GPS Studies of TEC Variations and Equatorial Scintillations

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Abstract

In the presence of ionospheric electron density irregularities, of scale sizes in the range of several hundred meters, measurements of the differential carrier phase of GPS signals by a dual frequency receiver have a contribution from the relatively fast phase scintillations on L1 and L2 signals. Using data from the equatorial station, Ancon(1.5° dip), it is shown that this contribution follows the pattern of intensity scintillations on either signal. On the other hand, intensity scintillations as measured by the S_4-index are also related to the slower variations in TEC due to the presence of irregularities. In order to quantify this relationship, an index DROTI, derived from the second time derivative of the TEC variations, is introduced. Dual frequency data from Ancon is used to demonstrate the relationship between DROTI and S_4.

Introduction

For an undisturbed ionosphere, where electron density does not vary significantly over scale lengths $\leq$ 1 km, dual frequency measurements of carrier phases of GPS L1(1.57542 GHz) and L2(1.2276 GHz) signals yield an estimate of the relative total electron content (TEC) of the intervening ionosphere along the signal path, since the effect that the ionosphere has on GPS signals is to essentially alter the optical path length. However, during periods of Equatorial Spread F, ionospheric irregularities of scale lengths $\leq$ 400 m may give rise to fluctuations or scintillations in amplitudes and phases of GPS signals which propagte through them. Scintillations in the intensity of recorded GPS signals are well documented(Weber et al., 1996; Beach, 1998). In the present study, the contribution of phase scintillations on the GPS signals to fluctuations in the estimated TEC are determined using dual frequency measurements at a rate of 1 Hz, at the equatorial station Ancon(11.77° S, 77.15° W, 1.5° dip).

The slower variations in TEC, which are directly associated with the presence of ionspheric irregularities, must also be related to scintillation activity arising from refractive index variations. In recent years, an index has been derived from data for relative TEC along GPS signal paths, which could be used to track ionospheric irregularities in a qualitative manner. This index ROTI is calculated using $d(TEC)/dt$ values derived from the GPS 30s TEC data obtained from the IGS network(Aarons et al., 1997; Pi et al.,1997). Musman et al. (1997) defined a "roughness" measure which was also based on the first derivative of TEC variations. The index ROTI has been compared with the S_4-index computed from simultaneously recorded intensity scintillations on an L1 GPS signal, which would largely be due to irregularities of scale sizes of a few hundred meters(Beach, 1998; Basu et al.,1999). The ratio of ROTI and S_4 is expected to depend on the component of the vector sum of the ionospheric projection of the satellite velocity and the irregularity velocity, in a direction transverse to the signal path, as well as the slant path length from an effective irregularity layer to the receiver. However, the nature of this dependence is unknown. A quantitative relationship between the slower TEC variations and intensity scintillations is explored by introducing a new index DROTI which can be derived from TEC variation data, on the basis of theoretical considerations.

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Contribution of phase scintillations to dual frequency measurements

In a campaign carried out in April 1997 by the Cornell University group, an Allen Osborne ICS-4000z dual frequency receiver was deployed at Ancon to collect data at a rate of 1 Hz(Beach, 1998). This receiver was adapted to log directly the phase TEC derived from the number of cycles of the carrier of each of the GPS frequencies, starting at the time the receiver locked onto the signals.The phase measurements only provide information about variations in TEC along the signal path as the satellite moves, after the receiver locks onto the signals.

