Prediction of Tropospheric Scintillation on Satellite Links from Radiosonde Data

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***Abstract*— On the basis of radiosonde data, a new method is proposed for predicting tropospheric scintillation effects on slant paths. It stems from a rigorous statistical development and consists of two steps. First, statistical features of tropospheric turbulence responsible for scintillation are extracted from the analysis of a large amount of radiosonde ascents. Second, long-term scintillation statistics are inferred from these turbulence characteristics, using the theory of propagation through a turbulent medium. The method is applied to a complete year of radiosonde data measured in Belgium and the predicted scintillation results are compared with measurements carried out on the same year near to the meteorological station. An agreement better than with any other usual prediction method is found. The method yields very accurate predictions of scintillation annual statistics and also adequately represents the seasonal and monthly variability of scintillation. Unlike the current prediction models, the proposed radiosonde-based method does not rest on empirical relationships derived from particular propagation experiments and could, therefore, be applied more widely.**

***Index Terms*—Satellite communication, scintillation, terrestrial atmosphere.**

I. Introduction

THE impact of tropospheric scintillation has to be considered in the design and planning of satellite communications systems at frequencies above about 10 GHz. Tropospheric scintillation is caused by small-scale fluctuations of the refractive index due to turbulence. It yields random fades and enhancements of the received signal, which could impair the availability of low-margin systems, particularly at low-elevation angles, and interfere with tracking systems and fade mitigation techniques.

A number of prediction methods has been proposed for evaluating statistical distributions of slant-path scintillation [1]–[4]. They are based on both theoretical and experimental studies and result in empirical formulations involving the main link parameters (frequency, elevation, and antenna diameter) and readily available meteorological information (long-term mean temperature and humidity at ground level). The main drawback of these empirical prediction methods is that they are strongly dependent on the measurement data on which they are based and, therefore, on the related experimental conditions (climate, link setup, data processing). Significant differences are observed between the scintillation effects predicted by the methods. For a given satellite link, it may be expected that the most reliable scintillation prediction method should be the one based on data obtained in the closest experimental conditions.

On the other hand, radiosonde data consist of a valuable source of information for characterizing tropospheric turbulence. A few papers [5]–[8] report on statistical methods for accurately estimating the intensity of turbulence, represented by means of the refractive index structure parameter, from radiosonde ascents. Hence, using radiosonde data, it could be ideally possible to derive propagation experiment-independent scintillation predictions, as theoretical relationships exist between the instantaneous structure parameter along the propagation path and the simultaneous scintillation effects [9], [10]. The scarcity of meteorological soundings (typically two ascents per day) prevents, however, from directly predicting scintillation statistics by this way.

This paper proposes a new method for predicting long-term scintillation statistics on the basis of radiosonde data. The prediction method stems from a rigorous statistical approach. The long-term distribution of scintillation effects is inferred from statistical features of the structure parameter profiles, which are extracted from a large amount of radiosonde data (more than one month), using the theory of propagation through a turbulent medium. The proposed method does not suffer from the limitations of the current empirical scintillation prediction models. It does not include any particular propagation measurements, but is only based on radiosonde data and theoretical considerations. Consequently, the radiosonde-based method could be successfully applied to any slant-path configuration, the climate-dependent aspect of scintillation being thoroughly accounted for by the radiosonde ascents.

After a general overview of scintillation effects and basic theory, the proposed radiosonde-based prediction method for scintillation is derived. Then the method is applied to one year of radiosonde data collected in Belgium and the prediction results are compared with scintillation measurements carried out on the same year near to the meteorological station with the ESA's Olympus satellite. The good agreement between measured and predicted scintillation statistics on an annual, seasonal, and monthly basis validates the method. Finally,

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comparisons with other current prediction models provide a further evidence of the interest of the proposed method.

II. Characterization of Tropospheric Scintillation

Typically, satellite links above 10 GHz may suffer from tropospheric scintillation fluctuations up to several decibels peak-to-peak with a time period of a few seconds. Scintillation occurs under clear-sky conditions and during rain as well. However, in the presence of rain, it is not straightforward to distinguish actual scintillation from rapid variations of rain attenuation. In addition, for low-availability satellite system design purposes, it is of less interest to investigate scintillation under rainy conditions, as rain attenuation is usually much more pronounced than scintillation fades. For those reasons, only clear-weather scintillation is accounted for in this paper.

A. Description of Scintillation Effects

Tropospheric scintillation is characterized by two main parameters.

1) The log-amplitude χ (in decibels); that is, the ratio of the instantaneous amplitude of the observed signal to the mean amplitude, expressed in decibels. The mean amplitude is generally calculated by a 60-s moving average filter (cutoff frequency around 0.01 Hz) [11], in order to separate rapid turbulence induced scintillation from spacecraft-induced variations and contributions of other propagation factors.
2) The scintillation variance σ_χ^2 in dB^2; that is, the variance of the log-amplitude χ. In order to produce a good estimator of the instantaneous scintillation effect and accounting for its time-variability, the variance is generally calculated in a sliding way over about 1 min [11].

