

Determination of Equatorial Ionospheric Scintillation S_4 by Dual Frequency GPS

J. Du (1), J. Caruana (1), P. Wilkinson (1), R. Thomas (2), M. Cervera (2)

(1) IPS Radio and Space Services, Sydney, NSW 1240

junhu@ips.gov.au, john@ips.gov.au, phil@ips.gov.au

(2) Surveillance System Division, Defence Science and Technology Organisation, Salisbury, SA 5108

dick.thomas@dsto.gov.au, manuel.cervera@dsto.gov.au

Abstract

To investigate the effects of equatorial ionospheric scintillation on space based global navigation and communication, IPS Radio and Space Services and the Defence Science and Technology Organisation collaborated to obtain scintillation and dual frequency GPS measurements at Vanimo. The station is located under the southern crest of the equatorial anomaly, where scintillation often occurs. An Ionospheric Scintillation Monitor (ISM) records S_4 and other parameters every minute, while a dual frequency GPS receiver records the carrier-to-noise ratio, carrier phase and pseudorange data at 2-second intervals.

The dual frequency GPS data were analysed to process rate of TEC (ROT), derivative of ROT (DROT) and their standard deviations (ROTI and DROTI). It appears that both ROTI and DROTI show similar changes with S_4 . The quantitative relationship between ROTI (and DROTI) and S_4 is explored. Our results show that S_4 can be estimated from ROTI or DROTI with similar accuracy.

1. Introduction

Equatorial ionospheric scintillation occurs quite often between local sunset and midnight. The decreased ionospheric conductivities, the pre-reversal enhancement of the eastward electric field and the neutral winds are believed to be responsible for the phenomena. Sometimes, these competing forces make the ionosphere unstable and cause plasma bubbles to form. If so, the scintillation takes place and the trans-ionospheric communication is affected.

For an undisturbed ionosphere, dual frequency GPS receiver observations can show a flat total electron content (TEC) distribution within several minutes. When spread F or an irregularity appears in the ionosphere, the calculated TEC will fluctuate in addition to the quick variations of the received carrier-to-noise ratio.

To investigate the effects of equatorial ionospheric scintillation on space based global navigation and communication, several people have focused their work on the relationship between the TEC variation and the scintillation index S_4 , which was widely used to estimate the scintillation effects on trans-ionosphere communication.

Pi et al. [1], Basu et al. [2] and Beach and Kintner [3] selected ROTI, the standard deviation of the rate of change of TEC (ROT), and σ_{TEC} , the standard deviation of TEC, to describe the ionospheric scintillation. Beach and Kintner concluded that the S_4 scintillation index is roughly proportional to measures of TEC fluctuation for weak scintillation. $\text{ROTI} \approx (2 \sim 5)S_4$ and $\sigma_{\text{TEC}} \approx (2 \sim 4)S_4$ are good expressions for their measurements. Similarly, Basu et al. found ROTI/S_4 varies between 2 and 10 using their dataset. They all stated that ROTI measurements could be used to predict the presence of scintillation. The quantitative

relationship between ROTI and S_4 varies considerably due to variations of the ionospheric projection of the satellite velocity and the ionospheric irregularity drift.

Bhattacharyya et al. [4] introduced the index DROTI, the standard deviation of the second derivative of TEC, to relate the measured S_4 . Very similar comparison results were obtained. Furthermore, they showed that the ratio of DROTI to S_4 is related to the satellite velocity and the irregularity drift velocity, as well as to the slant path length from an effective irregularity layer to the receiver.

In this paper, we will examine the relationships between S_4 , ROTI and DROTI and explore methods of estimating S_4 by these indices. The purpose of this study is to provide a simple formula to predict the scintillation index S_4 by operating a dual frequency GPS receiver where no Ionospheric Scintillation Monitor (ISM) is available. Most importantly, the possibility of determining S_4 by using single frequency GPS receiver such as collected by the International GPS Service for Geodynamics (IGS) network.

2. Experiment and data processing

From August 1999, IPS Radio and Space Services (IPS) and the Defence Science and Technology Organisation (DSTO) conducted a campaign to monitor equatorial scintillation at Vanim, PNG (2.4 °S, 141.2 °E, magnetic latitude: 10.8 °S) as part of DSTO's regional GPS receiver network. With a dual frequency GPS receiver already operating there, we can explore the relationship between the scintillation index S_4 and the TEC changes.

