

Combined use of MultiEXCELL and Numerical Weather Prediction to improve the prediction of rain attenuation at Q band

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Abstract—The future communication systems will use higher frequencies, Ka and Q band. For the implementation of fade mitigation techniques, it is important to have representative time series representing the degradations of the received signal for GEO and LEO satellites. This paper presents a model combining numerical weather prediction software WRF and MultiEXCELL rain cells model in order to have more accurate representation of the dynamics of the attenuation for GEO and non-GEO satellite links.

Index Terms—Propagation, Tropospheric Attenuation, Millimeterwave, Numerical Weather Prediction models, non-geostationary satellite links.

I. INTRODUCTION

The high frequencies requested by future satellite-to-ground communication systems necessitate a better characterization of the degradation due to the troposphere at Ka and Q band, all over the world. On-going propagation experiments, such as the Alphasat propagation campaign, give a precise information on the attenuation due to the troposphere (time series of received signal and complementary cumulative distribution function - CCDF) but limited to the location of receiving stations. Even if the ASAPE (Group of AlphaSat Aldo Paraboni Propagation Experimenters) group [1,2] already provides a reasonable coverage of Western and Central Europe, it is unrealistic to assume that a propagation campaign of 3 to 5 years could be performed in each location where a communication system is to be deployed.

Furthermore, the increasing frequencies and the subsequent high attenuation require the implementation of fade mitigation techniques. This implies a knowledge of the fade slope at the frequency of interest and the use of representative time series of attenuation to test the system. International Telecommunication Union Recommendations (ITU-R) propose models for CCDF of attenuation, second order statistics and also for the generation of time series [3,4]. Even if those models nicely represent the degradations of the signal crossing the troposphere, they do not represent adequately the local climatic particularities. Finally, ITU-R does not provide appropriate model for the generation of time series of attenuation for Earth-LEO (Low Earth Orbit)

links. This is a shortcoming for the data download link of future Earth Observation satellites.

A simulator has been developed in the frame of an ESA contract [5], to transform the local weather conditions (temperature, humidity, pressure profiles, liquid water content, wind, etc.) issued from a Numerical Weather Simulator (WRF), into propagation parameters for a Low Earth Orbit link [6]. It accurately evaluates the gaseous attenuation, and in particular, it can deliver the gaseous attenuation in the absence of a radiometer. The model has been improved and various types of cloud models have been compared in [7, 8]. The model however exhibits limitations in the evaluation of rain attenuation, mostly owing to the limited space (2 km) and time (5 minutes) resolutions between two sets of meteorological output data.

The purpose of this paper is to improve the space resolution of rain events by using the MultiExcell model [9] for the generation of more realistic rain cells.

II. RAIN ATTENUATION USING NWP DATA

The data used for the estimation of the rain attenuation are extracted from the Weather Research and Forecast (WRF) software over three nested domains around Louvain-la-Neuve. The details of the configuration used for running WRF are given in [7] and [10]. The Tiedtke model is used for cumulus clouds and cloud liquid water content is used to calculate cloud attenuation, as cloud is always present when it rains. Two models are used for the rain attenuation:

- the first model (identified as “Mie” in the graphs) uses the Mie theory of scattering by spherical raindrops, the Marshall-Palmer dropsize distribution and the Ray model for dielectric permittivity of water; eventually, the Mie specific attenuation is function of temperature (T) and liquid water content (M_{rain} in $[g/m^3]$) for which the 3D information is produced every 5 minutes by WRF.
- the second model (identified as WRF in the graphs) calculates the specific rain attenuation by using the rainfall rate at ground level, produced every 5 minutes by WRF.

A. Time and space resolution

The space-time resolutions of 2 km and 5 minutes are a limiting factor for the accurate characterization of the rainfall rate evolution. This results in an averaging of the rainfall rate and liquid water content, in both space and time. The purpose of the new model is to reduce this effect, as explained in the following section.

B. Impact of the lead time for running WRF

Trying to improve the resolution of the rain attenuation is useless if the rainfall is badly predicted. The boundary/initial conditions and the lead-time are important. For the calculation of the attenuation, WRF is using initial and boundary conditions from global models and more specifically from ECMWF operational archive.

