 9.9° C and an average humidity of 80.7%, along with a calculated average water vapour density of 6.9 g/m³.

As can be seen in this case the rain attenuation dominate all other sources of attenuation except for scintillation in the S-band.
In order to obtain a more detailed picture of this worst case, we can observe the total attenuation for each respective frequency band (S-, X-, Ku- and Ka-bands), in figure 8.

(a) Total attenuation in the S-band, maximum precipitation.

(b) Total attenuation in the X-band, maximum precipitation.

(c) Total attenuation in the Ku-band, maximum precipitation.

(d) Total attenuation in the Ka-band, maximum precipitation.

Figure 8: Total attenuation as a function of frequency for each respective band. The precipitation is taken to be 13 mm/h with an average temperature of 9.9° C and humidity 80.7% and a calculated average water vapour density of 6.9 g/m³.

As we can see, the attenuation can in the worst case be approximately 57 dB in the Ka-band at 31 Ghz.
5 Discussion

5.1 Results

Overall, when the results are compared to classified documents provided, the attenuation values for the S- and X-bands are within, or close to, the expected levels of attenuation when considering atmospheric sources. Therefore, I have assumed that the implementation is correct.

As we can see in figures 2a, 4a, 6a and 8a the level of attenuation does not change, or at least not to a discernable level, between each scenario. Therefore, the rain, humidity, and temperature appear to have no discernable impact on the total attenuation in the low GHz range and stay within 1.15-1.23 dB. This indicates that for a more reliable communication that is not as dependent on the weather, the S-band should be used.

When we look more closely on the other bands for the different cases, then we see that the level of attenuation that we can expect varies more the higher the frequency. However, the attenuation in the X-band as seen in figures 2b, 4b, 6b and 8b shows that between the different scenarios the change is not that profound. We can expect a level of attenuation in the range of 2.6-6 dB. Where quite the majority of change happens when the rainfall rate is higher than 2.9 mm/h.

When it comes to the worst case scenarios for all frequency ranges, remember that the fraction of the data since 2016 that indicate a precipitation above the yellow SMHI warning limit of 2.9 mm/h is 0.16 %. The 0.16% fraction of data points from the start of 2016 until the end of 2022 is equivalent to approximately 98 hours. So there is a low likelihood that we would observe these high levels of attenuation. However, since the weather cannot be predicted, it is hard to say the probability of this occurring again in the future. And if we look at figures 2c, 4c, 6c and 8c for the Ku-band, we can see that the attenuation is in the range 2.7-16 dB and quite large changes occurs for the extreme precipitation cases. And for the Ka-band we see in figures 2d, 4d, 6d and 8d that we have a large range of attenuation, all in the range 5-55 dB. This wide range of attenuation shows further that for a more stable connection the S- and X-bands should be used and the Ku- and Ka-bands under the best of circumstances.

One large factor that needs to be addressed is the attenuation that the signals experience from clouds. As can be seen in figures 1, 3, 5 and 7 if the attenuation due to rain is ignored then the gases in the troposphere are the largest source of attenuation. Since this attenuation is not dependent on a variable that can be controlled, it is the one most important to take into consideration when calculating a power budget and compensating for data losses.

It is also important to note that for lower frequencies we can see that the scintillation is the dominant source of attenuation. Since the scintillation is dependent on the physical antenna diameter, and have been at a set size of 7.3m for the whole frequency range, we know that this is a source of error. Antenna sizes are predetermined by the frequency range it operates in, and the calculations could therefore be more optimized. Moreover, this problem can in the real world be mitigated by optimizing the antenna diameter to lower this attenuation.

5.2 Errors

Even if errors have not been brought up previously, it is good to note a few aspects. To start, the ITU-R model used may well be the most implemented in the industry, however there are no sources available or description of how certain values and equations have been achieved, which
raises some concerns. Due to the absence of this information, the model in itself might have 
some underlying error that is not taken in to consideration. If these errors take the form of 
wrong methodology or in the form of wrong coefficients used in the calculations due to bad 
instruments or bad usage of instruments are not possible to know.

