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Predicting total tropospheric attenuation on monthly basis

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Lorenzo Luini[1] ✉, *Carlo Capsoni*[1], *Carlo Riva*[1], *Luis David Emiliani*[2]

[1]*Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133, Milano, Italy*
[2]*SES, Château de Betzdorf, L-6815, Betzdorf, Luxembourg*
✉ *E-mail: lorenzo.luini@polimi.it*

Abstract: This contribution presents a comprehensive methodology for the global prediction of monthly total tropospheric attenuation statistics. This goal is achieved by combining the outputs of physically-based models for the estimation of the attenuation induced by each relevant atmospheric constituent (gases, clouds and rain). To evaluate the model's accuracy, worst month total attenuation statistics are first derived from the monthly attenuation predictions, and tests are performed against the measurements included in the global DBSG3 database of International Telecommunication Union-Radiocommunication Sector. Results show a good prediction accuracy, which corroborates the use of the proposed physical model to aid engineers in planning future high-frequency satellite communication systems on the basis of the worst month concept.

1 Introduction

The temporal characteristics of tropospheric attenuation phenomena is a key topic of current research activities on radio wave propagation, as reflected by the International Telecommunication Union-Radiocommunication Sector's (ITU-R) focus on the temporal behaviour of attenuation phenomena at various time scales (evidenced by Questions 201-4/3 and 209-1/3 [1, 2]). The short-term temporal variability and fade dynamics are required to model fade mitigation techniques such as adaptive coding and modulation and uplink power control. Longer-term behaviour (monthly, seasonal) is needed to estimate the expected variability within the year of the predictions obtained from models on yearly basis. The analysis of the month-to-month variability of various tropospheric phenomena and the capability of predicting the magnitude of fades on a monthly basis are of particular importance considering that design objectives (performance and availability) for terrestrial and satellite microwave systems are already defined by the ITU-R as applicable to 'any month': see for example ITU-R F.1668 [3], S.1424 [4], ITU-R BO.1696 [5].

The current approach recommended by the ITU-R to system planners is to consider the objectives as applicable to the worst propagation conditions that could occur in a whole year, that is, to perform predictions of worst-month propagation statistics using ITU-R Recommendation P.841 [6]. The disadvantage of this approach is that it is limited in scope – strictly speaking, limited to rain attenuation – and in applicability, given the empirical nature of the model included in P.841 [6]. Moreover, in the context of satellite payload planning, reliable monthly statistics of propagation impairments are very important: direct to home (DTH) satellite services (with design objectives referred to 'any month' and given by [4]) are amongst the top revenue-generating satellite services [7]. As the required power emitted by the transponder is dictated by the results of a link budget which could be driven by the worst rain attenuation conditions (in Ku and Ka bands), monthly cumulative statistics of propagation impairments play a key role in the sizing of a DTH satellite payload following the ITU-R framework.

The abovementioned elements frame the need for – and the importance of – adequate predictions of the main tropospheric impairments (gaseous absorption, clouds and rainfall attenuation) on a monthly scale. This contribution addresses this need by presenting a comprehensive methodology for the prediction of these propagation impairments, using a unified physically-based approach. Specifically, the proposed methodology, hereinafter referred to as monthly attenuation statistics prediction (MASP), combines physically sound models for the estimation of the attenuation due to rain, clouds or gases to predict total attenuation. Section 2 describes each of the propagation models, whose combination allows the prediction of monthly total attenuation statistics. Section 3 discusses the performance of MASP when used for the prediction of the worst month total attenuation statistics, taking as reference the data included in the DBSG3 database of ITU-R. Finally Section 4 draws some conclusions on the work.

2 Prediction of monthly statistics of total tropospheric attenuation

The rationale of the methodology proposed in this contribution to predict monthly statistics of total tropospheric attenuation is to combine some models that have been originally proposed in the literature to allow the prediction of yearly statistics of attenuation due to a given atmospheric constituent but, owing to the solid physical concepts which they rely on, have been extended to the monthly time scale with very limited effort, that is, by simply providing monthly instead of yearly inputs. Such models, described in more detail in the sections below, are:

- SC EXCELL for rain attenuation statistics prediction [8].
- The models adopted in ITU-R recommendations P.676-10 [9] and P.840-6 [10] for the statistical prediction of the attenuation due to gases and clouds, respectively.

