Ionospheric Scintillation Study of the Southern High Latitude Ionosphere

N.M. Shilo (1), E.A. Essex (1) and A.M. Breed (2)

(1) Cooperative Research Centre for Satellite Systems
Department of Physics, La Trobe University,
Bundoora, Victoria 3083, Australia

(2) Atmospheric and Space Physics Group
Australian Antarctic Division, Kingston,
Tasmania 7050, Australia.

Abstract

The monitoring of Ionospheric Scintillation over Casey station has been achieved by using the GSV4000 GPS Ionospheric Scintillation Monitor (GISM) which was installed during the summer of 1997-1998. This system is capable of tracking up to 11 GPS satellites simultaneously at the L1 frequency (1575.42 MHz). Amplitude and phase measurements recorded in 60 second intervals have been used to observe scintillation activity in the southern high latitude ionosphere, especially that associated with auroral activity, particularly during days 121-126 in May 1998. Other potential causes of scintillation activity, such as patches, have also been investigated.

Introduction

In passing through the ionosphere, radio signals sometimes show rapid phase and amplitude variations that are called ionospheric scintillation [1]. These fluctuations are caused by large electron density gradients along the ray path of the signal. Severe amplitude fading and strong phase scintillation affect the reliability of GPS navigational systems and satellite communications. Therefore, it is desirable to obtain further understanding of ionospheric scintillation and its effects on GPS by means of a receiver capable of performing in such conditions.

Experimental Work

The GISM installed at Casey station consists of three major components, as follows: 1. The GPS antenna (model type NovAtel 503) which is located on the roof of the Casey science building and is fitted with a choke ring ground plate to minimise ground multipath effects. 2. The GPS receiver (model NovAtel 3951R GPSCard), installed into a computer located in the science lab. 3. The conversion board (GSV-3003, 5 or 10 MHz) which provides a reference clock signal (20.473 MHz reference signal) required for the NovAtel GPSCard. This signal is phase locked either to the on board 10 MHz oven controlled SC-cut crystal oscillator (OCXO), which provides the phase reference, or to the externally applied 5 or 10 MHz local station frequency.

This single frequency GPS receiver is capable of tracking up to 11 GPS Coarse Acquisition (C/A) signals at the L1 frequency of 1575.42 MHz. The receiver records measurements of both phase and amplitude at a 50-Hz rate, and code/carrier divergence at a 1-Hz rate. The receiver software controls the data recording and sampling rate. More information on this type of receiver can be obtained from [2] and [3].

Amplitude Scintillation

The GISM used in this analysis measures both amplitude and phase scintillation. Amplitude scintillation is defined by the S_4 index that is derived from detrended intensities of signals received from satellites [3]. The S_4 index is computed over 60-second intervals and stored in the Ionospheric Scintillation Monitor Receiver (ISMR) data log along with the phase measurements. This is referred to as the Total S_4 (or S_{4T}). The normalised S_4 index, including the effects of ambient noise, is defined as follows [2], [4]:

$$S_{4T} = \sqrt{\frac{\langle P^2 \rangle - \langle P \rangle^2}{\langle P \rangle^2}} \qquad 1$$

The amplitude measurements are filtered using a Low Pass Filter (LPF) and the effects of ambient noise removed from the S_{4T}. This is achieved by estimating the average signal-to-noise ratio over the 60-second interval. The 60-second estimates are then used to determine the expected S_4 correction (or S_{4N_o}) due to ambient noise. The use of this average signal-to-noise ratio (S/N_o) is feasible because the amplitude scintillation fades do not significantly alter the S/N_o. Knowing the S/N_o, S_{4N_o} due to ambient noise becomes [3]:

$$S_{4N_o} = \sqrt{\frac{100}{S/N_o}\left[1 + \frac{500}{19S/N_o}\right]} \qquad 2$$

Equation 2 is referred to as the S_4 correction (or S_{4N_o}). By subtracting the square of the right hand side of Equation 2 from the square of the right hand side of Equation 1, and replacing the S/N_o with the 60-second estimates. Equation 1 may be modified to give the S_4 index, with the effects of ambient noise removed, as follows:

$$S_4 = \sqrt{\frac{\langle P^2 \rangle - \langle P \rangle^2}{\langle P \rangle^2} - \frac{100}{\overline{S/N_o}}\left[1 + \frac{500}{19\overline{S/N_o}}\right]} \qquad 3$$

Phase Scintillation

Phase scintillation is determined from monitored measurements of the standard deviation, $\sigma_{\Delta\phi}$, and the power spectral density of de-trended carrier phase from signals received from GPS satellites [5]. The phase is measured over 1, 3, 10, 30 and 60-second intervals. As with the amplitude measurements, the 60-second averages are used in this analysis. The detrended phase measurements are used to define the spectral parameters strength, $T_{\phi 1}$, and slope, P_ϕ, and are given by Equation 4 [3] as a function of the frequency ν in rad^2/Hz for frequencies greater than 1 Hz:

$$\Phi_\phi(\nu) = T_{\phi 1}\nu^{-p_\phi} \qquad 4$$

Similar to the amplitude measurements the phase is also detrended but by using a High Pass Filter (HPF). This removes any low frequency effects below the frequency cut-off of 0.1 Hz. The oscillator effects therefore should be filtered out, except for any high frequency phase noise. The quality of the oscillator must be such that this unfiltered phase noise is low relative to the desired scintillation monitoring performance.

