Measurement and Modelling of Tropospheric Scintillation in Ka/Q band

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***Abstract*—The purpose of this paper is to present the use of Numerical Weather Prediction software to generate 4D-meteorological parameters for the characterization and simulation of tropospheric scintillation for geostationary and non-geostationary Earth-satellite links. A preliminary test has been performed against measurements at 30 degree elevation for a geostationary satellite link and an analysis of the turbulence characteristics on a low elevation Earth-space link has been proposed.**

***Index Terms*—propagation, troposphere, turbulence, Numerical Weather Prediction.**

I. INTRODUCTION

The evolution of the communication and/or the Earth Observation data download systems, leads to a review of the classical ITU-R models available and a development of new methodologies to predict tropospheric degradation. Higher frequencies in Ka or Q band are envisaged for High Throughput Communication satellites and for Earth Observation satellite data download.

All those systems require a careful prediction of the link budget, for geostationary but also for non-geostationary links, for high and low elevation angles. The implementation and testing of Fade Mitigation Techniques need a full 4D (spatial and temporal) characterization of the propagation channel and more specifically, an accurate representation of the propagation channel for low elevation angles. A description of the meteorological conditions around the receiving station is needed.

This paper makes a brief review of the limitations of the existing models for tropospheric scintillation and further introduces the use of Numerical Weather Prediction models for the characterization of the scintillation in low earth orbit (LEO) links. Up to now, there are very few propagation measurements made with LEO satellites above X band and there is no scintillation analysis available. The atmospheric channel simulator presented provides simulation of time series of scintillation on earth-LEO links; the results can however not be tested in the absence of measurements. So, the simulator has been checked against scintillation measurements made during Olympus campaign (geostationary satellite). Furthermore, the possibilities offered by this new type of atmospheric simulator are illustrated on propagation measurements of a 3.2 degree elevation link at Isfjord Radio, Svalbard.

II. TROPOSPHERIC SCINTILLATION MODELS AND MEASUREMENTS

Various statistical models exist for the prediction of the Complementary Cumulative Distribution Function (CCDF) of scintillation intensity χ (dB) and variance σ_χ^2 (dB^2), using temperature and/or humidity at ground level [1-6], profiles [7] or information about clouds [8]. Various measurements have been performed during Olympus and Italsat campaigns in Europe and as well as during other propagation campaigns in tropical climate [9][10].

The existing models have however inherent limitations because they have been developed using geostationary Earth-space propagation measurements [11]

- the statistical models are only valid for yearly or monthly complementary distribution function (CCDF)
- generation of scintillation time series is proposed in ITU-R Recommendation P.1853 [25] only for geostationary satellites
- the elevation angle is linked to the latitude in most of the cases. Only a few measurements have been made at low elevation angles in mid –latitudes
- no Low-Earth Orbit scintillation measurements are available and the dynamics of the scintillation in Earth-LEO links is not characterized

As a consequence, a full description of the tropospheric half space surrounding the Earth station, in space and time, is needed in order to develop new models. The use of Numerical Weather Prediction software has been proposed to build an atmospheric simulator able to generate realistic time series of attenuation and scintillation [12].

III. NUMERICAL WEATHER PREDICTION MODELS FOR SIMULATION OF TROPOSPHERIC DEGRADATION ON EARTH-SPACE LINKS

The use of Numerical Weather Prediction (NWP) models for the generation of the atmospheric parameters around the receiving station has been introduced for the characterization of Earth Observation Ka band data downlinks in the case of

Low Earth Orbit satellites [12]. This usage has been further developed to give meteorological information at a few receiving stations during the Alphasat campaign, in the frame of an ESA contract [14].

A. The Weather Research and Forecasting simulator

Numerical Weather Prediction and atmospheric simulation models are widely used for operational applications (weather forecast) as well as for research purpose. Various operational software are used all over the world and most of the national meteorological offices have developed their own software, based on the classical models. Some models are freely available for operational centers but also researchers who are not specialists in meteorology.

