Sensitivity of tropospheric scintillation models to the accuracy of radiosonde data

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***Abstract*— The increase of the frequency of Earth-Low Earth Orbit satellite links leads to the development of new propagation models in order to accurately characterize the propagation channel. Space-time models are developed for tropospheric attenuation and scintillation but their validation is difficult in the absence of measured data. The verification of scintillation models can be performed worldwide against models using radiosonde data. The sensitivity of the propagation model to measurement errors in radiosonde data is critical. This paper shows an analysis of the effect of radiosonde measurement errors on the refractive index structure constant, which is the main parameter used in the radiosonde scintillation models, and on the scintillation variance complementary cumulative distribution (CCDF). It is shown that the CCDF is mostly sensitive to errors on temperature so that temperature measurements have to be carefully checked before scintillation modelling.**

***Index Terms*—Propagation, clear air tropospheric scintillation.**

I. INTRODUCTION

The amount of data to download increases due to the development of on-board sensors in Earth Observation satellites. The bandwidth being generally a fraction of the center frequency, going from 8 GHz (X-band) to 26 GHz (Ka-band) will drastically increase the available bandwidth, at the price however of an increased degradation of the received signal. The attenuation exceeded for 0.1 percent of a year varies between 10 and 35 dB in Louvain-la-Neuve for an elevation angle decreasing from 50 to 10 degrees. Such a large attenuation cannot be compensated by a fixed margin during the design of the system or by a gain margin in the power amplifier. Fade mitigation techniques are necessary for maintaining the quality of the link.

The classical Complementary Cumulative Distribution function (CCDF) [1] is used for the evaluation of the link budget but time series are needed for the design of the fade mitigation. If the Earth-Space links are well characterized for geostationary satellites, it is not yet the case for Earth-LEO links; models for CCDF are proposed in [1] but there are only a few measurements available for verification [2] [3].

Space-time models are now developed for the simulation of the attenuation along Earth-LEO links [4]. Due to the very short contact time between the LEO satellite and the Earth station (as low as 10 minutes for a LEO satellite), the contact is kept for elevation angles lower that 10 degrees. At such low elevation angles, scintillation due to tropospheric turbulence becomes important. Among the propagation effects (attenuation, depolarization, etc.) the scintillation represents the fast fluctuation of the signal due to tropospheric turbulences. This phenomenon takes its origin from wind shear which mixes atmospheric layers with different levels of temperature, pressure and humidity and involves a variation of the refractive index. Various statistical models exist for scintillation effects [1][5][6] and new models able to generate time series are under development to assess its impact on non-GEO satellite communication system [7]. It has been assessed that scintillation intensity increases with increasing frequency and decreasing elevation angle and it becomes crucial to accurately predict the scintillation variance in function of the elevation angle of the link, on a worldwide basis.

In the absence of Earth-LEO measurements, the space-time models for scintillation can be tested against Earth-GEO scintillation data measured on Earth-Space links but also scintillation models such as the model using meteorological data developed by Vasseur [8]. This model uses radiosonde data available worldwide for the calculation of scintillation parameters and improves the statistics with respect to the ITU-R model based on the wet term of the refractivity (N_{wet}) at ground level. Radiosonde equipment measures temperature, pressure, humidity, wind intensity and direction that can be used to characterize the propagation medium.

In the scintillation model developed by Vasseur [8], the CCDF of scintillation variance obtained from radiosonde data is however very sensitive to the accuracy of the measured temperature and humidity, as it has been shown in [9] and [10]. This paper presents an analysis of the sensitivity of the refractive index structure constant as well as scintillation statistics to the accuracy of the temperature and humidity measured by the radiosonde.

II. CLEAR AIR TROPOSPHERIC SCINTILLATION

The tropospheric scintillation intensity is represented by the variance of the log-amplitude σ_χ^2 of the received signal. The theory of radiowave propagation through a turbulent medium [11] links the value of σ_χ^2 to the refractive index structure constant C_n^2 in $m^{-2/3}$.

$$\sigma_\chi^2 = 42.48 \frac{k^{7/6}}{\sin^{\frac{11}{6}}(\theta)} \int C_n^2(z) z^{5/6} dz \quad (1)$$

where k is the wavenumber ($k = 2\pi/\lambda$), λ the wavelength, θ is the elevation angle, z is the height above the ground level, $C_n^2(z)$ is the height dependent refractive index structure constant. The low resolution of the radiosoundings imposes the use of a probabilistic approach to evaluate $C_n^2(z)$ in order to take into account the non-uniformity of the turbulence in a layer (intermittency) [8]:

$$< C_n^2(z) > = 2.8\, M_0^2(z) < R(z) >$$
$$\int_0^\infty L_0^{4/3} P_{L_0} \int_0^\infty P_S \int_{-\infty}^{S^2/4} (N^2)^2 P_{N^2}\, dN^2 dS dL_0 \quad (2)$$

$$M_0(z) = -77.6 \times 10^{-6} \frac{p(z)}{gT(z)} \langle R(z) \rangle = \left[1 + 1.5510^{-4} \frac{q(z)}{T(z)} - 0.77510^{-4} \frac{g \frac{\partial q}{\partial z}(z)}{\langle N^2(z) \rangle T(z)} \right]^2 \quad (3)$$

$$\langle N^2(z) \rangle = g \frac{\partial Ln\theta}{\partial z}(z) \quad (4)$$

P_{LO} is the uniform distribution of the outer scale of turbulence (L_0) with L_{0min} chosen as 3 m and L_{0max} chosen as 100m [8]

$$P_{LO} = \begin{cases} \frac{1}{L_{0max} - L_{0min}} & \text{for } L_{0min} \le L_0 \le L_{0max} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