Another important parameter is the “spin-up” or “lead time”. This is the time needed by WRF to be in steady state, starting with the initialization data. For the evaluation of gaseous and cloud attenuation in [7] and [10], a lead-time of 12 hours has been taken, followed by a simulation of 24 hours. This gave good results. In the case of rain, and more specifically for heavy rain events, this lead-time of 12 hours seems too long. As the initialization data are available every 6 hours, a lead-time of 6 hours has been used in this paper, followed by a simulation of 12 hours. This choice is based on the results in [11]. It is however important to remember that the output of WRF is a prediction and, as such, the rain does not necessarily occur at the place and time it is predicted.

III. COMBINING MULTIEXCELL AND WRF RAIN OUTPUT DATA

The purpose of the newly developed model is to replace the rainfall rate issued from WRF by a series of exponential rain cells, using the MultiEXCELL model [8].

The first step is the determination of the center of the rain cells. Two possible choices have been examined:

- the location of the peak rainfall rate
- the “rain center” formula, similar to the definition of the mass center of a body. The rain rate or integrated water content M [g/m²] are then used instead of mass in the calculation

An example of rain cell centers using both definitions is illustrated in Figure 1. The first definition is used in the following sections of the paper showed by X.

The second step is the extraction of the cell parameters: R_{th} and ρ_{th} are the lower limit of rain rate in a rain cell and the maximum radius of a rain cell, R_M is the maximum rain rate, ρ_0 is the equivalent radius for which $R = R_M/e$. Fig. 2 represents a typical rain cell. During the calculation, many possibilities may be found for the parameters R_M and ρ_0 . The most appropriate profile is defined by comparing other descriptors of WRF and synthetic rain cells, namely, the peak rainfall amount (R_{max}), the root mean square of the rain intensity R_{rms} and the cell dynamics R_{dyn} , the three parameters being defined hereafter:

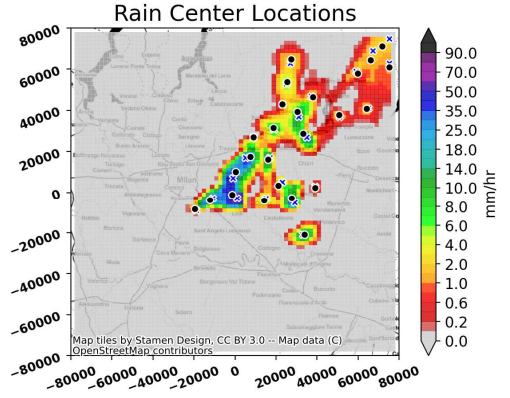


Fig. 1. Example of determination of rain cells centers using peak rainfall rate (X) and rain center (O).

$$\bar{R}_{max} = \frac{1}{A_p} \int_0^{\bar{\rho}} R(\rho) 2\pi\rho d\rho = \frac{k \pi R_M \rho_0^2}{A_p} \gamma(k, \bar{x})$$

$$\bar{x} = \left(\frac{\bar{\rho}}{\rho_0} \right)^{2/k}$$

$$\bar{\rho} = \sqrt{A_p/\pi}$$
(1)

$$R_{rms} = \sqrt{\frac{1}{A_{th}} \int_0^{\rho_{th}} R^2(\rho) 2\pi\rho d\rho}$$

$$= \sqrt{\frac{k R_M^2}{2^k \ln^k(R_M/R_{th})} \gamma(k, 2 \ln(R_M/R_{th}))}$$
(2)

$$R_{dyn} = \frac{\bar{R}_{th}}{R_M} = \frac{k}{\ln^k(R_M/R_{th})} \gamma(k, \ln(R_M/R_{th}))$$
(3)

The left side of the equations are calculated from WRF and the right side are calculated from the synthetic cell parameters. The parameters R_M and ρ_0 are chosen to minimize the error. They are illustrated in Figure 2.

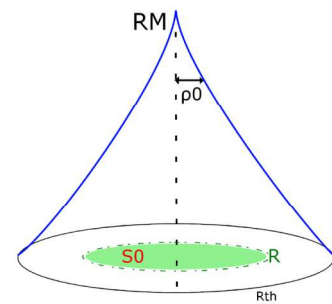


Fig. 2. Typical rain cell parameters.

