

# Joint Effects of Clouds and Rain on Ka-Band Earth Observation Data Downlink Systems

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**Abstract**— This contribution addresses the evaluation of the simultaneous impact of clouds and rain on a Ka-band Data Downlink System involving a Low Earth Orbit (LEO) satellite for Earth Observation. To this aim, MultiEXCELL (Multi EXponential CELL) and SMOC (Stochastic MOdels of Clouds), two physically-based models recently developed to synthesize realistic rain and cloud fields as large as 10 km×200 km×200 km (height×width×depth), are employed. Taking advantage of their physical soundness, the two models are combined to derive the simultaneous attenuation due to rain and clouds on a Earth-LEO link operating at 26 GHz. Results obtained for Rome, NY, USA indicate that the data downlink system is affected by clouds for approximately 72% of the visibility time and that a 30-dB margin would be required to counteract the attenuation due to rain and clouds for 99.9% of the visibility time.

**Index Terms**—Radio wave propagation, atmospheric effects, LEO satellite, Earth Observation.

## I. INTRODUCTION

Modern satellite communication (SatCom) systems are gradually shifting to operational frequencies in the spectrum portion above the traditional Ku band, mainly to take advantage of the larger bandwidths available. This is the case of satellites already operating in the Ka band (e.g. DirectTV-12 in the USA [1]) and of Smart Gateways, which are foreseen to upload contents with carriers in the Q/V band [2]. The same increase in the operational frequency is taking place in Earth Observation systems, which are progressively moving to the employment of the Ka band to support the transmission to ground stations of the always growing amount of data collected by the onboard high-resolution sensors.

As is well known, the main drawback to the use of higher frequencies comes from atmospheric constituents, i.e. gases, clouds and hydrometeors, which attenuate the radiated electromagnetic power. As a result, significant research activities have been promoted so far mainly to develop models for the prediction of propagation impairments. These investigations assume even higher significance for those scenarios for which scarce or no experimental data are available (e.g. link between a Low Earth Orbit – LEO – satellite and Earth stations). In this case, the design and performance assessment of the system can only be achieved by using accurate and reliable prediction models. For this reason, the recent tendency in the theoretical research on radio wave propagation is to move from empirical models, typically developed on the basis of experimental data and valid mainly in specific climatic regions and/or frequency ranges, to highly

sophisticated physically-based methodologies which inherently aim at being globally applicable and suited for the simulation of different scenarios.

This contribution addresses the assessment of the simultaneous impact of clouds and rain on a Ka-band Data Downlink System involving a Low Earth Orbit (LEO) satellite for Earth Observation. To this aim, we exploit MultiEXCELL (Multi EXponential CELL) [3] and SMOC (Stochastic MOdels of Clouds) [4], two physically-based models recently developed to evaluate the impact on Earth-space systems of rain fields and cloud fields as large as 10 km×200 km×200 km (height×width×depth). Taking advantage of their physical soundness, the two models are particularly useful to accurately estimate the attenuation due to clouds and rain on satellite communication systems when very low elevation links (i.e. long path through the troposphere) are considered, as in the case of Earth Observation LEO satellites. Specifically, Section II briefly presents MultiEXCELL and SMOC, and describes how their combination is achieved to model the meteorological environment. Section III describes the main features of the Ka-band data downlink system and deals with the transmission link performance assessment. Finally, Section IV draws some conclusions.

## II. THE METEOROLOGICAL ENVIRONMENT

### A. MultiEXCELL (Multi EXponential CELL)

MultiEXCELL (Multi EXponential CELL) is a model for the generation of synthetic rain rate fields (1 km×1 km spatial resolution, lateral dimension ranging between 200 and 300 km), developed with the main aim of predicting the impact of precipitation on wireless (both terrestrial [5] and Earth-space [6]) systems operating at frequencies higher than 10 GHz [3]. As the model's name suggests, synthetic rain fields, whose ensemble preserves the local rainfall statistics and reproduces the correct rainfall spatial correlation, originate from combining multiple synthetic exponential cells according to their natural aggregative process and from reflecting the local fractional rainy area  $f_R$ . This latter goal is achieved by starting from coarse meteorological information extracted from the ECMWF (European Centre for Medium-range Weather Forecast) ERA-40 database [3], namely the total rain amount accumulated every 6 hours,  $M_t$ , associated with a large NWP pixel of dimension  $2^\circ \times 2^\circ$  (latitude×longitude). While the spatial distribution of the rain rate is strongly uneven, MultiEXCELL assumes a constant rain rate profile with height, from the ground up to the 0 °C isotherm height.