Because turbulence-induced scintillation is a stochastic process, it is important to assess its statistical features. It appears that a scintillation event is characterized by a stationary period of a few minutes (up to ten or fifteen minutes). Within this period, the scintillation variance remains approximately constant and the scintillation log-amplitude distribution can be fitted quite well by a zero-mean Gaussian distribution whose variance is the mean scintillation variance during the period. For a period longer than several minutes, the variability of σ_χ^2 must be taken into account and the long-term probability density function of scintillation amplitude can be modeled by a Gaussian distribution with log-normally distributed variance [12]

$$p_{\text{long-term}}(\chi) = \int_0^\infty p_{\text{short-term}}(\chi|\sigma_\chi^2)\,p(\sigma_\chi^2)\,d\sigma_\chi^2 \quad (1)$$

where $p_{\text{long-term}}(\chi)$ is the long-term probability density function (pdf) of scintillation log amplitude and $p_{\text{short-term}}(\chi|\sigma_\chi^2)$ is the conditional short-term pdf of χ, assuming a constant value of σ_χ^2 for the scintillation variance, which is Gaussian

$$p_{\text{short-term}}(\chi|\sigma_\chi^2) = \frac{1}{\sqrt{2\pi\sigma_\chi^2}}\exp\left(\frac{-\chi^2}{2\sigma_\chi^2}\right) \quad (2)$$

$p(\sigma_\chi^2)$ is the long-term pdf of scintillation variance, which is log-normally distributed

$$p(\sigma_\chi^2) = \frac{1}{\sqrt{2\pi}\sigma_\chi^2 s}\exp\left(\frac{-\left[\ln\left(\sigma_\chi^2/m\right)\right]^2}{2s^2}\right) \quad (3)$$

where m (in dB^2) and s (dimensionless) are the two parameters of the log-normal distribution: m is the median value of the scintillation variance distribution and s is the standard deviation of $\ln(\sigma_\chi^2)$.

Cumulative distributions of scintillation fade and variance, a commonplace way of representing long-term scintillation statistics, may be obtained by integrating (1) and (3), respectively. For scintillation variance, an analytical expression is easily derived

$$\text{cdf}(\sigma_\chi^2) = \frac{1}{2}\,\text{erfc}\left(\frac{\ln\left(\sigma_\chi^2/m\right)}{\sqrt{2}s}\right) \quad (4)$$

where $\text{cdf}(\sigma_\chi^2)$ is the scintillation variance cumulative distribution function or the probability that scintillation variance exceeds σ_χ^2 and $\text{erfc}(\cdot)$ is the complementary error function.

B. Theory of Turbulence-Induced Scintillation

The theory of wave propagation through a turbulent medium has been quite well dealt with in the literature [9], [10]. Thanks to this theory, general characteristics of a stationary scintillation event such as σ_χ^2 can be related to a measure of the turbulence-induced refractive index inhomogeneities called the structure parameter C_n^2 in $m^{-2/3}$. For centimeter- and millimeter-wave earth–space paths with elevation angles above about 5°, it is acknowledged that scintillation variance usually satisfies the following expression [9], [10]:

$$\sigma_\chi^2 = 42.48\,\frac{k^{7/6}}{(\sin\theta)^{11/6}}\int_{\text{height}} C_n^2(z)z^{5/6}\,dz \quad [\text{dB}^2] \quad (5)$$

where $k = 2\pi/\lambda$ with λ the wavelength, the frequency wavenumber (in m^{-1}); θ is the elevation angle; z is the height above the ground level (in meters); and $C_n^2(z)$ is the height-dependent refractive index structure parameter (in $m^{-2/3}$), or synonymously the structure parameter vertical profile.

It should be pointed out that several hypotheses have been assumed for deriving the previous theoretical relationship. The major assumptions are as follows [9], [10].

1) Turbulence is considered to be well developed so that it satisfies the Kolmogorov theory of turbulence.
2) The incident wave in the turbulent medium is supposed to be a plane wave.
3) Scintillation is assumed to be weak so that a smooth perturbation method is used to determine the effect of refractive index inhomogeneities on wave propagation.
4) Equation (5) actually consists of the asymptotic approximation of a much more complicated relationship valid for $L_0 \gg \sqrt{\lambda(z/\sin\theta)}$, where L_0 $[m]$ is the outer scale of turbulence.

5) Scintillation variance as calculated from (5) characterizes the fluctuations of the signal received by a hypothetical point receiver. As a matter of fact, the finite aperture of an actual receiving antenna creates an integrating or smoothing effect that leads to a reduction of the scintillation variance.

Hypotheses 1–3 are not very restrictive and seem to be always fulfilled by slant-path scintillation effects at centimeter and millimeter waves. Hypothesis 4 restricts the use of (5) to earth–space paths with elevation angles above about 5–10° [13]. Hypothesis 5 imposes to multiply the point receiver scintillation variance as calculated by (5) by a so-called antenna averaging factor [1], [14], g^2, to get the scintillation variance of the signal received by the actual antenna aperture.

III. Scintillation Prediction Method Based on Radiosonde Data

The ultimate goal of the proposed method is to infer the two parameters m and s required for evaluating the long-term probability distributions of both the scintillation variance [see (3)] and scintillation log-amplitude [see (1)] from a statistical analysis of long-term radiosonde data. Atmospheric soundings may indeed be used to estimate the vertical profile of the refractive index structure parameter $C_n^2(z)$, which is related to the scintillation effect on earth-space paths by (5). The method comprises two main steps. First, representative statistical characteristics of the C_n^2 profile are derived from an analysis of the available radiosonde data. Second, the parameters m and s governing the scintillation long-term statistics on a given slant path are predicted from the inferred C_n^2 vertical profile features.