In addition to the aforementioned models, the next section deals with MOdel for Rainfall Statistics Estimation (MORSE), which has been presented in [11] for the prediction of rain rate statistics on monthly basis, a necessary input to MASP.

2.1 Rain rate modelling: MORSE

The knowledge of the local rain rate occurrence is a mandatory element for any model aimed at estimating rain attenuation on

Earth-space links. Being global rain rate statistics with 1-minute integration time not easily retrievable worldwide (such a short sampling time is required for propagation applications to properly catch the high temporal variability of precipitation), several models have been developed to predict the complementary cumulative distribution function (CCDF) of the rain rate, commonly referred to as $P(R)$. The most acknowledged of such methodologies is the one currently adopted in Annex 1 of ITU-R recommendation P.837-6, which requires as input coarse information on the local precipitation, that is, the stratiform and convective mean yearly rain amounts, M_s and M_c, respectively, and the probability to have rain in 6 hours, P_{r6}. Recently, a new rain rate prediction model has been proposed in [11], named MORSE, which relies on the same meteorological inputs of the ITU-R P.837-6 model (except for P_{r6}, which is no longer required) and, as shown in [11], intrinsically offers the same level of accuracy. Besides this, the main advantage of MORSE lies in the chance to predict the local $P(R)$ at different time scales, including on monthly basis ($P(R)^{m}$), which is of specific interest for MASP: indeed, this kind of information is the key element to estimate monthly rain attenuation statistics as shown in Section 2.2.

According to MORSE, the local $P(R)$ can be predicted using the following analytical expression [11]:

$$P(R) = P_0\left[\ln\left(\frac{R_a + R_{low}}{R + R_{low}}\right)\right]^{n} \tag{1}$$

In (1), R is the rain rate (mm/h) exceeded with probability P, while P_0, R_a, n and R_{low} are tuning parameters that allow adapting the expression in (1) to the site of interest according to the local values of $M_t = M_s + M_c$ and $\beta = M_c/M_t$ (both M_s and M_c are expressed in mm):

$$\begin{aligned} n &= -36.18\overline{\beta}^{0.1242} + 36.92 \\ n &= 8.43\times 10^{-4} R_a^{1.3531} + 1.44 \\ R_{low} &= \begin{cases} 31.85\overline{\beta}^{-0.0086} - 31.94 & \overline{\beta} \le 0.72 \\ 10^{-4} & \overline{\beta} > 0.72 \end{cases} \\ P_0 &= \frac{M_t}{(R_a + R_{low})\gamma\big(n+1,\ \ln(R_a + R_{low}/R_{low})\big)} \end{aligned} \tag{2}$$

where γ is the incomplete gamma function. In (2), the first and third equations allows to estimate n and R_{low}, respectively, from $\overline{\beta}$, while the second one needs to be inverted for the derivation of R_a from n. It is worth noticing that it is necessary to set $\overline{\beta} = \beta$ for $\beta \geq 0.001$ and $\overline{\beta} = 0.001$ for $\beta < 0.001$ to prevent R_{low} from approaching infinity.

MORSE was developed by using as reference a limited set of long-term 1-minute integrated $P(R)$s (yearly basis) collected worldwide and gathered in the DBSG3 database of ITU-R [12], and by using as input the same M_t and β values made available by the ITU-R in recommendation P.837-6 as gridded global maps (spatial resolution: 1.125° × 1.125° latitude × longitude grid). As for the use of MORSE on monthly basis, the meteorological inputs are derived from the same source, that is, the ERA40 database of European Centre for Medium-range Weather Forecast (ECMWF), which includes 40 years of meteorological reanalysis data: in this case M_t and β are calculated on mean monthly basis (henceforth M_t^{m} and β^{m}).

