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Statistical Modeling of Atmospheric Propagation Channel at W-Band through Sun-Tracking Microwave Radiometric Measurements for Non-Geostationary Satellite Links

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***Abstract*— In this work we propose a model for the Probability Density Function (PDF) of the elevation angle and the PDF of the attenuation conditioned to the elevation angle at W-band and in all-weather conditions. The proposed models are suitable to retrieve the PDF of the total attenuation at variable elevation for application to non-geostationary satellite communication links at W-band. The models, based on the Generalized Extreme Value (GEV) distribution, were developed and tested exploiting W-band Sun-tracking microwave radiometer measurements available from two independent measurements campaigns in Milano (Italy) and Rome (New York, USA), the only two datasets available in the world to date. The obtained results are satisfactory with a good agreement between models and measurements and highlighting a potential relationship between the GEV parameters and the local climatology.**

***Index Terms*— Millimeter waves, radiopropagation models, Sun-Tacking microwave radiometry, slant path attenuation**

I. Introduction

Due to the growing need for larger bandwidths and to the continuous improvements in the technology development of radiofrequency components, Satellite Communications (SatCom) are moving towards higher microwave frequencies. Indeed, current High Throughput Satellites operate at Ka-band and their next implementation will likely use Q- and V-bands. In this context, W-band is the natural evolution of future SatCom systems. At such high frequencies, the interaction of the signal with atmospheric constituents (rain, liquid water clouds and atmospheric gases) becomes more and more important [1], [2] thus requiring accurate propagation models needed by SatCom systems in order to setup and optimize the transmission operations [3], [4].

Current propagation models, such as the ones proposed by the Radiocommunication Sector of the International Telecommunication Union (ITU-R) [5], are based on experimental campaigns at Ku-, Ka-, Q-, and V-bands. ITU-R provides recommendations for estimating the different attenuation contributions implying that, to estimate the total attenuation, several models must be combined. Moreover, the application of such models to W-band should be tested and may led to some uncertainties, arising the need for proper characterization of the W-band propagation channel. Ideally, this objective would be pursued by using a beacon signal at the frequency of interest, but only a few space-borne W-band beacons are currently available. An alternative possibility is to resort to ground-based Microwave Radiometers (MWR) [6], though only a few measurements obtained from campaigns at W band frequencies are available.

When dealing with non-geostationary (NGEO) satellites applications, another important point is the characterization of the atmospheric channel at different slant-paths. Indeed, typical measurements (such as those from classical MWRs) are obtained at a fixed pointing direction (e.g., zenith). The most frequent approach to convert zenithal attenuation to the corresponding

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slant path value is the cosecant law. Such an approach, however, may lead to important overestimation errors, especially in rainy and cloudy conditions [7].

Few attempts to statistically describe the atmospheric attenuation at varying elevation angles can be found in the literature [8], [9] but they focus on rain attenuation at Ka-band and are obtained through a fitting procedure of ITU-R global models.

In this context, the Sun-Tracking (ST) technique, which consists in using the Sun as an equivalent beacon signal, is an interesting and recently developed microwave radiometric technique that can be used to characterize the Earth-space channel at different elevation angles. Unlike classical MWRs, Sun-Tracking microwave radiometers (ST-MWRs) were proven to be appealing instruments to infer the atmospheric slant-path attenuation in all weather conditions and at variable elevation angles, especially at millimeter-wave and submillimeter-wave frequencies where experimental satellite-to-Earth data are not easily available [6], [10], [11]. ST-MWRs are based on a variable antenna pointing following the ecliptic of the Sun, thus inherently providing measurements at variable elevation angles that are suitable for modeling and characterizing the atmospheric channel for NGEO orbit applications. The main limitation of ST-MWRs is that measurements in ST mode are obviously available only during the day.

To date, only two sites in the world are equipped with ST-MWRs collecting data from K up to W band frequencies: Rome (NY, USA) and Milano (Italy). In this work, we exploit data available from two independent measurements campaigns, collected by these two ST-MWRs, to statistically model the atmospheric channel at W band as a function of the elevation angle.

In general, to compute the marginal probability distribution function (PDF) of total attenuation (that is influenced by the elevation angle profile), both the PDF of the elevation angle and the PDF of the attenuation conditioned to the elevation angle are required. Concerning the latter, preliminary studies were already presented in [12] and [13], but they were focused on models extremely tailored to the specific site of interest. On the other hand, the PDF of the elevation angle is strictly connected to the specific satellite mission [14], [15]. On this perspective, we exploit ST-MWR measurements available in Rome (NY) to derive a new model for both the PDF of the elevation angle and of the total attenuation conditioned to the elevation angle at W-band and in all-weather conditions. The developed models are then tested by exploiting independent ST-MWR measurements from the Milano (IT) campaign.

The work is organized as follows. Section II presents the working principles of the Sun-Tracking. The available data is illustrated in Section III. Section IV describes the model derivation and testing. Finally, conclusions and ideas for future work are reported in Section V.

II. SUN-TRACKING MICROWAVE RADIOMETRY

The general concept of ST-MWR is to use the Sun as an equivalent beacon: two consecutive measurements are performed by fixing the elevation angle θ_0 while switching the azimuth angle from φ_0 to φ_1 to alternatively point the instrument toward-the-Sun (twS) and off-the-Sun (ooS), respectively. In the twS measurements the antenna beamwidth is centered on the Sun, so the radiometer measures the contribution coming from the Sun attenuated by the atmosphere, as well as the contribution of the atmospheric emission itself. In the ooS measurement, the Sun is out of the antenna beamwidth, and the radiometer measures only the contribution from the atmosphere. Details about the ST-MWRs operation, deeply described in [10] and [16], are recalled in this section.