A. Long-Term Statistical Characterization of C_n^2 Profile from Radiosonde Data

C_n^2 is a highly variable quantity whose values can be found between about 10^{-10} and 10^{-20} $\mathrm{m}^{-2/3}$. There are mainly two regions in the troposphere in which turbulence is likely to be strong and C_n^2 to be high: near the earth surface and in clouds. It has been demonstrated that turbulence in clouds (particularly fair weather cumulus) is responsible for most of the significant scintillation effects observed on satellite links [15].

The inference of fair estimates of the structure parameter profile from meteorological soundings is extensively dealt with in several papers [5]–[8]. The method summarized hereafter is based on the work by Warnock *et al.* [5]–[7].

Basically, according to the Kolmogorov theory [9], [10], the radio frequency refractive-index structure parameter for well-developed turbulence is given by

$$C_n^2(z) = aM(z)^2 L_0^{4/3} \quad [\mathrm{m}^{-2/3}] \tag{6}$$

where $a \approx 2.8$ is a dimensionless constant, $M(z) = dn(z)/dz$ is the vertical radio frequency refractive index gradient, in m^{-1}, and L_0 [m] is the outer scale of turbulence.

As the refractive-index gradient depends on meteorological parameters available in radiosonde data (values and gradients of pressure, temperature, and humidity), (6) could ideally be used to derive the structure parameter profile from a radiosonde ascent. Actually, however, several considerations prevent from calculating directly the structure parameter profile by using (6) and a probabilistic approach has to be used instead to estimate the mean structure parameter at height z [6], [7]

$$\langle C_n^2(z)\rangle = 2.8 M_0(z)^2 \langle R(z)\rangle \int_0^\infty L_0^{4/3} P_{L_0} \int_0^\infty P_S \cdot \int_{-\infty}^{S^2 R_{ic}} (N^2)^2 P_{N^2}\, dN^2\, dS\, dL_0 \tag{7}$$

where $M_0(z)$ and $R(z)$ are defined by $M(z) = M_0 N^2 R^{1/2}$ and R represents the humidity contribution to M^2; L_0, S, and N^2 are random variable representing the outer scale of turbulence, the wind shear, and the buoyancy forces, respectively, and characterized by the pdf P_{L0}, P_S, and P_{N^2}; and $Ric \approx 0.25$ [5] is the critical value of the Richardson number (dimensionless ratio of buoyancy to square wind shear) used to assess the instability of the medium.

Equation (7) yields expected values of $C_n^2(z)$, denoted $\langle C_n^2(z)\rangle$, that may be regarded as the mean structure constant at height z through an atmospheric slab whose thickness is related to the vertical resolution of the sounding. The direct calculation of the C_n^2 profile from radiosonde data would have indeed required a vertical resolution of the order of 1 m or so, in order to detect the fine structure and random behavior of the turbulent troposphere, while the height resolution of balloon-borne soundings is limited to several tens of meters. As detailed in Appendix A, all the parameters involved in (7) are derived from the basic meteorological profiles measured by radiosounding: $p(z)$ (pressure in hPa), $T(z)$ (temperature in K), $e(z)$ (water vapor pressure in hPa), $v(z)$ (wind speed in m/s), and $\varphi(z)$ (wind direction in degrees).

Numerically solving the triple integral, (7) evaluates the vertical profile of mean refractive index structure constant $\langle C_n^2(z)\rangle$ from meteorological data collected during one radiosonde ascent. As soundings are usually carried out twice a day, a considerable amount of $\langle C_n^2\rangle$ profiles is obtained on a long-term basis (a month, a season, a year, several years). A statistical analysis is, hence, performed on the structure constant profiles inferred from long-term radiosonde data measured at the same location, as suggested in [16] and [17]. Profiles of the mean, median, and standard deviation values of $\langle C_n^2(z)\rangle$ are calculated, denoted by $\overline{\langle C_n^2(z)\rangle}$, $p50_{\langle C_n^2\rangle}(z)$ and $\sigma_{\langle C_n^2\rangle}(z)$ (all in $m^{-2/3}$), respectively. As an example, $\overline{\langle C_n^2(z)\rangle}$ represents the average (over the time period for which radiosonde data are available) of the estimated mean value of the structure parameter through a tropospheric slab of height z and of thickness related to the sounding vertical resolution (several tens of meters). In addition, long-term statistical distributions of $\langle C_n^2\rangle$ at height z are produced. It is experimentally found (evidences are given in Section IV) that long-term probability density functions of $\langle C_n^2(z)\rangle$ are fairly well approximated by a log-normal distribution whatever the height z, as reported in [16], [18], and [19], providing the distribution is calculated over a period of at least one month.

B. Derivation of Long-Term Distributions for Scintillation on Slant-Path

Using the mean structure parameter profile extracted from a balloon-borne sounding, the scintillation effect on a satellite link could be easily deduced from (5). We have just to replace the integral of $C_n^2(z)z^{5/6}\,dz$ by a summation of $\langle C_n^2(z)\rangle z^{5/6}\Delta z$, where Δz represents the thickness of the horizontal slab through which $\langle C_n^2(z)\rangle$ has been calculated and the summation has to be done over all the height values for which meteorological information are available. By this way, we would obtain an instantaneous value of the scintillation variance during the radiosonde ascent. On the contrary, the goal of this study is to predict long-term statistics of scintillation from a large amount of radiosonde data. For this purpose, (5) is used in order to relate the statistical moments of the scintillation variance to the long-term characteristics of the mean structure parameter profile. As it appears in (3) that two parameters are enough for a thorough description of the scintillation variance distribution, we focus on the simplest moments of the scintillation variance: the mean and variance, denoted by $\overline{\sigma_\chi^2}$ (in dB^2) and $\sigma_{\sigma_\chi^2}^2$ (in dB^4), respectively. A similar approach has been proposed in [16] and [17] for evaluating statistics of the power received on tropospheric transhorizon radio links.

