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Empirical statistical model relating scintillation indices with solar and geomagnetic activity for L band GNSS receivers at high latitudes

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ABSTRACT

The main objective of this study was to figure out a relationship between space weather environment phenomena (solar activity and geomagnetism) and ionospheric events that impact L-band satellite navigation systems (scintillations, electron content gradients) in the Nordic European area.

Ionosphere events observed at high latitudes are strongly linked to the solar activity and its impact on the magnetic field of the Earth, especially due to the solar wind. The consequences on GNSS signals impairments have been the subject of several recent investigations [1] [2].

In the Northern area, the main effects of solar activity and of charged particles penetration in the Earth's atmosphere through the poles are linked with:

- the evolution of the auroral oval location, correlated to the intensity of the particle precipitation and generally depending on the solar wind - magnetosphere interaction, and reconnection in the magnetosphere tail,
- drifting plasma clouds with small scale features following the polar cap convection pattern and causing density gradients, connected with the appearance of scintillation,
- sub-storms caused by reconnection in the Earth's magnetic field and triggered by solar wind parameters,
- ionospheric storms caused by energetic events on the Sun, such as flares or coronal mass ejections.

All of these events cause strong electron content gradients and scintillations at the ionosphere layer level. Unfortunately no sufficient prediction model exists for the intensity of these phenomena. In a previous activity [3] [4], a simple empirical model to forecast the ROTI (Rate Of change of TEC Index) anywhere under high latitude was developed associated with Kp geomagnetic index prediction and the use of solar electron energy flux obtained from NOAA POES satellites datasets. This model is currently being improved because the time resolution of Kp (3 hours) seems to be too long compared to the inertia of the magnetosphere. Kp index is replaced by the alpha index estimated from a better station location repartition and with a higher time rate (1 h seems reasonable).

Moreover the prediction of ROTI was only the first step towards the final objective of that study, and relationships with scintillation parameters (and mainly phase scintillation σ_φ) have been also investigated. Based on a physical scintillation model [5], a theoretical relationship between ROTI and σ_φ has been established. This formulation is valid only if the integration time is the same. However, the parametrization of such an approach is hardly possible, as many input parameters on the ionosphere medium are necessary but unknown. Thus, in order to have a simpler relation between ROTI and σ_φ, we investigate an empirical approach, keeping in mind the integration time should be the same.

For the purpose of this study, 100 Hz scintillation measurements with ISM (Ionospheric Scintillation Monitor) have been collected at several stations in Norway: Tromsoe, Vega, Ny-Alesund. ROTI measurements in Norway from the SATREF network of conventional 1 Hz GPS stations available since 1994 have also been used. Tromsoe data have been first processed.

Correlations between σ_φ and ROTI values for sampling rate at 100 Hz and integration window of 60 seconds (which is the common value for the estimation of σ_φ) have been first looked at. Then similar correlations for sampling rate at 100 Hz and integration window of 10 min (which is the common value for the estimation of ROTI) have been analysed. Finally the same analysis was performed over data sampled at 1 Hz. The sampling rate seems to have minor influences on the scatterplot as the correlation coefficients are still close to 1 if the integration windows are coherent (same values of the integration window for both σ_φ and ROTI). The model was finally developed on 1 Hz and 60 s integration window basis.

Our empirical model is based on the fact that, on the collected measurements, for a given value of ROTI, σ_φ can be considered as a random variable whose conditional Probability Distribution Function (PDF) of σ_φ knowing the value of ROTI, $p(\sigma_\varphi | ROTI)$, is assumed to be log-normal with parameters μ and σ:

$$p(\sigma_\varphi | ROTI) = \frac{1}{\sigma_\varphi \sigma \sqrt{2\pi}} \exp\left(-\frac{[\ln(\sigma_\varphi) - \mu]^2}{2\sigma^2} \right) \tag{1}$$

It has also been observed that the σ-parameter can be approximated by a unique value independent of ROTI values. Moreover, the expected mean value $E[\sigma_\varphi | ROTI]$ can be approximated by $E[\sigma_\varphi | ROTI] = K \cdot ROTI$ where K is a constant.

As $E[\sigma_\varphi | ROTI] = e^{\mu + \frac{\sigma^2}{2}}$ it results that : $\mu = \ln(K \cdot ROTI) - \frac{\sigma^2}{2}$

As the ROTI values are supposed to be forecasted, it means that the model is able to forecast the PDF of σ_φ knowing the ROTI value.

