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A Study Of Ionospheric GPS Scintillation During Solar Maximum at UTeM Station

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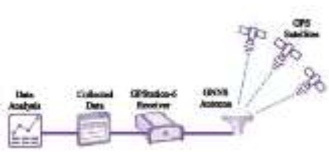
Graphical abstract



Abstract

Wireless signals propagated along global positioning system (GPS) channel are affected by ionospheric electron density irregularities such that GPS signals may experience amplitude and phase fluctuations. The global navigation satellite system (GNSS), ionospheric scintillation, and total electron content (TEC) monitor (GISTM) receiver has been installed at UTeM, Malaysia (2.3139˚N, 102.3183˚E) for monitoring ionospheric scintillation at several frequencies. In this paper, the GPS ionospheric scintillations are concerned for the dual frequency L1 (f_{L1} = 1.57542 GHz) and L2C (f_{L2}= 1.2276 GHz). Ionospheric scintillation data has been collected during solar maximum cycle 2013-2014 for six months October 2013–March 2014. Solar activities significantly impact the ionospheric GPS scintillation, especially in the equatorial region where Malaysia is located. The GPS link is analyzed to investigate how the scintillation increases during the solar maximum cycle. When the sun flux is maximum, the total of electrons is increased in the ionospheric layer and the scintillation values gradually become high. The ionospheric amplitude/phase scintillation, carrier-to-noise (C/No) ratio, and availability of GPS satellites are reported in the proposed experimental GPS model. Consequently, for Malaysia, typical threshold received C/No ratio is 43 dB-Hz, implying that C/No ratio should be greater than 43 dB-Hz to receive good signals at the GPS receiver.

Keywords: GPS, Ionospheric irregularity, Ionospheric scintillation, Solar maximum

■1.0 INTRODUCTION

The global positioning system (GPS) signal is an electromagnetic wave generated by oscillating energy from a GPS satellite. The GPS signal propagates along the space channel to the GPS user on Earth; this channel is called the GPS link. The GPS signal strength decreases because several factors affect the signal quality depending on the length of the GPS link. This is essentially because of attenuation caused by geometric spreading and the attenuation in the troposphere and ionosphere layers [1]. One of these factors is ionospheric scintillation which is defined as rapid fluctuations of the amplitude and phase of satellite radio signals when they propagate through the ionosphere due to electron density irregularities [2,3]. This implies that the movements of irregularities and satellite produce time variations in amplitude and phase on areceiver, which is known as amplitude and phase scintillation [4, 5]. This phenomenon is more prominent in the equatorial region of the Earth, especially during maximum solar cycles [6].

Solar maximum is a normal period of greatest solar activity in the 11 years solar cycle of the sun [7]. During solar maximum, numerous sunspots appear and the sun's irradiance output increases by approximately 0.07% [8]. Figure 1 shows the solar cycle where the 24th solar maximum appears during 2013/2014. The equatorial region is shown in Figure 2. At equatorial latitudes, where the GPS scintillation phenomenon is stronger, induced fading can exceed 20 dB [9]. Because Malaysia is located in this region, the GPS link ionospheric scintillation and availability is studied in Malaysia during solar maximum.

Basu et al. [10] investigated the morphology of scintillation during solar maximum and minimum and concluded that the occurrence of scintillation peaked during solar maximum when F region ionization density increased. They also found that scintillation was the most intense in equatorial ionization anomaly (EIA) regions, and their associated irregularities occurred in the background of high ionization density. Weak or strong levels of scintillation can produce disruptions of the communication and navigation links that utilize low or high altitude orbiting satellites. The impact of scintillation on GPS navigation has generated a new impetus in view of the increasing reliance on satellite-based positioning systems in critical application [11]. Muella et al. [12] presented the variations of the scintillation and zonal drift velocity of Fresnel-scale ionospheric irregularities with local time, season, and magnetic activity during solar maximum period of March 2001 to February 2002 at the equatorial station. They concluded that on geo-magnetically disturbed nights, scintillation activities appeared to be strongly affected by the prompt penetration of magnetospheric electric fields and disturbance dynamo effects.

