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Executive Summary of the Thesis

Development and test of models to scale rain attenuation from Ka to EHF bands

Laurea Magistrale in Space Engineering - Ingegneria Spaziale

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1. Introduction

In the telecommunication systems between satellites and ground station high frequencies are used. The pro of high frequency is the high amount of data that can be exchanged between the link. The large amount of data is fundamental for complex missions (maintain the attitude, perform a maneuver, do a fly-by...). Another problem of low bands is that they are congested so it is almost mandatory nowadays use always higher frequencies. The frequencies of interest in this thesis are the Ka band (18.7 GHz), the Q band (39.6 GHz) and the V band (49.5 GHz). The link of interest is the one between spacecraft (SC) and ground station (GS). The signal between SC and GS occurs some disturbances due to atmosphere presence, in particular this thesis goes thorough the tropospheric attenuation contribution, characterized by the following effects: gas attenuation, divided into its component: oxygen and water vapour attenuation, cloud attenuation, Rain attenuation and scintillations. The downside of the use of high frequency between SC and GC is the lack of attenuation models of the high frequencies, for this reason one of the most common and used approach to cope with this problem is to use frequency scaling. Two possible ways exist to perform frequency scaling: the first one is an empirical approach (where the principal method is Drufuca's one), the second one is a physical approach: the frequency scaling is performed based on the physical formulation of the attenuation of interest.

In the second part of this thesis, it is proposed a frequency scaling model for rain attenuation based on a physical approach and Drufuca's scaling is used as comparison.

As last step the scaled model are evaluated with respect to the data and the goodness of the scaling is assessed computing the mean value (MV) and the root mean square (RMS) of the prediction error.

2. ITALSAT experiment and dataset

The data-set used in this thesis come from the ITALSAT-1 experiment. ITALSAT-1 is a geostationary satellite (its orbital parameter are reported in table 1)

Table 1: ITALSAT-1 orbital parameter

NORAD ID:	24208
Perigee:	35541.1 km
Apogee:	35753.5 km
Inclination:	13.2°
Period:	1428.7 minutes
Semi major axis:	42020 km

used for telecomunications and moved to graveyard orbits in January 2001. The data-set is coming from the biennium 1995-1996 and it is characterized by:
One data point per second for:

- Total attenuation.

One data point per minute for:

- Meteorological data:
    - Temperature in °C (T)
    - Total pressure in hPa (P)
    - Relative humidity in % (RH)
    - Wind intensity and direction are provided too but they are not used in this thesis.
- Rain measurements.

To homogenise the data and reduce the computation time, total attenuation measurements are converted into the same format of the meteorological data.
To perform that operation, the 86400 points (for each day) are subdivided into 1440 groups with 60 elements; each group and the mean value of the group is taken.

3. Attenuation computation

The aim of this thesis is to perform a frequency scaling from Ka to EHF bands of the rain attenuation part. To do that the first, necessary, step is to have a reliable dataset representing the real rain attenuation. It is not a trivial task isolating only the contribution from rain and the way adopted in this thesis to retrieve this kind of data, it is to compute each component of the total attenuation vector at 18.7, 39.6 and 49.5 GHz.

3.1. Scintillations

The scintillations part is present on the dataset of the total attenuation retrieved form ITALSAT. This contribution it is not directly computed but filtered out with a moving average filter. The cut-off frequency of the filter used is equal to 0.03 Hz.

3.2. Gas attenuation

The gas contribution is computed using the ITU-R P.676-13 model [2], the specific gas attenuation is retrieved with the equation 1. It is summed up the specific attenuation of oxygen and the specific attenuation of water vapour.

$$\gamma = \gamma_{ox} + \gamma_{wv} = 0.1820 f \left(N''_{ox} + N''_{wv} \right) \quad (1)$$

where:

- f is the frequency
- $N''_{ox}(f)$ and $N''_{wv}(f)$ are the imaginary parts of the frequency-dependent complex refractivities

$N''_{ox}(f)$ and $N''_{wv}(f)$ are function of the frequency and of the meteorological data retrieved from the weather station of Spino D'Adda.

