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FREQUENCY SCALING OF RAIN ATTENUATION FOR VERY HIGH THROUGHPUT SATELLITE SYSTEMS

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Abstract

In this paper, we present a methodology to compare frequency scaling techniques of rain attenuation. This methodology consists in obtaining rain attenuation from beacon measurements, selecting a subset of events, and applying metrics on the obtained time series. Are also discussed methodologies to separate the contributions of clouds and rain to attenuation, as well as a method to identify events affected by noise. The relevance of the approaches is evaluated on a database of satellite beacon attenuation: Italsat beacon measurements from Spino d'Adda (7 years).

1. Introduction

Some Very High Throughput Satellite (VHTS) systems in preparation plan to use Q/V band for their feeder links and Ka band for their user links in order to maximise global system capacity. At such frequencies, according to the local meteorological conditions, the tropospheric attenuation can become prohibitive. Ever since, in order to provide an acceptable link availability, UpLink Power Control (ULPC) and Adaptive Coding and Modulation (ACM) techniques are not sufficient and gateway diversity needs to be implemented. Switches of gateway to counteract propagation at Q/V band may be activated from estimation of the attenuation at 50 GHz [1]. This estimation can be carried out from measurements of attenuation from a downlink beacon at 40 GHz and/or at 20 GHz scaled at 50 GHz using frequency scaling techniques.

Frequency scaling is a technique to infer the attenuation at a given frequency from the knowledge of the attenuation at another frequency. It gives more accurate results than prediction methods using solely rainfall rate measurements [2]. It can be used either to convert Cumulative Distribution Functions (CDF) of attenuation from the lower frequency toward the higher or to synthesize attenuation time series for system design, or to perform real time frequency scaling to trigger ULPC or to switch from a gateway to another one using N+P diversity. At microwave frequencies, among all the tropospheric effects (rain, clouds and gases), rain attenuation is the most difficult to scale because its frequency scaling ratio can exhibit strong variations, in particular during a rain event [3].

A major part of the frequency scaling models presented in the open literature are empirically derived. This is the case of the model developed by L. Boithias, which is one of the model recommended by Rec. ITU-R P.618-13 [2], section 2.2.1.3.2, for scaling equiprobable attenuations (CCDF). A statistical model is proposed in section 2.2.1.3.1. Recently, two rain frequency scaling techniques have been proposed, both relying on a physical approach:

- Frequency scaling relying on the synthetic storm technique (SST) [5].
- Frequency scaling relying on dual beacon measurements with an inversion of the rain Drop Size Distribution (DSD) [6].

Because empirical models have been derived from measured propagation data, they have a limited frequency range (7 to 50 GHz for Boithias' model). On the contrary, physical models of rain frequency scaling rely on hypotheses on the rain drop size distribution, and should therefore have a wider frequency validity range (k and α coefficients of Rec. ITU-R P.838 are obtained from a Laws-Parsons rain DSD and are accurate up to 1000 GHz [7]). As a consequence, these physical models are expected to be more accurate for the design of future systems, such as W band for which no propagation data are available so far.

This paper aims to introduce a methodology to objectively compare frequency scaling models using error metrics. The models are briefly recalled in Section 2. Then, in Section 3, the full process to obtain a clean database of rain attenuation is explained. The error metrics used to evaluate the frequency scaling models are presented in Section 4. Their performances are finally compared in Section 5 by comparisons with experimental attenuation time series collected at Spino d'Adda (Italy, 7 years, frequencies 18.7 GHz, 39.6 GHz and 49.5 GHz).

2. Frequency scaling models

In this paper, three frequency scaling models are compared:

- The model proposed by L. Boithias, currently used by Rec. ITU-R P.618-13 (section 2.2.1.3.2) for frequency scaling of equiprobable attenuations. It was derived empirically using a fitting procedure on measurements at various frequencies.
- A frequency scaling technique based on the Synthetic Storm Technique (SST) for slant paths [4], or rather on an updated version, the so-called E-SST [5]. The SST is a physical model to reconstruct rainfall rate fields along the direction of the wind. Using a power relationship $\gamma_R = k \cdot R^\alpha$ to convert rain rate R [mm/h] into specific rain attenuation γ_R [dB/km], it is possible to calculate a frequency scaling ratio to scale the rain attenuation measurements from one frequency to the other.
- A model using measurements at two frequencies, based on an inversion of the drop size distribution of the rain along the propagation path [6].