A NovAtel MiLLennium dual frequency L1/L2 GPSCard is used to measure the pseudorange at L1 (1575.42 MHz) and carrier-to-noise ratio C/N, phase advance at L1 and L2 (1227.60 MHz). The data is recorded every 2 seconds. The geometrical parameters are updated every minute. The fortnightly data are saved to an external 1 GB Iomega JAZ drive and posted to IPS for re-distribution and processing.

The ISM is configured to measure amplitude and phase scintillation from the L1 frequency GPS signals. It measures satellites signals at a rate of 50 Hz under computer control. The sampled data are processed, the C/N, total S_4 , correction to total S_4 , 1, 3, 10, 30 and 60 second phase sigma, average of code/carrier divergence, phase spectral strength, phase spectral slope and four amplitude spectrum coefficients are recorded every minute. The monthly data are saved to an external JAZ drive and sent to DSTO. When sufficient post-processed data are accumulated, DSTO archives and copies to a CD-ROM and distributes to IPS and other partners. The detailed ISM description can be found in Van Dierendonck [5]. The ISM is on loan to DSTO from AFRL Hanscom.

Different from the IGS network, we hope our 2 s-sample rate will capture the Fresnel scale, the predominant scale size of weak amplitude scintillation patterns. In our case, the Fresnel scale $((2\lambda z)^{1/2})$ is about 390 m. Taking 120 ms^{-1} as the most possible ion drift velocity (eastward) between sunset and midnight [Fejer, 6], we estimate the equatorial ionospheric scintillation time scale to be around 4s.

For ISM measurements, as the S_4 index is affected by ambient noise, two related indices were recorded: total S_4 (S_{4t}) and correction to S_4 (S_{4c}). The following formula is used to calculate the S_4 index discussed in this paper.

$$S_4 = (S_{4t}^2 - S_{4c}^2)^{1/2} \quad (1)$$

This is the same as Van Dierendonck [5] suggested. When there is no scintillation, $S_{4c} \ll S_{4t}$, so we simply set S_4 to zero during data processing.

Normally, the S_4 values are computed over every 1-minute interval. To compare the ISM values with those calculated from the dual frequency GPS observations, 3 minute and 5 minute average values are also introduced and defined as follow,

$$S_4(t) = \sum S_4(t \pm \tau) / N \quad (2)$$

where, $N=3$ and $\tau=0, 1$ for 3 minute average, and $N=5$ and $\tau=0, 1, 2$ for 5 minute average. Spline interpolation is employed if there is no measurement data available.

The dual frequency carrier phase and pseudorange data of L1 are combined to determine the TEC. To remove noise spikes, in the determined TEC and simulate the IGS network, we use the median value of 15 measurement stands for the 30-s interval measurement. Standard deviations of ROT and DROT are all derived from these median values.

3. Method

Beach and Kintner [3] derived expressions of S_4/σ_{TEC} and $S_4/ROTI$ using a one- dimension phase screen model with the observer situated directly under the dip equator with a satellite at zenith. Their results show S_4/σ_{TEC} and $S_4/ROTI$ are functions of the power law index, outer scale of selected power law applicability and are insensitive to the ionospheric drift velocity. Although there is a good agreement between measurement and theoretical estimate, it is impracticable because we do not have measurements pertaining to the power law index and the scale of the power law if only a dual frequency GPS receiver is used. The purpose of exploring the relationship between TEC and S_4 is to find a way to calculate S_4 from variations in TEC.

Bhattacharyya et al. [4] explored the relationship between S_4 and DROTI. They used a one-dimensional phase screen and assumed phase varies along the x-direction only. If so, the transport of intensity equation can be written as

$$(2\pi/\lambda) \partial I/\partial z = -\partial (I \partial \phi / \partial x) / \partial x \quad (3)$$

where I , ϕ and λ are the intensity, phase and wave length.

Integrating equation (3) from the phase screen ($z = 0$) to the ground z and use following hypotheses

$$(\partial I / \partial x)(\partial \phi / \partial x) \ll I (\partial^2 \phi / \partial x^2) \quad (4)$$

$$I (\partial^2 \phi / \partial x^2) = I_0 (\partial^2 \phi_0 / \partial x^2) \quad (5)$$

we have

$$I / I_0 = 1 - \lambda z / 2\pi \, d^2 \phi / dx^2 \quad (6)$$

Considering

$$\phi(x) = -\lambda r_e \Delta N(x) \quad (7)$$

$$x = vt \quad (8)$$

we can re-write equation (6) as

$$d^2\Delta N / dt^2 = C v^2 / z (1 - I(t,z) / I_0) \quad (9)$$

If left side of equation (9) is expressed in unit of TECU (10^{16} el/m²)/min², we have

$$C = 6.2135 \times 10^{-3} \quad (10)$$

where v and z are in unit of ms⁻¹ and km, respectively.