The antenna noise temperature T_A from ground-based observations is the convolution between the received sky brightness temperature and the normalized antenna power radiation pattern $F_n(\theta_0,\varphi_0,\theta,\varphi)$ (neglecting the frequency dependence for simplicity of notation):

$$T_A(\theta_0,\varphi_0)=\frac{\int_{4\pi}T_B(\theta,\varphi)\,F_n(\theta_0,\varphi_0,\theta,\varphi)\,d\Omega}{\int_{4\pi}F_n(\theta_0,\varphi_0,\theta,\varphi)\,d\Omega} \quad (1)$$

with

$$\int_{4\pi}F_n(\theta_0,\varphi_0,\theta,\varphi)\,d\Omega=\Omega_{Pant} \quad (2)$$

where Ω_{Pant} is the solid angle subtended by the antenna radiation-pattern. When performing an ooS measurement, the sky brightness temperature received by the antenna $T_{BooS}(\theta,\varphi)$ is given by

$$T_{BooS}(\theta,\varphi)=T_{mr}(\theta,\varphi)\left(1-e^{-\tau(\theta,\varphi)}\right)+T_{cos}e^{-\tau(\theta,\varphi)} \quad (3)$$

where $T_{mr}(\theta,\varphi)\,[K]$ is the sky mean radiative temperature, $\tau\,[neper]$ is the atmospheric optical thickness, and $T_{cos}\cong 2.73\,[K]$ is the cosmic background temperature at microwave frequencies. When performing a twS measurement, instead, the sky brightness temperature received by the antenna $T_{BtwS}(\theta,\varphi)$ is given by

$$T_{BtwS}(\theta,\varphi)=T_{Bsun}e^{-\tau(\theta,\varphi)}+T_{mr}(\theta,\varphi)\left(1-e^{-\tau(\theta,\varphi)}\right)+ +T_{cos}e^{-\tau(\theta,\varphi)} \quad (4)$$

For each elevation angle θ_0, the difference between the twS and ooS measurement can be expressed by

$$\Delta T_A(\theta_0,\varphi_0,\varphi_1)=T_{AtwS}(\theta_0,\varphi_0)-T_{AooS}(\theta_0,\varphi_1) \quad (5)$$

If the switching is fast enough and the azimuth is chosen such that the Sun is just outside the field of view of the instrument, the mean radiative temperature and the optical thickness can be considered constant between the two observation modes (twS and ooS). Assuming a uniform Sun brightness and a constant atmospheric contribution within the antenna beam (i.e., $T_{AooS}\cong T_{BooS}$ at (θ_0,φ_0)), (6) becomes

$$\Delta T_A(\theta_0,\varphi_0)\cong f_\Omega(\theta_0,\varphi_0)T_{Bsun}e^{-\tau(\theta_0,\varphi_0)}= T^*_{BSun}e^{-\tau(\theta_0,\varphi_0)} \quad (6)$$

where f_Ω is the so-called beam-filling factor expressing the ratio between the Sun radiation-pattern solid angle and the antenna beamwidth radiation-pattern solid angle. Note that, as described in [16], the contribution of the sidelobes can be neglected with respect to the one of the main lobe.

Equation (6) gives the basis for estimating the brightness temperature of the Sun and the atmosphere path attenuation as

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described in [10] and [16]. Finally, the atmospheric attenuation A_{ST} (in dB) can be obtained from (6) as:

$$A_{ST}(\theta_0,\varphi_0) \cong 4.343\, ln\left[\frac{T^*_{BSun}(\theta_0,\varphi_0)}{\Delta T_A(\theta_0,\varphi_0)}\right] \quad (8)$$

provided that T^*_{BSun} estimations from ST measurements in clear sky conditions are available.

In presence of clouds or precipitation, the atmospheric attenuation increases, thus leading to a decrease in the Sun contribution and, consequently, in the ΔT_A difference. In case of heavy precipitation, the contribution of the Sun becomes negligible due to the strong attenuation by rain particles. In these cases, ΔT_A may reach zero or even negative values, depending on the radiometer noise and the atmospheric variability between φ_0 and φ_1. This explains the upper limit to the application of the ST technique for the retrieval of tropospheric attenuation under rainy conditions [10]. According to [16], the maximum path atmospheric attenuation that can be measured depends on both the T^*_{BSun} at the considered frequency and the minimum detectable $\Delta T_{A,min}$. For typical $\Delta T_{A,min}$ values of about 0.7 K at Ka-band and 1.4 K at V- and W-band, and typical T^*_{BSun} values of about 121.5, 187.2, 572.1, and 710 K at 23.8, 31.4, 72.5, and 82.5 GHz respectively, the maximum attainable attenuation with the STMWR method using (8) is about 22.5 and 24.3 dB at Ka-band and about 26.1-27.1 dB at V- and W-band. Regarding the accuracy of such measurements, a detailed analysis is provided in [16]: path attenuation A_{ST} is directly affected by antenna noise temperature difference uncertainties. In clear sky conditions, for an uncertainty in ΔT_A of 6 K, the error in path attenuation is about −0.05 dB at 72.5 GHz and 82.5 GHz. Under rainy conditions, an uncertainty in ΔT_A of 6 K gives an error in path attenuation of about −1.5 dB at 72.5 and 82.5 GHz. Note that the receiver is continuously calibrated using internal noise diodes and an external ambient target, covering well beyond the expected dynamic range. However, when precipitation is so intense to extinguish the Sun radiation, both the mean radiative temperature and the measured brightness temperature approach ambient temperature. In such a situation, which corresponds to the maximum attenuation mentioned above, both the classical radiometric estimation and sun-tracking method get inapplicable for different reasons. The classical method for the uncertainty affecting T_A and T_{mr} (rispectively ~0.5 K and ~1-2 K), while the sun-tracking method for the uncertainty affecting T_{AtwS} and T_{AooS}.

III. AVAILABLE DATASETS

This work relies on measurements collected by two different ST-MWRs in different periods and locations (Milano, Italy, and Rome, NY, USA). This section describes the main characteristics of the two systems and datasets.

A. Rome (NY) ST-MWR measurements

Ground-based measurements were collected by the ST-MWR located at the Air Force Research Laboratory (AFRL) in Rome, NY, USA (43.2°N, 75.4°W). The AFRL ST-MWR has four channels with receivers at 23.8, 31.4, 72.5, and 82.5 GHz sharing a common parabolic antenna of 30 cm diameter with half-power beamwidths of 3.4, 2.97, 1.47 and 1.30 degrees, respectively [11]. The instrument is a commercial water-vapor and cloud-liquid MWR modified in order to allow an automatic Sun-switching and tracking operation mode. The scan step of the radiometer is 0.15° in elevation and 0.1° in azimuth [11], [16]. Collected data covers the 04/05/2015–25/09/2018 period.

A careful data quality-check was performed in order to fix possible errors occurring during the measurement campaign (e.g., obstacles inside the antenna pattern, failures in the acquisition software, …). This procedure, already accomplished in [10] and [16] for the period 2015 – 2016, was applied by analyzing the data day by day. Table I summarizes the availability of the Rome-NY data on a monthly basis for all the four years 2015 – 2018.