3. Data and processing

3.1. Sources of Data

The data used for this analysis are:

- Propagation data: a database of beacon attenuation, measured in Spino d'Adda, from 1994 to 2000 (7 years), for the three frequencies of the Italsat beacons (18.7, 39.6 and 49.5 GHz), collected and processed by Politecnico di Milano. The time series are sampled at 1 Hz. Beacon attenuation is obtained by measuring the power level of the signal received by a satellite beacon, from which is subtracted a so-called 0 dB level corresponding to the level of power received in clear sky conditions. It is therefore the combination of clouds, rain and tropospheric scintillation.
- Rainfall rate time series from a tipping bucket rain gauge (60s integration time), collocated with the beacon receiver in Spino d'Adda.

- Reanalysis data (ERA5) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF): wind speed at 700 hPa and 0°C isotherm altitude as an input for the SST, and columnar cloud liquid water content to be used to compute the CDF of cloud attenuation. The conversion between columnar cloud liquid water content and cloud attenuation is done using Rec. ITU-R p.840-8, section 3.2 [8]. These data are interpolated at the location of the beacon receiver from a 0.25° grid in longitude and latitude. The time resolution is 1 hour.

All data are used with a strict sample-by-sample concurrency.

3.2. Selection of high quality periods for beacon attenuation

Beacon attenuation measurements are used, after a procedure described in the following section, as an input for rain frequency scaling models (at 18.7 and 39.6 GHz), but also as a reference (at 49.5 GHz). Consequently, these measurements must not be too affected by unwanted signals in order to obtain significant results. The amplitude of tropospheric scintillation can be quite high in beacon measurements [9]. Issues with the beacon receiver, for instance due to aging of the components, might cause errors in the data as well. This section describes an automated procedure to identify the parts of the database with the highest quality.

It is generally accepted that the power spectral density (PSD) of beacon attenuation is composed of several parts. The PSD for frequencies below 0.02 to 0.1 Hz are the result of rain and cloud attenuation, and display a typical -20 dB/decade slope [10]. The PSD for higher frequencies is ordinarily caused by scintillation, with a flat part up to a cut-off frequency, followed by a -80/3 dB/dec slope [11]. Figure 1 shows examples of PSD of attenuation derived from daily experimental time series. The blue curve corresponds to a rain event with very low noise levels, whereas the red curve corresponds to a day affected by strong scintillation, which happens more often during the summer period [11]. For the classical modelling of scintillation, with a flat spectrum below its cut-off frequency, a measurement of the power spectral density in a narrow band around 0.1 Hz is expected to be representative of the relative level of noise in the measurements. Eventual issues of the receiver causing noise with high frequency spectral components (such as white noise) could be detected as well.