Solar activities significantly impact the ionospheric GPS scintillation, especially in the equatorial region where Malaysia is located. The GPS link is analyzed to investigate how the scintillation increases during the solar maximum cycle. When the sun flux achieves maxima, the total of electrons is increased in the ionospheric layer and the scintillation values gradually become high. This paper analyzes the maximum GPS scintillation in the period starting from October 2013 to March 2014. The results will be discussed with scintillation amplitude (S4), phase scintillation (σ_φ), availability of GPS satellites, and carrier-to-noise (C/No) ratio for the dual GPS frequency (L1, L2C).

This paper is organized as follows: Section 2 explores the experimental setup and data collection, and the results are analyzed and discussed in Section 3. The paper is finally concluded in Section 4.

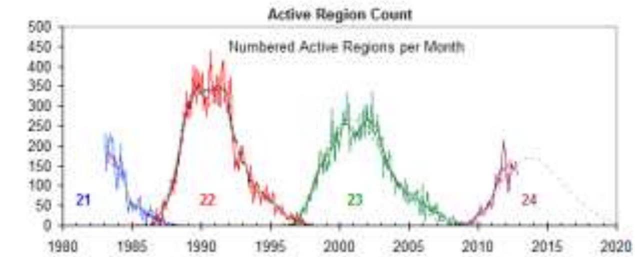


Figure 1 Solar cycle

Figure 2 Equatorial region

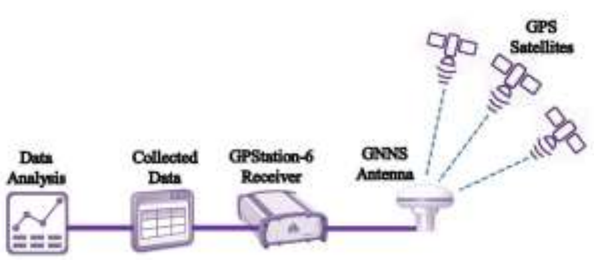


Figure 3 Experimental setup

■2.0 EXPERIMENTAL SETUP AND DATA COLLECTION

2.1 Experimental Setup

Figure 3 shows the experimental setup to measure and analyze the GPS ionospheric scintillation. The dataset used for this study has been collected at postgraduate research laboratory, faculty of electronics and computer engineering (FKEKK), UniversitiTeknikal Malaysia Melaka (UTeM), Malaysia (2.3139˚N, 102.3183˚E), using a scintillation monitor developed by GPStation-6 GISTM Receiver. The average distance between GPS satellite and the GPS receiver is approximately 24000 km. The antenna of GPS receiver is installed at high position to avoid side effects such as wireless multipath phoneme.

Because multipath effects appear at small elevation angles, ionospheric scintillation will be analyzed at elevation angles greater than 30° [13, 14]. For low elevation angles (Elv< 30°), GPS signals suffer large fluctuations due to multipath effects [15].Data has been collected over six months; time interval for daily measurements is 24 hours starting after sunset. The data structures are then organized and analyzed using MATLAB programming software.

2.2 Data Collection

The GNSS Ionospheric Scintillation and TEC Monitor (GISTM) receiver is a multi-frequency, multi-constellation receiver capable of simultaneously tracking GPS L1-C/A, L2-P(Y), L2C, L5; GLONASS L1, L2; Galileo E1, E5a, E5b, AltBOC; SBAS L1, L5; COMPASS; QZSS. The GISTM provides algorithms for ionospheric scintillation monitoring (ISM) and total electron content (TEC) measurements for all tracked signals. For sampling at 50 Hz, the receiver gives the following main output parameters:

1. the amplitude scintillation index (*S4*) calculated over 60 s;
2. the phase scintillation index (σ_φ) calculated over different time intervals (10, 30, 60 s);
3. the*TEC* and the rate of TEC change (*ROT*) every15 s;
4. the azimuth (*Az*) / elevation (*Elv*) angle for the tracked signal.
5. the average carrier-to-noise (C/N_o) ratio (60 s);
6. the lock time (60 s).

This project considers all the available GPS satellites (with pseudo random numbers (PRNs) PRN01–PRN32) at dual frequency L1/L2C. Data are used for analyzing ionospheric scintillation effects on the GPS communication system during October 2013–March 2014, which has been considered during the rising phase of the maximum solar activity which increases the ionospheric scintillation. The universe time (UT) is considered in the collected data which must be converted to the local time (LT) as $LT = UT + 8$.