3.3. Cloud and Rain attenuation computation

To isolate the rain part from the cloud part it is not a easy procedure, in this thesis is implemented the methodology presented in "Enhancement of the Synthetic Storm Technique for the Prediction of Rain Attenuation Time Series at EHF" [1].
First of all the excess attenuation A_{RC} (representing the cloud and rain attenuation both) is computed subtracting from the total attenuation the gas contribution:

$$A_{RC} = A_{TOT} - A_{GAS} \quad (2)$$

Then the instantaneous discrimination ratio R_{RC} is evaluated as:

$$R_{RC} = a exp(-b A_{RC}) + (1-a) exp(-c A_{RC}) \quad (3)$$

The correlation between the excess attenuation and the instantaneous discrimination factor is a monotonically decreasing exponential (as reported in the figure 1): when the link is about to enter in the rain cell the attenuation will be caused only by the clouds ($R_{RC} = 1,\ A_R = 0$), as the rain event increases its presence on the link R_{RC} decreases its value and the rain attenuation takes over as dominant attenuation in the A_{RC}.

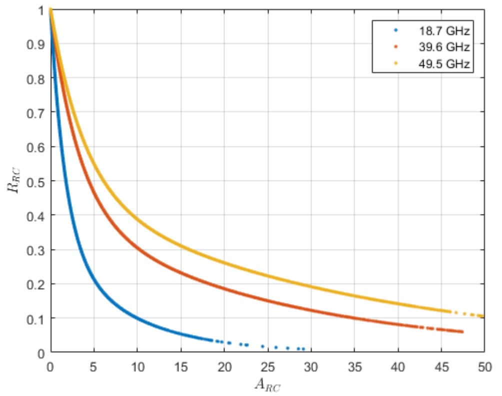

Figure 1: Trend of R_{RC} in function of A_{RC}

The last step to get the cloud attenuation and the rain attenuation is presented in the equations 4 and 5:

$$A_C = \begin{cases} R_{RC} A_{RC} & if \ A_{RC} \le A_{RC}^{max} \\ A_C^{max} & if \ A_{RC} > A_{RC}^{max} \end{cases} \quad (4)$$

$$A_R = A_{RC} - A_C \quad (5)$$

The coefficients a,b,c and A_{RC}^{max}, A_C^{max} depend from the frequency and their value is reported in the table 2.

Table 2: cloud coefficients

	a	b	c	A_C^{max} [dB]	A_{RC}^{max} [dB]
18.7 GHz	0.676	0.5905	0.12	1.1	11
39.6 GHz	0.5830	0.3065	0.04087	3.85	16.9
49.5 GHz	0.53	0.26	0.03	5.8	30

The paper used proposes the coefficients for the frequency of 19.7 and 39.4 GHz. To compute the coefficients for the frequencies of interest (18.7, 39.6 and 49.5 GHz), it is made a minimization of the difference between the ccdf of the cloud attenuation (from the equation 4) and the one estimated from radiosonde observations (RAOBS), collected at Milano-Linate airport using P-RH-T vertical profiles to derive the liquid water content by means of the TKK cloud detection algorithm. The cloud attenuation of comparison is calculated through the Liebe MPM93 model. Also the therm A_C^{MAX} is retrieved from the cloud attenuation derived with RAOBS data: A_C^{MAX} is set as the value reached from the ccdf exceeding the probability of 0.01%.

3.4. Overall attenuation

All the effects that are reducing the power of the signal due to tropospheric effects have been computed, the results are reported in ccdf form and for a day (1-datapoint per minute) for the three frequency of interest.