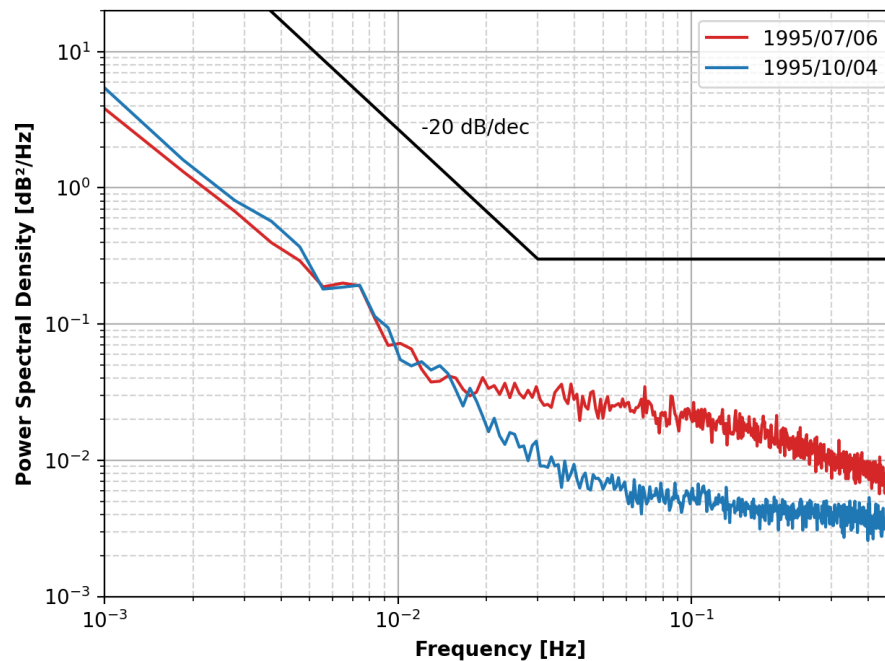


Figure 1: Power spectral density of beacon attenuation of 2 distinct days, at Spino d'Adda, 39.6 GHz.

3.3. Processing of experimental beacon measurements

The conventional method [12] to obtain validated rain attenuation (in-excess attenuation) time series consists in several steps. First, the high frequency components of the signal, dominated by tropospheric scintillation or noise, are removed with a low-pass filter (with a typical cut-off frequency of 0.025 Hz). Then, the rain events are marked (often with a visual inspection of beacon attenuation and rain gauge time series), to remove a value linearly interpolated between the attenuations at the beginning and at the end of the rain event. Nevertheless, the identification of rain events is not an easy task, especially on a slant path for which the presence of rain on the beacon receiver (measured punctually by a rain gauge) may not be representative of the presence of rain along the propagation path. In addition, cloud attenuation is likely to increase with rain intensity, which would cause rain attenuation to be overestimated.

To overcome this difficulty, this study uses the statistical method proposed in [5] to remove the contribution of clouds from the beacon attenuation. This method consists in defining the attenuation due to clouds as a function of the beacon attenuation. The function is defined so that the distribution of cloud attenuation matches as well as possible a reference distribution. In [5], the reference cloud distribution is computed from radiosonde measurements (RAOBS). Particularly, the cloud attenuation A_C is calculated from the beacon rain+cloud attenuation A_{RC} from: a, b, c, A_C^{max} and A_{RC}^{max} :

$$A_C = \begin{cases} R_{RC} \cdot A_{RC}, & A_{RC} \leq A_{RC}^{max} \\ A_C^m, & A_{RC} > A_{RC}^{max} \end{cases} \quad (1)$$

$$R_{RC} = a \exp(-bA_{RC}) + (1 - a) \exp(-cA_{RC}), \quad (2)$$

where a, b, c, A_C^m and A_{RC}^m are parameters determined by an optimization procedure to fit the equiprobable values of A_C and the reference cloud attenuation derived from RAOBS. The rain attenuation $A_R = A_{RC} - A_C$ is then obtained by subtracting the cloud attenuation A_C to the beacon attenuation A_{RC} .

In the present paper, as ERA5 data are used instead of RAOBS measurements, a new formulation is proposed for A_C :

$$A_C = \frac{\log_{10}(\beta \cdot A_{RC} + 1)}{\beta} \quad (3)$$

$$\beta = a \cdot (1 - e^{-b \cdot A_{RC}}), \quad (4)$$

where a and b are obtained by fitting the values of A_C exceeded for various time percentages to the reference values of cloud attenuation, exceeded for the same time percentages, derived from ERA5 data. Equations (3) and (4) have been derived empirically, and gave good results for the site of Spino d'Adda (at 18.7, 39.6 and 49.5 GHz) as can be observed on Figure 2 where the cloud attenuation Complementary CDF (CCDF) is represented from ERA5 data (the reference), from equations (1) and (2) (methodology of [5]) and from equations (3) and (4) (our approach). Similar results have been observed using beacon attenuation collected in Toulouse. Nevertheless, it is not obvious that this particular function will provide a good fit for all datasets, especially if the climatology is different. Using tabulated values of A_C and A_{RC} could be a more practical approach for a larger number of sites. It is worthwhile to note that above probabilities of exceedance of 10%, the cloud attenuation computed from ERA5 data is higher than the beacon attenuation, presumably because of the spatial resolution of ERA5 (the columnar cloud liquid water content is averaged over $0.25^\circ \times 0.25^\circ$ pixels). Figure 3 shows the rain attenuation CCDF (in-excess attenuation) derived from the experimental measurements once the cloud contribution is removed with equations (3) and (4).