TABLE I
AVAILABILITY FOR THE ROME (NY) DATA FROM 04/05/2015 TO 25/09/2018. AVAIL. INDICATES THE NUMBER OF DAYS FOR WHICH THE DATA ARE AVAILABLE AND HAVE BEEN USED IN THIS WORK. FIXED INDICATES THE NUMBER OF DAYS FOR WHICH THE DATA WERE PROBLEMATIC AND HAVE BEEN CORRECTED. BROKEN INDICATES THE NUMBER OF DAYS FOR WHICH THE DATA WERE PROBLEMATIC AND IT WAS NOT POSSIBLE TO FIX THEM. FINALLY, UNAV. INDICATES THE NUMBER OF DAYS FOR WHICH THE DATA WERE NOT AVAILABLE SINCE THE RADIOMETER WAS NOT OPERATIONAL.

Month	Avail.	Fixed	Broken	Unav.
January	76	13	4	0
February	75	3	7	0
March	67	11	15	0
April	67	8	14	1
May	111	5	1	4
June	117	1	2	0
July	116	3	0	5
August	116	4	2	2
September	94	20	1	0
October	79	2	0	12
November	60	0	0	30
December	36	14	12	31
Total	1014	84	58	85

B. Milano (IT) ST-MWR measurements

Data in Milano (Italy) were collected in the framework of the WRad project funded by the European Space Agency (ESA) and started in 2019 with the objective of performing a 2-year W-band ST-MWR measurement campaign. The ST-MWR is located at Politecnico di Milano main campus (45.48°N, 9.23°E) and includes two channels at Ka-band (23.8 and 31.4 GHz) and two channels at W-band (72.5 and 82.5 GHz), as the one in Rome, NY (USA). The scan step of the radiometer is of 0.05° in elevation and 0.1° in azimuth, the integration time is set to 1 s and the azimuth positioner switches every 6 s in order to perform the integration with fixed antenna position [6], [17].

Though the WRad data set is nominally available from October 2019 to August 2021, the control of the antenna pointing system was optimized only at the end of October 2020. Moreover, around mid-January 2021 the noise diode of the W-band channels failed, which further limited the collection of W-band data. Table II reports the actual period of Ka- and W-band

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data availability between 2019 and 2021; two partially overlapping periods are defined: 'Period 1' (for the W-band channel availability) and 'Period 2' (for the Ka-band channel availability).

TABLE II
AVAILABILITY FOR THE MILANO (IT) ST-MWR MEASUREMENTS

Channel availability	Availability period
W-band	01/11/2020 – 15/01/2021 (Period 1)
Ka-band	01/11/2020 – 08/08/2021 (Period 2)

IV. STATISTICAL PREDICTION MODEL OF SLANT-PATH ATTENUATION FOR NGEO LINKS

The PDF of the slant path attenuation $A(\theta)$ for NGEO satellite links with a variable antenna-pointing elevation angle θ can be calculated as

$$p_A(A) = \int_{\theta_m}^{\theta_M} p_{A\theta}(A(\theta),\theta)d\theta = \int_{\theta_m}^{\theta_M} p_{A|\theta}(A(\theta)|\theta)p_\theta(\theta)d\theta \quad (9)$$

where $p_A(A)$ is the marginal PDF of the total path attenuation A, $A(\theta)$ is the elevation-dependent slant path attenuation, θ_m and θ_M are the minimum and maximum elevation angles for the considered NGEO satellite link, $p_{A\theta}(A(\theta),\theta)$ is the joint PDF of A and θ, $p_{A|\theta}(A(\theta)|\theta)$ is the PDF of A conditioned to θ; finally, $p_\theta(\theta)$ is the marginal PDF of θ.

If $p_A(A)$ is known, so is the Cumulative Distribution Function (CDF) F_A, and the Complementary CDF (CCDF) C_A can be simply derived as:

$$C_A(A > A_0) = 1 - F_A(A \le A_0) = 1 - \int_0^{A_0} p_A(A)\,dA = 1 - \int_0^{A_0}\int_{\theta_m}^{\theta_M} p_{A|\theta}(A(\theta)|\theta)\,p_\theta(\theta)\,d\theta\,dA \quad (10)$$

where A_0 is the exceeded value of total path attenuation. Thus, the computation of the CCDF for the statistical prediction of A in NGEO links basically requires knowledge of:

- the PDF of the elevation angle ($p_\theta(\theta)$) within its minimum and maximum values (θ_m and θ_M). This depends on the specific satellite mission and receiving station of interest, and can be typically derived from ephemeris data.
- PDF of the attenuation conditioned to the elevation angle ($p_{A|\theta}(A(\theta)|\theta)$) which should provide, for each elevation, the conditional PDF of $A(\theta)$, depending on the climatology of the receiving site as well as the wave-atmosphere interaction due to the variable link geometry.

The log-normal PDF is very often used for radiopropagation application to describe both the rain attenuation and the rain rate statistical distribution for GEO links. However, for NGEO links, we expect the statistical distribution to be much more asymmetric and rough than for GEO satellite links. Thus, asymmetric multi-parameter PDFs, such as the Generalized Extreme Value (GEV) distribution, may better describe this behavior. The GEV distribution is parameterized with a location parameter μ, a scale parameter σ and a shape parameter k. The GEV PDF of a random variable x is expressed by [18]:

$$p_{GEV}(x) = \frac{1}{\sigma}[g(x)]^{k+1}e^{-g(x)} \quad (11)$$

where the function $g(x)$ is given by

$$g(x) = \begin{cases} \left[1 + k\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{k}} & if\ k \neq 0 \\ e^{-\left(\frac{x-\mu}{\sigma}\right)} & if\ k = 0 \end{cases} \quad (12)$$

being the x-support

$$x \in \begin{cases} \left[\mu - \frac{\sigma}{k}, +\infty\right] & if\ k > 0 \\ [-\infty, +\infty] & if\ k = 0 \\ \left[-\infty, \mu - \frac{\sigma}{k}\right] & if\ k < 0. \end{cases} \quad (13)$$

A. MODELING THE ELEVATION ANGLE PROBABILITY

During the measurement acquisition of the ST-MWR, the elevation angle varies continuously. This allows the collection of information about the atmospheric channel as a function of the considered slant path. Fig. 1 shows the PDF of the elevation angle in Milano for the two available periods together with the best fits using different PDF models such as the Gaussian, Log-Normal, Gamma, Rayleigh, and Exponential, as well as the GEV and the Kernel one. Apart from the latter, that is not an analytical model but an envelope-like approach, the GEV PDF is significantly better than the others especially when the asymmetric feature is relevant.