On the basis of (5), the mean scintillation variance is easily expressed as a function of the average profile of the mean structure parameter $\overline{\langle C_n^2(z)\rangle}$ over the period of available radiosonde data

$$\overline{\sigma_\chi^2} = 42.48\,\frac{k^{7/6}}{(\sin\theta)^{11/6}}\sum_z \overline{\langle C_n^2(z)\rangle} z^{5/6}\Delta z. \tag{8}$$

On the other hand, the calculation of the variance of the scintillation variance $\sigma^2_{\sigma^2\chi}$ requires a much more elaborate development described in Appendix B, which results in the following relationship:

$$\sigma_{\sigma_\chi^2}^2 = \left(\sum_z\sum_{z'}\left[42.48\,\frac{k^{7/6}}{(\sin\theta)^{11/6}}\right]^2 \cdot \Gamma_{C_n^2}(z,\,z',\,0)z^{5/6}z'^{5/6}\Delta z\Delta z'\right) - \overline{\sigma_\chi^2}^{\,2} \tag{9}$$

where $\Gamma_{C_n^2}(z,\,z+\Delta z,\,\tau) = E\{C_n^2(z,\,t)C_n^2(z+\Delta z,\,t+\tau)\}$, $E\{\bullet\}$ denoting the expected value is the two-dimensional (2-D) (height–time) cross-correlation function of the refractive index structure parameter whose expression is given in Appendix B.

Finally, assuming that long-term scintillation variance is log-normally distributed as stated in (3), the two key parameters of the distribution m and s are related to the inferred mean and variance values of scintillation variance

$$m = \frac{\overline{\sigma_\chi^2}^{\,2}}{\sqrt{\sigma_{\sigma_\chi^2}^2 + \overline{\sigma_\chi^2}^{\,2}}} \quad [\text{dB}^2] \tag{10}$$

$$s = \sqrt{\ln\left(1 + \sigma_{\sigma_\chi^2}^2/\overline{\sigma_\chi^2}^{\,2}\right)} \quad [\text{dimensionless}]. \tag{11}$$

IV. Results and Validation of the Prediction Method

A. Application of the Method to One Year of Radiosonde Data

The structure parameter profile inference method has been applied to a complete year (1990) of radiosonde data measured at Uccle (Brussels, Belgium) by the Belgian Meteorological Institute. The available radiosonde observations are made twice daily (nominally at 00.00 and 12.00 UT), with modern Vaisala sondes. The high-resolution raw data (height resolution is typically about 10 m) are automatically processed in order to extract the so-called significant level data. This procedure for reducing the amount of data consists of only recording the radiosonde data when a significant change is observed in the slope of one of the measured meteorological features. Thus, the vertical profiles of meteorological quantities can be fairly well estimated by linear piecewise interpolations of the significant level radiosonde data. The overall height resolution is assumed to be of the order of 20 to 50 m.

From each recorded radiosonde ascent, the mean refractive index structure parameter profile $\langle C_n^2(z)\rangle$ is evaluated by means of (7). The structure parameter is calculated every 50 m at heights between 150 and 5000 m and every 100 m from 5 km up to about 10 km, in agreement with the height resolution of the data. The thickness of the atmospheric slab through which the inferred structure parameter is considered to be averaged is, therefore, of 50 and 100 m, respectively, according to the height. Both the useful meteorological quantity values and gradients are estimated at the considered fixed heights by interpolating the available significant level radiosonde data (linear piecewise interpolations of ln p, T, e, v cos φ, and v sin φ). The three-dimensional integral in (7) is numerically solved by using a repeated one-dimensional (1-D) integration approach [20]. The basic 1-D integration, which is performed recursively, is computed by a Romberg's method of order 10 [20]. In order to accelerate the convergence and to avoid infinite limits or singularities, the integration bounds have been somewhat tightened around the area where the integrand peaks. It has been checked that the following lower and upper limits may be used in (7) without significantly decreasing the integration accuracy: from $L_{0\,\min}$ to $L_{0\,\max}$ for the integral in L_0, from zero to $\sqrt{\langle S(z)\rangle^2 + \sigma_S^2} + 5\sigma_S$ for the integral in S, and from $\langle N^2(z)\rangle - 5\sigma_N$ to S^2R_{ic} for the integral in N^2. The extraction of the mean structure parameter profile from one radiosonde ascent takes one minute or so on a SUN-SPARC computer.

The extraction process has been carried out on the 730 available radiosonde ascents measured in 1990 and the long-term statistical characteristics of $\langle C_n^2(z)\rangle$ are determined on a monthly, seasonal and annual basis, as illustrated in Figs. 1 and 2. Fig. 1 displays the mean (solid line), median (dashed line) and standard deviation (dashed-dotted line) profiles of the mean structure parameter for the complete year. It may be deduced from these profiles that, as expected, strong turbulence occurs almost permanently in the lower troposphere (below about 300 m) and intermittently at heights between about 800 m and 4 km, related to the presence of clouds. The cloud-induced turbulence is of great interest for our study, as