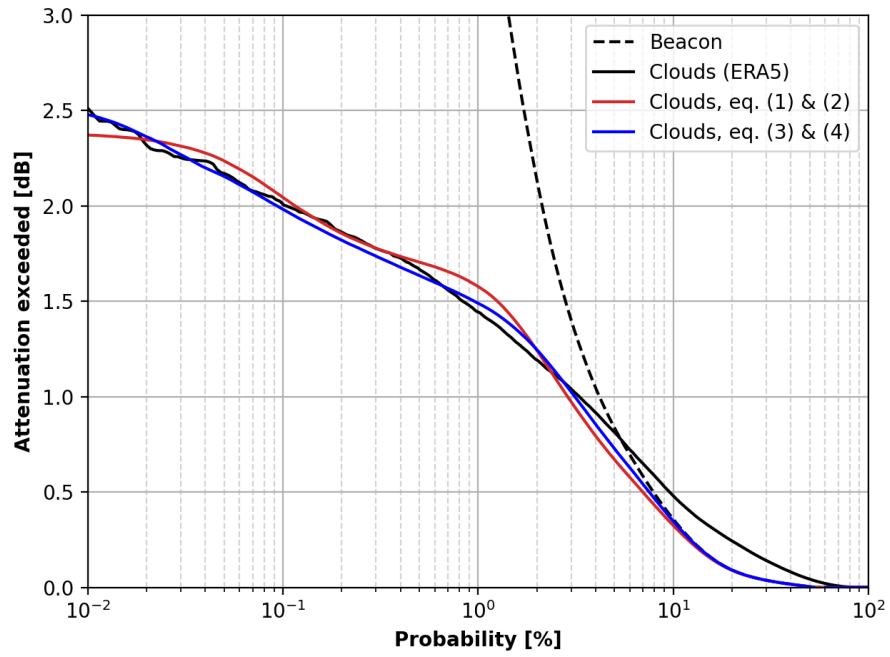


Figure 2: CCDF of attenuation over 7 years (1994-2000), at Spino d'Adda, 39.6 GHz, for clouds from ERA5 data (reference CCDF), from [5] with (1) and (2), and from (3) and (4).

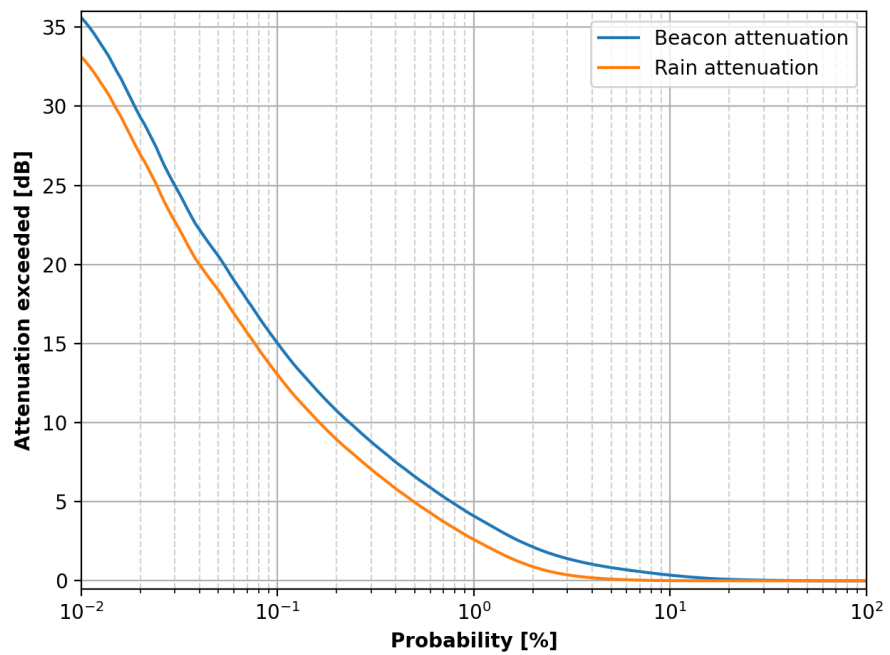


Figure 3: CCDF of rain attenuation at 39.6 GHz derived from beacon measurements once (3) and (4) are applied.