Total Electron Content (TEC)

For this study the equivalent vertical TEC was used. Vertical TEC is defined as the electron content in a vertical column of unit cross-sectional area from the sub-ionospheric point at the ground to the satellite. A TEC unit is defined as 1×10^{16} electron m^{-2}. Vertical TEC can be written as:

$$\int_o^h \mathrm{N}dh = \cos\chi_m \int_o^s \mathrm{N}ds \qquad 5$$

or as:

$$\mathrm{VerticalTEC} = \cos\chi_m \times \mathrm{slantTEC} \qquad 6$$

where χ_m is the zenith angle in the ionosphere of the satellite relative to an observer. N (number of electrons per m^{-3}) is defined as the ionospheric electron density at an assumed height of 400 km, H is the height of the satellite, and S is the slant range from the satellite to the ground observer.

Comparisons of TEC and Scintillation Activity

Scintillation and TEC have been monitored for 1998 over Casey station. Approximately 3 to 5 days of data were analysed for each month subject to the availability and quality of data. This particular model of GISM does not have TEC recording capabilities. Therefore, the Australian Surveying and Information Group (AUSLIG) recorded all TEC data separately on a receiver also located at Casey. As a result it was not always possible to have TEC measurements for each satellite recorded at the same time as the corresponding scintillation measurements. During May 1998, days 121 to 126, a magnetic storm occurred. The K_p (planetary index) and Dst (Disturbance Storm Time) for this time period are illustrated in Figure 1. The maximum K_p reached was approximately 9.0 on day 124 with a Dst reading of -216 nT. Phase and amplitude scintillation was observed for various satellites over the five days. One example is presented here for day 121. Shown in Figure 2 is the phase and amplitude scintillation observed for satellite PRN 5 on day 121. Also shown is the corresponding TEC for PRN 5.

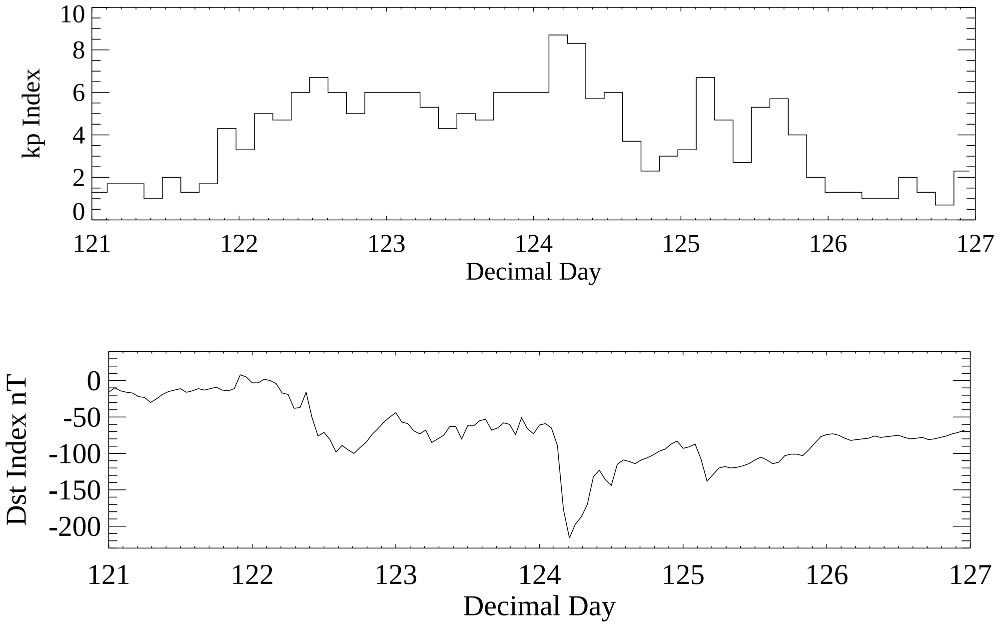

Figure 1. shows the K_p and Dst for May (days 121 - 126).