The linear regressions over experimental results lead to:

$$\begin{cases} \sigma = 0.5023 \\ e^{\mu + \frac{\sigma^2}{2}} = 0.0471 \cdot ROTI \end{cases} \tag{2}$$

Finally, the complementary cumulative distribution function (CCDF) of σ_φ knowing the value of ROTI is:

$$P(\sigma_\varphi > \sigma_\varphi^* | ROTI) = \frac{1}{2} erfc\left(\frac{\ln(\sigma_\varphi^*) - \ln(0.0471 \cdot ROTI) + \frac{\sigma^2}{2}}{\sqrt{2}\sigma} \right) \text{ with } \quad \sigma = 0.5023 \tag{3}$$

The accuracy of the prediction model seems to improve with higher ROTI. Indeed, the low ROTI values are linked to low magnetic activity. During low magnetic activity, some computed ROTI values are probably coming from the receiver noise and not really from ionospheric scintillation. Moreover, as it can be observed from the retrieval of the log-normal parameters, the effort has been made for values of ROTI between 4 and 16 TECU/min (for a sampling rate of 1 Hz and an integration window of 60 s). For values of ROTI lower than 4 TECU/min, the σ value tends to decrease significantly.

The same analysis has been performed for raw measurements sampled at 1 Hz but for an integration window of 10 min (which is the common value for the estimation of ROTI). The linear regressions over experimental results lead to very close parameter values as compared to those derived for an integration window of 60 s. The integration window has a great impact on high values of ROTI and σ_φ. The higher is the integration time, the lower are ROTI and σ_φ values. So, it can be assumed that the log-normal parameters do not depend on the integration window and it is advised to use parameters derived for an integration window of 60 seconds which are statistically more reliable.

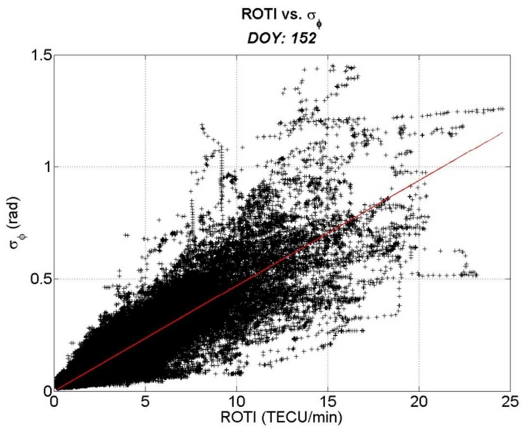

Figure 1 : ROTI vs. σ_φ for sampling rate at 1 Hz and integration window of 60 seconds

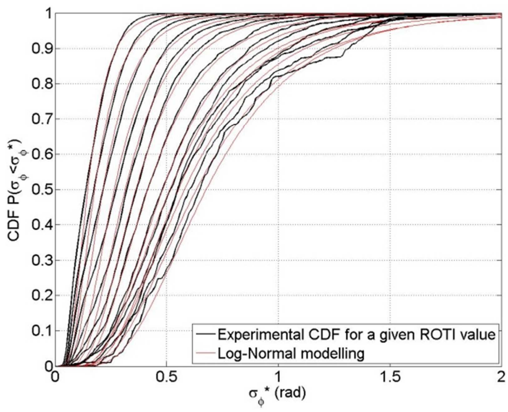

Figure 2 : Log-Normal regressions on experimental conditional probability distributions

Cascading the two formulations, we have the possibility to predict the level of phase scintillation from the prediction of a geomagnetic parameter Kp (or alpha parameter) and solar electron energy flux. This model has to be tested now on a larger database.

Key words: Ionosphere, GNSS, Scintillation, high latitude polar areas

References:

[[1] P. Prikryl, P. T. Jayachandran, S. C. Mushini, D. Pokhotelov, J.W. MacDougall, E. Donovan, E. Spanswick, and J.-P. St.-Maurice, (2010). GPS TEC, scintillation and cycle slips observed at high latitudes during solar mínimum, Ann. Geophys., 28, 1307–1316

[2] Forte B. et al. (2010). Optimum parameter for estimating phase fluctuations on transionospheric signals at high latitudes, J. Adv. Space Res., doi:10.1016/j.asr.2010.04.033

[3] Boscher D., Fabbro V., Lemorton J., Carvalho-Lechat F., Fleury R., Jacobsen K. (2013). Empirical modelling of the ROTI at high latitudes for L band ionospheric channel studies, 10th European Space Weather Week, ESWW 2013, Antwerp, Belgium

[4] Boscher D., Carvalho F., Fabbro V., Lemorton J., Fleury R. (2014). Modelling ionospheric effects for L band GNSS receivers at high latitudes, 8th European Conference on Antennas and Propagation, EUCAP 2014, The Hague, The Netherlands

[5] Galiègue H. (2015). Modélisation des effets des scintillations ionosphériques sur la propagation des ondes électromagnétiques en bande L aux latitudes polaires, PhD dissertation, University of Toulouse, September 2015.

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