P_S is the Rice distribution of the wind shear S following the assumption of Gaussian distribution for both components of the wind shear vector S

$$P_S = \frac{S}{\sigma_S^2(z)} exp\left(-\frac{S^2 + \langle S(z) \rangle^2}{2\sigma_S^2(z)} \right) I_0 \left(\frac{S \langle S(z) \rangle}{\sigma_S^2(z)} \right) \quad (6)$$

$$\langle S(z) \rangle = \sqrt{ \left(\frac{\partial v \cos\varphi}{\partial z}(z) \right)^2 + \left(\frac{\partial v \sin\varphi}{\partial z}(z) \right)^2 } \quad (7)$$

$$\sigma_S = 0.18\, L_0^{-0.3} |\langle N^2(z) \rangle|^{0.25} \rho(z)^{-0.13}$$

P_N^2 is the Gaussian distribution of the buoyancy forces N with a mean equal to $\langle N^2(z) \rangle$ and a standard deviation given by

$$\sigma_N(z) = \sqrt{\frac{6}{5}} \sigma_S(z) \sqrt{|N^2(z)|} \quad (8)$$

where g is the acceleration of gravity, q is the specific humidity, $\langle N^2(z) \rangle$ is the mean value of buoyancy forces, θ is the specific temperature, $\langle S(z) \rangle$ is the mean wind shear, $\rho(z)$ is the mean density of dry air in kg/m^3. All the parameters that are z-dependent are introduced as vertical profiles. This model has been developed by H. Vasseur (UCL) [8], based on Warnock intermittency model [14]. The justification of the model and its limitations can be found in [8].

The sensitivity of C_n^2 to measured temperature and humidity cannot be easily extracted. In order to perform a sensitivity analysis of $<C_n^2(z)>$ to errors in temperature and humidity, relative errors are introduced in the equations:

$$T_\varepsilon(z) = T(z)(1 + \varepsilon_T) \quad (9)$$

T(z) is the exact temperature profile and ε_T the relative error. Similar equation holds for humidity. This expression can be modified to add biases in the error, represented by a constant value or enter relative errors function of the temperature value ($\varepsilon_T(T)$). The mathematical expression is retrieved in function of the errors in temperature (ε_T) and humidity (ε_h).

III. SENSITIVITY ANALYSIS

A full year of radiosonde data measured at Uccle, Belgium, in 1990 has been processed. The choice of this year has been driven by the existence of propagation measurements during that year and more specifically scintillation statistics (CCDF). The radiosondes were launched twice a day (at 00h00 and 12h00 UTC) and the data have been interpolated to obtain a vertical spatial resolution of 50 m. The $<C_n^2>$ vertical profiles are computed from measured pressure, temperature, humidity and wind parameters (equation (2)) and the yearly mean profile is presented in Fig. 1. The plain blue curve shows the exact $<C_n^2>$ compared with $<C_n^2>$ calculated with an injected relative error of 0.5, 1 and 2.5% in temperature or 5 and 10% in humidity. The errors introduce a shift in the $<C_n^2>$ values.

It has to be stressed that the accuracy of radiosonde relative humidity profiles is limited and depends on the type of radiosonde used. Furthermore, day-night differences near 10% have been observed, daytime measurements suffering from bias due to solar radiation [12]. Various types of error sources in the humidity measurement have been determined: dry bias due to inaccurate calibration of the humidity sensor at low temperature and to chemical contamination, altitude shift due to low sensor response, icing at low temperatures, etc. Correction methods have been proposed [13]. The radiosondes used in 1990 by the Royal Meteorological Institute (RMI) are RS80-A Vaisala radiosondes. The mean bias for the RS80-A radiosonde is of about +/- 10% in relative humidity [15]. The accuracy of the humidity measurements has improved from 1990 on: the recent humidity sondes have an accuracy of 5% in relative humidity (Vaisala RS92). The accuracy of the temperature measurement, for the same sonde, is of the order of 0.5 degree.

Figure 1 represents the mean C_n^2 profile calculated from British Atmospheric Data Centre (BADC) radiosonde data from Uccle (B), 20 km away from Louvain-la-la-Neuve, for year 1990. This year was chosen because beacon measurements were made at Louvain-la-Neuve during that year. It is clearly visible that C_n^2 is mostly sensitive to errors in temperature (dashed curve for 2.5% error in temperature). As a consequence, the accuracy of the temperature measurements is important.