There are some errors due to the missing data, and the fact that the measurement frequency is 
not sufficiently high enough, which could hide a much higher rainfall rate in a smaller time span. 
This missing data could indicate that the average precipitation is higher than 0.7 mm/h, and 
therefore lead to a higher level of attenuation, and what fraction of time we see a precipitation 
above the yellow warning from SMHI of 2.9 mm/h.

5.3 Improvements

As mentioned in section 2.2.1 the Ionosphere is a turbulent region. Therefore, a way to better 
predict effects on electromagnetic waves would perhaps be a finite element simulation. This, in 
order to gain a more realistic picture of how both small scale and large scale structures affect 
the electromagnetic waves. Combining this with a statistical approach would make for a clearer 
picture. If this could be done for different regions of the Earth and combined with a statistical 
analysis, by itself it could prove for a useful study, or be added to the ITU-R recommendations 
to enable engineers worldwide having a more comprehensive tool when designing ground stations.

Throughout this project, no sources were found that can calculate the attenuation in the case 
where snow is the dominant precipitation. Since there are ground stations being built further 
up north, a model of snow attenuation should already be available. Since a model for this was 
unfortunately not found, I would strongly recommend for the next phase of improving this to 
include a model that could calculate the attenuation in falling snow. My guess is that since 
the snow is a solid form of water, a statistical simulation of a granular, homogeneous and in 
in-homogeneous material as a function of the snow fall rate, of small prisms or lenses would be 
a good starting point.

5.4 Recommendations

After analysing the data, one thing that is noticeable is the absence of reliable data. No weather 
station is close to the ground station, the temporal resolution is lower than optimal, and most 
importantly there is a significant amount of data absent from critical periods. Due to this low 
quality data, I recommend that Arctic Space Technologies AB invest in a weather station with 
a temporal resolution of one measurement per minute up to one hour, with the ability to mea-
sure all relevant variables. By doing this, a more reliable calculation of the expected level of 
attenuation can be performed and presented to customers as a selling point and ensuring that 
the infrastructure meets the required specifications without spending too much money or losing 
too much data.

A major benefit to purchasing a weather station with all the things mentioned above would 
be the ability to build a more robust local model, especially if a partnership with a satellite 
operator is established where a known signal is sent for the entire frequency range of interest. 
By performing these tests regularly, the model can continuously be revised and improved for 
a whole range of different scenarios. Furthermore, the instantaneous attenuation could more 
easily be calculated in such a way that the infrastructure could compensate for the attenuation 
more precisely. And having the weather station is also a direct source of data instead of having 
to obtain it from other sources, along with being able to have more control over the temporal 
resolution and the accuracy of the instruments.
One other way that the data could become more reliable, and possibly another source of income, would be to build this weather station with an all-sky camera. By investing in an all-sky camera taking photos in regular intervals and combining this with an algorithm that could detect the presence of clouds and fog, a more reliable model of the probability of cloud attenuation could be achieved. Further, by expanding the algorithm to detect auroras, a contribution to space weather analysis. And it could also act as a source of revenue by selling the data to SMHI or other vendors.
6 Conclusion

We can conclude that the sources of attenuation at the site are from precipitation in the form of rain, clouds/fog, scintillation, and gases. The sources of attenuation from the Ionosphere that were first thought to have an impact could be ignored.

From the results, we can conclude that the attenuation with a satellite at an apparent elevation of $5^\circ$ is highly dependent on the weather and which band is considered. When utilising the S-band no significant change to the attenuation is observed and therefore the most stable to use alongside the X-band which varies quite little in the level of attenuation dependent on the weather. However, when it comes to higher frequencies, the attenuation can vary a lot and should therefore be utilized under the best possible conditions or have a robust and dynamic infrastructure in order to have the capability to compensate for large fluctuations in the attenuation.

Under the best of conditions, the lowest attenuation we can expect is in the S-band at 1.09 dB and the worst case is in the Ka-band at approximately 57 dB, based on weather data from the area in the last decade.
7 Bibliography


A Appendix

A.1 Missing data

From the preprocessing of the data, it was found that the fraction of NaN data points, for each year, are represented in figure [9].