In order to have the adequate spatial resolution for the description of the space above an Earth station, meso-scale models are the most appropriate. Global models do not accurately represent convective events and Large Eddy Simulation (LES) models should only represent a small area around the experimenter station. In the frame of ESA contracts [13,14], the freely available Weather Research and Forecasting model (version 3) [15] has been chosen.

The methodology used in the ESA contract [13], is reused here; with the following main hypotheses:

- the model is constrained every 6 hours using re-analysis databases.
- successive grid nests are necessary to reach the target resolution of about 1-2 km in the horizontal plane and 100 m in the vertical direction.
- the output 4D-matrices of pressure, temperature, humidity can be used with a propagation software or compared with measured meteorological data.

The nesting procedure uses centered square domains of equal grid sizes scaling down to 1/3. These domains have respective resolutions of 18 km, 6 km and 2 km. The size of the outermost domain is 1422 km x 1422 km and of the innermost, 158 km x 158 km. This covers the troposphere down to 10° elevation for most latitudes. Figure 2 shows an example for the Alphasat Earth-Station located in Athens.

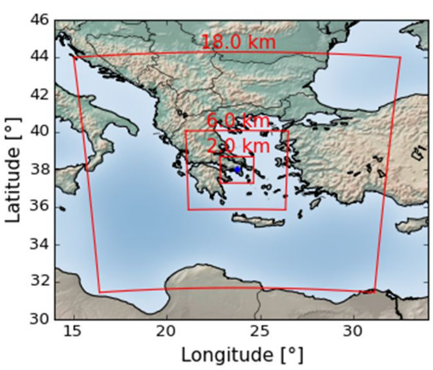


Fig. 1. Example of domains for Alphasat receiving station near Athens.

WRF includes physics drivers which can be called between dynamic solver time-steps to provide tendencies for the model equations. The physics categories are: micro-physics, cumulus parametrization, planetary boundary layer (PBL), land-surface model, radiative model. These models are important because 2 km resolution is not enough for the calculation of propagation effects of turbulence.

WRF individual runs covers 1 day periods with 12 h of set-up (i.e. 36 h runs).

B. Input meteorological data

Initial and boundary conditions for the coarse regional domain must come from a meteorological center able to run global simulations and to assimilate observation data. The European Center for Medium-range Weather Forecasts (ECMWF) offers some products suiting our needs:

- re-analysis datasets, they offer a consistent description of past atmospheres and are often considered to be equivalent to observations.
- operational analysis/forecast datasets, they offer a description of the atmosphere in the close past or a prediction in the near-future.

The ERA-Interim [16] dataset is a re-analysis dataset covering the period from 1979 to present, but only available with a 2-month delay. These data cannot be used for daily comparison with the Alphasat propagation data but it might serve as a reference to validate the results of the simulator.

The operational archive [17] contains an analysis dataset and a forecast dataset available in near real-time (24h). These data fit with the needs of the project but might be farther away from reality than a re-analysis archive is.

C. Output Meteorological parameters needed for radiowave propagation simulation

Results from the NWP software must be extracted and then post-processed.

The desired data from WRF netCDF output file(s) are:

- latitude, longitude and terrain height,
- altitude (from geopotential height),
- temperature and pressure,
- (u, v, w) wind components,
- mixing ratio for water vapor, cloud water, cloud ice, rain, snow, graupel.

Post-processing of the WRF output to produce propagation data uses ITU-R models for the calculation of specific attenuation of gases, clouds and rain [1].

The pressure, temperature and humidity profiles are used for the calculation of the attenuation due to gases but also for the calculation of the refractive index and the structure constant of the refractive index, indicating the intensity of turbulence. The clouds and rain attenuation are also calculated, using the output of WRF.

The Numerical Weather Prediction software can be used for the extraction of the parameters of the turbulent layer around each station participating in the project to further characterize and simulate the scintillation.

The next part of the paper will describe the calculation of turbulence parameters used for the simulation of amplitude scintillation.