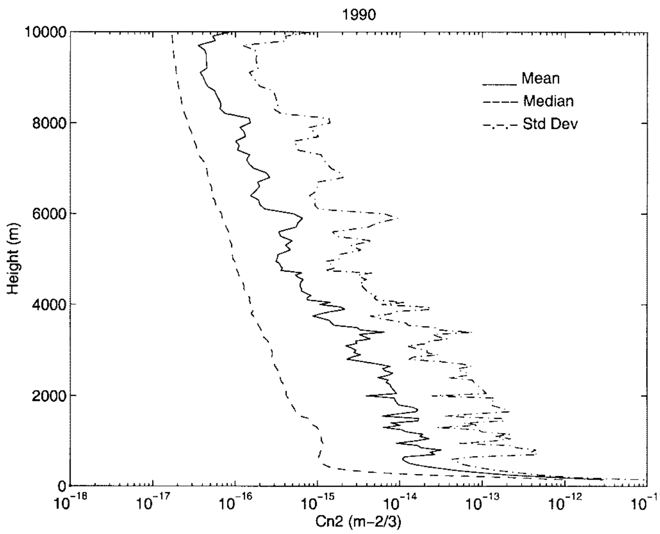

Fig. 1. Annual statistical characteristics of vertical profile of mean refractive index structure parameter inferred from radiosonde measurements: mean (solid line), median (dashed line), and standard deviation (dashed-dotted) profiles.

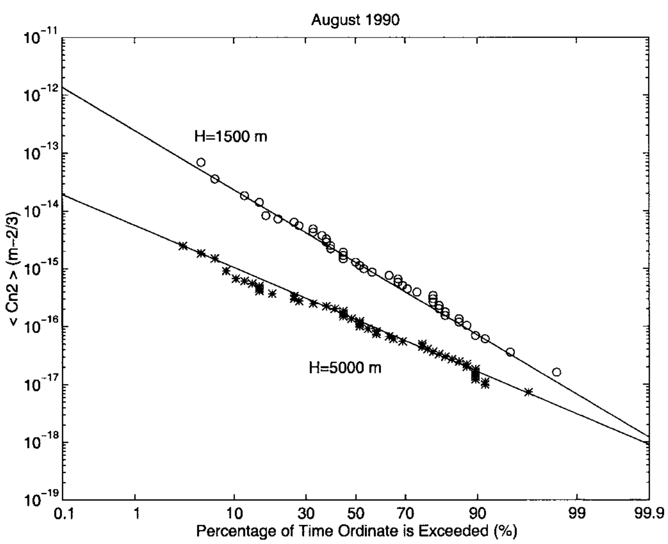

Fig. 2. Measured annual cumulative distributions of $\langle C_n^2 \rangle$ at heights of 1500 m (open circles) and 5000 m (asterisks) together with lognormal distributions (solid lines), using a log-Gaussian plot.

it is recognized that it consists of the main cause of slant-path scintillation. Fig. 2 presents in a Gaussian scale a monthly cumulative distribution of $\langle C_n^2(z) \rangle$ at two different heights (1500 and 5000 m). They are found to be in good agreement with log-normal distributions (solid lines). The hypothesis of log-normal distribution for the structure parameter is furthermore confirmed by a χ^2 goodness-of-fit test with a level of significance higher than 75%.

Finally, on the basis of the statistical features of $\langle C_n^2(z) \rangle$, the scintillation long-term distribution parameters, $\overline{\sigma_\chi^2}$, $\sigma_{\sigma_\chi^2}^2$, m, and s, are inferred from (8)–(11) and pdf or cumulative statistics of scintillation amplitude or variance are predicted by means of (1), (3), and (4), respectively.

To get scintillation predictions, the satellite link parameters have to be specified: frequency (or wavenumber k) and elevation angle θ, which directly appear in the equations, as well as the effective antenna diameter D, which is necessary to calculate the antenna averaging factor g^2 (a conservative turbulent height H of 1000 m is assumed). The averaging factor is indeed required to scale the point receiver scintillation variance parameters to their actual values: $\overline{\sigma_\chi^2}$ and m have to be multiplied by g^2, while $\sigma_{\sigma_\chi^2}^2$ should be multiplied by g^4. On the other hand, s is independent of link parameters.

B. Comparison of Predicted and Measured Scintillation Statistics on a Satellite Link

Long-term statistical distributions of scintillation have been predicted from radiosonde data for the following link parameters: frequency of 12.5 and 30 GHz, elevation angle of 27.6°, and illumination effective antenna diameter of 1.3 and 1 m at, respectively, 12.5 and 30 GHz (g^2 is about 0.9 for both cases). These parameters correspond to the experimental setup in operation in Louvain-la-Neuve, Belgium, from 1990 to 1993. During the experiment, beacons at 12.5 and 30 GHz from the ESA's Olympus satellite were received simultaneously and continuously at a sampling rate of 1 Hz. The data were processed and clear-weather scintillation variance statistics were produced [11]. Hence, we have the opportunity to compare scintillation distributions predicted using one year of radiosonde data with scintillation measurements carried out on the same year (1990). Measurement locations for meteorological observations (Uccle) and beacon receivers (Louvain-la-Neuve) are about twenty kilometers apart.

Fig. 3 compares predicted (dashed lines) and measured (solid lines) annual cumulative statistics of scintillation variance at 12.5 and 30 GHz. The agreement is excellent. The inferred statistical parameters of the variance log-normal distribution are $m = 1.49\times 10^{-3}$ dB^2 at 12.5 GHz and 4.13 $\times$ 10^{-3} dB^2 at 30 GHz, and $s = 1.21$ in both cases. The relative error between measured (M) and predicted (P) scintillation variance, defined as 100 $(M\text{-}P)/M$ in percent, has been calculated. The mean error and root mean square error are, respectively, -4.4 and 13.5% at 12.5 GHz and 3.8 and 7.8% at 30 GHz. A good behavior of the proposed prediction method is also found on a seasonal and monthly basis and it appears that monthly and seasonal variability is well accounted for. Overall, considering monthly and seasonal predictions at both frequencies, the average mean and rms errors are about -5 and 23%, respectively, while maximum values are -59 and 62%.