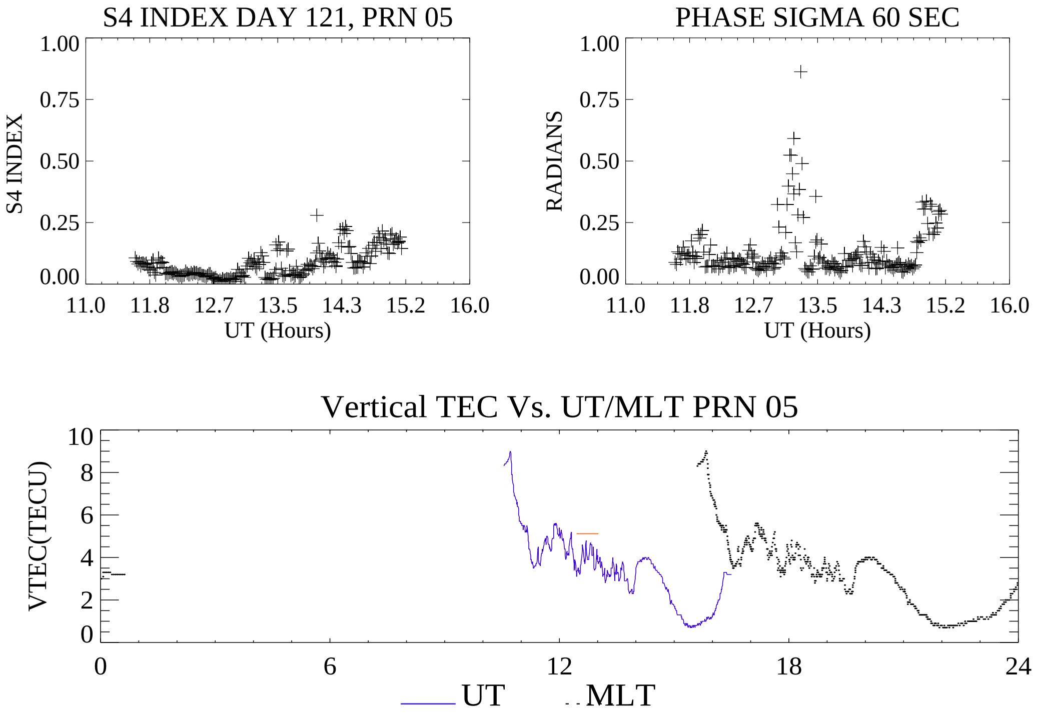

Figure 2. The top panel shows both the S_4 index and phase scintillation recorded in 60-second intervals. The bottom panel shows the corresponding TEC for satellite PRN 5. The dotted bar indicates the area in which the scintillation activity was observed.

For PRN 5 the phase scintillation reached a maximum of approximately 0.863 radians at approximately 1300 UT hours. At this time there was moderate activity with the K_p reaching 2.0. The S_4 index reached a maximum value of approximately 0.25 at 1400 UT hours. However, it is possible that the phase scintillation observed may be associated with oscillator phase noise, as opposed to any ionospheric disturbance. Oscillator noise is prominent for satellites at very low elevation angles with low received signal (C/N_o) values (less than 30 dB-Hz). This may also be due to multipath. However, during the observed phase scintillation activity, PRN 5 is at an elevation of 73.5° and the C/N_o is approximately 54 dB-Hz as shown in Figure 3. Also shown in Figure 3 is the lock-time of the satellite. Lock-time is defined, as the time required for the receiver to lock onto a satellite. For the data to be useful the receiver must maintain lock for more than 240 seconds. This is the time required for the detrending HPF (High Pass Filter) to re-initialise lock with the carrier phase signal. If the receiver loses lock on a satellite for less than 240 seconds unrealistic high phase values are present (greater than expected for scintillation) and so the phase data is ignored. It can be seen that the receiver maintains lock on PRN 5 for the duration of the pass.

