Simulation of tropospheric scintillation on LEO satellite link based on space-time channel modeling

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***Abstract*—Tropospheric scintillation effect is well modelled for Earth to satellite communication in clear air conditions. Statistical models are available for geostationary and non-geostationary satellites. Time series simulators have been developed for geostationary links and are not valid for spatial applications involving LEO satellites such as Earth Observation Satellites. A new scintillation model is proposed in order to take into account both the dynamic behaviour of the troposphere and the movement of the LEO satellite. This model takes advantages of the outputs generated by Weather Research and Forecasting software which simulates the space-time behaviour of the turbulent troposphere. From its outputs, the refractive index structure constant and the standard deviation of the signal log-amplitude caused by the scintillation are computed and the time varying scintillation spectrum is defined by its two asymptotes. Finally, time series of clear air scintillation can be generated by filtering white noise with the spectrum obtained.**

***Index Terms*— Radiowave propagation, tropospheric scintillation, LEO satellites, space-time varying channel.**

I. INTRODUCTION

The necessity of increasing the data rate for new spatial applications forces the utilization of higher frequencies, such as Ka-band (26.5-40 GHz), which offers the advantage of being less congested than lower frequency bands and increases the capacity of conventional communication systems. For similar reasons, Ka-band is envisaged for Earth Observation satellites. At these frequencies however, the signal transmitted becomes more sensitive to the tropospheric impairments. In the absence of rain, the scintillation generated by tropospheric turbulences [1] in the lower part of the atmosphere impacts significantly the performances of the systems.

Tropospheric scintillation has been widely analysed and modeled for fixed Earth-space links [2][3][4]. For Earth Observation data downlink applications, the Earth-LEO satellites path and elevation angle change quickly.

This paper proposes a scintillation modelling based on a space-time varying meteorological environment simulated by a Numerical Weather Research and Forecasting simulator (WRF). The atmospheric data are used to quantify the turbulence intensity and predict the scintillation properties. In this abstract, the procedure for the simulation of time series of scintillation is described and results are presented. Further results and analysis will be presented at the conference.

II. TURBULENCE EVALUATION

A. The WRF simulator

The WRF simulator [5] provides high resolution reanalysis and weather forecast simulating the space-time variation of the troposphere, with as output vertical profiles of pressure, temperature, humidity, rain, wind speed, etc. These parameters obtained with a kilometric space resolution enable the evaluation of propagation effects as attenuations due to gases, cloud, etc. [6]. In the frame of this study, the outputs of this simulator are also used to compute the refractive index and its constant structure parameter for the assessment of the turbulent intensity and the calculation of its effects on radio wave propagation.

B. The turbulence intensity

The pressure, temperature and humidity parameters are used in order to compute the refractive index. Hence, the turbulence intensity is obtained by the constant structure of the refractive index C_n^2 [$m^{-2/3}$] calculated by:

$$C_n^2 = \langle (n_{(r+\delta)} - n_{(r)})^2 \rangle / |\delta|^{2/3} \qquad (1)$$

where n is the refractive index, r is the spatial vector position [m], δ is the spatial separation [m] and the brackets $\langle\rangle$ represent the spatial average operator.

This parameter is retrieved along the propagation paths in form of profiles at each time step of the LEO satellite movement and then integrated in order to compute the standard deviation of the signal log-amplitude caused by the scintillation.

C. The scintillation modeling

The standard deviation of the signal log-amplitude σ_χ describes the intensity of the scintillation, exhibiting variations caused by the turbulences encountered during the propagation of the electromagnetic wave.

The amplitude scintillation spectrum density is usually represented by its two asymptotes $W^0_\chi(\omega)$ and $W^\infty_\chi(\omega)$ [7] forming a low-pass filter and calculated by:

$$W^0_\chi(\omega) = 2.765\ (\sigma_\chi^2/\ \omega_t) \quad (2)$$

$$W^\infty_\chi(\omega) = 7.130\ (\sigma_\chi^2/\ \omega_t)\ (\omega/\omega_t)^{-8/3} \quad (3)$$

where ω_t is the Fresnel frequency computed with the transversal wind component. A filter is calculated for each time step of the satellite movement forming the time varying spectrum used in a Time Linear Varying (TLV) system schematized in figure 1. The scintillation time series are then generated by filtering a White Gaussian Noise with the scintillation spectrum.