Tests performed in [11] using as reference 84 monthly curves collected in seven sites for at least 5 years, show an average root mean square (RMS) of the relative prediction error around 25%, fully in line with the one typically achieved on yearly basis. Such a good score, derived from a limited database, is mostly ascribable to the use of raingauge-derived M_t values as input to MORSE (instead of M_t^{m}), which better reflects the rain amount actually accumulated in the site, thus allowing to evidence the intrinsic accuracy of MORSE.

As an example, Fig. 1 shows some monthly $P(R)$s predicted using MORSE for the site of Spino d'Adda, Italy (latitude: 45.4 °N and longitude: 9.5 °E), which points out the marked variability of the rainfall process from month to month. As expected from the temperate climate in the site, precipitations in winter and autumn tend to be more frequent but less intense (stratiform like) than those falling during Spring and Summer (convective like).

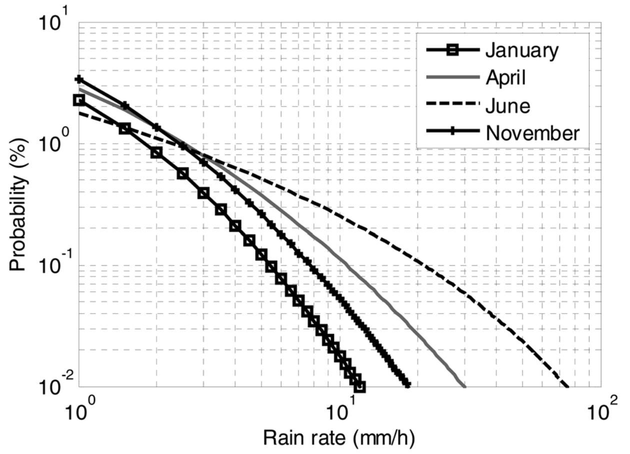

Fig. 1 *Example of the monthly P(R)s predicted using MORSE for the site of Spino d'Adda, Italy (latitude: 45.4 °N and longitude: 9.5 °E)*

2.2 Rain attenuation modelling: SC EXCELL

First proposed in [8] as a model to estimate yearly rain attenuation statistics, SC EXCELL relies on the cellular representation of precipitation to simulate the interaction of the radio link with the rainfall environment in different scenarios. The synthetic rain cells generated by SC EXCELL are all exponentially shaped with rotational symmetry but are characterised by different peak rain rate R_M and equivalent radius ρ_0. Every cell, completely identified by a couple of R_M and ρ_0, is associated with a different probability of occurrence, which, in turn, is calculated analytically from the local $P(R)$ [13]. The key feature of SC EXCELL is the ability to separately take into account the effects of stratiform and convective precipitation on the system: while the former typically carries moderate rain rates of limited vertical extent but large horizontal coverage, the latter consists of localised intense precipitation, which may develop vertically up to several kilometres. Indeed, SC EXCELL classifies synthetic rain cells into stratiform and convective and considers different rain heights to derive rain attenuation. Furthermore, only for stratiform rain cells, the model also includes the additional attenuation induced by the bright band, that is, the transition layer typically close to the 0 °C isotherm height, where ice/snow particles gradually melt into water drops in their fall to the ground.

SC EXCELL has been successfully applied for the prediction of rain attenuation impairing Earth-space [8] and terrestrial links [14]. Recently, the model has been updated in the framework of a European Space Agency research activity focused on the assessment of propagation effects in the W band [15] with the main aim to extend its application to frequencies up to the 85 GHz. The upgrades to the model, mainly concerning the expressions to calculate the convective rain height and the equivalent vertical extent of the bright band, are all listed in detail in [16], where, in addition, SC EXCELL was validated as for the prediction of $P(A_R)^{m}$, the CCDF of rain attenuation on monthly basis: thanks to its physical soundness, when receiving as input monthly CCDFs of the rain rate, $P(R)^{m}$, and monthly rain height values extracted from the ERA40 database, with no additional changes, SC EXCELL has shown a satisfactory performance in predicting $P(A_R)^{m}$, though obviously lower than that obtained for yearly statistics, mainly due to the reduced statistical stability of the curves (average RMS of the error figure, defined according to ITU-R recommendation P.311-14 [17], equal to 0.17 and 0.26 for yearly and monthly predictions, respectively). In both cases, tests were performed against the rain attenuation data collected in Spino d'Adda during the long-term ITALSAT propagation experiment (7 years, beacon receivers at 18.7, 39.6 and 49.5 GHz, co-located ancillary equipment such as raingauge and radiometers).