These results validate the prediction method for long-term scintillation effects based on radiosonde data. The method yields indeed accurate predictions of scintillation variance statistics on a monthly, seasonal and yearly basis. This means that, using a probabilistic approach, a fair estimate of the propensity of troposphere to generate turbulence and induce scintillation on slant paths is obtained from two daily radiosonde ascents. Of course, predicting scintillation from radiosonde data only makes sense on a long-term basis. By that way, a sufficient amount of meteorological observations is analyzed and it may be expected that the extracted statistical characteristics fairly reflect the tropospheric features over the considered period. In our case, with a distance of 20 km be-

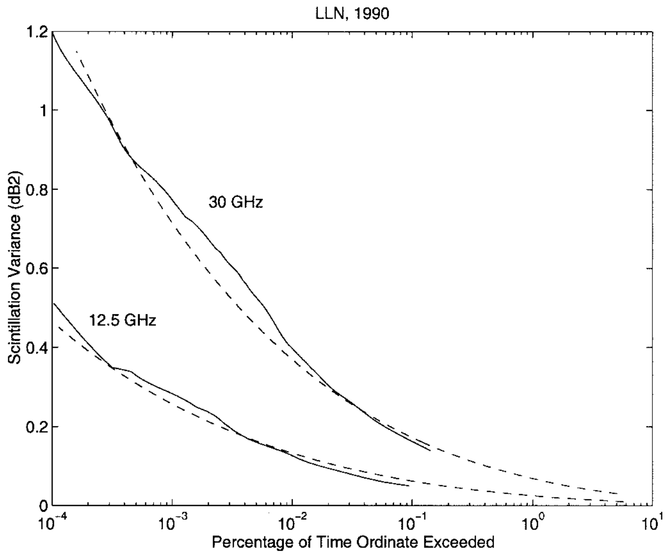

Fig. 3. Comparison of measured (solid lines) and predicted (dashed lines) annual scintillation variance cumulative distributions at 12.5 and 30 GHz.

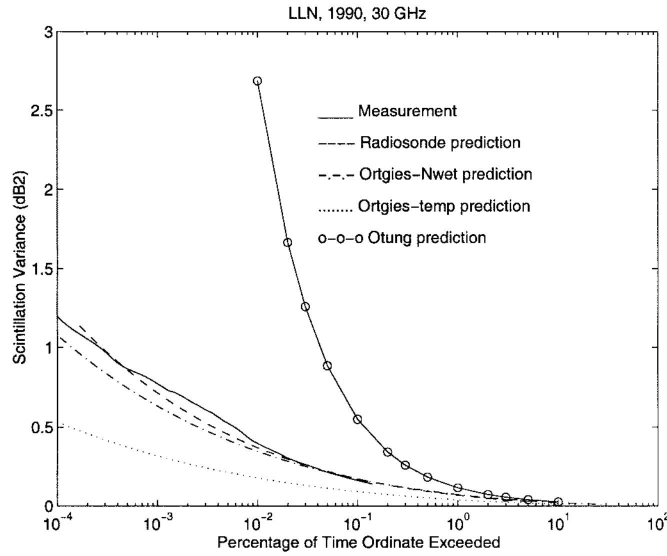

Fig. 4. Comparison of measured annual scintillation variance cumulative statistics at 30 GHz (solid line) with predictions using proposed radiosonde-based method (dashed line), Ortgies-temperature method (dotted line), Ortgies-wet refractivity method (dashed-dotted line) and Otung method (open circles).

tween the meteorological station and the satellite receiver site, it is demonstrated that a time period of one month is enough to get adequate prediction results. For a longer distance, a longer averaging time period could be required. It seems that the good behavior of the proposed prediction method stems from the relative "stability" of clear-weather scintillation effects in both the time and space domains (as opposed to the highly variable rain attenuation). It is indeed reported [11] that scintillation variance statistics do not indicate significant variabilities neither from year to year nor from site to site (in Western Europe).

C. Comparison with Other Scintillation Prediction Methods

The scintillation prediction results derived from radiosonde data are compared with those of other usual prediction methods based on ground meteorological observations. Regarding the prediction of annual statistics of scintillation variance, three other methods are considered: the Otung method [3] and the Ortgies models [4] based, respectively, on temperature and wet term of refractivity (Nwet). The Otung method proposes an expression for the annual scintillation variance distribution on the basis of the mean surface temperature t and relative humidity H over the complete year (according to measurements carried out in Louvain-la-Neuve, $t = 10.65°$C and $H = 82.4\%$). On the other hand, the Ortgies models predict monthly scintillation variance distributions from monthly mean temperature and wet refractivity. The monthly statistics have then been soundly combined in order to get the annual distribution (the annual percentage of time a given scintillation variance is exceeded is obtained as the mean value of the corresponding monthly percentages of time). Fig. 4 compares the predicted results with the annual scintillation variance statistics measured in Louvain-la-Neuve at 30 GHz. It is observed that the proposed radiosonde-based method leads to the most accurate prediction. The large overprediction of the Otung method could be attributed to the fact that it includes the scintillation effects due to rain. The Ortgies