2.3 Methods

The amplitude scintillation S4 index is defined as the standard deviation of the de-trended signal intensity by normalization. It is calculated as:

$$S4 = \sqrt{{S4_t}^2 - {S4_{cor}}^2} \tag{1}$$

where the amplitude scintillation recorded by the GPStation-6 receiver has two parameters: total scintillation ($S4_t$) and corrected scintillation ($S4_{cor}$). The total $S4_t$ is recorded over a 60-second interval in real-time but includes the effect of ambient noise, whereas the corrected $S4_{cor}$ was calculated by removing the ambient noise.

The values of S4 are on the interval [0,1], where

$S4 > 0.4$ (strong scintillation)
$0.2 \leq S4 \leq 0.4$ (moderate scintillation) (2)
$S4 < 0.2$ (low and negligible scintillation)

The GPS satellites with elevation angle greater than 30° are only considered at measurements because the signals from satellites with low elevation angles usually suffer large fluctuations due to multipath effects. The C/N_o threshold and the availability of GPS satellites will be estimated according to these conditions.

The GISTM receiver calculates the phase scintillation component by monitoring the measurements of the standard deviation of the detrended carrier phase σ_φ received from GPS satellites as:

$$\sigma_\varphi{}^2 = \frac{\pi D}{k f_n^{p-1} \sin\left(\frac{[2k+1-p]\pi}{2k}\right)} \quad \text{radian} \qquad (3)$$

where D is the spectral strength of the phase (PSD) at 1 Hz, p is the spectral slope of the phase PSD, k is the order of the phase-locked loop (PLL) in the receiver (equal to 3), and f_n is the loop natural frequency (equal to 1.91 Hz).

The collected data is analyzed to determine the suitable range of phase scintillation with minimum negative effect on the GPS signals. The GISTM receiver also computes the *TEC* which is reported in TEC Units (TECU = 1×10^{16} electron/m^2). In addition, the collected data is used to find the availability of GPSs with the *LT*.

The lock time indicates how long the receiver has been locked to the carrier phase on the signal. Since the phase detrending high-pass filter has to be reinitialized whenever lock is lost, all the phase parameters (σ_φ's) should be discarded for any lock time less than 180–240 seconds (for a 0.1 Hz bandwidth) to allow the detrending filter to settle. For other bandwidths, this time may be inversely proportional to the bandwidth. For the S4 parameters, it suffices to only discard data for any lock time value less than 60 seconds. S4 may also be valid for lock time of less than 60 seconds because the power measurements are non-coherent measurements that do not require phase lock.

3.0 RESULTS AND DISCUSSION

During the solar maximum period, the ionospheric scintillation S4 index has been calculated from the collected data and analyzed for the dual frequency (L1 and L2C) considering an available GPS satellite with PRN = 17, as shown in Figure 4. The S4 index for L1 frequency is denoted by green circles, whereas the red circles denote L2C frequency. Each plot shows the S4 index for the corresponding month versus the local time (LT) at Elv ≥ 30°. During this period, the S4 index has values almost in the range [0, 0.4] which imply moderate and low scintillation for the dual frequency L1 and L2C. It is clear that several values of S4 index greater than 0.4 arise during January 2014, especially in the morning. This result is consistent with sunspot maximum which occurred in January, February, and March 2014 [16, 17]. Figure 4 also shows that the S4 index for L2C (red circles) is almost greater than that for L1 (green squares).