Fig. 2 depicts the monthly rain attenuation statistics predicted by SC EXCELL for the months reported in Fig. 1 using the characteristics of the radio link between the Spino d'Adda station and the ITALSAT satellite: elevation angle of 37.7°, 39.6 GHz operation frequency and circular wave polarisation.

2.3 Predicting the attenuation induced by clouds and gases: the ITU-R recommendations

Rainfall is certainly the prevalent impairments to electromagnetic waves above 5 GHz travelling through the atmosphere, but also the impact of gases and clouds might become relevant depending on the frequency range considered (e.g. absorption peaks of water vapour and oxygen around 22 and 60 GHz, respectively) and, in any way, because of the much higher occurrence probability of such constituents with respect to precipitation.

In this work, the attenuation induced by clouds is taken into account by resorting to the methodology included in ITU-R recommendation P.840-6 [10], that is, the Teknillinen KorkeaKoulu – Helsinki University of Technology model originally proposed in [18]. The calculation of cloud attenuation statistics relies on the reduction of the liquid water content to a given temperature, namely 0 °C, which allow to circumvent the need of full vertical profiles of liquid water content w and temperature T; in fact, a single specific attenuation coefficient K_w can be defined and used to calculate the attenuation due to clouds A_C using the statistics of reduced integrated liquid water content W_R attached to recommendation ITU-R P.840-6 in the form of global gridded maps (resolution of 1.125° × 1.125°, latitude × longitude grid):

$$A_C = K_w \, W_R \tag{3}$$

Thanks to its solid physical foundation, recently the application of the ITU-R P.840-6 model has been extended to the monthly basis with the provision by ITU-R of monthly statistics of W_R with the same previous resolution and spatial coverage. Tests on its prediction accuracy are reported in [19]: results indicate that the accuracy of recommendation P.840-6 decreases marginally when shifting from yearly to monthly statistics (again mostly depending on the reduction in the statistical stability of the curves), though keeping absolutely within acceptable levels (overall RMS of the prediction error, defined again according to ITU-R recommendation P.311-14 [17], equal to 0.17 and 0.23, respectively).

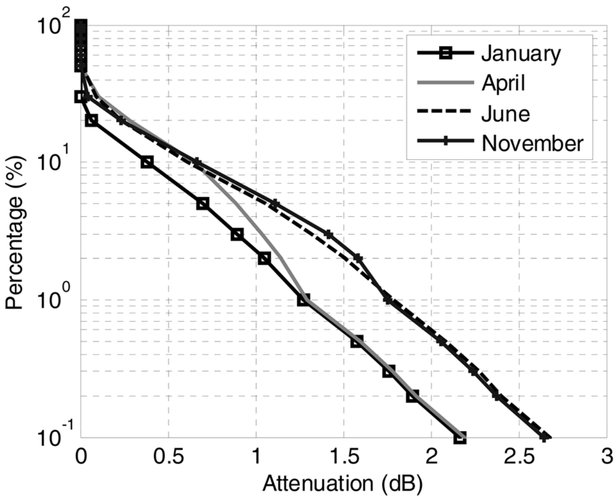

Fig. 3. *Example of the monthly P(A)s due to clouds predicted by ITU-R recommendation P. 840-6 for the months reported in Fig. 1, using the characteristics of the radio link established between the Spino d'Adda station and the ITALSAT satellite (elevation angle of 37.7°, 39.6 GHz operation frequency)*