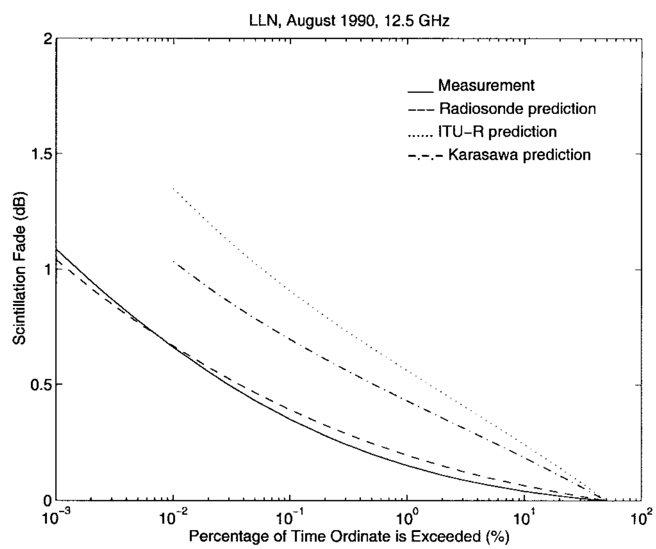

Fig. 5. Comparison of scintillation fade cumulative distributions measured at 12.5 GHz in August 1990 (solid line) with predictions using proposed radiosonde-based method (dashed line), ITU-R method (dotted line) and Karasawa method (dashed-dotted line).

method from wet refractivity also appears in good agreement with the measurement. This is not surprising as this method was derived from propagation data collected in Germany during the Olympus experiment under experimental conditions very similar to the measurements.

Concerning statistics of scintillation fade, we compare measurements carried out at 12.5 GHz on the same slant path in August 1990 with three prediction methods: the proposed radiosonde-based method, the ITU-R method [1], and the Karasawa method [2]. The two last methods derive scintillation fade statistics from monthly average surface temperature and humidity ($t = 18.8°$C, $H = 77\%$). Results are displayed in Fig. 5. Again, the radiosonde-based method yields prediction in excellent agreement with measurements. On the other hand, the ITU-R and Karasawa methods largely overpredict scintillation fades. This seems to be corroborated by recent propagation experiments [21] where it is established that both the ITU-R model and the Karasawa model tend to overestimate the magnitude of scintillation.

V. Conclusion

Based on a rigorous statistical approach, a new method is described that predicts long-term statistical distribution of tropospheric scintillation on satellite links from radiosonde data. The method consists of two steps. In the first step, the statistical characteristics of the refractive index structure parameter vertical profile are extracted from the analysis of radiosonde ascents collected during a long time period. For this purpose, a statistical model described in [5]–[7] to estimate turbulence parameters from meteorological soundings is used. In the second step, long-term statistics of slant-path scintillation are derived from the inferred tropospheric turbulence features, using theoretical considerations. In addition to radiosonde data, the only parameters required for scintillation prediction are the link characteristics: frequency, elevation angle (the method is valid at elevations higher than about 5 to 10°), and antenna diameter. Comparisons of the radiosonde-based predicted scintillation effects with measurements carried out simultaneously near to the meteorological site demonstrate the efficiency of the proposed prediction method on a monthly, seasonal, and annual basis. Furthermore, the method is proved to be more accurate than other current prediction models. The adequacy of the radiosonde-based prediction method rests on the relative stability of the clear-weather tropospheric conditions responsible for scintillation: a thorough long-term statistical characterization of tropospheric turbulence and of the related scintillation effects is possible from only two radiosonde ascents a day.

The major advantage of the proposed method over current scintillation prediction models (ITU-R, Karasawa, Otung, Ortgies) is that it does not include any empirical relationship based on a particular propagation experiment. Moreover, by providing fair estimates of the turbulence intensity in clouds (responsible for slant-path scintillation), the radiosonde data adequately reflect the actual climatic dependence of scintillation. The proposed method is, hence, expected to be of a more general application than other prediction models and to yield more reliable scintillation predictions, whatever the link parameters and geographical location of the considered earth-space path.

Appendix A

The expressions of all the parameters involved in (7) are given hereafter in terms of the basic meteorological profiles [6], [7]:

$$M_0(z) = -77.6 \times 10^{-6}\, \frac{p(z)}{gT(z)} \tag{A.1}$$

with $g = 9.81$ m/s^2 is the acceleration of gravity

$$\langle R(z)\rangle = \left[1 + 1.55 \times 10^4\, \frac{q(z)}{T(z)} - \frac{1.55 \times 10^4}{2}\, \frac{g\, \frac{\partial q}{\partial z}(z)}{\langle N^2(z)\rangle T(z)}\right]^2 \tag{A.2}$$

with

$$q(z) = 0.6225\, \frac{e(z)}{p(z)} \text{ is the specific humidity (dimensionless)}$$

$$\langle N^2(z)\rangle = g\, \frac{\partial \ln \theta}{\partial z}(z) \text{ is the mean value of buoyancy forces (in } s^{-2})$$

$$\theta = T(z)\left(\frac{1000}{p(z)}\right)^{0.2858} \text{ is the specific temperature (in K)}$$

P_{L0} is a uniform distribution between $L_{0\,\min} = 3$ m and $L_{0\,\max} = 100$ m:

$$P_{L0} = \begin{cases} \dfrac{1}{L_{0\,\max} - L_{0\,\min}} & \text{if } L_{0\,\min} \le L_0 \le L_{0\,\max} \\ 0, & \text{otherwise.} \end{cases} \tag{A.3}$$

