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GNSS Ionospheric Scintillation Models

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NANYANG TECHNOLOGICAL UNIVERSITY

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GNSS Ionospheric Scintillation Models

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Abstract

The project first details the Ionospheric scintillation analysis in Singapore based on the collected scintillation data in this region. They include statistical analysis of scintillation parameters such as S4, phi60 and ROTI in Singapore. Relatively high scintillation parameters are observed in equinox months (March, April, September and October). Diurnally, these scintillation events occur mostly around local time of 8 p.m. to 12 a.m, which is during the post sunset period. It can also be observed that high S4 is generally accompanied by high phi60, indicating that amplitude and phase scintillations usually occur concurrently. Besides that, we also observe fluctuations in the ROT and high ROTI during this period, which shows the presence of plasma bubble irregularities in the ionospheric layer. Evidently, both signal intensity and the carrier phase of the GPS signal exhibit fluctuations during this period, which signifies propagation through the plasma bubble irregularities of the ionosphere layer.

Next, the project investigates the applicability of existing scintillation models such as frequency dependent model and Fremouw and Rino model on Singapore equatorial region. These models are further modified and improved based on the locally collected scintillation data. Subsequently, we propose a Gaussian model to describe the scintillation behaviour in Singapore equatorial region. The inputs to the Gaussian model are sunspot number and local time. The Gaussian coefficients are determined based on fitting of 90th percentile of scintillation data in Singapore. For high scintillation activity months (i.e. the equinox months) and low scintillation activity months (i.e. summer and winter months), different set of model parameters are obtained. Overall, it is found that the Gaussian model predicts the scintillation level in Singapore relatively well.

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1. Introduction

1.1. Ionospheric Scintillation

Ionosphere is ionized atmosphere layers located between altitudes 50 km to 500 km. It is a region of the upper atmosphere where charged particles occur because of sun radiation. Ionosphere consists of 3 layers:

- D-layer (60 km – 90 km)
 - High recombination, low ionization
 - High absorption of radio waves
- E-layer (90 km – 120km)
 - Reflective to low frequency radio waves (< 10 MHz)
 - Absorption in higher frequency
- F-layer (120 km – 500 km)
 - High ionization and electron density
 - Facilitates sky wave propagation of radio waves over long distance

Influences of ionosphere as mentioned by [1]:

- Changes the Velocity of the Signals
- Group Delay
- Refraction of Radio Waves
- Amplitude and Phase Variations

Errors Are a Function of [1]:

- Carrier Frequency
- Solar Activity
- Magnetic Latitude
- Seasonal and Time of Day/Night Variations
- Elevation and Azimuth of the Satellite

Ionosphere scintillation is electron density fluctuation within the ionosphere that causes random fluctuation of radio waves in amplitude and phase. Random refraction and diffraction happen in the ionosphere because of the electron density fluctuation. It is most common in

equatorial and polar regions. GPS, GLONASS and GALILEO are susceptible to the effects of such scintillation. Figure 1-1 which is taken from [1] shows the possible effects of ionosphere on wireless communication. Ionosphere causes code delay, carrier advance, and Faraday rotation on the radio wave between satellite and earth. Besides that, amplitude and phase variation will also occur when scintillation happens. Ionosphere layer also reflects the radio wave between transmitter and receiver station on earth.

In [1], equatorial scintillation process is also described. After sunset lower layer recombines more quickly which results in an inversion. Lower density regions “bubble up” through the heavier atmosphere. Bubbles create diffraction grating causing amplitude and phase variations. Scintillation lasts from sunset until shortly after midnight. It has strong seasonal dependence with March and September is typically the worst.