D. Turbulence and Scintillation Modeling

Tropospheric turbulence induces rapid variations of the signal in Earth-Space links. In the absence of rain, these rapid variations, called scintillation, significantly affect the performances of communication systems at Ka and Q band.

Following Kolmogorov, the energy is introduced into turbulence as a result of variation of the average wind velocity. The outer scale of turbulence L_0 (m) is the scale at which the energy enters the turbulence. Large eddies break down into smaller eddies until dissipating when the energy dissipation rate is of the same order of magnitude as the kinetic energy. The smallest scale of eddies is called the inner scale of turbulence l_0 (m). If the Reynolds number Re (ratio between inertial and viscous forces) is large enough, the input range is separated from the dissipation range by the inertial range where eddies can be considered as isotropic in fully developed turbulence. The propagation of radiowaves through turbulence has been extensively analyzed by Tatarskii [18] and Ishimaru [19]. The theory is built around C_n^2 ($m^{-2/3}$) the structure constant of the refractive index n which it is given by [18]

$$C_n^2(r) = \frac{\langle (n(r+\delta) - n(r))^2 \rangle}{\delta^{2/3}} \tag{1}$$

where r (m) is the distance along the earth-space link and δ is the amplitude of the distance between two points (statistically isotropic turbulence hypothesis). For Earth-space links with a turbulent layer extending to a distance L (m) from the antenna, the scintillation variance σ_χ^2 (dB^2) depends on the respective size of the first Fresnel zone $\sqrt{\lambda L}$ and the outer scale of turbulence L_0. For $L_0 > \sqrt{\lambda L}$ [3][26]

$$\sigma_\chi^2 = 42.88 \left(\frac{2\pi}{\lambda}\right)^{7/6} \int_0^L C_n^2(r) r^{5/6} dr \tag{2}$$

and if C_n^2 does not vary along the path it integrates to

$$\sigma_\chi^2 = 23.39 \left(\frac{2\pi}{\lambda}\right)^{7/6} C_n^2 L^{11/6} \tag{3}$$

For $L_0 < \sqrt{\lambda L}$

$$\sigma_\chi^2 = 29.5 \left(\frac{2\pi}{\lambda}\right)^{2} L_0^{5/3} \int_0^L C_n^2(r) dr \tag{4}$$

and if C_n^2 does not vary along the path it integrates to

$$\sigma_\chi^2 = 29.5 \left(\frac{2\pi}{\lambda}\right)^{2} C_n^2 L L_0^{5/3} \tag{5}$$

From these equations, it is clear that the length of the path along the turbulent layer L is important, as well as the value of the outer scale L_0. The case $L_0 > \sqrt{\lambda L}$ is usually valid for elevation angles above 10° and the case $L_0 < \sqrt{\lambda L}$ can be reached for beacon data measured at low elevation angles.

In order to generate time series of scintillation, a white Gaussian noise is filtered by a time varying linear system representing the scintillation spectrum, similarly to the procedure shown in [20]. The cut-off frequency of the resulting low pass filters depends on the component of the velocity of the frozen turbulence transverse to the link. For GEO satellites the wind dominates while for non-GEO satellites the satellite movement dominates.

As a conclusion, the main parameters needed for the simulation of scintillation are C_n^2 and the wind velocity components(u, v, w). Those parameters are calculated using WRF output available every 5 minutes.

IV. VALIDATION OF THE APPROACH FOR SCINTILLATION MODELLING

Only a few measurement results are available in the open literature for Earth-satellite LEO links:

- ROCSAT-1 satellite from Taiwan [21]
- FedSat, an Australian microsatellite, using a Ka band transponder devoted to the collection of propagation data [22]

In the absence of long term propagation measurement, validation of the model has been performed on fixed geostationary links versus ITU-R models or versus measured data [13]. Time series of clear air scintillation are generated at 1 measurement per second during one year, using the profiles of C_n^2 generated by the atmospheric channel model.