Bhattacharyya et al.[4] used Fresnel frequency $v_F = v / (2\lambda z)^{1/2}$ in equation (9), and they obtained v_F from the measured power spectrum of the intensity data. Their results, generally speaking, are very similar to those of Beach and Kintner [3], Basu et al. [2] and Pi et al. [1] who selected first, not second, derivative of TEC as the index to compare with S_4 . So it seems both of ROTI and DROTI can be used to describe or calculate S_4 .

In this paper, we assume both ROTI and DROTI are proportional to S_4 and the coefficient is determined by Cv^2/s . The velocity v and the slant distance between phase screen (400 km) and GPS receiver can be expressed by

$$v^2 = [v_p^2 + v_I^2 - 2v_p v_I \cos(55^\circ)] \cos^2\phi \quad (11)$$

$$s = (r+h) \cos(\phi + \theta) / \cos\theta \quad (12)$$

$$\phi = \sin^{-1} [r \cos\theta / (r + h)] \quad (13)$$

where θ is elevation angle, v_p is the velocity of the pierce point moving at an altitude of h , and v_I is the ion drift velocity. If the satellite moving in a circular orbit the relationship between v_p and satellite velocity v_s can be written as follows

$$v_p = v_s (r + h) / (20000 + r) \quad (14)$$

We selected $v_s = 3874$ ms⁻¹, $h = 400$ km, $r = 6378$ km and $v_I = 120$ ms⁻¹ in our calculation.

4. Results and discussions

Figure 1 shows the comparison between estimated and observed S_4 for satellite PRN 3 on 20 September 1999. It is clear that the irregularity in the ionosphere causes fluctuation of the signal strength and changes of TEC. Both of ROTI and DROTI can illustrate the main features of the S_4 variation, but neither of them can trace the fine structure exactly.

The top panel shows the amplitude data measured by the dual frequency GPS receiver at L1. The second panel shows the calculated TEC variations with UT. The last two panels are comparisons between ISM measurements and estimates made by the method presented in section 3. DROTI is better correlated to S_4 than ROTI for the first bubble at around 1108 UT but the reverse is true for the second one at 1124 UT.

As differentiation emphasises the high frequency components of TEC and ROT, the effects of glitches and measurement noise are amplified and therefore the calculated S_4 is sensitive to the adopted processing method.

Another feature arising in Figure 1 is that ISM S_4 is larger than the calculated value most of the time. This happens to other satellites and at other time. If ISM S_4 is 0.15 smaller than the present value, the agreement between the measured S_4 and our estimate will be highly improved.

It seems possible to obtain quantitative estimates of the scintillation index S_4 by use a dual frequency GPS receiver. We provide a simple method to calculate S_4 from an analysis of ROTI and DROTI.

References

- 1 Pi X., A. J. Mannucci, U. J. Lindqwister and C. M. Ho, Monitoring of global ionospheric irregularities using the worldwide GPS network, *Geophys. Res. Lett.*, 24, 2283, 1997.
- 2 Basu S., K. M. Groves, J. M. Quinn and P. Doherty, A comparison of TEC fluctuation and scintillations at Ascension Island, *J. Atmos. Sol. Terr. Phys.*, 61, 1219-1226, 1999.
- 3 Beach T. L. and P. M. Kintner, Simultaneous Global Position System observations of equatorial scintillations and total electron content fluctuations, *J. Geo. Res.*, 104, A10, 22553-22565, 1999.
- 4 Bhattacharyya A., T. beach and S. Basu, GPS studies of TEC variations and equatorial scintillations, 1999 Ionospheric Effects Symposium, Alexandria, Virginia, May 4-6, 1999.
- 5 Van Dierendonck A. J., Measuring ionospheric scintillation effects from GPS signals, 1999 Ionospheric Effects Symposium, Alexandria, Virginia, May 4-6, 1999.
- 6 Fejer B. G., low latitude electrodynamic plasma drift: a review, *J. Atmos. Sol. Terr. Phys.*, 53, 677-693, 1991.