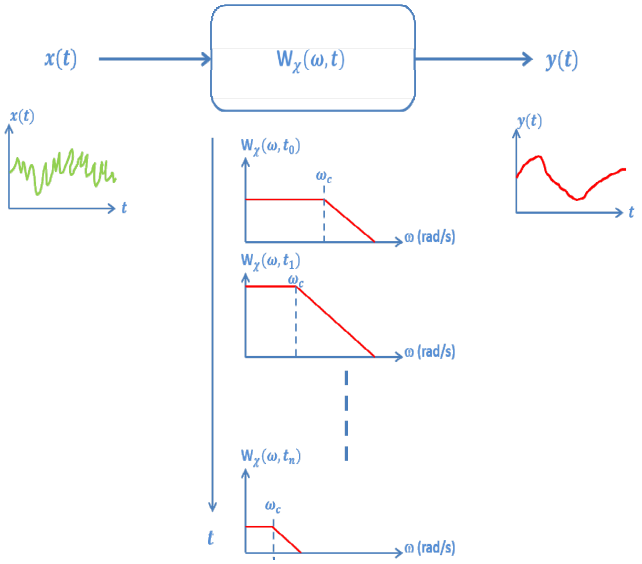


Fig. 1. Generation of time series from a White Gaussian Noise with a Time Linear Varying system

III. APPLICATION

The WRF simulator is first applied on a place/time where scintillation was measured [4]. Figure 2 represents the horizontal repartition of the C_n^2 above Louvain-La-Neuve (LLN) in Belgium on 7 July 1990, 10h00 am with a turbulent layer located around 2000 m altitude.

This turbulent layer is characterized by a small region with strong values of C_n^2 close to LLN antenna (at the centre of figure), surrounded by larger regions with weaker turbulence intensity, moving toward the left edge of the picture under the action of the wind. The time evolution of the troposphere is simulated by the WRF simulator with a time step of 5 min.

The analysis of figure 2 also suggests that the turbulences encountered along the propagation path and then the scintillation effect undergone will greatly vary during the satellite pass, as observed during fixed beacon measurements.

The LEO satellite movement is simulated by an orbit generator with characteristics similar to the Metop-A satellite (altitude 800 km) in order to be visible from LLN antenna. The earth-observation data downlink is at 26 GHz.

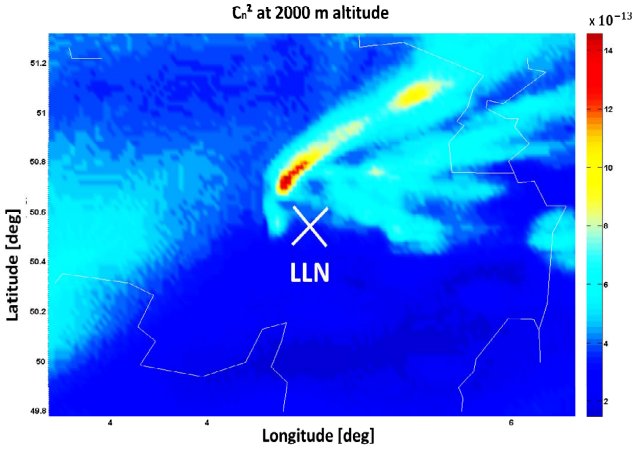


Fig. 2. C_n^2 repartition at 2 km above Louvain-La-Neuve on 07/07/1990 at 10h00

Figure 3 represents the evolution of the standard deviation σ_χ and the elevation angle during the satellite visibility. The elevation angle is ranging from 10° to 85°. Around 6 minutes, the elevation angle is at its maximum while σ_χ reaches its minimum.