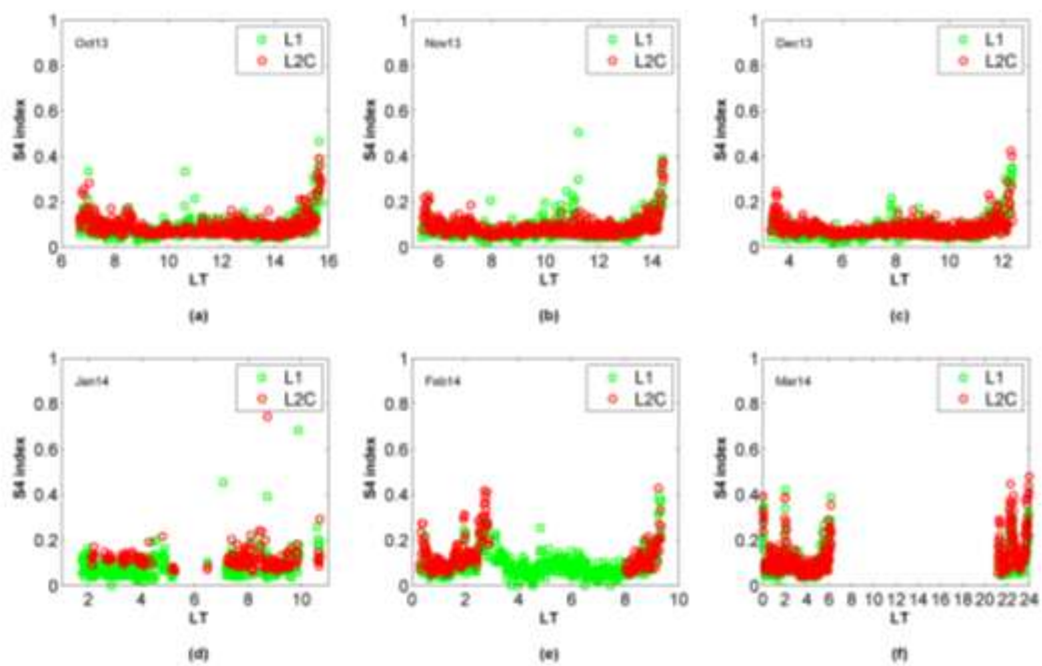


Figure 4 Amplitude scintillation index during solar maximum period for the GPS PRN17