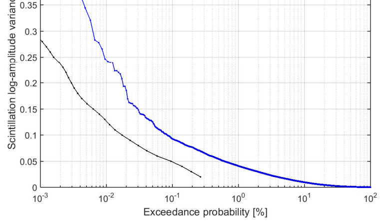
The CCDFs of scintillation variance are calculated and compared with measured scintillation statistics available at Louvain-la-Neuve (Belgium) for 12.5 GHz and 30 GHz, during the Olympus measurement campaign in 1990 (Fig. 2). It can be observed that

- The simulator overestimates the variance by about 90% at 12 GHz and 70% at 30 GHz
- The shape of the measured and simulated CCDF curves are very similar

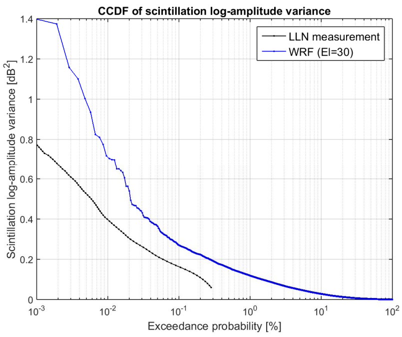
It has however to be stressed that the simulated and measured scintillation are completely independent from each other and have no common parameters.

Various possible origins of the discrepancy have been analysed:

- The calculation of σ_χ^2 using WRF necessitates an integration over the thickness of the turbulent layer and the simulator uses fixed values corresponding to the mean thickness of the turbulent layer, from 1km to 3km. It however appears that σ_χ^2 is very sensitive to the values of the boundaries.
- A single thick turbulent layer is considered for facility, it is however known that turbulence is concentrated in thin turbulent layers [7].



(a)



(b)

Fig. 2. Comparison between scintillation measured at Louvain-la-Neuve ((a) 12.5 GHz and (b) 30 GHz) and obtained from the Atmospheric Channel Simulator using WRF and ECMWF input data for a full year (1990).

Fig. 3 shows an example of the profiles of C_n^2 over a 150x150 km^2 region around Louvain-la-Neuve on 2/7/1990, a day where scintillation was measured. It is visible that the peak value of C_n^2 is just below 2 km and that the turbulence is mostly contained in a layer going from 1 km to 3 km.

- The WRF data are stored every 5 minutes due to the size of the dataset for one year and the turbulence, so meteorological data are under-sampled with respect to the turbulence time scales.
- Planetary boundary layer (PBL) cannot explicitly be resolved at the grid scale of WRF and is introduced as a model. This influences the accuracy of the meteorological parameters during turbulence.
- The data used for verification are old (1990) and the accuracy of the ECMWF data has improved in 26 years

As a preliminary conclusion, the estimation of the limit of the turbulent layer used for the calculation of the variance is probably the main cause of the difference between the curves.

An Alphasat receiving station will be installed at Louvain-la-Neuve, beginning of 2017, and the turbulent status of the troposphere will hence be investigated using the output meteorological data of WRF.

The meteorological data can also be used to further characterise the tropospheric turbulence. In the absence of Louvain-la-Neuve data, the propagation data from Isfjord Radio (78.1°N), located at Svalbard, measuring Eutelsat Ka-Sat at 19.68 GHz [23][24], have been used with 2.5 km resolution data from the AROME Arctic weather forecast, to make a preliminary analysis of the turbulence parameters of the troposphere and get information on the evolution of the height of the turbulent layer. The use of AROME Arctic is preferred to WRF for Svalbard due to its geographical characteristics (mountainous island). A comparison with WRF is foreseen. The geometry of the link is represented in Fig. 4, with the grid of AROME Artic. The elevation angle is 3.2 degree.

The combined analysis of the meteorological data and the scintillation at Isfjord Radio shows, in Fig. 5, that scintillation on the beacon corresponds to the presence of a thin turbulent layer of a few hundred meters, located just below 1 km of altitude (Fig. 5(b)).