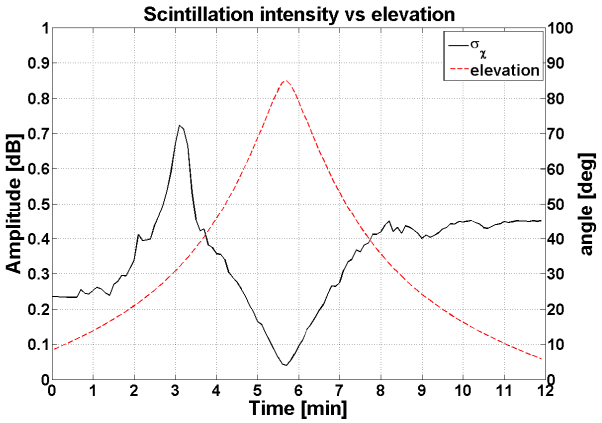


Fig. 3. Scintillation standard deviation and elevation angle versus time for the Earth-LEO link

For a better illustration of the phenomenon, figure 4 shows the C_n^2 profile extracted at 85° corresponding to T=6 minutes. The figure reveals significant values of C_n^2 in a short range of distance (roughly 800 m) representing the thickness of the turbulent layer above LLN. The result of the integration for the calculation σ_χ is however smaller than for low elevation configurations as the one represented in figure 5 corresponding to 30 degree elevation and a time of about 3 minutes (max in figure 3). In the last figure, the C_n^2 values present along the propagation axis show strong C_n^2 values over a larger distance range (around 16 km), due to the oblique crossing of the turbulent layer. At this elevation angle, the standard deviation of scintillation log-amplitude reaches its maximum.

From the analysis of these results representative of one specific configuration, the evolution of the scintillation intensity with respect to the elevation angle is in agreement with the simulations of Liu [8] and the intensity of scintillation is coherent with the measurements made during the Olympus campaign in Louvain-la-Neuve (2 dB peak-to-peak at 20 GHz). The WRF model gives us access to large scale intermittent turbulence and these data seem to reasonably represent the tropospheric turbulence affecting the radiowave propagation.

High elevation angles represent however a small portion of time for LEO satellite links (around 2 min in this example). For the rest of the time, scintillation keeps a stronger level except when the propagation path crosses regions with low turbulences (for T= 0 min to 1.5 min in figure 3).

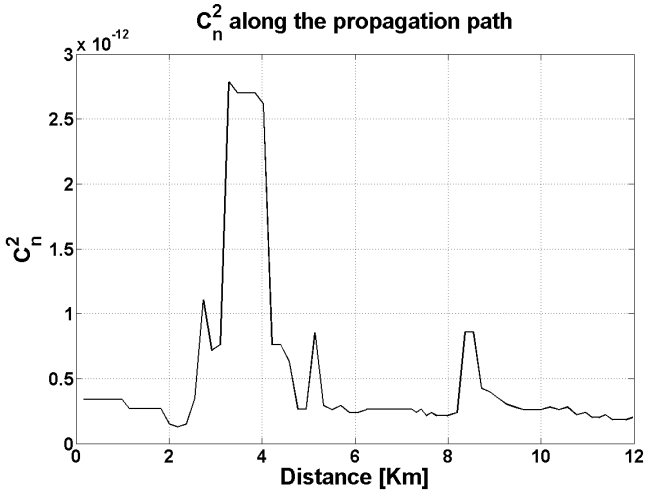


Fig. 4. C_n^2 values along the propagation path for an elevation angle of 85°. The maximum distance of 12 km represents the height of the atmospheric volume generated by the WRF simulator.

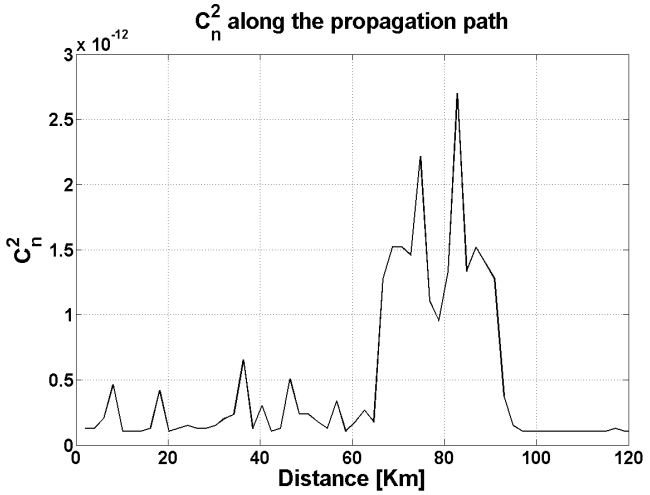


Fig. 5. C_n^2 values along the propagation path for an elevation angle of 30°. The maximum distance of 120 km represents the horizontal distance from the center of the atmospheric volume to its edges.