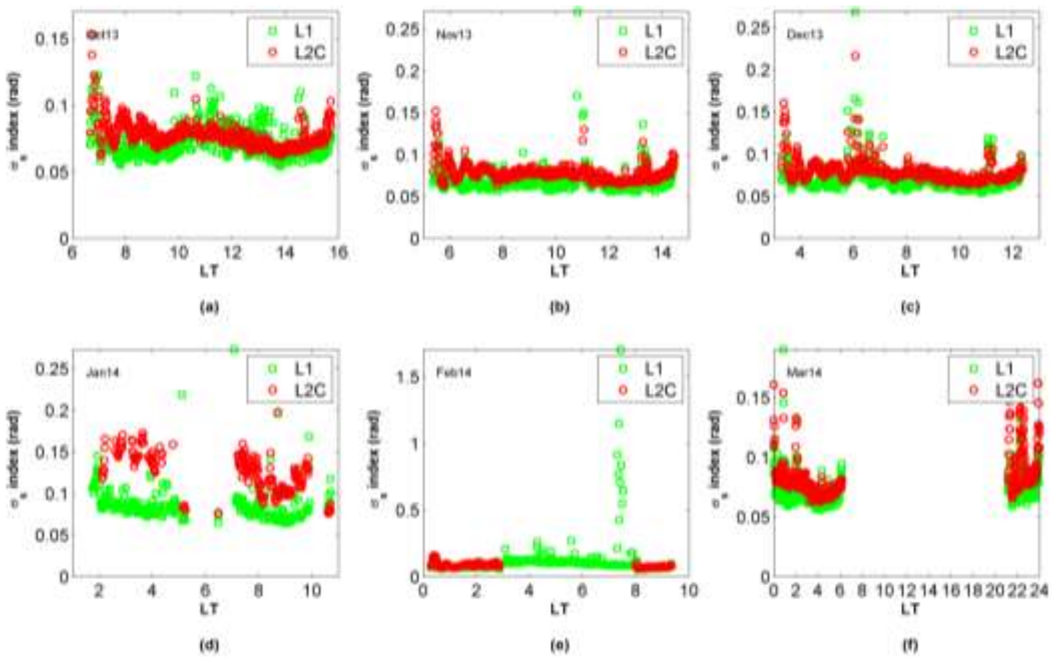


Figure 5 Phase scintillation during solar maximum period for the GPS PRN17

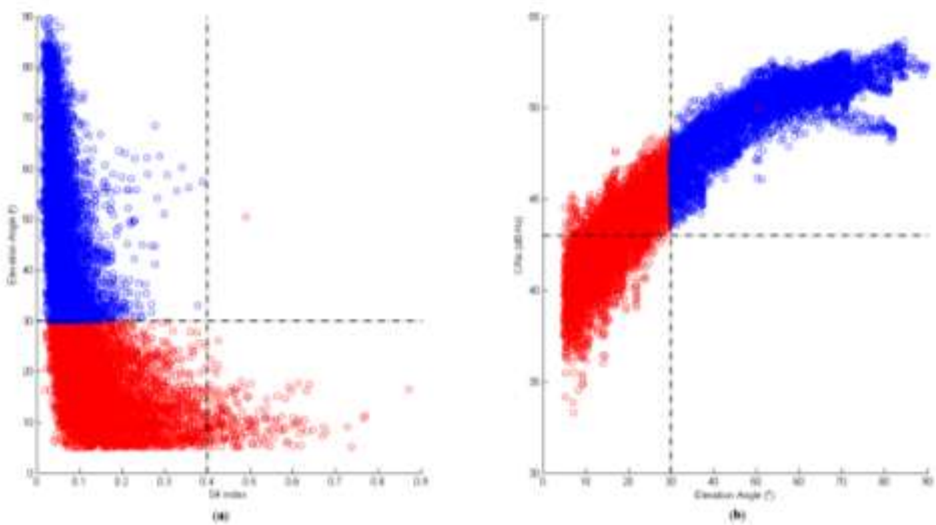


Figure 6 C/No ratio threshold

Figure 5 shows the month-to-month variations of the phase scintillation (σ_φ) activities observed at UTeM, Malaysia from October 2013 to March 2014 for GPS with PRN = 17. The most suitable range of the phase scintillation is [0, 0.1] rad, as shown in Figure 5. The phase scintillation sometimes exceeds the normal range in early morning 2:00–8:00 am during the months of December 2013, January 2014, February 2014, and March 2014. In addition, the phase scintillation overshoots for the frequency L1 (average 2 rad) are greater than that for frequency L2C (average 1.4 rad) at different GPS satellites; however, for the GPS satellite with specified PRN, the phase scintillation for L2C is almost greater than that for L1, as shown in Figure 5 as an example for the GPS with PRN = 17.

C/N_o ratio values should be compared against the values required to acquire and track GPS signals. The thresholds are dependent on receiver design for acquisition and are required to maintain tracking lock [18]. Figure 6 (a) shows the threshold values of scintillation index S4 and elevation angle. The good condition for receiving the GPS signals suitably occurs when the Elv ≥ 30° and S4 ≤ 0.4, which is denoted by blue circles in Figure 6 (a). The red circles denote the bad condition for receiving the GPS signals where Elv< 30° or S4 > 0.4. According to this result at UTeM, typical threshold received C/N_o is 43 dB-Hz (which implies that C/N_o should greater than 43 dB-Hz), as shown in Figure 6 (b).

The C/No ratios for the dual frequency L1 and L2C during the solar maximum are shown in Figure 7. During solar maximum, the C/No ratios mostly have good levels because the Elv is greater than 30°. During January 2014 and February 2014, the C/No ratios clearly decrease under the threshold C/No ratio during early morning, especially for L2C. This is observed because the phase scintillation at this time increased, as shown in Figure 5 (d) and (e).

32 GPS satellites are available around the Earth (PRN 01–32), but all of them are not available for one region on the surface of the Earth. Figure 8 shows the availability of GPS satellites for the corresponding months (October 2013–March 2014) according to