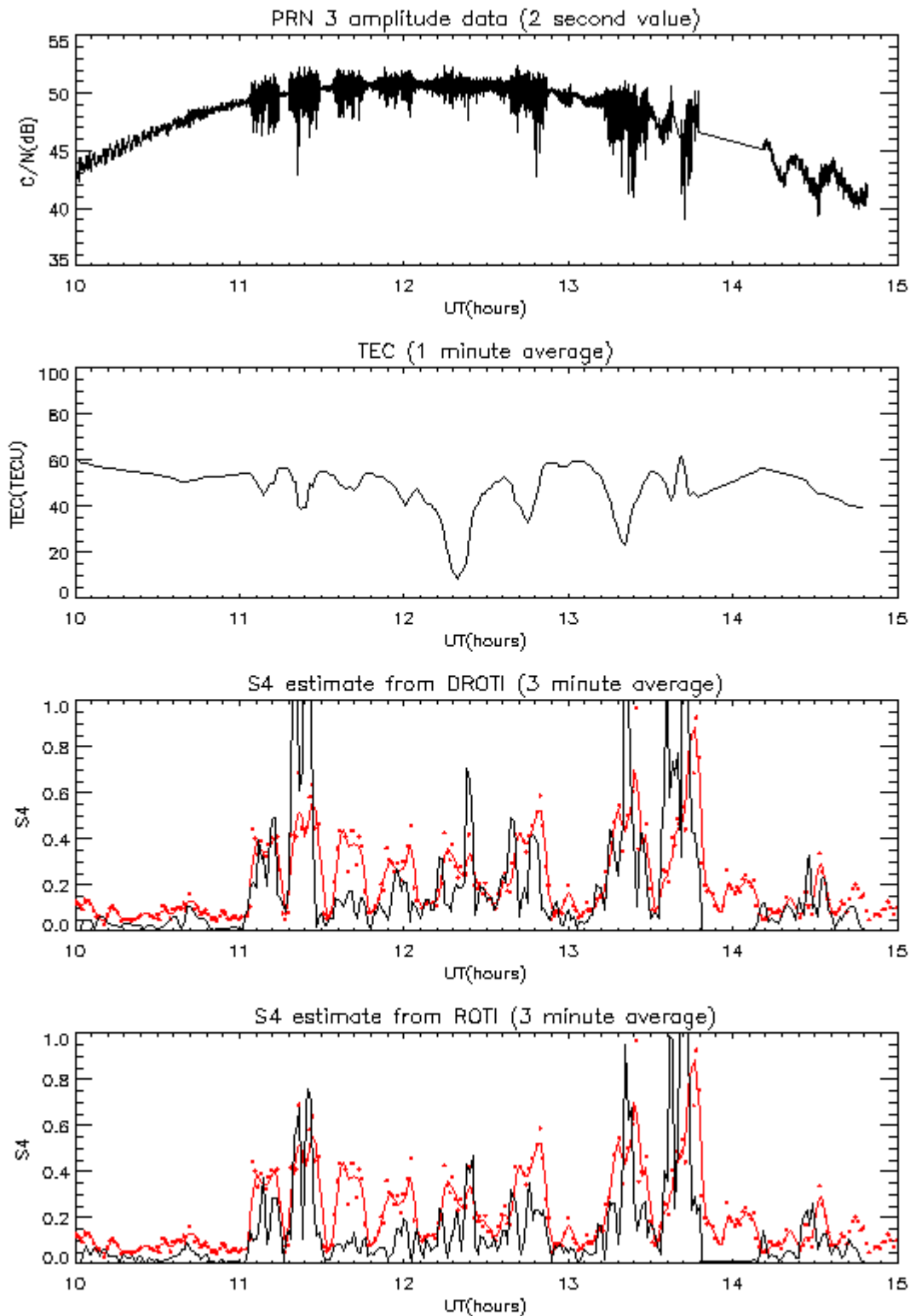


Figure 1. Comparisons between ISM S_4 and estimates from ROTI and DROTI from PRN 3 observation at Vanimo on 20 September 1999. The top panel shows the received carrier-to-noise ratio of GPS L1 signals, the second panel shows variation of TEC, the third and fourth panels show the comparison between ISM measured S_4 (dots) and calculated values (heavy lines) from DROTI and ROTI respectively. Light lines are for 3 minutes average of measurements.