4. Error metrics

Usual metrics used to compare synthetic attenuation time series (i.e. derived from frequency scaling algorithms) with experimental ones are the following: the root mean square error (RMSE), the standard deviation, and the mean error (or bias). One common approach is to compute these metrics on the full set of samples of the database, and to give the result as a single number [5], [13]. While this approach has the advantage of being simple, it is problematic for several reasons:

- Due to the lognormal distribution of rain attenuation [14], most samples refer to low attenuation values: typically, half of the identified rain events in the database of Spino d'Adda have peak attenuations below 5 dB at 49.5 GHz. Consequently, usual single-figure error metrics will be mainly determined by the performance of frequency scaling models at low attenuations, while higher attenuations are of grand interest for fade mitigation techniques.
- It is expected that the mean error of the frequency scaling models depends on the attenuation (the frequency scaling model currently proposed by the ITU predicts that the frequency scaling ratio decreases with increasing attenuation [2]). Averaging the mean error on the entire database could cancel out attenuation dependent biases of opposite signs.

Giving the RMSE and bias for bins of attenuation solves these issues. In this paper, error figures use equal frequency binning (all bins contain the same number of samples), so that all points have the same statistical significance.

5. Results

The three frequency scaling models previously mentioned have been applied on the database of Italsat beacon attenuation, recorded in Spino d'Adda between 1994 and 2000 by Politecnico di Milano. The procedure to remove noisy events described in section 3.2 significantly reduced the RMSE of all frequency scaling models (specifically, Figure 4 shows improvements in terms of RMSE for the model of the ITU).

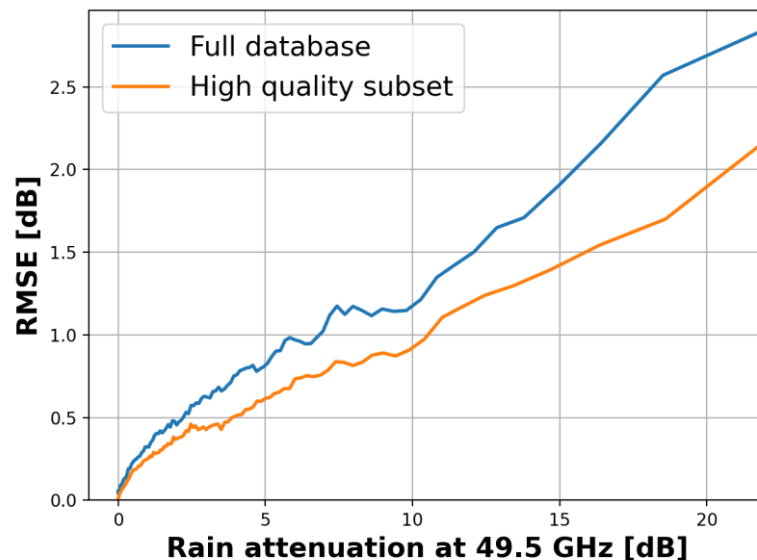


Figure 4: Binned root mean square error of the frequency scaling technique of Rec. ITU-R P.618-13 for (blue curve) the full database of rain events and (orange curve) a reduced set of events selected using an analysis based on the power spectral density of the rain events.

All later results use a database with noisy events excluded. A rain event for the three beacon frequencies is shown in Figure 5, with the three frequency scaling models previously mentioned.

The prediction frequency is 49.5 GHz, the models from ITU and SST use measurements at 39.6 GHz (frequency scaling techniques give better results when the frequencies are close). The bi-frequency scaling technique uses measurements at 18.7 GHz and 39.6 GHz. Figure 6 gives the performance of the three frequency scaling models on the full database.