Figure 9: Fraction of rain data that is unavailable for each year, respectively. Obtained from the station operated by Trafikverket.

As we can see in figure [9] the fraction of data in the years 2012-2015 are close to 3 months of missing data and more. Therefore, this data was excluded to save time and focus more on the years with less significant data loss.

By inspecting each month for every year in the range 2016-2022 in table [2] we obtain a clearer picture of where the data is missing.
Table 2: Fractions of data per month in percent [%] that are NaN for each year, rounded to the closest second decimal point.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.27</td>
<td>2.82</td>
<td>0.67</td>
<td>0.0</td>
<td>1.21</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Feb</td>
<td>1.29</td>
<td>0.0</td>
<td>0.30</td>
<td>0.60</td>
<td>1.44</td>
<td>0.0</td>
<td>10.27</td>
</tr>
<tr>
<td>Mar</td>
<td>1.34</td>
<td>0.54</td>
<td>0.27</td>
<td>0.94</td>
<td>2.02</td>
<td>0.94</td>
<td>0.40</td>
</tr>
<tr>
<td>Apr</td>
<td>1.94</td>
<td>2.5</td>
<td>45.28</td>
<td>0.14</td>
<td>1.39</td>
<td>2.22</td>
<td>5.56</td>
</tr>
<tr>
<td>May</td>
<td>1.94</td>
<td>2.5</td>
<td>45.28</td>
<td>0.14</td>
<td>1.39</td>
<td>2.22</td>
<td>5.56</td>
</tr>
<tr>
<td>Jun</td>
<td>8.89</td>
<td>1.53</td>
<td>6.81</td>
<td>2.92</td>
<td>1.39</td>
<td>0.56</td>
<td>11.81</td>
</tr>
<tr>
<td>Jul</td>
<td>6.18</td>
<td>11.43</td>
<td>1.34</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Aug</td>
<td>1.88</td>
<td>1.34</td>
<td>3.90</td>
<td>2.02</td>
<td>0.13</td>
<td>0.81</td>
<td>0.0</td>
</tr>
<tr>
<td>Sep</td>
<td>3.47</td>
<td>0.56</td>
<td>0.14</td>
<td>2.22</td>
<td>10.56</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Oct</td>
<td>1.08</td>
<td>3.09</td>
<td>1.34</td>
<td>0.94</td>
<td>0.0</td>
<td>1.21</td>
<td>0.94</td>
</tr>
<tr>
<td>Nov</td>
<td>1.67</td>
<td>0.69</td>
<td>0.83</td>
<td>0.83</td>
<td>0.42</td>
<td>1.39</td>
<td>0.83</td>
</tr>
<tr>
<td>Dec</td>
<td>0.94</td>
<td>0.67</td>
<td>0.94</td>
<td>1.75</td>
<td>2.15</td>
<td>1.88</td>
<td>1.08</td>
</tr>
</tbody>
</table>

As we can see in table 2 the missing rain data is predominantly centred at and around the periods of the year when rain is most present.

Since the data used have a significant amount of data missing, especially for April and May in 2018, the results do not give an accurate representation.
A.2 Attenuation algorithm