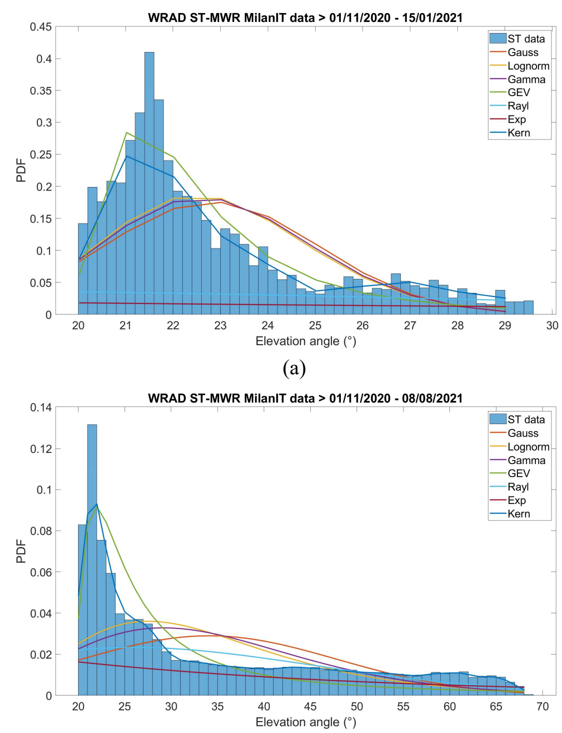

Fig. 1 GEV best fits of elevation angle PDF in Milano (IT) for Period 1 (a) and Period 2 (b).

The same fitting procedure has been performed using the Rome (NY) data in Fig. 2. In this case, none of the considered distributions seems to capture the PDF of the elevation angle as

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there is not an evident single peak, like in Milano, but at least two peaks (a narrow one at 25° and a wider one at 50°). This is likely due to the much longer period for Rome (NY) than for Milano (IT) datasets. To support this, the same analysis was performed on the Rome NY dataset but on a monthly basis (see Fig. 5). The monthly analysis shown in Fig. 5 highlights again a good agreement between the measurements and the proposed models with the GEV model providing the best approximation of the PDF of the elevation angle. This is confirmed by the evaluation of the Root Mean Square of the fitting Error (RMSE) computed and shown in Fig. 3.

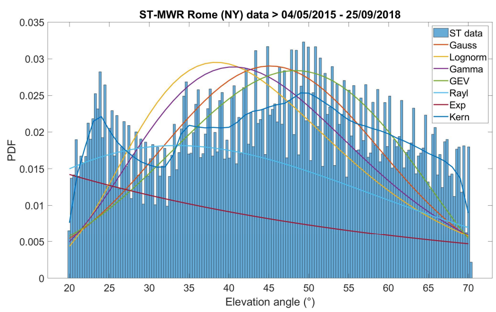


Fig. 2 GEV best-fitting of elevation angle PDF in Rome-NY.

Note that, from Fig. 3, RMSE error values for the month of December are generally higher: this is probably due to a limited data availability on that month (cf. Table I). For this reason, for graphical representation, the RMSEs of the Rayleigh and Exponential distribution for December are not shown (they exceed the y-axis scale in Fig. 3). Fig. 4 shows the monthly analysis for the three parameters of the GEV function (k, σ, μ) used for modeling the distribution of the elevation angle PDF in Rome (NY), from which a regular seasonal trend can be noted.

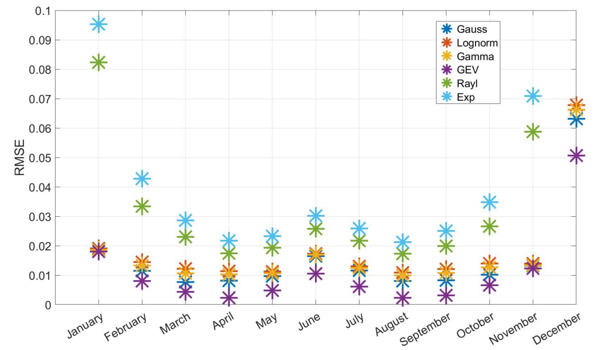
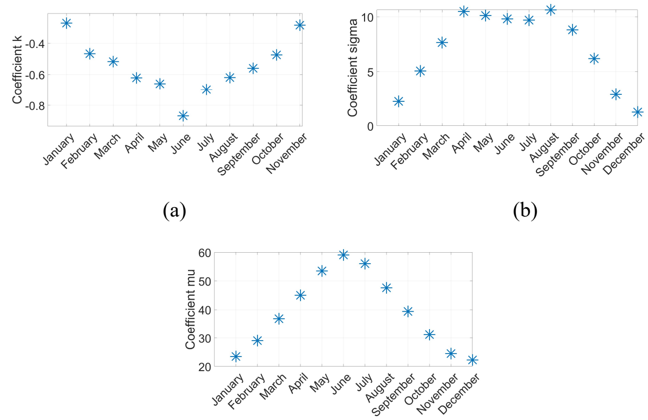


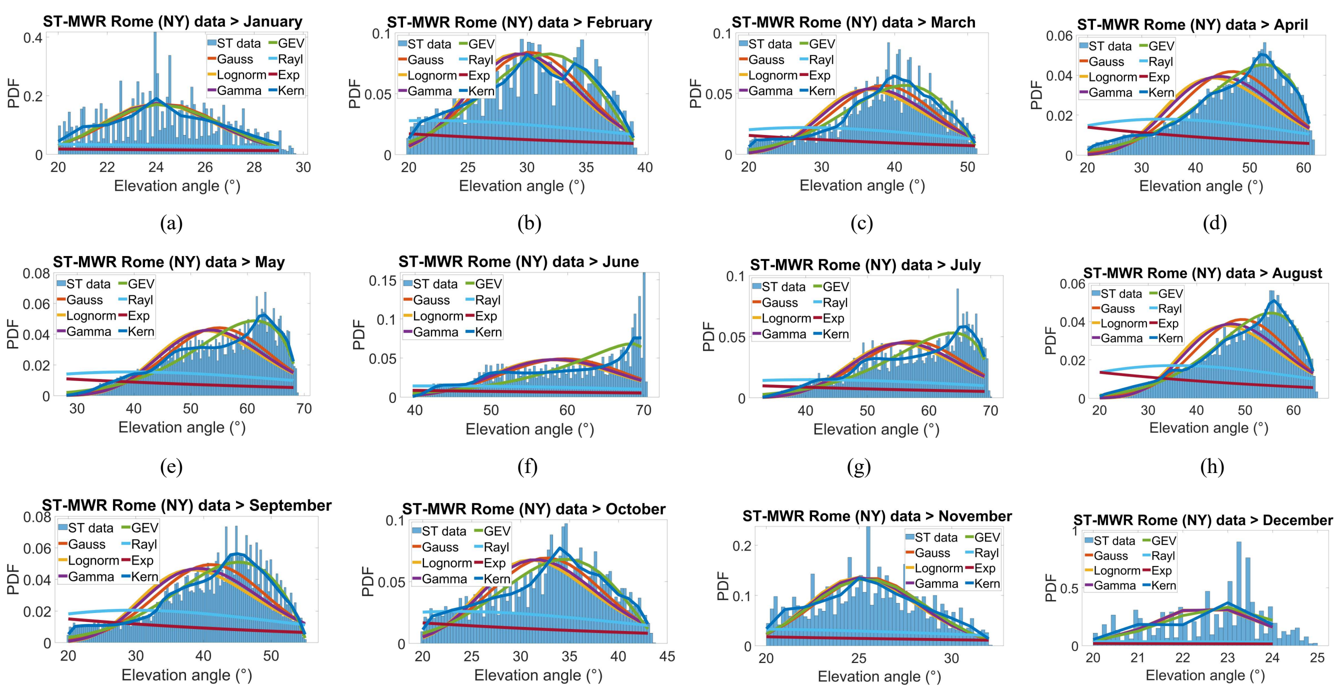
Fig. 3 Monthly RMSE of the considered distributions for the elevation angle PDF in Rome (NY) as plotted in Figure 4.