Fig. 3 shows a comparison between the rain rate from WRF and synthetic rain cells extracted with R_{th} of 1 and 5 mm/h and ρ_{th} of 10 and 20 km. The parameters chosen for the following section are 1 mm/h and 10 km because they ensure the best coherence between the original rain rate and the synthetic rain cells. A higher rain rate threshold misses the

lower rain events while a larger rain cell radius does not enable the detection of small-scale rain cells.

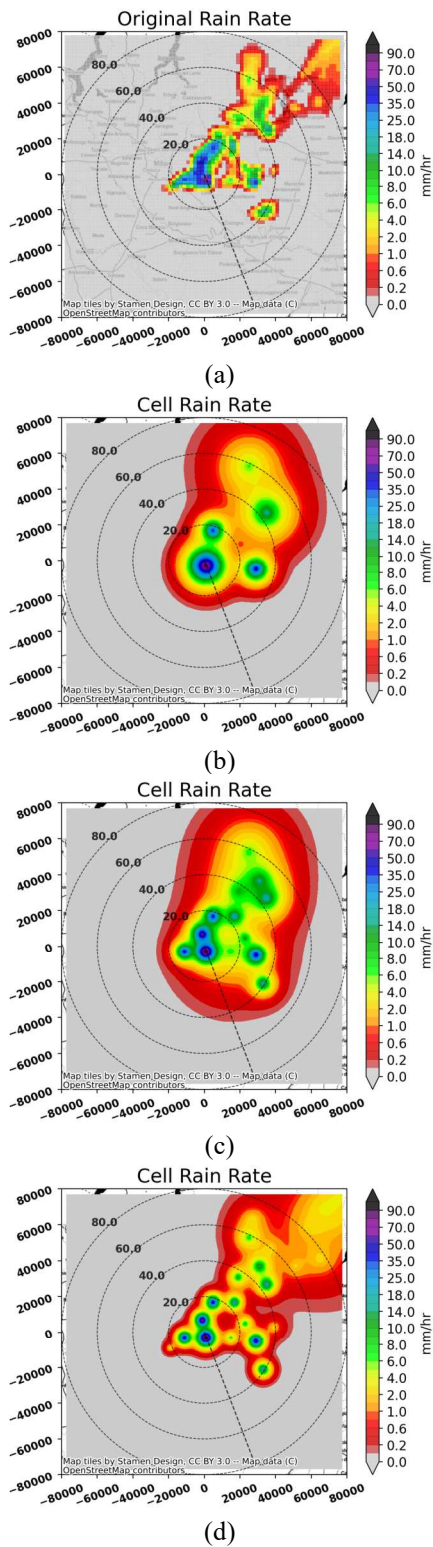


Fig. 3. Example of 2D representation of the rainfall rate (a) original rain rate, (b) synthetic rain cell with $\rho_{th} = 20$ km and $R_{th} = 5$ mm/hr, (c) synthetic

rain cell with $\rho_{th} = 10$ km and $R_{th} = 1$ mm/hr, (d) synthetic rain cell with $\rho_{th} = 10$ km and $R_{th} = 1$ mm/hr.

The initial spatial resolution of 2 km is now reduced by the use of rain cells. The next step is the improvement of the time resolution of 5 minutes given by the output of WRF. To achieve this, the cells structure are moved from one snapshot to the next one, 5 minutes later, at the wind speed. A simple determination of the wind speed governing the movement of the cells is not straightforward. A simple choice is the use of the mean wind speed over the domain ($160\text{km} \times 160\text{km}$) at 700 hPa pressure level. The cells are moved every minute for the following simulations.

IV. RAIN ATTENUATION TIME SERIES

The next step is the generation of time series of the signal issued from a GEO satellite and arriving at the earth station. As an Alphasat propagation experiment is running at Louvain-la-Neuve ($50^{\circ}40'$ N, $4^{\circ}37'$ E, 160m amsl), at 19.7 GHz and 39.6 GHz, this location is used for validation of the simulator, in comparison with the measured data in case of GEO link.

The calculation of the specific attenuation along the earth-space path necessitates a change in coordinates, from WRF Cartesian coordinates to Azimuth-Elevation-Range centered at the Earth station. If the rainfall rate is used (second model in Section 2), the path length is limited by the zero-degree isotherm.