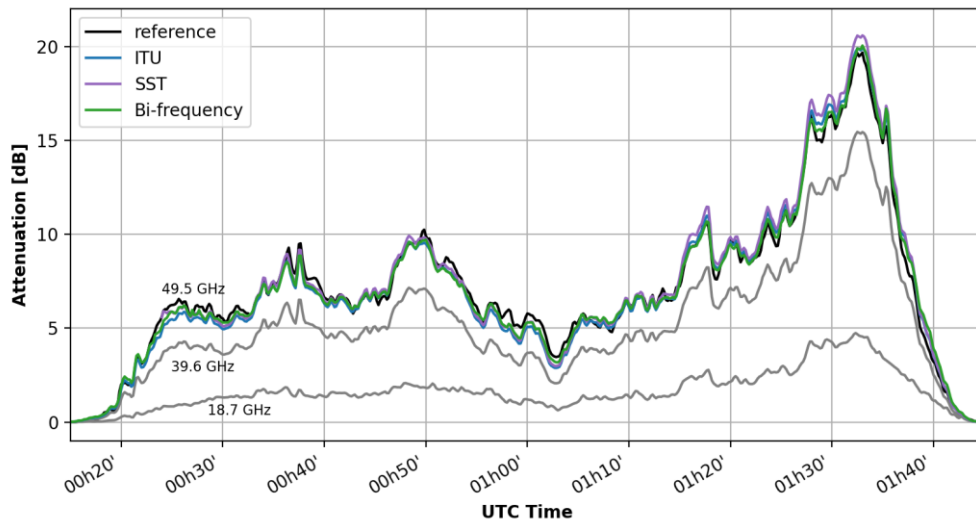


Figure 5: Example of a rain event in Spino d'Adda (11th of June, 1995), with the rain attenuation at the three frequencies, and attenuation from frequency scaling models.

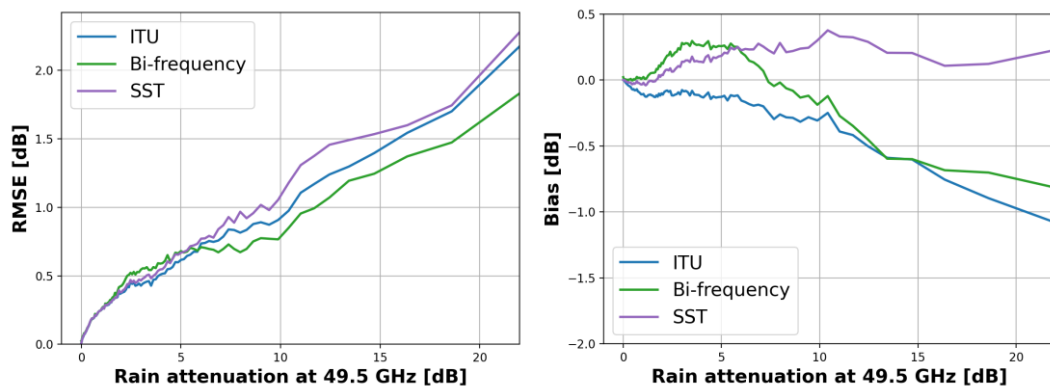


Figure 6: Binned error metrics for frequency scaling models at 49.5 GHz, Italsat, Spino d'Adda. Left: RMSE. Right: mean error.

In terms of RMSE (Figure 6, left), the three models give similar results. The bi-frequency model presents a slightly lower RMSE than the model of Rec. ITU-R P.618-13 for attenuations above 5 dB, but it is biased: it overestimates attenuations lower than 5 dB, and underestimates attenuations above 10 dB (Figure 6, right). The SST is the less biased, but its RMSE is slightly higher. An analysis showed that high values of error came from convective events, for which the rain rate measured by the rain gauge was low when compared to the level of attenuation.

6. Conclusion

Three frequency scaling models of rain attenuation have been compared on the propagation database of Italsat, in Spino d'Adda (7 years). To this aim, a new formulation of the statistical method to derive the attenuation due to rain from satellite beacon measurements has been proposed. A procedure to automatically detect noisy events has also been implemented, which results in a cleaner database with reduced errors for the frequency scaling models. The two physical frequency scaling models (one using the Synthetic Storm Technique, the other based on an inversion of the rain drop size distribution) show promising results when compared with the current empirical frequency scaling model of the Recommendation ITU-R P.618-13. Their physical basis place them as better candidates for higher frequency bands for which no measurements are currently available, though their validity to other climatological areas has still to be demonstrated.

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