P_S is a Rice distribution (inferred from the assumption of Gaussian distribution for both components of vector shear)

$$P_S = \frac{S}{\sigma_s^2(z)} \exp\left(-\frac{S^2 + \langle S(z)\rangle^2}{2\sigma_s^2(z)}\right) I_0\left(\frac{S\langle S(z)\rangle}{\sigma_s^2(z)}\right) \tag{A.4}$$

with

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

is the mean wind shear (in s^{-2}); $\sigma_S = 0.18\ L_0^{-0.3}|\langle N^2(z)\rangle|^{0.25}\rho(z)^{-0.15}$; and $\rho(z) = 0.348(p(z)/T(z))$ is the mean density of dry air in the slab, in kg/m^3. P_{N^2} is a Gaussian distribution

$$P_{N^2} = \frac{1}{\sqrt{2\pi}\sigma_N(z)} \exp\left[-\frac{(N^2 - \langle N^2(z)\rangle)^2}{2\sigma_N^2(z)}\right] \tag{A.5}$$

with

$$\sigma_N(z) = \sqrt{\frac{6}{5}}\, \sigma_S(z)\sqrt{|\langle N^2(z)\rangle|}.$$

Appendix B

The theoretical development leading to the expression of the variance of the scintillation variance $\sigma^2_{\sigma^2_\chi}$ summarized in (9) is presented hereafter.

Using the well-known relationship

$$\sigma^2_{\sigma^2_\chi} = E\left\{\left(\sigma^2_\chi\right)^2\right\} - \overline{\sigma^2_\chi}^2 \tag{B.1}$$

the problem reduces to evaluate the expected value of the square scintillation variance which is related to the autocorrelation function of σ^2_χ

$$E\left\{\left(\sigma^2_\chi\right)^2\right\} = \Gamma_{\sigma^2_\chi}(\tau = 0) \tag{B.2}$$

where $\Gamma_{\sigma^2_\chi}(\tau) = E\{\sigma^2_\chi(t) \quad \sigma^2_\chi(t+\tau)\}$ is the autocorrelation function of the scintillation variance.

Because in (5) the scintillation variance is expressed as the spatial integral of the structure parameter profile, its autocorrelation function depends on the 2-D (height–time) cross-correlation function of the refractive index structure parameter [22], referred to as $\Gamma_{C_n^2}(z, z+\Delta z, \tau)$ and may be formally written as

$$\Gamma_{\sigma^2_\chi}(\tau) = \int_z\int_{z'}\left[42.48\,\frac{k^{7/6}}{(\sin\theta)^{11/6}}\right]^2 \cdot \Gamma_{C_n^2}(z, z', \tau) z^{5/6} z'^{5/6}\, dz\, dz'. \tag{B.3}$$

The 2-D cross-correlation function of the structure parameter cannot be derived from radiosonde data because of their inadequate resolution in space and time, but an expression developed by Ravard and Chevrier [16], [17] on the basis of a model proposed by Hufnagel [18] enables to relate it to the long-term characteristics of the mean-structure parameter profile

$$\Gamma_{C_n^2}(z, z+\Delta z, \tau) = p_{50_{\langle C_n^2\rangle}}(z) p_{50_{\langle C_n^2\rangle}}(z+\Delta z) \cdot \exp\left(\frac{s^2_{\langle C_n^2\rangle}(z) + s^2_{\langle C_n^2\rangle}(z+\Delta z)}{2}\right) \cdot \exp[\Gamma_r(z, z+\Delta z, \tau)] \tag{B.4}$$

where $s_{\langle C_n^2\rangle}(z)$ is a parameter of the $\langle C_n^2(z)\rangle$ log-normal distribution

$$s_{\langle C_n^2\rangle}(z) = \sqrt{\frac{1}{2}\ln\left(\frac{\overline{\langle C_n^2(z)\rangle}^2 + \sigma^2_{\langle C_n^2\rangle}(z)}{p^2_{50_{\langle C_n^2\rangle}}(z)}\right)} \tag{B.5}$$

$\Gamma_r(z, z+\Delta z, \tau)$ is an empirical cross-correlation function [18]:

$$\Gamma_r(z, z+\Delta z, \tau) = \frac{s_{\langle C_n^2\rangle}(z) s_{\langle C_n^2\rangle}(z+\Delta z)}{2} \cdot \left[A\left(\frac{\Delta z}{L_1}\right)\exp(-\tau/5) + A\left(\frac{\Delta z}{L_2}\right)\exp(-\tau/80)\right] \tag{B.6}$$

with $A(\Delta z/L) = 1 - |\Delta z/L|$ if $|\Delta z| < L$ and zero otherwise $L_1 = 100$ m and $L_2 = 2000$ m.

It is easily verified that the calculation of the cross-correlation function $\Gamma_{C_n^2}(z, z+\Delta z, \tau)$ for $\Delta z = 0$ and $\tau = 0$ by using (B.4) and (B.6) yields, as expected from basic statistical theory $\overline{\langle C_n^2(z)\rangle}^2 + \sigma^2_{\langle C_n^2\rangle}(z)$.

Equations (B.1)–(B.6) allow us to derive the long-term variance of the scintillation variance $\sigma^2_{\sigma^2_\chi}$ from the long-term statistical characteristics of the mean structure parameter profile. The integrals which appear in (B.3) are replaced by summations over the available mean values of the integrand through horizontal slabs in order to get (9).

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