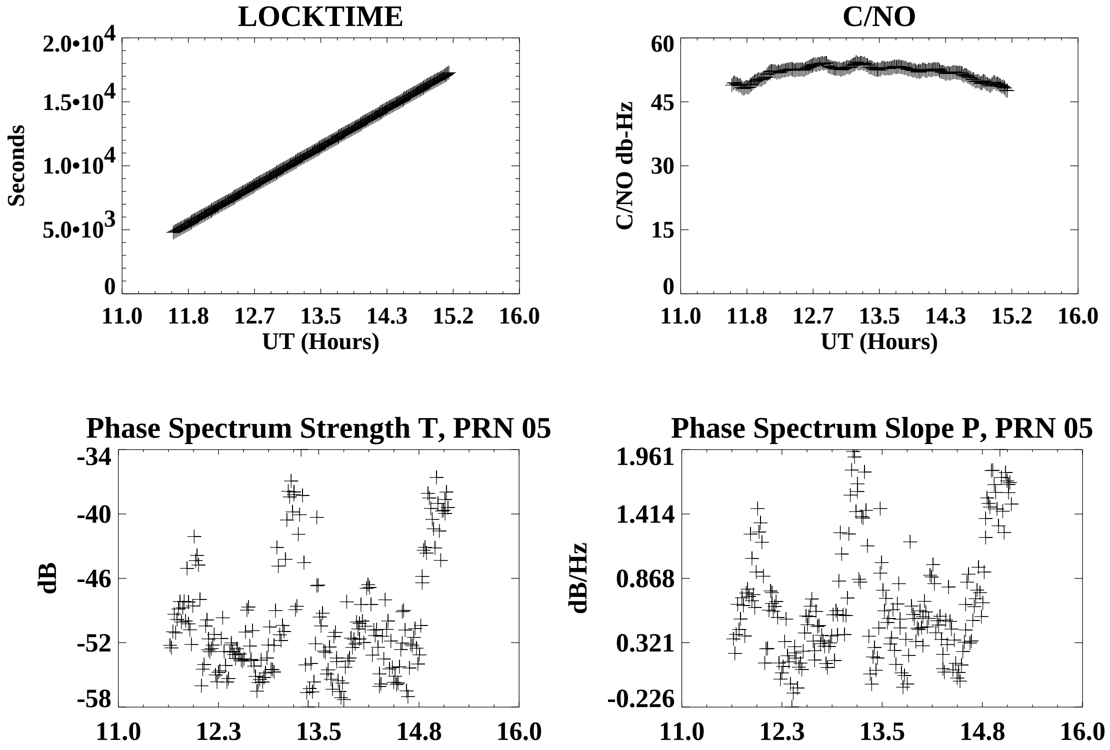

Figure 3. The top plot shows both the lock-time and C/N_o of PRN 5. The bottom plot shows the spectral strength and spectral slope.

Furthermore, it has been shown by [5] that when the spectral strength is high and the slope small (less than 0.5 dB) the signal fluctuation is not characteristic of phase scintillation but rather of thermal noise. Therefore, the scintillation is not regarded as being significant and is disregarded. Examination of the two spectral parameters (spectral strength $T_{\phi,}$ and spectral slope P_ϕ) in Figure 3 shows that the spectral strength during the time of observed scintillation is approximately -40 dB and the slope P_ϕ is 1.77 dB.

Referring back to Figure 2 and the TEC for PRN 5, it can be seen that the TEC shows large increases during the period of scintillation activity. These increases are more typical of auroral activity than patches. In TEC measurements, observations of patches are defined as those that have an increase of 3 TEC units or more with smooth variations, and patches drift antisunward across the polar cap [6]. The TEC presented here does not show these characteristics during the time of observed scintillation.

Summary and Conclusions

With the presence of magnetic activity during the days 121-126 scintillation activity was observed by the use of the GSV4000 GPS Ionospheric Scintillation Monitor. Even in these disturbed conditions (where K_p reached a maximum of approximately 9.0) the receiver performed adequately and maintained lock on all the satellites viewed. Although there was not much amplitude scintillation present, there was strong phase scintillation. The spectral parameters and the C/N_0 suggest that the observed phase scintillation is not due to receiver noise, but perhaps due to the presence of enhanced auroral activity during increased magnetic activity.

References

[1] **Knight, M., and Finn, A**., The Impact of Ionospheric Scintillations on GPS Performance. *Proc. of ION GPS-96, Kansas City, MO, September, p555, 1996.*

[2] **Van Dierendonck, A. J., John Klobuchar and Quyen Hua**, Ionospheric Scintillation Monitoring Using Commercial Single Frequency C/A Code Receivers, *Proceedings of ION GPS-93, Salt Lake City, UT, September 1993.*

[3] **Van Dierendonck, A. J., Fenton, P., and Klobuchar, J**., Commercial Ionospheric Scintillation Monitoring Receiver Development and Test Results. *Proc. of ION 52nd Annual meeting. The institute of Navigation, Cambridge, June 1996.*

[4] **Fremouw, E.J., Leadabrand, R.L., Livingston, R.C., Cousins, M.C., Rino, C.L., Fair, B.C**., **and Long, R.A**., Early Results from the DNA WideBand Satellite Experiment-complex Signal Scintillation., *Radio Sci, 13, No.1, January-February, p167, 1978.*

[5] **Van Dierendonck, A. J., Klobuchar, J., and Fenton, P**., Measuring Ionospheric Scintillation Using GPS Receivers. *Proc. of KIS-97, Banff, Alberta, June, p103, 1997.*

[6] **Weber, E.J., Klobuchar, J.A., Buchau, J., Carlson Jr., H.C., Livingston, R.C., de la Beaujardiere, O., McCready, M., Moore, J.G., and Bishop, G.J**., Polar cap F layer patches: Structure and dynamics, *J. Geophys. Res., 91, p12,121, 1986.*