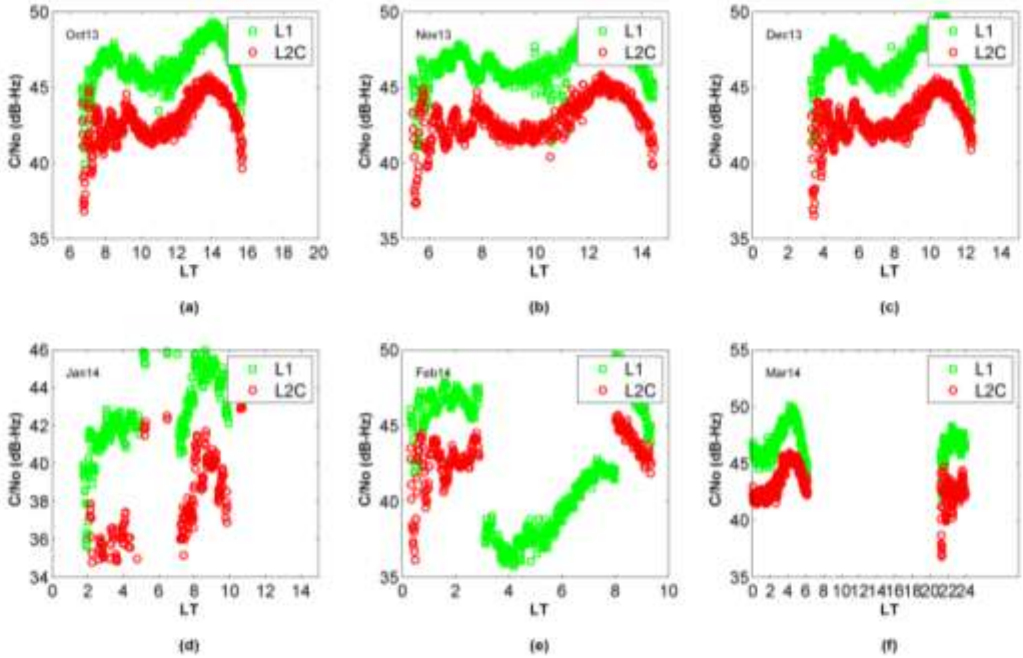


Figure 7 C/No ratios during solar maximum for the GPS PRN17

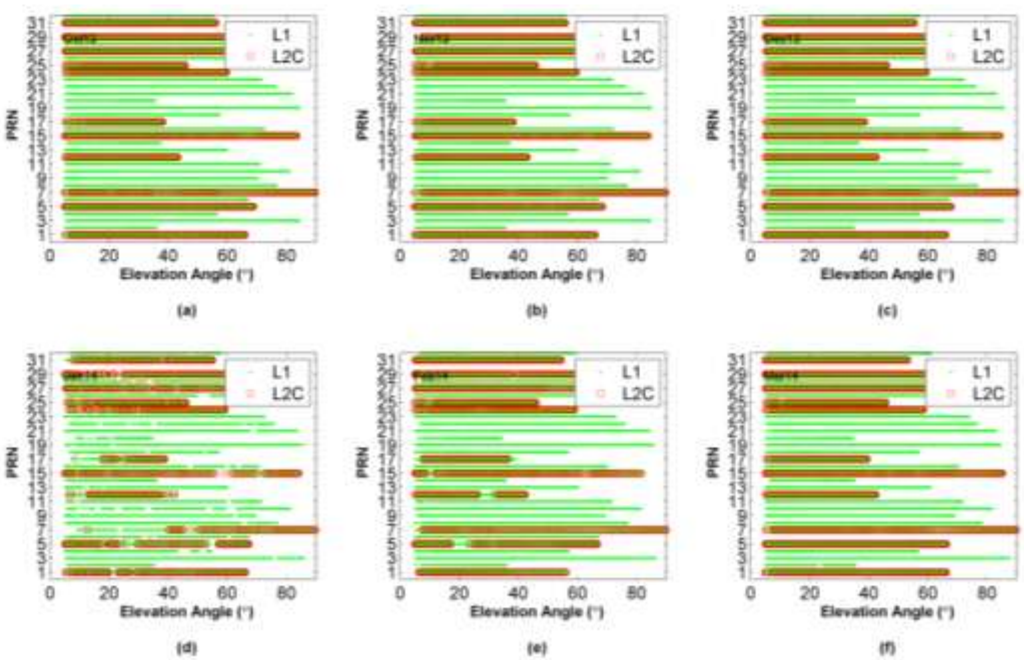


Figure 8 Availability of GPS satellites versus elevation angle

the elevation angle. The availability of L1 frequency is presented by green dots, whereas the red circles represent the availability of L2C frequency. It is very clear that the total number of available GPSs with L1 frequency is more than that with L2C frequency. In addition, the GPS that generates wireless signals at L1 frequency almost generates wireless signals at L2C frequency in the same time. Figure 8 (d) and (a) show that the availability of GPS decreased during the months of January and February 2014. The solar activities are the maximum during these two months. As a result, the ionospheric scintillation increased until large scale irregularity spots occurred along the GPS link, which induces a loss of lock for some GPSs.

■4.0 CONCLUSION

The study of ionospheric scintillations has been conducted using GPS measurements recorded at UTeM, Malaysia during solar maximum between October 2013 and March 2014. Strong scintillations with S4 > 0.4 and σ_φ> 0.1 rad often occurred during January 2014, February 2014, and March 2014, especially during early morning. Radio signals at the GPS receiver is received with good quality from the GPS satellite when the C/No ratio is greater than the threshold value of 43 dB-Hz. In this paper, the availability of the GPS satellites has also been investigated during solar maximum. The availability of GPS satellites at L1 frequency is also better than that at L2C frequency. In the future, the TEC and ROT will be analyzed and linked with the ionospheric scintillations for this period.

Acknowledgement

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