The same exercise was repeated in [19] with the method adopted in ITU-R recommendation P.676-10 to estimate the attenuation due to water vapour A_V [9], whose applicability has been extended as well through the introduction of monthly meteorological maps. The prediction procedure originates from a simplification of the Liebe's MPM93 model [20] that allows to estimate A_V using maps of the integrated water vapour content V and of the water vapour scale height V_H attached to the said recommendation. The tests in [19] reveal a very satisfactory prediction performance of the ITU-R P.676-10 model in predicting A_V, basically independent of the frequency and the considered time scale (overall RMS of the prediction error, defined again according to ITU-R recommendation P.311-14 [17], equal to 0.035 and 0.038, on yearly and monthly basis, respectively).

Figs. 3 and 4 show sample CCDFs of the attenuation due to clouds and water vapour, respectively, again for January, April, June and

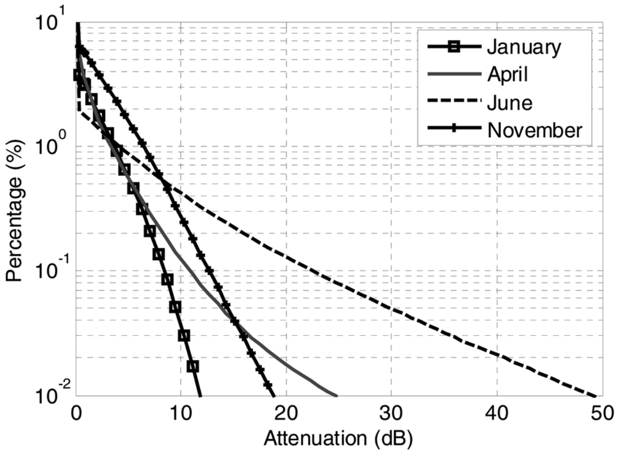

Fig. 2 *Example of the $P(A_R)^m$s predicted by SC EXCELL for the months reported in Fig. 1, using the characteristics of the radio link established between the Spino d'Adda station and the ITALSAT satellite (elevation angle of 37.7°, 39.6 GHz operation frequency and circular wave polarisation)*

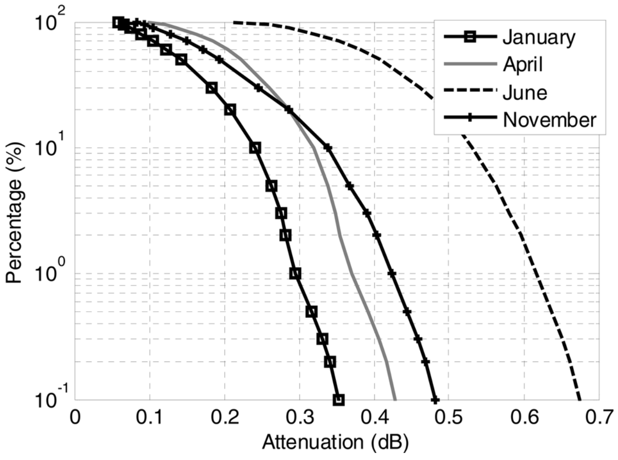

Fig. 4 *Example of the monthly P(A)s due to water vapour predicted by ITU-R recommendation P. 676-10 for the months reported in Fig. 1, using the characteristics of the radio link established between the Spino d'Adda station and the ITALSAT satellite (elevation angle of 37.7°, 39.6 GHz operation frequency)*