(a) (b)

(c)

Fig. 4 Monthly analysis of the GEV parameters used for modeling the distribution of the elevation angle PDF in Rome (NY) as plotted in Fig. 5: (a) k, (b) σ, (c) μ.



(a) (b) (c) (d)

(e) (f) (g) (h)

(i) (j) (k) (l)

Fig. 5 GEV best fits of elevation angle PDF in Rome (NY) on a monthly basis.

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B. MODELING THE SLANT PATH ATTENUATION PROBABILITY

A similar modeling procedure using the GEV distribution was performed on the PDF of the total (i.e., all-weather) attenuation conditioned to the elevation at W-band, exploiting the ST-MWR measurements in Rome (NY). To evaluate the conditional PDF we have divided the elevation angle in classes of 2° width and calculated the PDF of the attenuation correspondent to each elevation-angle class. Fig. 6 shows the conditional PDF with the best fit using the GEV distribution and the lognormal distribution in the case of Rome (NY) at 72 GHz (the same plot was produced at 82 GHz). Twenty-five conditional PDFs, one for each elevation class, were calculated, but only the ones corresponding to the first and last elevation angle classes are visualized as an example. A fit using the two distributions (GEV and lognormal) has been performed for each elevation class highlighting that the GEV model fits better than the lognormal one.

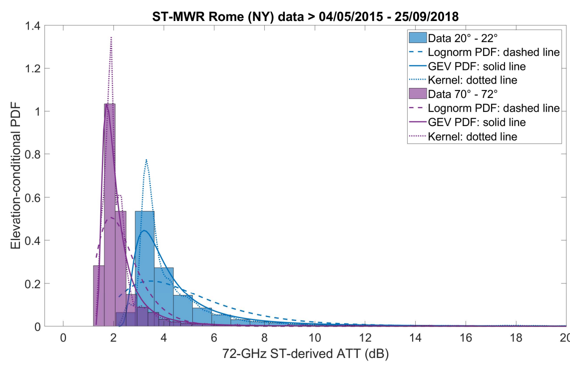

Fig. 6 Best-fitting on the conditional attenuation-elevation PDF using GEV (solid line) and Log-Normal (dashed line) distributions in Rome (NY) at 72 GHz. Each color represents an elevation-angle class.

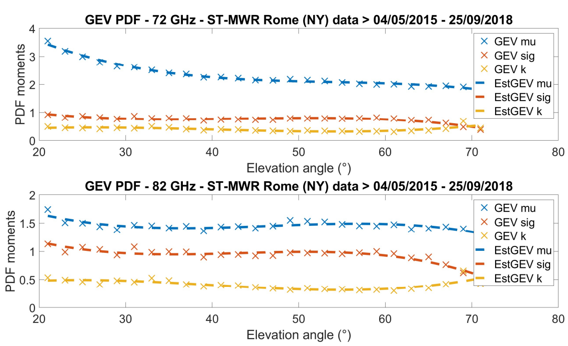

Fig. 7 GEV PDF parameters as estimated using a 3rd degree polynomial best-fitting with respect to the elevation angle using Rome (NY) data.

Starting from the results in Fig. 6, to obtain a general model we need to find a relationship between the parameters of the GEV distribution and the elevation angle. To this aim, we have used a 3rd-order polynomial regression on the three GEV parameters (k, σ, μ) as follows:

$$\begin{cases} \mu(\theta, f) = a_{0mf} + a_{1mf}\theta + a_{2mf}\theta^2 + a_{3m}\ \theta^3 \\ \sigma(\theta, f) = a_{0sf} + a_{1sf}\theta + a_{2sf}\theta^2 + a_{3sf}\theta^3 \\ k(\theta, f) = a_{0kf} + a_{1kf}\theta + a_{2kf}\theta^2 + a_{3kf}\theta^3 \end{cases} \tag{14}$$

where the coefficients a are frequency dependent. Table III and Table IV report the value of the coefficients a for the Rome (NY) site at 72.5 and 82.5 GHz, while Fig. 7 shows the parameters of the best-fitted GEV distribution and their 3rd-order polynomial regression as a function of the elevation angle.

The correlation between the effective GEV parameters and the ones estimated with the 3rd-order polynomial regression are always higher than 0.7, as shown in Table V.