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A key advantage of MultiEXCELL is that a relatively small set of synthetic rain fields (around 400/500 maps) is sufficient to reliably represent the local rainfall process and, thus, to allow the efficient simulation of the interaction between a wireless telecommunication system and precipitation.

### B. SMOC (Stochastic Model of Clouds)

Recently presented in [4], SMOC (Stochastic Model of Clouds) is a model for the synthesis of the three-dimensional distribution of the liquid water content  $w$  (resolution: 1 km $\times$ 1 km horizontal, 100 m vertical; extent: 200 km $\times$ 200 km horizontal, 10 km vertical), starting from coarse integral information on clouds typically available as part of global gridded NWP products. This is achieved by exploiting features observed in real cloud fields (MODIS and CloudSat data) and from the knowledge of the fractional cloud cover ( $f_w$ ) and the average integrated cloud liquid water content ( $E_w$ ), both associated with a large NWP pixel of dimension 2 $^\circ$  $\times$ 2 $^\circ$  (latitude $\times$ longitude). The cloud base height  $h_0$  is constant across the whole area but, for each field, its value comes from a random draw from a generalized extreme value distribution with peak value around  $h_0 = 1$  km. More details on the rationale and the features of SMOC are reported in [4], which also shows that the generated cloud fields reflect the spatial correlation of  $w$  observed in real cloud fields and reproduce with good accuracy the local statistics of the integrated liquid water content.

### C. Combination of rain and cloud fields

For a more realistic simulation of the impact of the meteorological environment on the system, it is necessary to combine the synthetic rain and cloud fields generated by MultiEXCELL and SMOC, respectively, in such a way that the real correlation existing between these two quantities is correctly reflected. Indeed, as mentioned in Sections II.A and II.B, both models receive as input coarse meteorological data extracted from the ERA40 database ( $M_t$  for MultiEXCELL,  $E_w$  and  $f_w$  for SMOC), but the synthesis of rain and cloud fields relies on markedly different approaches. As a result, the combination of the fields, not at all straightforward, requires some care and is achieved according to the following guidelines:

1. For a given site, MultiEXCELL is first applied to synthesize 400/500 rain fields, starting from the probability density function (PDF) of  $M_t$  and from the local complementary cumulative distribution function of the rain rate (point statistics with 1-minute integration time),  $P(R)$ .
2. For each rain map, a cloud field is generated with the obvious constraints that the fractional cloud cover  $f_w$  is larger than the fractional rainy area  $f_R$  and that all rainy pixels are covered by clouds. As a result, a suitable couple of  $f_w$  and  $E_w$  is extracted from the associated ERA-40 derived PDFs.
3. In addition to point 2, while synthesizing the cloud field, a simple pattern matching algorithm is implemented to ensure that, as it is physically the case, precipitation originates from heavier clouds.

4. As for the vertical profile, the rain rate is kept constant from the ground up to the 0 $^\circ$  C isotherm height, where the cloud base height is assumed to lie.
5. The last step consists in generating a suitable number of rain-free cloud fields to maintain the local yearly probability to have rain ( $P_{0,R}$ ) and to have clouds ( $P_{0,C}$ ), inferred from the input  $P(R)$  and from all the ERA-40 derived values of  $f_w$ , respectively. While completing this last step, couples of  $f_w$  and  $E_w$  are selected so as to maintain the respective ERA-40 derived PDFs.

As an example of the combination of the two models, Fig. 1 depicts a rain field generated by MultiEXCELL (ground rain rate) and a cloud field (integrated liquid water content) synthesized by SMOC: note that the constraints in points 2 and 3 are satisfied.

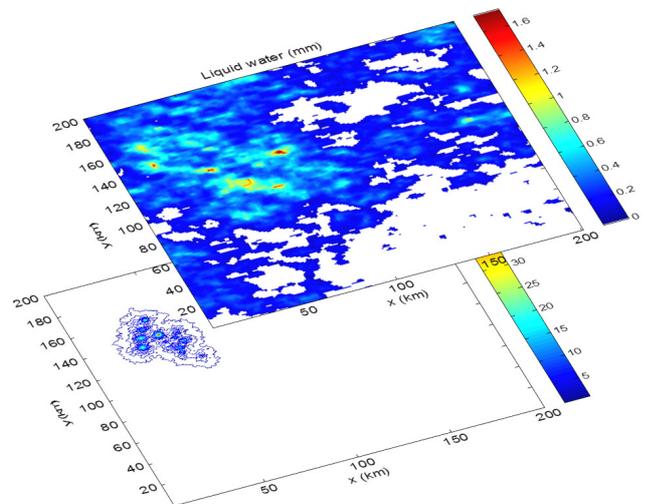


Fig. 1. Example of the combination of a rain field generated by MultiEXCELL (ground rain rate) and of a cloud field (integrated liquid water content) synthesized by SMOC