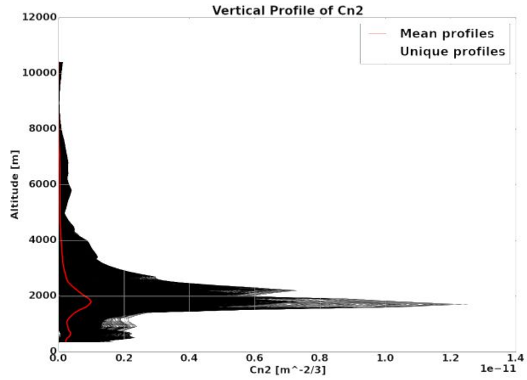


Fig. 3. Profiles of C_n^2 over a 150x150 km² region around Louvain-la-Neuve on 2/7/1990.

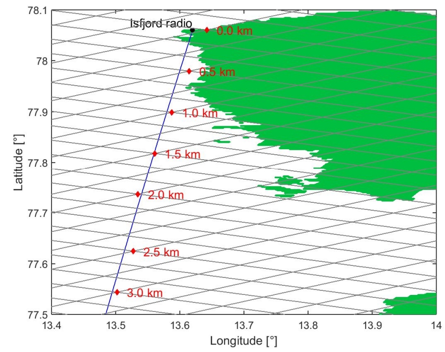


Fig. 4. AROME Arctic grid around Isjord Radio and Ka-Sat link

This layer is quite stable and present during about 12 hours. This stability is the reason why we can correlate the presence of the layer and the scintillation. We have to keep in mind that, in general, Numerical Weather Predictions fail to represent exactly what happens at a given place and time. The calculation of the spectrum confirms that the scintillation measured is above the noise level of the system.

V. Conclusion

New atmospheric channel models, using Numerical Weather Prediction software, have been developed in order to improve the design of Earth-space links with geostationary and non-geostationary satellites, at Ka band and above. A more detailed analysis of the scintillation model has been presented in this paper. Preliminary testing of the model has been performed using geostationary measurements made at Louvain-la-Neuve in 1990 and shows an overestimation of the scintillation intensity probably due to the difficulty to correctly define the turbulent layer thickness.

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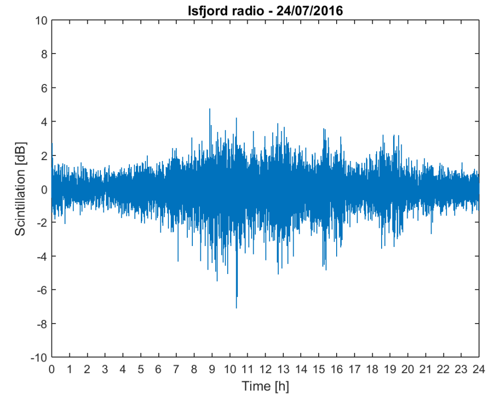
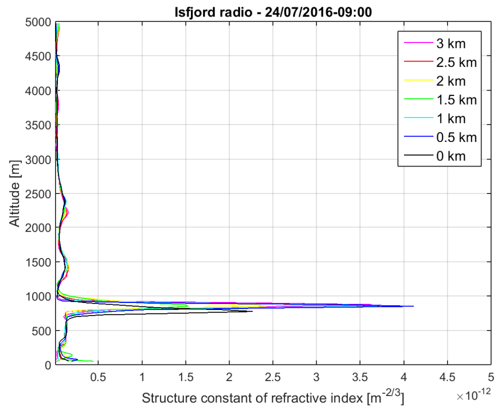
“Channel modelling for design of Earth observation Ka-band data downlink systems”.



(a) Beacon measurement of scintillation at Isfjord Radio on 24/7/2016



(b) C_n^2 retrieved from AROME Arctic data along the Ka-Sat link at 9 AM

Fig. 5. Scintillation at Isfjord Radio on 24/7/2016 and profiles of C_n^2.

The upgrade of the atmospheric simulator for geostationary application has been partially done in the field of another ESA contract “Large Scale Assessment of Ka/Q Band Atmospheric Channel using the Alphasat TDP5 Propagation Beacon”. The data at Isfjord Radio were collected within the ESA contract "Ka-band radio characterisation for SatCom services in arctic and high latitude regions".

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