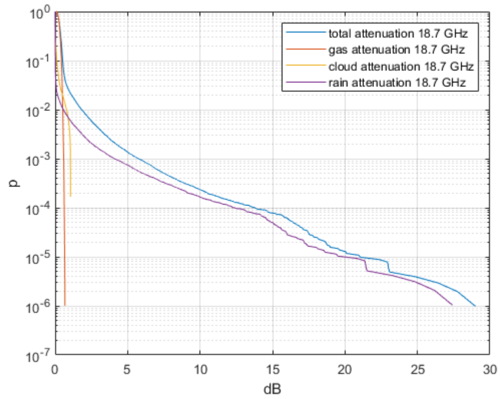

Figure 2: Every attenuation component for the frequency of 18.7 in ccdf form

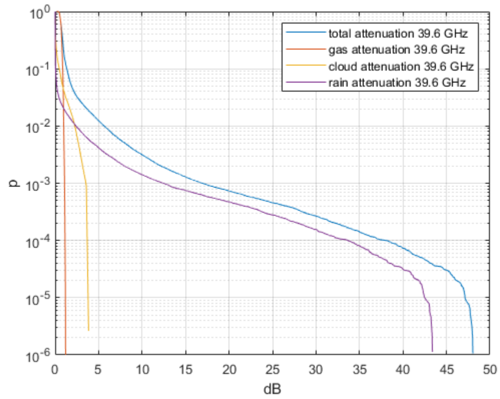

Figure 3: Every attenuation component for the frequency of 39.6 GHz in ccdf form

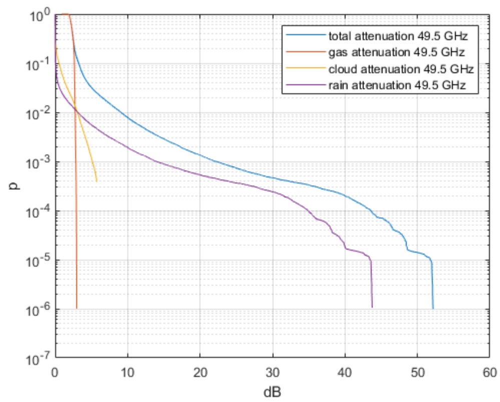

Figure 4: Every attenuation component for the frequency of 49.5 GHz in ccdf form

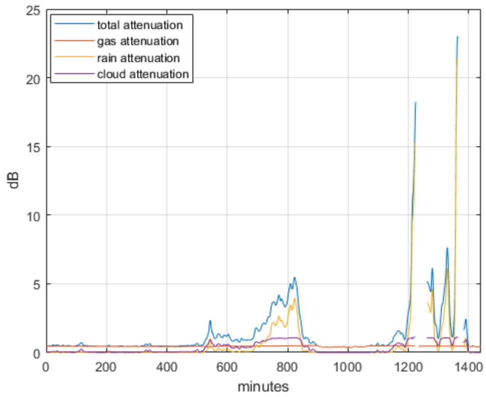

Figure 5: Total attenuation and its component at 18.7 GHz, 26 may 1995.

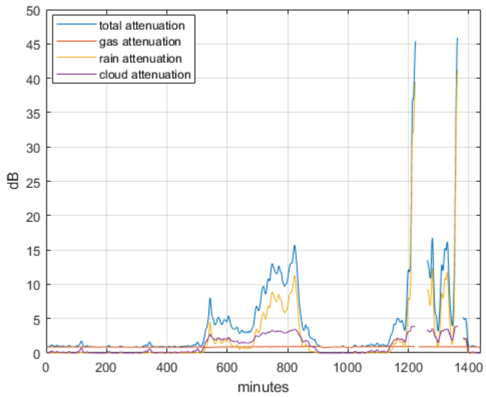

Figure 6: Total attenuation and its component at 39.6 GHz, 26 may 1995.

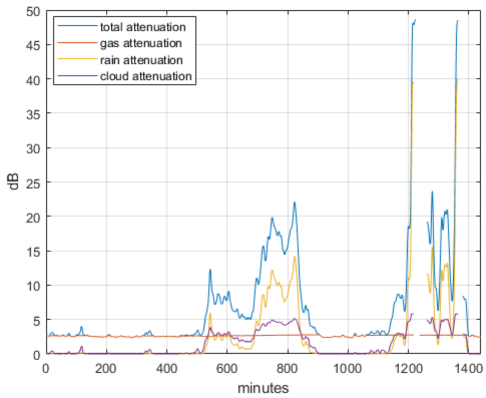

Figure 7: Total attenuation and its component at 49.5 GHz, 26 may 1995.

The figures 5, 6 and 7 present some "holes", these holes represent a missing data. This is due because the attenuation value goes beyond the dynamic range of the receiver and the data is interpreted as a `NaN` by `Matlab`. This issue is not present in the results in ccdf form because the `NaN` values are ignored by the function.