In order to simulate scintillation time series, the scintillation standard deviation σ_χ is used to calculate the time varying spectrum (3) and (4). By applying a TLV filter, the model provides a first example of clear air scintillation time series shown in figure 6.

The envelope of the time series follows the shape of the scintillation standard deviation curve (figure 3) and ranges from -2 dB to 2.5 dB. During the satellite pass, the scintillation peak-to-peak intensity can vary quickly from 1.5 dB to 0 in a short period or stay stable during a few minutes (from minute 8 to 12) at a significant level.

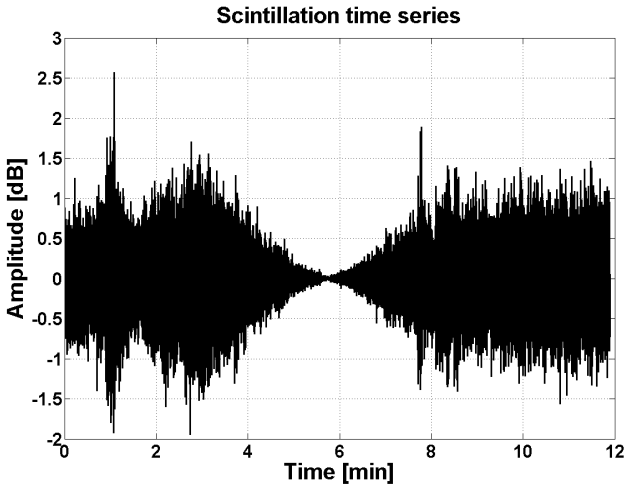


Fig. 6. Example of simulated scintillation time series for Earth-LEO link at 26 GHz.

IV. CONCLUSION

The tropospheric scintillation is an important impairment on earth-satellite communication in clear air conditions and its dynamics has an impact on communication systems (noise and fade mitigation techniques).

The proposed model combines the movement of a LEO satellite and the movement of the air masses for the simulation of realistic time series giving access to the dynamics of the received signal. As expected, Ka-band communication systems are more exposed to scintillation at low elevation angle due to the oblique crossing of turbulent layers.

Finally, the results are coherent with the scintillation measured on Earth-GEO satellite links and support the use of this model for Earth Observation Data Download Ka-band link simulation and earth-LEO communication links.

Further analysis and comparison will be performed on a larger time scale (one year) for the validation of the model.

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REFERENCES

[1] Vanhoenacker-Janvier D., Bouchard P., Bråten L. E., Fabbro V., Kourogiorgas C., Rodgers D., "Channel models for aeronautical and low elevation radio links", 7th European Conference on Antennas and Propagation, EuCAP 2013, pp. 3184 – 3186, 2013.

[2] Otung I., “Prediction of tropospheric amplitude scintillation on a satellite link”. IEEE Trans. on Antennas and Propagation, vol. 44, pp. 1600–1608, 1996.

[3] Moulsley T., Vilar E., Experimental and theoretical statistics of microwave amplitude scintillations on satellite down-links. IEEE Trans. on Antennas and Propagation, vol.30, pp. 1099–1106, 1988.

[4] H. Vasseur, Prediction of Tropospheric Scintillation on Satellite Links from Radiosonde Data, IEEE Trans. on Antennas and Propagation, vol.47, pp. 293–301, 1999.

[5] Michalakes, J., et al., “The Weather Research and Forecast Model: software architecture and performance”. 11th Workshop on the Use of High Performance Computing in Meteorology, United Kingdom, ECMRWF, 2004.

[6] Jeannin N., Outeiral M., Castanet L., Pereira C., Vanhoenacker-Janvier D., Riva C., Capsoni C., Luini L., Cossu M., Martellucci A., “Atmospheric channel simulator for the simulation of propagation impairments for Ka band data downlink”, 8th European Conference on Antennas and Propagation, EUCAP2014, April 2014.

[7] Ishimaru A., Wave Propagation and Scattering in Random Media, vol. 2, Academic Press, 1978.

[8] Liu W, Michelson D.G., “Effects of turbulence layer height and satellite altitude on tropospheric scintillation on Ka-band Earth-LEO satellite links”, IEEE Trans. on Vehicular Technology, vol. 59, pp. 3181-3192.