TABLE III
COEFFICIENTS OF THE 3RD-ORDER POLYNOMIAL REGRESSION IN ROME (NY) AT 72.5 GHZ

	a_0	a_1	a_2	a_3
μ	7.4403	-0.2862	0.0052	$-3.2201 \cdot 10^{-5}$
σ	2.4139	-0.1213	0.0029	$-2.2027 \cdot 10^{-5}$
k	-0.1571	0.0564	-0.0016	$1.3229 \cdot 10^{-5}$

TABLE IV
COEFFICIENTS OF THE 3RD-ORDER POLYNOMIAL REGRESSION IN ROME (NY) AT 82.5 GHZ

	a_0	a_1	a_2	a_3
μ	3.1569	-0.1212	0.0027	$-1.9372 \cdot 10^{-5}$
σ	2.7259	-0.1307	0.0031	$-2.4154 \cdot 10^{-5}$
k	-0.0545	0.0522	-0.0015	$1.2866 \cdot 10^{-5}$

TABLE V
GEV PARAMETERS CORRELATION USING 3RD-ORDER POLYNOMIAL REGRESSION IN ROME (NY)

Frequency	**Correlation for GEV μ**	**Correlation for GEV σ**	**Correlation for GEV k**
72-GHz	0.99	0.92	0.75
82-GHz	0.79	0.92	0.80

The GEV model (11), with the coefficients in (14), is used to estimate the PDF of the attenuation conditioned to the elevation angle shown in Fig. 8a and Fig. 8b. The latter, combined with the PDF of the elevation angle, is used to estimate the marginal PDF of the total attenuation through (9). Fig. 8c and Fig. 8d shows the obtained results for 72.5 and 82.5 GHz, comparing the model with the actual PDF derived by ST-MWR measurements, which confirms the expected good performance of the model. In order to prove the goodness of the proposed model, a comparison between the marginal PDF of total attenuation derived from measurements (i.e., blue histogram in Fig. 8c and Fig. 8d) and from the model (i.e., red solid line in Fig. 8c and Fig. 8d) is performed in terms of mean, mode, median and standard deviation and is shown in Table VI highlighting a great agreement between model and measurements. Thus, we can conclude that, referring to the PDF model in (9) and GEV formulation in (11), the total attenuation PDF is given by

$$p_A(A) = \int_{\theta_m}^{\theta_M} p_{A|\theta}(A(\theta)|\theta)\, p_\theta(\theta) d\theta = \int_{\theta_m}^{\theta_M} \frac{1}{\sigma} [g(A(\theta))]^{k(\theta)+1} e^{-g(A(\theta))}\, p_\theta(\theta) d\theta \tag{15}$$

where $p_\theta(\theta)$ is the measured (or best-fitted) PDF of the elevation angle and the GEV parameters (k, σ, μ) are derived from the elevation angle and frequency using (14) with the coefficients in Table III and Table IV.

It is important to note that, the proposed model for the PDF of the attenuation is independent of the adopted model for the PDF

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of the elevation angle (which, in principle, can be derived by ephemeris data or satellite mission specifics). In this case, to calculate the PDF of total attenuation shown in Fig. 8 and obtained through the application of (15), the actual measured PDF of the elevation angle (i.e., the histogram in Fig. 2) is used rather than the GEV-model one. This is because, as explained in the previous section, the GEV model for the PDF of the elevation angle was not suitable for the whole period but only on a monthly scale.

Finally, using (10) we can evaluate the CCDF of the total attenuation from the conditional attenuation-elevation PDF. Fig. 9 shows the comparison between the CCDF of the total attenuation obtained using the model and one obtained from the Rome (NY) ST-MWR measurements, together with a comparison with the total attenuation evaluated using the ITU-R recommendations. For the latter, we have used ITU-R P.618 [5] for total and rain attenuation, ITU-R 840 [19] for cloud attenuation and ITU-R 676 [20] for gas attenuation.

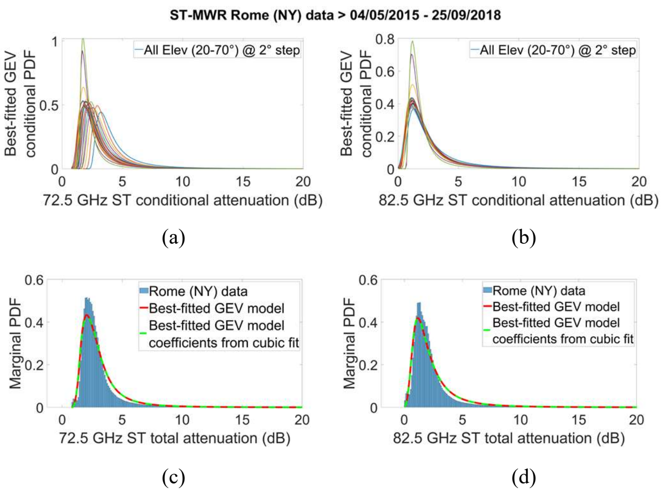

Fig. 8 Model vs data in Rome (NY). Top panels: PDF of the attenuation conditioned to the elevation angle derived from the GEV model (11) at (a) 72 GHZ and (b) 82 GHz. Bottom panels: marginal PDF of total attenuation derived by the GEV model using (9) and compared to Rome (NY) ST-MWR measurements (blue histogram): (c) 72 GHZ and (d) 82 GHz. Note that the model-derived conditioned PDF of the attenuation comes from the GEV model (11) using both the exact coefficients (red solid line) and the ones derived by the cubic fit (14) (green dashed line).

A final verification of whether the simulated (with GEV model) and measured (with ST-MWR) distributions differ, we have performed the two-sampled Kolmogorov-Smirnov test and obtaining a test decision equal to 1 that indicates that test rejects the null hypothesis at the 5% significance level. Note that, Fig. 9 highlights a good agreement between measurements and GEV model between 0 and 5 dB, which is the range where the great part of the distribution is gathered (cf. Fig. 8c and Fig. 8d) and where the proposed GEV model performs better than the ITU-R, thus indicating margins for improving the ITU-R current NGEO models at W band. The deviation between the GEV-model and measurements occurring for attenuation larger than 5 dB is likely due to the fact that, within this range, a small number of measurements is available (if compared to lower attenuation values, as can be noted again from Fig. 8c and Fig. 8d) thus causing an decrease in the model accuracy.

The obtained results confirm the suitability of the GEV PDF best-fitting model approach to reproduce the statistical variability of the measured slant path attenuation.

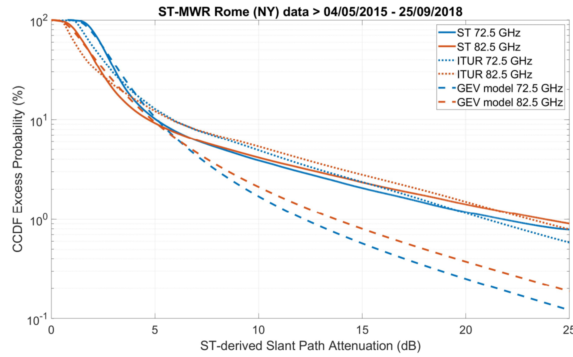

Fig. 9 CCDF of ST-MWR measured Rome (NY) data compared with GEV PDF model and ITU-R models at W-band.