Algorithm 1 Calculate Atmospheric Attenuation as a Function of Frequency

1: # Load and preprocess tropospheric data
2: $T_{\text{air}}, T_{\text{surface}}, \text{Humidity, Snow}\_\text{mm\_30min}, \text{Rain}\_\text{mm\_30min}$
3: $\text{Mix}\_\text{mm\_30min} \leftarrow \text{TroposphericStats.load\_and\_preprocess\_data()}$
4: # Convert precipitation from mm/30min to mm/h
5: $\text{Snow}\_\text{mmh}, \text{Rain}\_\text{mmh}, \text{Mix}\_\text{mmh} \leftarrow$
6: TroposphericStats.sum\_dataframes\_by\_datetime\_index($$
7: \text{Snow}\_\text{mm\_30min}, \text{Rain}\_\text{mm\_30min}, \text{Mix}\_\text{mm\_30min}$$)
8: # Calculate water vapor density
9: $\rho_{\text{30min}} \leftarrow \text{TroposphericStats.water\_vapour\_density(}$
10: $\text{Humidity, T}_{\text{surface}}$$)$
11: # Define function parameters
12: $\text{lat\_GS, lon\_GS, el, p, D, T, H, hs, R001, P, rho, eta, tau, V}_t$
13: # Function starts here:
14: mode $\leftarrow \text{'exact'}$ ▷ Gaseous attenuation mode
15: $hL \leftarrow 1e3$ ▷ Turbulent layer height in meters
16: $\text{Ls} \leftarrow \text{None}$ ▷ Automatically calculate slant path length
17: $f \leftarrow \text{Array().itur.u.GHz}$ ▷ Frequency range in GHz
18: # Set boolean operators for attenuation components
19: return$contributions \leftarrow \text{True}$
20: include$\text{rain, gas, scintillation, clouds} \leftarrow \text{True}$
21: # Calculate atmospheric attenuations
22: $A_g, A_c, A_r, A_s, A_t$ $\leftarrow$
23: CalculateAttenuations($\text{lat\_GS, lon\_GS, f, el, p, D, hs,}$
24: $\rho, \text{R001, eta, T, H, P, hL, Ls, tau, V}_t, \text{mode,}$
25: include$\text{scintillation, rain, gas,}$
26: include$\text{clouds}$
27: $\text{return contributions, include\_rain, include\_gas,}$
28: $\text{return\_clouds}$
29: # Plot the results
30: PlotAttenuationResults($A_g(f), A_c(f), A_r(f), A_s(f),$)
31: $A_t(f))$
32: return 0
A.3 Statistical weather analysis

Analysing the data from the start of 2016 until the end of 2022 in order to determine the fraction of time with no rain, yellow warning, maximum measured precipitation and what fraction of the data indicates a temperature below $0^\circ$ C we find the results presented in Table 3.

Table 3: Fraction of data from the years 2016-2022 that are in the set range in the first column. For rain cases [mm/h] and temperature [°C]. As well as the fraction of the data including and excluding NaNs.

<table>
<thead>
<tr>
<th></th>
<th>Including NaNs</th>
<th>Excluding NaNs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{0.01} = 0$ mm/h</td>
<td>93.27%</td>
<td>95.52%</td>
</tr>
<tr>
<td>$R_{0.01} = 0.7 \pm 0.1$ mm/h</td>
<td>0.59%</td>
<td>0.60%</td>
</tr>
<tr>
<td>$R_{0.01} = 2.9 \pm 0.1$ mm/h</td>
<td>0.04725%</td>
<td>0.04839%</td>
</tr>
<tr>
<td>$R_{0.01} = 13$ mm/h</td>
<td>0.00163%</td>
<td>0.00167%</td>
</tr>
<tr>
<td>$T &lt; 0^\circ$ C</td>
<td>40.56%</td>
<td>41.4%</td>
</tr>
</tbody>
</table>

As we can see above, a large fraction of the temperature data is below $0^\circ$ C and for a $R_{0.01} = 0$ makes up the majority of the data set.
A.4 Monthly data

A clearer picture of the average mm/h of rain we can expect each month in the period 2016-2022 can be found in figure 10 below:

As we can see, there is little to no rain in the period of January to March. And the majority of the rain season is centred around August ± two months.

Moving on, the average temperature for each month in figure 11 below:
As we can see above, the average temperature is below 0° C for the months November to March, where little to no rain occurs.

The average humidity for each month can be found in figure 12.
As we can see from the graph above, the humidity is at its highest during the winter and autumn part of the year, while the summer have a lower average humidity.

Finally, we see in figure 13 the average snowfall rate:
Figure 13: Average mm/h of snow for each respective month from data provided from 2016-2022.

As we can see, the occurrence of snow is predominantly concentrated to the months of December-March. However, there is some snow in the two months preceding and following this period but none there between.