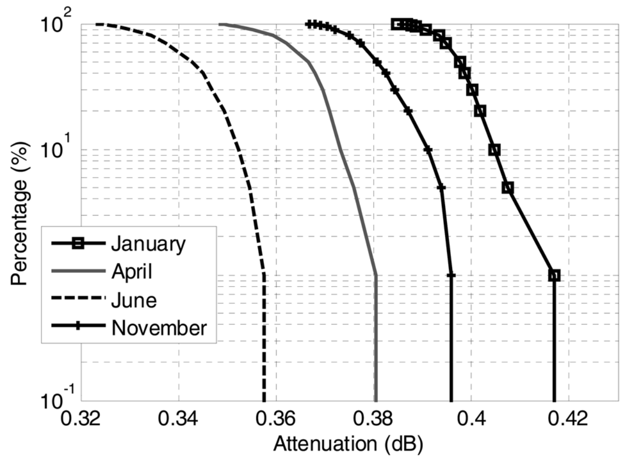

Fig. 5 *Example of the monthly P(A)s due to oxygen predicted by ITU-R recommendation P. 676-10 for the months reported in Fig. 1, using the characteristics of the radio link established between the Spino d'Adda station and the ITALSAT satellite (elevation angle of 37.7°, 39.6 GHz operation frequency)*

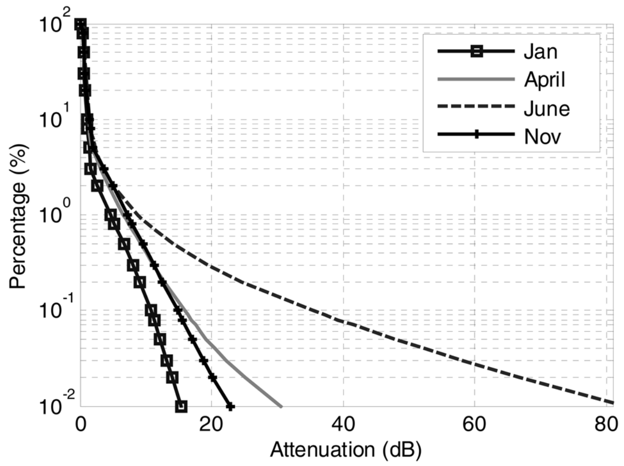

Fig. 6 *Example of the monthly P(A)s due to all constituents predicted by combining all the prediction models for the months reported in Fig. 1, using the characteristics of the radio link established between the Spino d'Adda station and the ITALSAT satellite (elevation angle of 37.7°, 39.6 GHz operation frequency and circular wave polarisation)*

November. As for the previous results, the ground station is Spino d'Adda and the link characteristics are derived from the ITALSAT experimental campaign mentioned above. While the contribution of water vapour is very limited at 39.6 GHz being such frequency far from the absorption peak around 22 GHz, the contribution of clouds is clearly not negligible and varies markedly from month to month.

The final contribution to attenuation comes from oxygen, whose impact is generally very limited, except for the frequency range around 60 GHz, where a very strong absorption peak lies. The ITU-R defines in recommendation P.676-10 a simplified approach for the calculation of the attenuation due to oxygen, A_{OX}, which also relies on the Liebe's MPM93 model, and receives as input the surface pressure P_{surf} and temperature T_{surf}, the latter having the highest impact on A_{OX}. Although not yet officially extended by ITU-R to address the prediction of monthly statistics, the model in ITU-R P.676-10 can be reliably applied using as input mean monthly maps of P_{surf} and T_{surf} derived from the ERA40 database: indeed, as obtained for water vapour, the estimation error is expected to remain approximately constant when shifting from yearly to monthly basis [21].

Fig. 5 shows sample CCDFs of the attenuation due to oxygen considering the ground station set in Spino d'Adda and the link characteristics of the ITALSAT link mentioned above. At 39.6 GHz, the impact of oxygen is comparable to that of water vapour, but the month-to-month variability of the former is much more limited.

2.4 *Combination of all the contributions to monthly tropospheric attenuation*

Except for the oxygen attenuation prediction method included in ITU-R P.676-10, all the models described in the previous sections have been separately evaluated in their ability to predict monthly CCDFs, providing satisfactory results. The combination of all these curves associated to different propagation effects can be achieved using the customary rule defined in ITU-R recommendation P.618-11 [22], that is:

$$A_{\mathrm{TOT}}(P) = A_{\mathrm{V}}(P) + A_{\mathrm{OX}}(P) + A_{\mathrm{C}}(P) + A_{\mathrm{R}}(P) \qquad (4)$$