Note that, for the calculation of the CCDF from the available measurements, attenuation values that exceeds the dynamic range (i.e., the maximum measurable), that occurs when the link crosses heavy rain, are saturated to high attenuation values as suggested in [21]. Indeed, such data cannot be simply discarded because, otherwise, the whole CCDF curve would be distorted.

TABLE VI
MEAN, MEDIAN, MODE AND STANDARD DEVIATION OF SIMULATED AND MEASURED PDF IN ROME (NY)

	72 GHz		82 GHz	
	Data	**Model**	**Data**	**Model**
Mean	0.025	0.025	0.025	0.025
Median	0.001	3.58e-04	0.001	5.39e-04
Mode	0	3.5e-05	0	5.74e-05
Std	0.087	0.079	0.081	0.075

C. *TESTING THE SLANT PATH ATTENUATION MODEL*

After defining the model using Rome (NY) data, we can apply the same procedure to the Milano (IT) data. Fig. 10 shows the conditional attenuation-elevation PDF with the best fits using the GEV distribution and the Log-Normal distribution in the case of Milano (IT) at 72 GHz during Period 1, for a 2°-step discretization of elevation (the same plot was produced at 82 GHz). For each elevation class there are 10 attenuation bins but only the ones corresponding to the first and last elevation angle classes are visualized as an example. Note that, in this case, due to the smaller range of elevation angle in Milano (IT) with respect to Rome (NY), we only have 5 elevation classes. We note again that the GEV model performs better than the lognormal one.

To estimate the conditional PDF from the elevation angle we have used again a 3rd-order polynomial regression on the three parameters of the best-fitted GEV, as shown in Fig. 11. The reference analytical equations are the same as in (14), with coefficients reported in Table VII and Table VIII for 72.5 and 82.5 GHz, respectively. The regression is applied with correlation values higher than 0.7, as shown in Table IX. Note that, coefficients for Milano (in Table VII and Table VIII) are quite different from the ones for Rome NY (in Table III and Table IV). This is somehow expected and confirms that, although the GEV model is able to reproduce the attenuation statistics in all-

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weather condition, its parameters are clearly related to the local climatology.

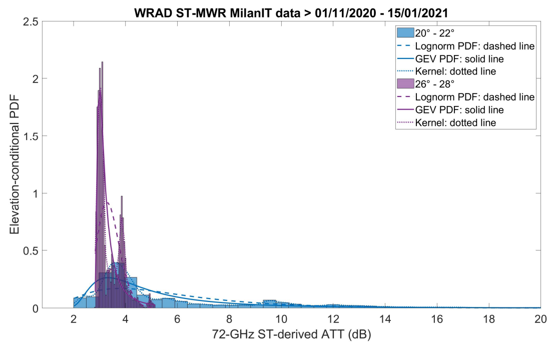

Fig. 10 Best-fitting on the PDF of attenuation conditioned to the elevation using GEV (solid line) and Log-Normal (dashed line) distributions in Milano (IT) at 72 GHz for Period 1. Each color represents an elevation-angle class.

To evaluate the model performances we used again (9) to estimate the marginal PDF of the total attenuation to compare with the one estimated from the ST-MWR measurements in Milano (IT). The results for 72.5 and 82.5 GHz are in Fig. 12. Table X shows the comparison between the two PDFs (model vs measurements) in terms of mean, mode, median and standard deviation confirming that, also in this case, the model gives good results in accordance with the data.

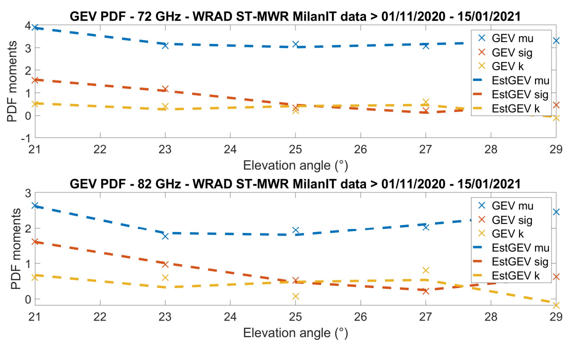

Fig. 11 GEV parameters as estimated using a 3rd degree polynomial best-fitting with respect to the elevation angle using Milano (IT) data.

Using (10), we have evaluated the CCDF of the total attenuation from the conditional attenuation-elevation PDF. Fig. 13 shows the comparison between the CCDF of the total attenuation obtained using the model and the one obtained from the Milano (IT) data, together with a comparison with the total attenuation evaluated using the ITU-R recommendations. Fig. 13 confirms the suitability of the GEV PDF best-fitting model approach to reproduce the statistical variability of the measured slant path attenuation also in the site of Milano (IT), as well as the less accuracy of the ITU-R prediction models. Note that, in the case of Milano (IT) site, the different distribution of attenuation values with numerous measurements available up to more than 10 dB (that can be noted in Fig. 12c and d), allows the GEV model to be reliable also at higher attenuation values if compared to Rome (NY). Also in this case, we have performed the two-sampled Kolmogorov-Smirnov test between the simulated and measured CDF and we have obtained a test decision equal to 1 that indicates that test rejects the null hypothesis at the 5% significance level.

TABLE VII
COEFFICIENTS OF THE 3RD-ORDER POLYNOMIAL REGRESSION IN MILANO (IT) AT 72.5

	a_0	a_1	a_2	a_3
μ	115.5768	-12.6804	0.4733	-0.0058
σ	-104.9972	14.0853	-0.6096	0.0086
k	154.6177	-18.9797	0.7746	-0.0105

TABLE VIII
COEFFICIENTS OF THE 3RD-ORDER POLYNOMIAL REGRESSION IN MILANO (IT) AT 82.5 GHZ

	a_0	a_1	a_2	a_3
μ	141.8100	-15.8587	0.5929	-0.0073
σ	-54.6895	8.0453	-0.3704	0.0055
k	184.3099	-22.5744	0.9195	-0.0124

TABLE IX
GEV PARAMETERS CORRELATION USING 3RD-ORDER POLYNOMIAL REGRESSION IN MILANO (IT)

Frequency	Correlation for GEV μ	Correlation for GEV σ	Correlation for GEV k
72-GHz	0.97	0.99	0.86
82-GHz	0.96	0.99	0.73