Three months of data are used for a first validation of the WRF+ MultiEXCELL simulator, compared with the simple WRF simulator. The excess attenuation due to rain and clouds is compared with the excess attenuation measured at the ground station of Louvain-la-Neuve (LLN). Figure 4 presents the CCDF of excess attenuation for 3 models: the WRF+MultiEXCELL simulator (synthetic rain cells + cloud), the WRF simulator using rainfall rate from WRF (original rain+cloud) and the WRF simulator using the liquid water content and Mie theory and Marshall-Palmer dropsize distribution (Mie-Marshall-Palmer+cloud).

A comparison between the two models of WRF, as introduced in section 2, denotes a systematic underestimation of the first model using Mie scattering and Marshall-Palmer dropsize distribution. The underestimation is less important for August. An in-depth analysis is in progress.

The new WRF combined with MultiEXCELL shows a better agreement with measurements over the three months considered (Figure 4d), when compared to the WRF model. An in-depth analysis is ongoing to better characterize the differences between the monthly CCDF of the two models.

V. CONCLUSION

A new model combining WRF weather prediction model and MultiEXCELL rain cells model has been implemented in order to improve the simulation of rain attenuation time series for frequencies in Ka band and above. A first validation, comparing measurements and simulation, shows an improvement of the CCDF of rain and cloud attenuation in Q band. Further analysis of time series is ongoing. It also generates time series with a better resolution. Further improvement of the transition between two cells structure will be implemented.

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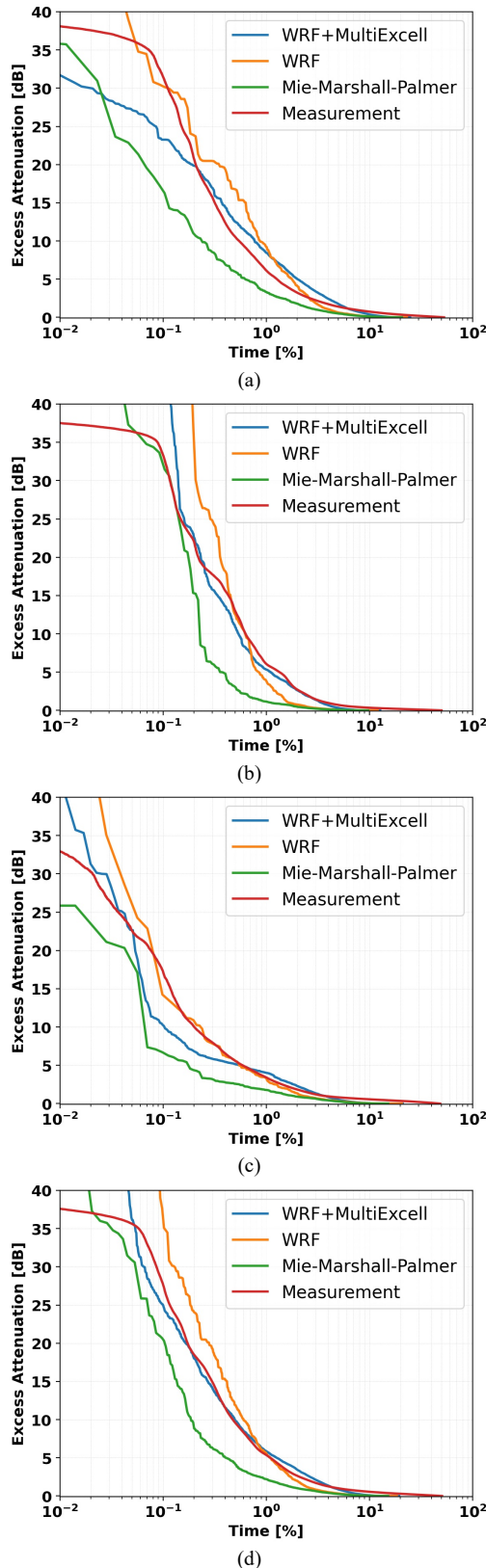


Fig. 4. Comparison between CCDF of time series of attenuation at Q band in Louvain-la-Neuve, measured and simulated, for (a) June 2019, (b)

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