where $A_{\mathrm{V}}(P)$, $A_{\mathrm{OX}}(P)$, $A_{\mathrm{C}}(P)$ and $A_{\mathrm{R}}(P)$ are the attenuation due to water vapour, oxygen, clouds and rain, respectively, all exceeded with probability P in each of the months. Equation (4) does not include the contribution of scintillations because one side no monthly meteorological maps of the wet term of the radio refractive index (N_{wet}) are yet available for the application of ITU-R P.618-11 scintillation model and, on the other side, the impact of scintillations also depends on additional parameters such as the antenna dimension and efficiency. Last but not least, their impact on attenuation statistics is typically very limited [23]. It is worth noting that the application of MASP is valid in the 5–85 GHz range, according to the limits imposed on the use of SC EXCELL for rain attenuation prediction (refer to Section 2.2).

Sample monthly CCDFs of the total tropospheric attenuation calculated according to (4) are reported in Fig. 6. Again, we have selected January, April, June and November, for the radio link at 39.6 GHz between the Spino d'Adda ground station and the ITALSAT satellite.

3 Performance of the proposed prediction model: worst month statistics

Though the proposed methodology for the prediction of monthly total tropospheric attenuation statistics relies on sound physical bases, nevertheless it is not easy to infer its overall accuracy from the knowledge of the performance of the single prediction models described in Section 2. A possible way to partially tackle this problem is to resort to tests on worst month attenuation statistics, $P(A_{\mathrm{TOT}})^{\mathrm{wm}}$, which can be readily calculated from $P(A_{\mathrm{TOT}})^{\mathrm{m}}$ by selecting the largest attenuation value among the 12 months for every exceedance probability P of interest. Indeed, the DBSG3 database of ITU-R also contains a table listing several propagation experiments during which $P(A_{\mathrm{TOT}})^{\mathrm{wm}}$ have been produced. Specifically, the database includes data collected in 20 different countries (from Finland to Australia) in the $11.1\ \mathrm{GHz} \le f \le 19.5\ \mathrm{GHz}$ range. In addition, we have added to the reference database worst month statistics collected by Politecnico di Milano in Spino d'Adda during the ITALSAT propagation experiment (duration: 7 years, beacon frequencies: 18.7, 39.6 and 49.5 GHz) and by Communication Research Center (CRC) in Ottawa during the ACTS research activities (duration: 5 years; beacon frequencies: 20.2 and 27.5 GHz).

The duration of the experiments included in the DBSG3 database varies from one month (Darwin, Australia) to 9 years (Stockholm, Sweden); to achieve a good compromise between data availability for the tests and statistical stability of the curves, we have discarded all experiments whose duration is shorter than 3 years. This leads to a total of 31 curves (including ITALSAT and ACTS data), against which the estimated $P(A_{\mathrm{TOT}})^{\mathrm{wm}}$ have been compared

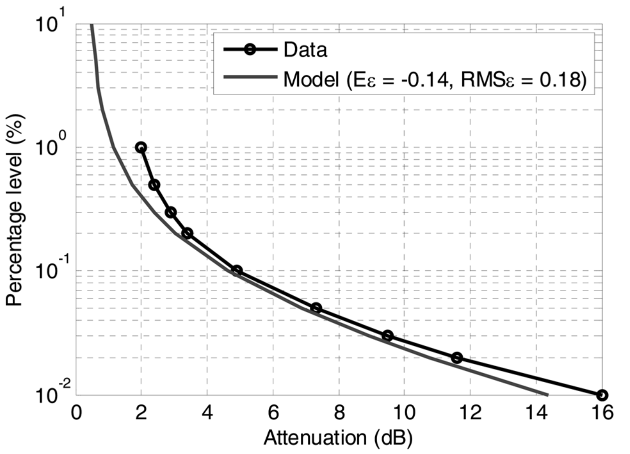

Fig. 7 *Sample worst month statistics of total tropospheric attenuation; comparison between data extracted from the DBSG3 database (Stockholm, Sweden, f = 11.8 GHz, duration: 9 years, elevation angle: 22°) and the prediction obtained from the proposed model (grey solid lines)*