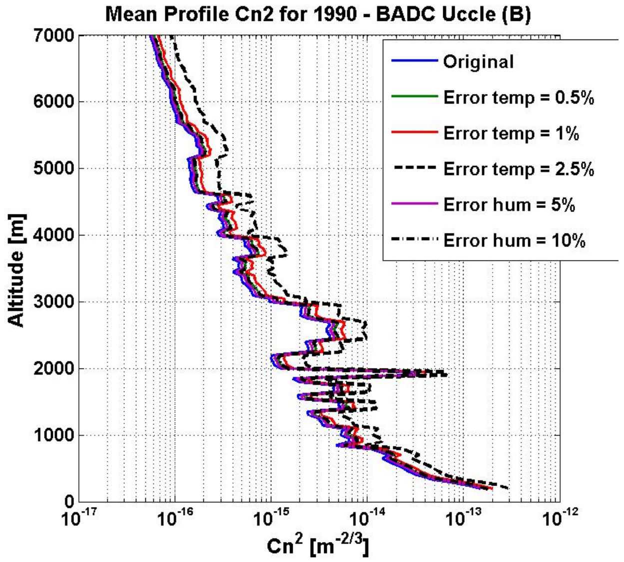

Fig. 1: Mean yearly profile of C_n^2 calculated from BADC radiosoundings from Uccle (B) for 1990 with the impact of errors in temperature and humidity.

For the new sondes, the accuracy is high enough but the precision of the measurements could become an issue when old radiosonde data are used, mainly for high altitude values where some icing effects can appear in humidity measurements. Those values should be discarded before the calculation of the scintillation variance CCDF. This is not a problem because the highest C_n^2 values appear below 3000m in temperate maritime regions.

The next step of the calculation is the evaluation of the impact of the errors on C_n^2 on the log-amplitude scintillation variance. In the model used [8], the long term CCDF of scintillation variance is log-normally distributed

$$p\left(\sigma_\chi^2\right) = \frac{2}{\sqrt{2\pi}\sigma_\chi^2 s} exp\left(-\frac{\left[ln\left(\sigma_\chi^2/m\right)\right]^2}{2s^2}\right) \quad (10)$$

where m (dB^2) is the median value of the scintillation variance distribution and s is the standard deviation of $ln\sigma_\chi^2$. The CCDF of scintillation variance is a complementary error function:

$$CCDF\left(\sigma_\chi^2\right) = \frac{1}{2} erfc\left(\frac{ln\left(\sigma_\chi^2/m\right)}{\sqrt{2}s}\right) \quad (11)$$

The calculation of m and s parameters is described in [8].

Figure 2 shows the CCDF of scintillation variance in Louvain-la-Neuve for a geostationary satellite at 26 GHz. For the link parameters chosen, the impact of an error in temperature on scintillation variance CCDF is reasonably small if the error in temperature remains below 1% and if the error on humidity remains below 5%.

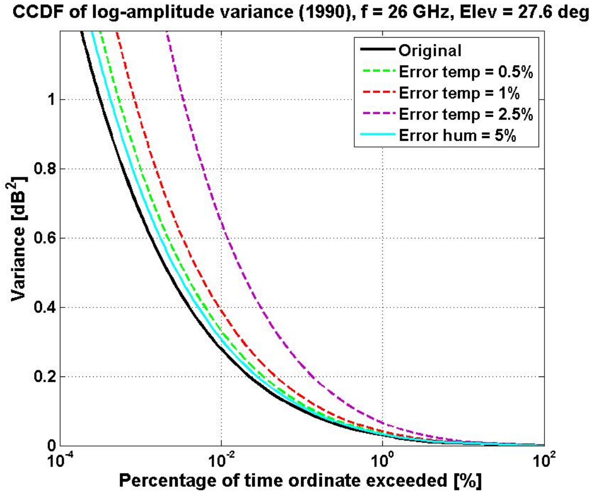

Fig. 2 Sensitivity of the CCDF of scintillation variance to an error of 0.5, 1 and 2.5% in temperature or 5% error in humidity in the radiosoundings.

Analysis of the effect of the low resolution and the presence of noise in the measured meteorological data has been performed in a previous paper [16] and it was noted that the main effect was the effect of the noise in the derivatives (see (3)) and that a four-points derivative was more appropriate to reduce this effect.

IV. Conclusion

In this paper, the sensitivity of the refractive index structure constant to temperature and humidity measured by radiosondes is evaluated as well as its impact on the CCDF of scintillation variance. The probabilistic model used has revealed that temperature errors have a larger impact on the scintillation estimation due to their impact on the refractive index structure constant $<C_n^2>$. The results show that the error on the CCDF of scintillation variance remains reasonable (less than 0.2 dB^2 for the largest values) if the temperature error is lower than 0.5%. So, the temperature profiles should be carefully checked to avoid errors in the calculation of $<C_n^2>$, mainly for old radiosonde measurements for which the accuracy of the sensors is lower. Another direct consequence is that the radiosonde meteorological measurements have to be checked because erroneous measurements have to be extracted from the files before the calculation of C_n^2, to avoid large degradation of the statistics.

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