This goal can be actually achieved because the generation methodology for cloud fields is stochastic (it relies on the synthesis of spatially correlated Gaussian fields [7]) and, as such, it is inherently characterized by some degree of randomness that can be advantageously exploited to satisfy the constraints in 2 and 3. This is also made easier by the fact that the field generation does not follow the time stream of the ERA-40 data (which, in other words, would mean tying  $M_t$  to a couple of  $f_w$  and  $E_w$ ), but, as originally devised for MultiEXCELL, the input values to the models are extracted from the respective ERA-40 derived PDFs. As a result, a reduced number of maps are necessary to properly reproduce the long-term mean yearly distributions of the rain rate and of the integrated liquid water content for a given location.

## III. THE DATA DOWNLINK SYSTEM

This section describes the main features of the Ka-band data downlink system considered in this work and the prediction of the link performance.

### A. System characteristics

Table I lists the main features of the Earth-LEO link: the ground station is set in the area of Rome, NY, USA, while the operational frequency  $f$  is 26 GHz. The radio wave is circularly polarized. On the other hand, the LEO Earth Observation satellite was selected by taking as a reference the near-polar orbit of MetOp-A (Meteorological Operational, approximately 14 revolutions per day and 800 km altitude). Starting from the orbital elements derived from MetOp-A (see Table II), the LEO satellite position and velocity was propagated using the Simplified General Perturbation model SGP4 [8], which provided, for each visibility window (minimum elevation angle  $\theta_{min} = 5^\circ$ ), the elevation and azimuth of the LEO satellite as seen from the ground station (an example is reported in Fig. 2).

TABLE I. MAIN GEOMETRICAL AND ELECTRICAL CHARACTERISTICS OF THE REFERENCE EARTH-LEO LINK

<b>Reference site name</b>	Rome, NY (USA)
<b>Site latitude</b>	43.22° N
<b>Site longitude</b>	75.41° W
<b>Site altitude <math>h_s</math></b>	150 m a.m.s.l.
<b>Frequency</b>	26 GHz
<b>Wave polarization</b>	Circular

TABLE II. KEPLERIAN ORBITAL ELEMENTS OF THE LEO SATELLITE

Orbital element	Value
Inclination	98.7°
Right Ascension of Ascending Node	95.7°
Argument of Perigee	107.7°
Eccentricity	$1.1 \times 10^{-4}$
Mean motion	14.21 rev/day
Mean anomaly	320.4°
Epoch	1 <sup>st</sup> of January 1996 (00:00:00 UTC)

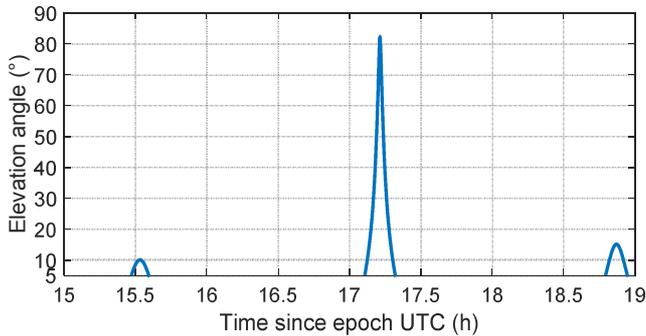


Fig. 2. Elevation angle for three sample Earth-LEO contact windows

### B. Link performance prediction

The impairment caused by each couple of combined rain and cloud fields was assessed by numerically integrating the attenuation along the path, considering the contact window associated to such fields.

As for rain attenuation, every voxel in the synthetic volume was associated to its specific attenuation  $\gamma_R = kR^\alpha$ , where  $R$  is the rain rate in the voxel, while  $k$  and  $\alpha$  are the rain rate to specific attenuation power law coefficients that have been extracted from ITU-R recommendation P.838-3 [9]. Afterwards the path rain attenuation  $A_R$  was obtained by numerically integrating  $\gamma_R$  along the link, considering its change in terms of elevation angle and azimuth during the contact window. A similar procedure was applied for cloud attenuation by relying on the methodology recently proposed in [10], which calculates the path attenuation due to clouds  $A_C$  from the sole knowledge of the liquid water content integrated along the link  $W$ , i.e.:

$$A_C(f) = a_w(f)W \quad (1)$$

where the liquid water mass absorption coefficient is calculated as [10]:

$$a_w(f) = \frac{0.819 (0.016f^{1.67} + 14.85f^{0.39} - 27.49)}{\varepsilon''(1 + \eta^2)} \quad (2)$$