4. Frequency scaling

The frequency scaling technique (FS) is a methodology used to predict an attenuation at the frequency f_2 (higher frequency) starting from a frequency f_1 (lower frequency). It is possible to proceed with two different approaches; the first one is based on empirical relationship of a satellite link for two channels through approximating the ratio $\left(\frac{f_2}{f_1}\right)^n$, n is a numerical coefficient that belong to an interval between 1.72 and 2.0. The second approach instead is based on physical formulation of the attenuation of interest. This is a more physically sound approach, i.e. on an expression aimed at modeling rain attenuation starting from the rain rate. The purpose of this thesis, it is to implement a valid, accurate and easy model, based on the physical process of the problem. This method is based on the minimization of the error, between the real rain attenuation A_R (retrieved from the first thesis part) and the estimated rain attenuation $(\tilde{A}_R)$ which can be computed as:

$$\tilde{A}_R(f,\tau,\theta) = k(f,\tau,\theta)R^{\alpha(f,\tau,\theta)}PRF \quad (6)$$

The coefficientsα and k are obtained following the methodology illustrated in ITU-R P.838-3 [3], R is the rain rate [mm/h] and PRF is the path reduction factor: PRF represents the ratio of the effective path length of a link where the rain rate is considered as uniform, to that of the actual link length. It accounts for the inhomogeneity of the spatial form of rain along a given path.
The error can be written as:

$$\epsilon = |A_R - \tilde{A}_R| \;\Rightarrow\; \epsilon = |A_R - kR^{\alpha}PRF| \quad (7)$$

Finding the optimal R and the optimal PRF it is not a trivial task: there is a single equation in two different unknowns. The approach employed is a "brute force" method: a double for cycle is used to find the best couple of R and PRF such that the error ϵ is minimized. All the elements are now available to perform the frequency scaling:
First of all best the scaling factor is computed

with the equation 8

$$R_{SF} = \frac{k(f_2)R^{\alpha}(f_2)PRF}{k(f_1)R^{\alpha}(f_1)PRF} \quad (8)$$

Then the rain attenuation at the frequency f_2 is computed starting from the rain attenuation at frequency f_1 multiplying it with the scaling factor, as reported in equation 9

$$A_R(f_2) = R_{SF}A_R(f_1) \quad (9)$$

In the equation 8 PRF does not give a real contribution because it is elided during the ratio operation. However it is important compute it to check if the frequency scaling method is maintaining the physics of the rain attenuation. The results obtained with the phisically based frequency scaling (PBFS) are compared with the well known and consolidated Drufuca's method ($n = 1.72$).
In the PBFS method α and k coefficients are computed with methodology presented in ITU-R P.838 and they are not based on the DSD of the rain event that is actually disturbing the link. To improve the accuracy of the method it is possible to use a DSD model [4] which gives twelve possible $\alpha - k$ couple for the instant rain attenuation. The approach implemented is again a brute-force one with a triple for cycle.
The scaling operations are carried out in three different ways for the three proposed methods:

1) From 18.7 to 39.6 GHz
2) From 18.7 to 49.5 GHz
3) From 39.6 to 49.5 GHz

The scaling results for the third case are reported in ccdf form and for one day (one point per minute).

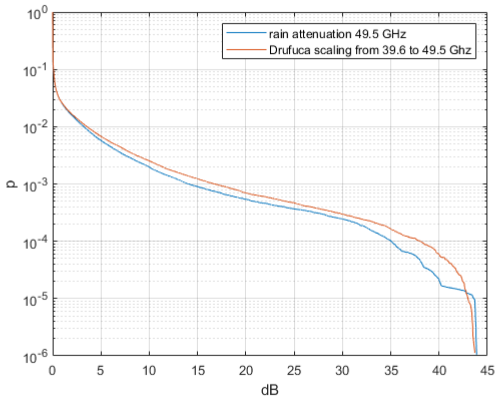

Figure 8: Frequency scaling from 39.6 to 49.5 GHz in ccdf form.