The TEC fluctuation data is a combination of actual TEC variations caused by the presence of ionospheric irregularities in the path of the radio waves, and short time scale fluctuations due to the contribution of phase scintillations on L1 and L2 signals. Carrier to noise ratio(C/No) records logged by the receiver give a measure of amplitude scintillations on the L1 signal. An example of intensity scintillations on a L1 signal transmitted from PRN 26 and simultaneous variations in the TEC along the same signal path, measured using a dual frequency receiver at Ancon, on April 9, 1997, is displayed in Figures 1(a) and (b). An approximate description of the ionospheric irregularities in terms of a phase changing screen demonstrates that the contribution of phase scintillations to the TEC variations measured by a dual frequency receiver would follow the pattern of intensity scintillations, and hence would consist only of fluctuations on time scales which are present in intensity scintillations. An estimate of this contribution may be obtained by removing the slower TEC variations from the TEC fluctuation data through application of an appropriate filter. A measure of the strength of amplitude scintillations is the S_4-index, which is the standard deviation of the normalized intensity. The cut-off frequency for the filter is chosen by the requirement that the lowest frequency present in the detrended data should be that present in intensity scintillations as measured by S_4. Thus the cut-off frequency would depend on the slant distance, z, along the signal path from the receiver to the irregularity layer, which determines the Fresnel scale length $d_F = \sqrt{(2\lambda z)}$ for the incident signal of wavelength λ, as well as the transverse drift speed of the irregularities relative to the signal path. A 6-pole Butterworth filter with a 3-dB cut-off at this frequency is applied to the TEC fluctuation data to obtain the detrended differential carrier phase, $\Delta\phi$ and its standard deviation, $\sigma_{\Delta\phi}$, is computed at 1 min intervals, along with the corresponding S_4 values determined from detrended intensity data. For the data shown in Figure 1, values of these indices plotted in Figure 2 follow nearly the same pattern during the scintillation event.

Relative TEC based measure of scintillation activity

In the present study, the possibility of deriving a measure for density gradients from the relative TEC data, which would allow a quantitative comparison with the S_4-index, is investigated. Once again, as in the case of ROTI, this index too is based on a phase screen description of the irregularities encountered by the signal. The intensity and phase of a radio wave, after it emerges from a phase screen and propagates to the receiver through free space, satisfy the so-called transport-of-intensity equation(TIE)(Teague, 1983). For a one-dimensional phase screen, an approximate version of the TIE relates the intensity I measured by a receiver, to the phase variations $\phi(x)$ that are present when the wave just emerges from the screen(Bhattacharyya, 1999):

$$\frac{d^2\phi}{dx^2} = -\frac{2\pi}{\lambda z}\left[1 - \frac{I(x,z)}{I_0}\right] \tag{1}$$

where z is the distance of the receiver from the phase screen along the signal path which is assumed to be perpendicular to the phase screen, and I_0 is the uniform intensity of the incident wave before it encounters the irregularities. Phase variations $\phi(x)$ imposed by the screen are related to variations $\Delta N_T(x)$, in TEC along the signal path, according to:

$$\phi(x) = -\lambda r_e \Delta N_T(x), \qquad r_e = 2.8 \times 10^{-15} m \tag{2}$$

Spatial variations along the x-direction are converted to temporal variations at the site of the receiver due to relative motion of the irregularities with respect to the signal path. Thus, representing the x-component of this motion by v and ignoring the changes in v with time over relatively short periods during the course of a scintillation event, (1) may be expressed as:

$$\frac{d^2}{dt^2}\Delta N_T = \frac{2\pi}{\lambda r_e}\frac{v^2}{\lambda z}\left[1 - \frac{I(t,z)}{I_0}\right] \tag{3}$$

This equation suggests that an index based on the standard deviation of $d^2\Delta N_T/dt^2$ rather than $d\Delta N_T/dt$ may be a more natural choice as a measure of scintillation activity. In fact, the S_4-index is the standard deviation of the normalized intensity I/I_0 which appears on the right hand side of (3). This provides the basis for the introduction of a new index DROTI, which is computed from GPS data for the relative TEC variation in the same manner as ROTI, except that the second time derivative of the variation in TEC is now used. The unknown factor v^2/z may be estimated from the Fresnel frequency $\nu_F = v/\sqrt{(2\lambda z)}$ where the power spectral density of weak intensity scintillations displays a maximum on account of Fresnel filtering(Yeh and Liu, 1982). For signals transmitted from GPS satellites, this factor may change considerably with satellite motion during a scintillation event lasting an hour or longer.

