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Wavelet analysis of radio scintillation inhibition at low latitudes

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ABSTRACT

A common feature of the low latitude ionosphere under geomagnetic storm conditions is the suppression of the plasma irregularities that form daily during post-sunset. When this happens, the ionosphere appears as a smooth medium, almost without TEC gradients. This inhibits ionospheric radio scintillations (IRS), usually happening in the quiet equatorial ionosphere. However, during a storm, both IRS inhibition and enhancement can concur. Such phenomenon has been widely observed and reported in the literature, but the physical processes determining such behavior, ruling the ionospheric impact on the GPS signals, are yet far from being understood. Here we claim that it is worth studying the multi-scale features of IRS as a remote sensing of ionospheric turbulence. Some results of *wavelet analysis* applied to the GPS L1 amplitude data are reported; these data were acquired at Tucuman (Argentina: 27°00′S, 65°30′W), under the Southern Crest of the Equatorial Ionospheric Anomaly, on March 2011, during the recovery phase of a moderate geomagnetic storm occurred between March 10 and 16 (Dst peak -80 nT on March 11). These are time series of the power of GPS signals, sampled at 50 Hz by means of a TEC and scintillation monitoring receiver. This study will integrate what reported in [1], where ionosonde and 1 minute GPS data were analyzed: high sampling rate power GPS data can provide further description of the ionospheric irregular environment.
In order to perform a wavelet analysis of a signal $w(t)$, a set of window functions $\psi_{\ell,\tau}(t)$, with support of size ℓ and centre $t=\tau$, are defined. Wavelet coefficients $\omega(\ell,\tau)$ are the scalar products:

$$\omega(\ell,\tau) = \int_I \psi_{\ell,\tau}(t) w(t) dt, \tag{1}$$

being I the time interval of interest. The assortment of parameters ℓ and τ may either be continuous or discrete: accordingly, one speaks about *continuous* wavelet analysis (CWA) or *discrete* wavelet analysis (DWA). CWA zooms continuously into the signal, looking at it at different scales synoptically; the distribution of signal energy as a function of ℓ and τ, namely $\varepsilon(\ell,\tau) = |\omega(\ell,\tau)|^2$, are named *scalograms*, and report the relative importance of the signal mode of scale ℓ at time $t=\tau$. $\varepsilon(\ell,\tau)$ tracks the multi-scale behavior of the signal with time, and give a striking outlook to the *time variability of multi-scale coupling*.

In DWA, the $\psi_{\ell,\tau}$ form an orthonormal basis and the signal $w(t)$ is the *independent components* $w_\ell(t)$ of assigned scale ℓ are found:

$$w_\ell(t) = \sum_\tau \omega(\ell,\tau) \psi_{\ell,\tau}(t), \quad w(t) = \sum_\ell w_\ell(t). \tag{2}$$

The ℓ-dependence of the statistics of the values $w_\ell(t)$ describes how the statistical properties of $w(t)$ vary with the scale.

We combine the CWA and DWA of IRS: doing so, one discovers that multi-scale statistical properties of power scintillation are correlated with the amplitude scintillation index S_4, which is in turn related with the enhancement/inhibition of equatorial IRS during storms [1].

As an example, we show the application of this technique to a GPS pass with varying S_4. Our $w(t)$, reported in the left plot of Figure 1, is the power from PRN19 satellite from UT 00:00 to UT 01:00 above Tucuman, on the day March 12, 2011: within the first 11.5 minutes, the S_4 index passes from $\approx 10^{-2}$, between UT 00:00 and UT 00:06 (interval I_1), to $\approx 10^{-1}$ after UT 00:07 (interval I_2). In the right part of Figure 1, the scalogram of $w(t)$ is reported, with the log-contour plot of the (normalized) wavelet energy [2]: when IRS appears, the "scales involved" in the fluctuations change. In I_1 the signal energy is concentrated in time scales lower than 0.4 *s*; very few energy pertains to scales between 0.4 *s* and 50 *s*, while above the latter some smooth energy distribution appears to be the remnant of the slow trend component. In I_2, instead, a complex pattern of multi-scale structures shows up throughout the 0.4 *s* to 50 *s* scale interval.

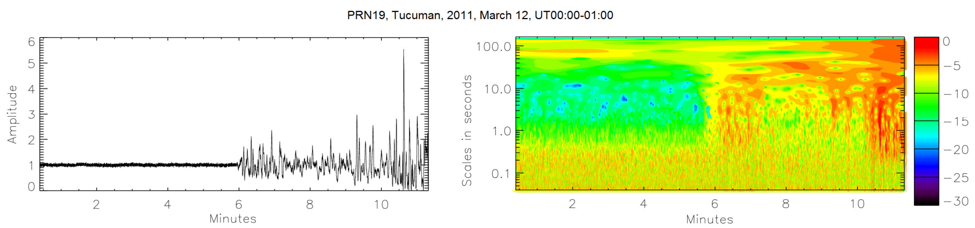

Figure 1. The time series and the (suitably normalized) scalogram of the amplitude signal from the PRN19 satellite received in Tucuman on March 12, 2011, in the first 11.5 minutes of the pass starting at UT 00:00.

The difference between very weak and moderate IRS is studied by comparing the DWA of the signal w restricted to I_1 and I_2 separately. The statistical distributions of the values of w_ℓ are studied as functions of ℓ: in particular, their *departure from Gaussian statistics* is studied by calculating their *kurtosis excess* (KE). In Figure 2, the plots of this KE are shown as a function of time scale in the scale range from 0.5 s to 300 s. The left hand plot refers to the I_1 data, while the right hand one reports the KE of the w_ℓ in I_2.

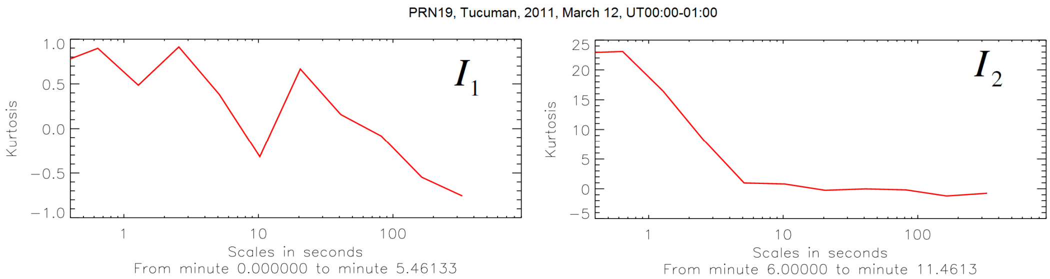

Figure 2. Kurtosis excess as a function of time-scale in the weak (left) and moderate scintillation data intervals.

It is evident that the power fluctuations are much more intermittent in the moderate IRS regime, indeed the KE monotonically increases up to values of about 23 for decreasing ℓ in I_2, while this happens in a more uncertain way in I_1.

These preliminary results encourage the use of wavelets to learn more on the impact of the ionospheric irregularities on the GNSS signals propagation [3] and on the possibility of using the multi-scale properties of IRS to study ionospheric turbulence [4].

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