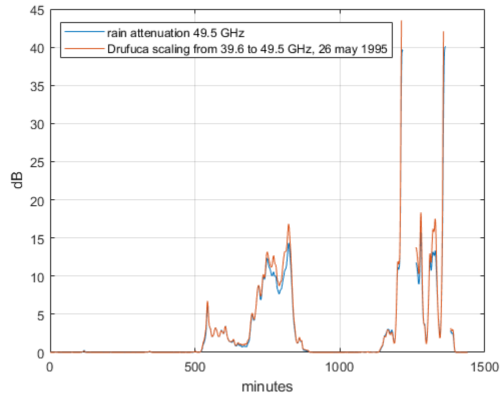

Figure 9: Frequency scaling from 39.6 to 49.5 GHz, 26 may 1995.

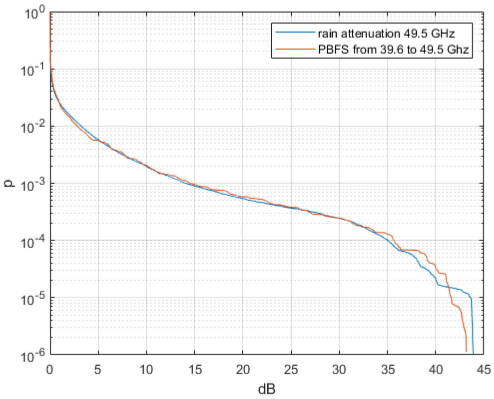

Figure 10: Frequency scaling from 39.6 to 49.5 GHz in ccdf form.

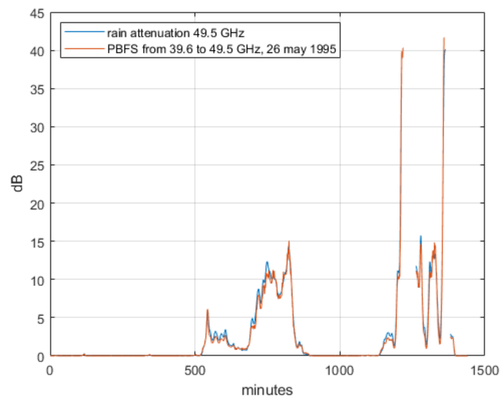

Figure 11: Frequency scaling from 39.6 to 49.5 GHz, 26 may 1995.

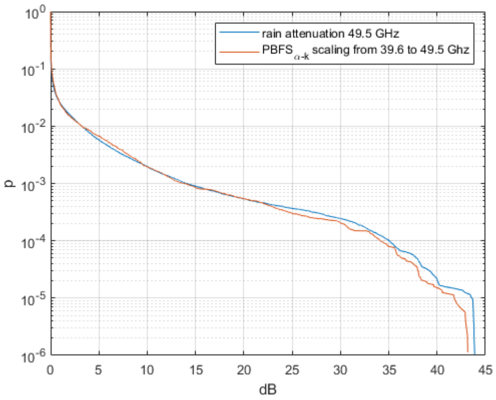

Figure 12: Frequency scaling from 39.6 to 49.5 GHz in ccdf form.

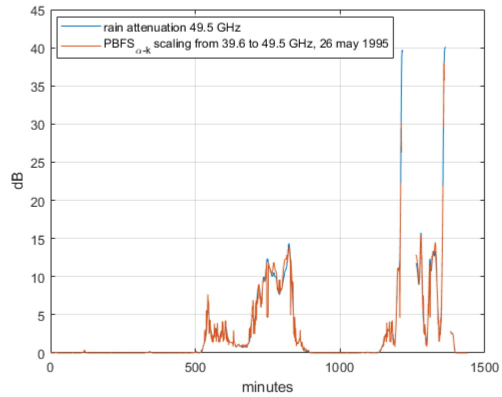

Figure 13: Frequency scaling from 39.6 to 49.5 GHz, 26 may 1995.