In (2),  $20 \text{ GHz} \leq f \leq 200 \text{ GHz}$ , while  $\varepsilon'$  and  $\varepsilon''$  are the real and imaginary parts of the dielectric permittivity of water, whose full expression can be found in [10]. Moreover,  $\eta = (2 + \varepsilon')/\varepsilon''$ . As a final step, the total path attenuation  $A$  is obtained by simply summing up the contributions of rain and clouds, i.e.  $A = A_R + A_C$ .

As an example of the results achievable using the proposed approach, Fig. 3 shows the CCDF of the rain attenuation affecting the Earth-LEO link (normalization to the total contact time). The probability for rain to impact the link turns out to be 4.3% and, due to the lower values of the link elevation angle, rain attenuation reaches very high levels (more than 70 dB are exceeded for 0.01% of the time, approximately 1 hour/year). Fig. 4 complements the results by reporting the CCDF of the attenuation due to clouds, which clearly indicates that, even at a relatively low frequency like 26 GHz, clouds have a marked impact on the system: cloud and rain attenuation exceeded for 1% of the time are comparable and  $A_C$  is higher than 10 dB for the exceedance probability  $P = 0.01\%$ .

Fig. 5 completes the investigation of the link performance by depicting the total attenuation statistics affecting the link (black dashed line). Results indicate that the data downlink system is impaired by the atmosphere for approximately 72% of the visibility time and that a 30-dB margin would be required to counteract the attenuation due to rain and clouds for 99.9% of the visibility time. Also reported in Fig. 5 are the attenuation curves conditioned to the elevation angle of the link: such curves not only indicate that, as expected, the lower

the value of  $\theta$ , the higher the attenuation affecting the link because of the longer path traveled by the electromagnetic wave in the troposphere, but they also point out that the link performance is mainly driven by the results associated to low elevations, due to their higher occurrence probability.

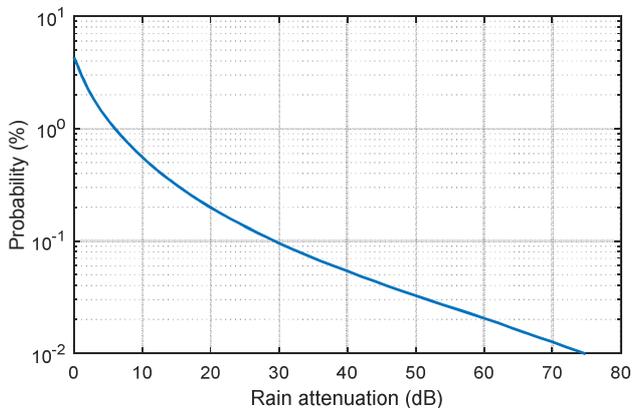


Fig. 3. Rain attenuation statistics for the Earth-LEO link considered in this work ( $f = 26$  GHz)

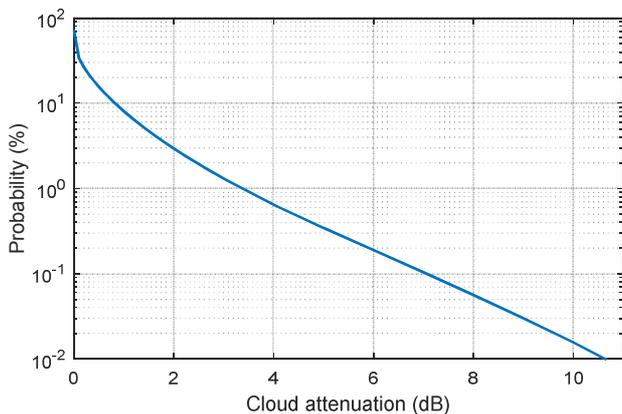


Fig. 4. Cloud attenuation statistics for the Earth-LEO link considered in this work ( $f = 26$  GHz)