using the customary error figure defined in ITU-R recommendation P.311-14 [17]:

$$\varepsilon(P) = \begin{cases} \left[A_{\mathrm{m}}(P)/10\right]^{0.2}\ln\left[A_{\mathrm{e}}(P)/A_{\mathrm{m}}(P)\right] & A_{\mathrm{m}}(P) < 10\ \mathrm{dB} \\ \ln\left[A_{\mathrm{e}}(P)/A_{\mathrm{m}}(P)\right] & A_{\mathrm{m}}(P) \geq 10\ \mathrm{dB} \end{cases} \quad (5)$$

where $A_{\mathrm{m}}(P)$ and $A_{\mathrm{e}}(P)$ represent the worst month attenuations, both correspondent to probability level P, extracted, respectively, from the reference and the estimated $P(A_{\mathrm{TOT}})^{\mathrm{wm}}$. For each curve, we have calculated the average ($E\varepsilon$) and root mean square (RMSε) values of ε considering the full $10^{-2}\% \leq P \leq 100\%$ range.

Fig. 7 shows an example of the curves extracted from the DBSG3 database (black solid line with circles, Stockholm, Sweden, f = 11.8 GHz, duration: 9 years, elevation angle: 22°) and predicted using the proposed model (grey solid line). The legend also reports $E\varepsilon$ and RMSε, which indicate a fairly good accuracy.

A more comprehensive picture of the model's performance is offered in Fig. 8, which depicts the trend of $E\varepsilon$ and RMSε for each of the experimental curves used in the testing activity. The general scores of the model are given by $M_{E\varepsilon} = 0.07$ and $M_{\mathrm{RMS}\varepsilon} = 0.27$, the overall average values of $E\varepsilon$ and RMSε, respectively. Results are fully in line with those typically achieved by several models to estimate the attenuation due to rain on yearly basis, which certainly drives the model's performance both due to the higher attenuation levels and because of the higher variability (and thus unpredictability) of precipitation in space and time.

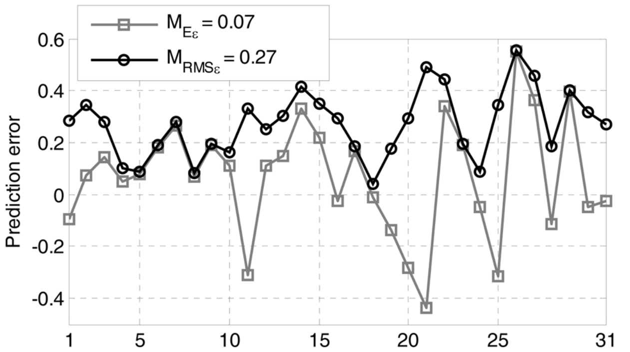

Fig. 8 *Detailed performance of the proposed prediction model for each of the experiments considered in this work*

Legend also includes the overall average values of Eε and RMSε, $M_{E\varepsilon}$ and $M_{\mathrm{RMS}\varepsilon}$, respectively

4 Conclusions

This contribution presents MASP, a model for the global prediction of total tropospheric attenuation statistics on monthly basis, originating from the combination of physically sound models for the separate prediction of the attenuation due to rain, clouds or gases. The contributions obtained from each of these models are added according to the customary rule included in ITU-R recommendation P.311-14.

Worst month total attenuation statistics are readily derived from the monthly curves to address the assessment of the proposed model's accuracy. Tests, performed against the CCDFs included in the global DBSG3 database of ITU-R, indicate an overall fairly good prediction accuracy in the $10^{-2}\% \leq P \leq 100\%$ probability range (overall average values of mean and RMS of the prediction error equal to 0.07 and 0.27, respectively). This corroborates the use of the proposed model to aid engineers in planning future high-frequency satellite communication systems based on the worst month concept. In addition, after fixing the system parameters, monthly total attenuation curves might give a hint on the expected performance of the system throughout the year.

5 Acknowledgments

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