5. Results

The statistical analysis of the results obtained is performed on the ccdf of the rain attenuation over the biennium of interest of the dataset. To perform the analysis recommendation ITU-R P.311-18 [5] error figure is adopted.
The results of the mean value and the root mean square of the drufuca scaling method, PBFS method and the PBFS method with α and k optimization are reported in the tables 3, 4 and 5

Table 3: RMS and MV of Drufuca method

	RMS	MV
18.7 to 39.6 GHz	0.1646	-0.0740
18.7 to 49.5 GHz	0.1936	0.0231
39.6 to 49.5 GHz	0.1010	0.0871

Table 4: RMS and MV of PBFS method

	RMS	MV
18.7 to 39.6 GHz	0.1552	-0.0839
18.7 to 49.5 GHz	0.1874	-0.0265
39.6 to 49.5 GHz	0.0743	0.0290

Table 5: RMS and MV of PBFS method with α and k minimization

	RMS	MV
18.7 to 39.6 GHz	0.0931	-0.0204
18.7 to 49.5 GHz	0.1406	0.0713
39.6 to 49.5 GHz	0.0822	0.0327

For sake of completeness it is computed also the MV and the RMS of the error on a time series for the three scaling methods and for the three different scalings. This error is calculated as the difference between the real attenuation and the scaled one as reported in equation 10. Results are computed on the day of 26 May 1995 and they are reported in table 6

$$E_t = A_{REAL} - A_{SCALED} \tag{10}$$

Table 6: RMS and MV of the time series error

	Drufuca scaling		$PBFS$		$PBFS_{\alpha-k}$	
	MV	RMS	MV	RMS	MV	RMS
Error 18.7 to 39.6 GHz	0.0223	1.3154	-0.2322	1.2444	0.1150	1.7607
Error 18.7 to 49.5 GHz	0.2112	2.2517	-0.3760	1.9430	0.1920	2.8737
Error 39.6 to 49.5 GHz	0.2525	0.7873	-0.1399	0.4666	-0.0218	0.8242

6. Conclusions and future developments

The aim of this work is to investigate the attenuations on the link between the satellite and the ground station for frequencies above 10 GHz and the pros and cons of the use of higher frequencies. It has been explained the frequency scaling and the reason to use it and a physically based frequency scaling (PBFS) model has been proposed. The PBFS has been compared with the well known Drufuca empirical scaling model. An optimization of the PBFS introducing a drop size distribution (DSD) model and obtaining α and k coefficients is performed. The scaling is done on rain attenuation retrieved from a biennial dataset (1995-1996) coming from the ground station of Spino D'Adda. The results of the two

frequency scaling methods between rain attenuations in ccdf form has been evaluated with ITU-R P.311-18 error figure. The mean value (MV) and the root mean square (RMS) has been computed.
The RMS results obtained with the scaling from 18.7 to 39.6 GHz are 0.1646, 0.1552 and 0.0931 for Drufuca method, PBFS method and α and k optimization PBFS respectively. As it is possible to see the best results are coming from the last method. From the frequency of 18.7 to 49.5 GHz the RMS results are: 0.1936, 0.1874 and 0.1406. As it is possible to see the RMS is increasing when the frequency scaling has to cover a much higher leap. In the end the scaling is performed from 39.6 to 49.5 GHz and RMS results for three methods are: 0.1010, 0.0743 and 0.0822.
As it is possible to note from the RMS results the PBFS method and its optimization with the DSD model, guarantee a very good scaling maintaining the physics of the problem.
The possible future development are the use of a genetic algorithm to surpass the "brute force" approach applied in the PBFS method and get a local optimization for each point of the rain attenuation. Another future development it is to check how the methods behaves when they are used to scale in a greater frequency range.

References

[1] Enhancement of the Synthetic Storm Technique for the Prediction of Rain Attenuation Time Series at EHF Lorenzo Luini , Senior Member, IEEE, Alberto Panzeri, and Carlo G. Riva , Senior Member, IEEE.IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 68, NO. 7, JULY 2020.

[2] Rec. ITU-R P.676-13. "Attenuation by atmospheric gases". (2022).

[3] Rec. ITU-R P.838-3. "Specific attenuation model for rain for use in prediction methods". (2005).

[4] LI GUANJUN, An Analytical Model for the Attenuation and Phase Delay due to Rain in the 6-100 GHz Range, Politecnico di Milano, 2022.

[5] Recommendation ITU-R P.311-18, Acquisition, presentation and analysis of data in studies of radiowave propagation, 09/2021.