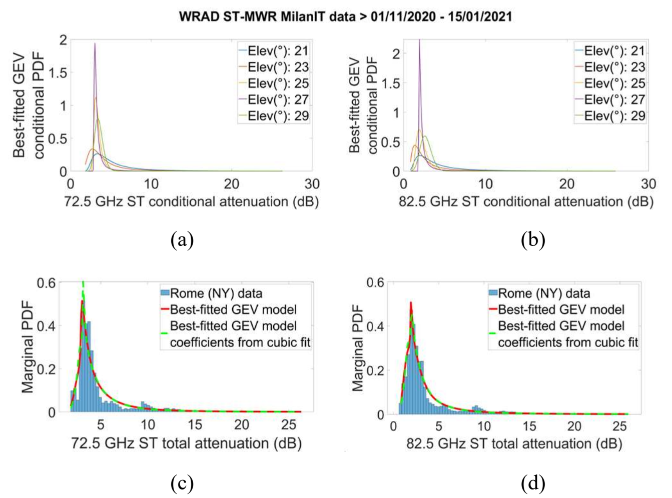

Fig. 12 Model vs data in Milano (IT). Top panels: PDF of the attenuation conditioned to the elevation angle derived from the GEV model (11) at (a) 72 GHZ and (b) 82 GHz. Bottom panels: marginal PDF of total attenuation derived by the GEV model using (9) and compared to Milano (IT) ST-MWR measurements (blue histogram): (c) 72 GHZ and (d) 82 GHz. Note that the model-derived conditioned PDF of the attenuation comes from the GEV model (11) using both the exact coefficients, red solid line, and the ones derived by the cubic fit (14) (green dashed line).

TABLE X
MEAN, MEDIAN, MODE AND STANDARD DEVIATION OF SIMULATED AND MEASURED PDF IN MILANO (IT)

	72 GHz		82 GHz	
	Data	**Model**	**Data**	**Model**
Mean	0.0407	0.0402	0.0392	0.0390
Median	0.0074	0.0050	0.0093	0.0051
Mode	1.7313e-04	6.9923e-04	5.7709e-05	9.0408e-04
Std	0.0951	0.0867	0.0871	0.0833

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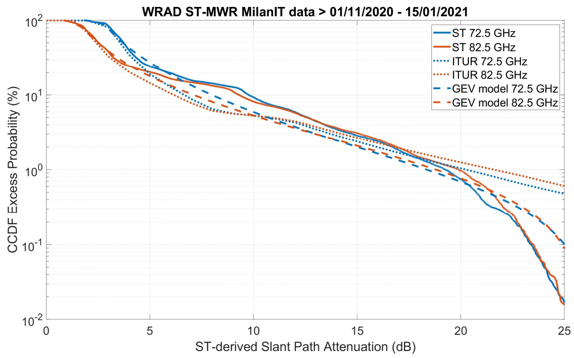

Fig. 13 CCDF of ST-MWR measured Milano (IT) data compared with GEV PDF model and ITU-R ones at W-band.

V. CONCLUSIONS AND FUTURE WORKS

In this work we have exploited W-band ST-MWR measurements to develop a model for retrieving the PDF of the elevation angle and a model for the PDF of the total attenuation conditioned to the elevation angle (suitable for NGEO links) in all-weather conditions at W band frequencies. Both probability models were derived exploiting the GEV distribution function. The proposed models were set up exploiting data collected in Rome (NY, USA) and tested on data collected in Milano (IT).

Concerning the modeling of the PDF of the elevation angle, the analysis confirms that the GEV model is suitable and well fits the data. Specifically, thanks to the monthly analysis performed on the 3 years extended dataset of Rome NY, we found a monthly periodicity in the GEV coefficients confirming that the GEV model can be exploited on a monthly or seasonal base to model the PDF of the elevation angle. Future work will be devoted to deriving a model suitable for the whole year and able to describe the cyclic behavior of the three parameters of the GEV.

Concerning the model to retrieve the PDF of the attenuation conditioned to the elevation, always based on the GEV function, it takes as input the elevation angle and, through the coefficients of the GEV distribution (which are frequency dependent and are modeled with a 3rd-order polynomial regression as a function of the elevation angle), it returns the conditional PDF of the attenuation for the desired elevation angle. The latter can be exploited to evaluate the CCDF of the total attenuation, too. The proposed model, which gives good results for both sites, can potentially be exploited to predict attenuation on NGEO links in order to improve the setup of SatCom operations.

The proposed model may be refined exploiting different fitting algorithms to update GEV parameters in order to improve the model reliability at high attenuation values where law measurements are available. Additional future works will be focused on studying larger periods and larger frequency ranges to investigate the monthly/seasonal trend of the model coefficients and frequency-dependence laws to further increase the accuracy of the estimation of the PDF of the total attenuation. Additional tests of the proposed model are foreseen to assess the relationship between the parameter of the model with local climatology. Finally, further studies for the characterization of the uncertainty associated to the optical thickness variation between an ooS - twS switch are planned.

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Antonio Martellucci received the Laurea degree in electrical engineering and the Ph.D. degree in applied electromagnetism from the Sapienza University of Rome, Rome, Italy, in 1987 and 1992, respectively. In 1988, he was an Optical Engineer with the Selenia Group (now part of Finmeccanica), where he worked on the development of optical active systems. From 1989 to 2000, he was a Researcher with the Radio Communication Systems Division, Ugo Bordoni Foundation, Rome, where he worked on atmospheric propagation effects for terrestrial and spatial radio communication systems. During this period, he participated at the OLYMPUS and ITALSAT propagation experiments (through the European Space Agency (ESA) OPEX and Italian CEPIT working groups) for the measurement and modeling of the atmospheric attenuation and depolarization at Ka-, Q-, and V-bands. He also took part in the European COST 210 and 255 projects and various ESA projects on rain scatter, clear air propagation modeling, and climatological databases. Since 2001, he has been a Radiowave Propagation Engineer with the Directorate of Technical and Quality Management, European Space Research and Technology Center, ESA, Noordwijk, The Netherlands, where he is currently involved in ESA Telecommunication (ARTES and ALPHASAT), Navigation (Galileo), Earth Observation (ENVISAT), and Science (Gaia and Bepi Colombo) Programs. At ESA, he is currently involved in models for multimedia satellite communication systems, including fade mitigation techniques, modeling and characterization of tropospheric effects for navigation systems, and development of ground propagation equipment. He is the author of more than 90 publications in books, international journals, and conference proceedings. Dr. Martellucci received the Young Scientist

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Award at the XXV International Union of Radio Science General Assembly in 1996. He has been the general Editor of the EU COST 255, and since 2001, he was a member of the COST 280 Management committee. Since 2008, he has been the Chair of the EU/FP7 COST Actions IC0802. He is also member of the ESA delegation at ITU-R SG3.

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