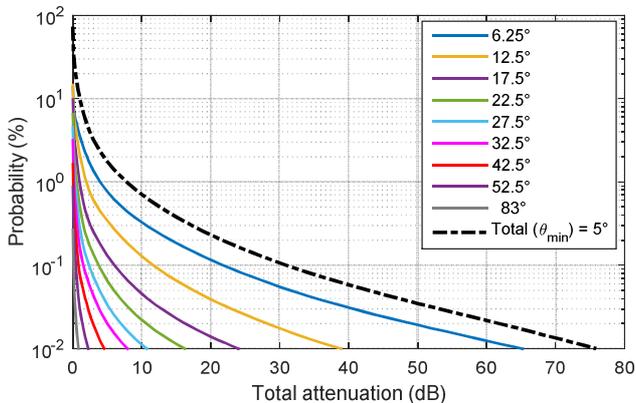


Fig. 5. Total attenuation statistics for the Earth-LEO link considered in this work ( $f = 26$  GHz), including curves conditioned to the link elevation angle

Fig. 6 shows the comparison between the total attenuation CCDF as derived by exploiting MultiEXCELL and SMOC and as obtained by applying the combination rule adopted in ITU-R recommendation P.618-11 [11], i.e. by summing up the  $A_R(P)$  and  $A_C(P)$  curves in Fig. 3 and Fig. 4 on equiprobable basis. Results indicate quite a marked difference between the two cumulative distributions: the curve slope changes for high exceedance probabilities as shown in the figure inset and the differential attenuation exceeded for 0.01% of the time is around 10 dB; this, in turn, points out the importance of further investigating how rain and clouds contributions to attenuation should be combined.

As a final remark, in comparison with classical statistical methods, the proposed approach for the prediction of joint rain and cloud attenuation presents a higher complexity and computational load, which, however, thanks to the mixed physical-statistical nature of MultiEXCELL and SMOC, are absolutely acceptable: as an example, the full procedure for the calculation of the results in Fig. 5 (rain and cloud fields generation plus numerical integration to obtain  $A$ ) requires approximately 20 minutes on a standard PC.

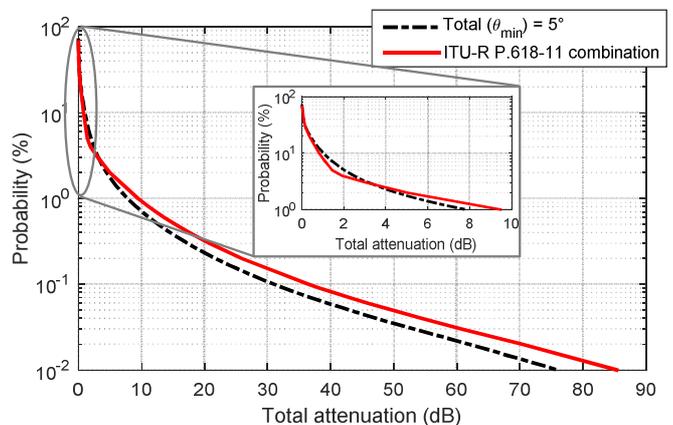


Fig. 6. Total attenuation statistics for the Earth-LEO link considered in this work ( $f = 26$  GHz): comparison between the proposed approach and the combination rule adopted in ITU-R recommendation P.618-11 [11]

#### IV. CONCLUSIONS

This contribution presents a new approach to the prediction of the impairments induced by rain and clouds on an Earth-space electromagnetic link. To this aim MultiEXCELL and SMOC are combined to estimate the performance of a Ka-band Earth observation data downlink system operating at 26 GHz and involving a LEO satellite. This allows not only to more realistically estimate propagation impairments for very low elevation links (down to  $5^\circ$ ) but also to combine the atmospheric effects on “real-time” basis rather than on statistical basis.

Results, obtained for a ground station set in the area of Rome, NY, USA considering a near polar orbit LEO satellite flying at 800 km altitude, indicate extremely high levels of rain attenuation (more than 70 dB are exceeded for 0.01% of the time, approximately 1 hour/year) and that clouds have a marked detrimental contribution on the link as well (cloud

attenuation higher than 10 dB for the exceedance probability  $P = 0.01\%$ ). Moreover, statistics of the joint impact of rain and clouds show that the data downlink system is impaired by the atmosphere for approximately 72% of the visibility time and that a 30-dB margin would be required to counteract the attenuation due to rain and clouds for 99.9% of the visibility time. Such results have been also compared with the curve obtained by applying the rule adopted in ITU-R recommendation P.618-11 to combine rain and cloud attenuation on statistical basis: the marked discrepancies found highlight the importance of further investigating how rain and clouds contributions to attenuation should be combined.

The present work contributes to the development of a simulator of the weather disturbances affecting radio wave propagation (primarily intended to support the design and performance assessment of Earth-space Communication Systems), which will be extended in the near future to include also the effects induced by gases (water vapour and oxygen) on electromagnetic waves.

#### ACKNOWLEDGMENT

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