In order to simulate the IGS data which has been used for earlier computations of ROTI(Pi et al., 1997), for every interval of 30s, the last ten samples of the phase TEC data, measured at 1 Hz rate, is averaged to obtain one value for the simulated data. $d^2\Delta N_T/dt^2$ is computed from this 30s data, and its standard deviation calculated for a 5 min interval yields DROTI. The corresponding intensity scintillation data for the L1 signal is used to compute the S_4-index for the same 5min intervals, and ν_F obtained from a power spectrum of the intensity data yields an estimate for $v^2/\lambda z$. According to (3), the scaling between DROTI and the corresponding S_4-index should be: DROTI(TECU min^{-2}) $= 8.5 \times 10^3 \nu_F^2 S_4$ when ν_F is in Hz. However, the data analyzed for April 9, 1997, indicates a DROTI which is smaller by a factor of nearly 5, yielding a scale factor of $\approx 1.6 \times 10^3 \nu_F^2$ between DROTI(TECU min^{-2}) and S_4. S_4-indices computed from intensity scintillations on L1, and derived by using the above scale factor with DROTI calculated from the corresponding TEC variation data for PRN 5 on the nights of April 9 and 17, 1997, are shown in Figures 3. The elevation angle for PRN 5 varied between 40 - 44° and 36 - 43° respectively, during the two scintillation events. Also shown in Figure 3 are S_4-indices derived from ROTI, calculated from the same data and with a scaling factor of 2.5 between ROTI(TECU min^{-1}) and S_4.

Depending on the relative drift speed between the irregularities and the signal path, a sampling interval of 30s implies that the scale lengths associated with fluctuations in ROT which contribute to ROTI or DROTI may be much larger than those which contribute the most to intensity scintillations. Thus a shorter sampling interval is expected to give a better agreement between S_4 derived from intensity scintillation data and that derived from DROTI. To test this conjecture, the 10s averages of the 1Hz relative TEC data is used to compute DROTI. The scaling factor between DROTI(TECU min^{-2}) and S_4 is now closer to the theoretical one being $\approx 3.4 \times 10^3 \nu_F^2$ for the data of April 9 and $\approx 9.4 \times 10^3 \nu_F^2$ for the data of April 11 and 17. S_4-indices computed from intensity scintillations on L1 and S_4-indices derived using the above scale factor with DROTI are compared for PRNs 5,9,and 26 on April 9, and PRN 5 on April 17 in Figures 4(a), (b), (c), and (d) respectively. The agreement is closest for PRN 5 on all 3 days when scintillations were recorded on the three satellites: PRNs 5,9,and 26, during the April ~~1997 campaign~~. ~~This is~~ expected since ~~there~~ is ~~least~~ variation in the elevation angle for this satellite during the scintillation events. For PRN 26, the S_4-index tends to diverge increasingly from the value predicted by DROTI as its elevation angle decreases. During the period shown in Figure 4(c), the elevation angle dropped from 80° to 40°, which would imply a large change in ν_F which has not been taken into account. Also the signal from PRN 26 to Ancon encounters a thick layer of irregularities for low elevation angles, since the trajectory of this satellite is nearly aligned with the magnetic meridian. This scenario would tend to invalidate the phase screen approximation since significant amplitude fluctuations may develope within the irregularity layer.

Conclusions

On the basis of results described in this paper, it is concluded that: (1) The contribution of phase scintillations on L1 and L2 signals, to the relative TEC fluctuations measured by dual frequency GPS recevers, may sometimes be a significant fraction of the measured 'TEC' variations. This contribution tends to follow the pattern of intensity scintillations, as measured by the S_4-index, irrespective of the geometry of the satellite to receiver signal path. (2) An equation which approximately relates the second derivative, $d^2\Delta N_T/dt^2$, of TEC variations on time scales $\geq \nu_F^{-1}$, to the measured intensity, suggests that a second derivative based index may be a natural choice as a quantitative measure of scintillation activity due to ionospheric irregularities. The conversion factor between DROTI and S_4-index is proportional to ν_F^2, which may be roughly estimated from the satellite trajectory if intensity scintillation data is not available. (3) Indices such as ROTI and DROTI are based on a phase screen description of the ionospheric irregularities. This description fails whenever the signal encounters a thick layer of irregularities such that considerable intensity scintillations develop within the irregularity layer itself.

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