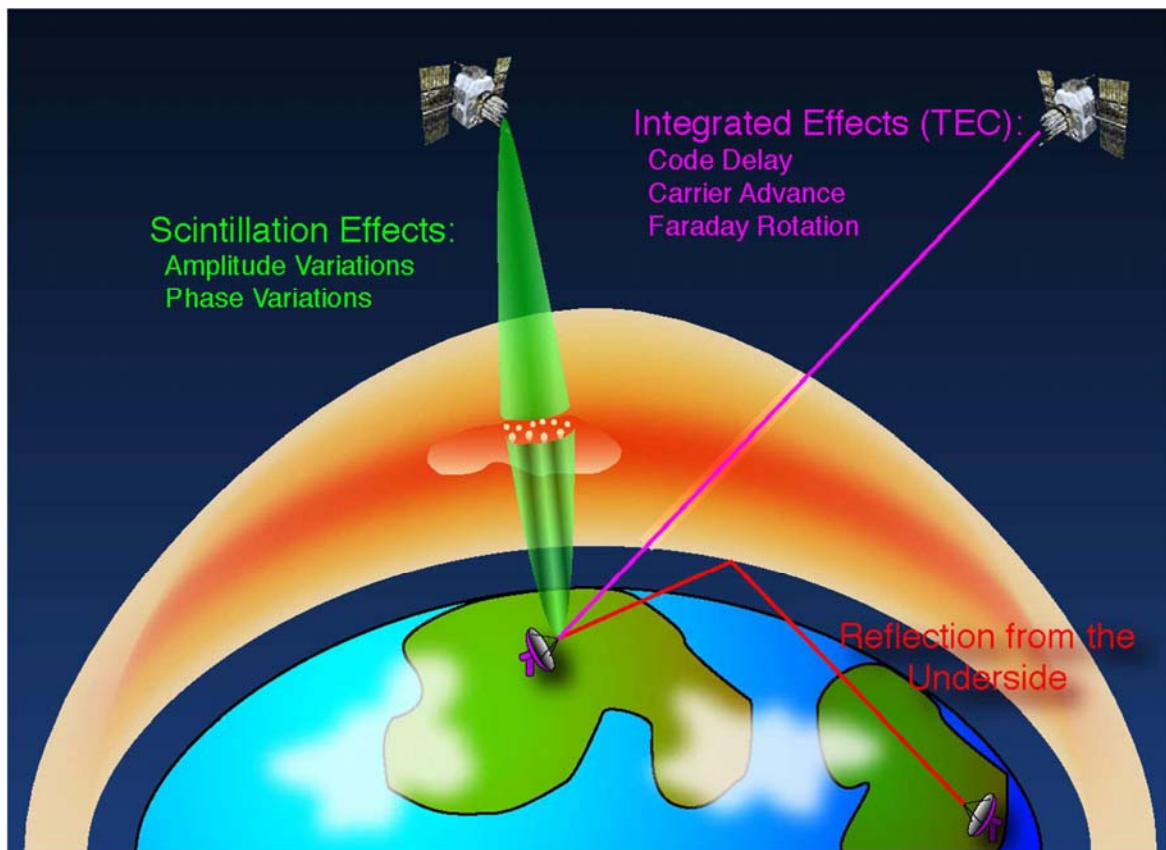


Figure 1-1 Ionosphere Effects on Communication

1.2. Global Navigation Satellite System

A Global Navigation Satellite System (GNSS) involves a constellation of satellites orbiting at about twenty thousand kilometers altitude over the earth surface, continuously transmitting signals that enable users to determine their three-dimensional position with global coverage [2]. GNSS consist of several satellite navigation systems:

- Global Positioning System (GPS)
 - by USA
 - fully operational
 - 32 satellites available
- Global Orbiting Navigation Satellite System or Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) [3]
 - by Russia
 - fully operational
 - 24 satellites available
- Galileo
 - by European Union
 - not fully operational
 - currently only 2 satellites available
 - 30 satellites are expected to be operational in 2019
- Compass or Beidou [4]
 - by China
 - not fully operational
 - only 12 satellites are available on 2012
 - 35 satellites are expected to be operational in 2020
- Satellite-based augmentation system (SBAS)
 - system that supports wide-area or regional augmentation through the use of additional satellite-broadcast messages

1.3. Equatorial Ionization Anomaly (EIA)

Figure 1-2 shows electric and magnetic fields around equatorial region at day. Eastward electric field is coupled with geomagnetic field to produce $\mathbf{E} \times \mathbf{B}$ upward force. Under the upward force the F region plasma is lifted up to higher altitudes. From the higher altitudes/topside F region the plasma flows out, by diffusion under pressure gradient and by gravity force, to off-equatorial latitudes leading to accumulation of large densities (ionization crests) at latitudes around $15^\circ - 18^\circ$ on either sides of the dip equator where an ionization trough is created. The resulting latitudinal structure in the ionization distribution, characterized by the two low latitude ionization maximum density with a minimum centered at the dip equator is known as the equatorial ionization anomaly (EIA) [5], [6].

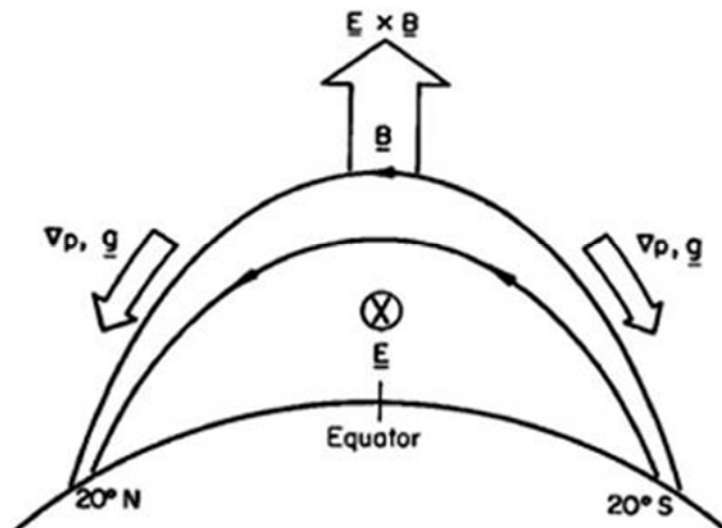


Figure 1-2 Electric Field and Magnetic Field of Earth at Equator

Singapore is located in equatorial region. Therefore, the ionosphere over Singapore is under influence of EIA. Figure 1-3 shows the IRI-2012 latitudinal total electron content (TEC) model over Singapore taken in April 2013. It shows the TEC trough in the magnetic equator and two crests in the north and south of equator. Our receiver's latitude coverage is shown by the light blue shaded area, which includes the trough and crest of EIA. This latitude coverage calculation will be shown later.

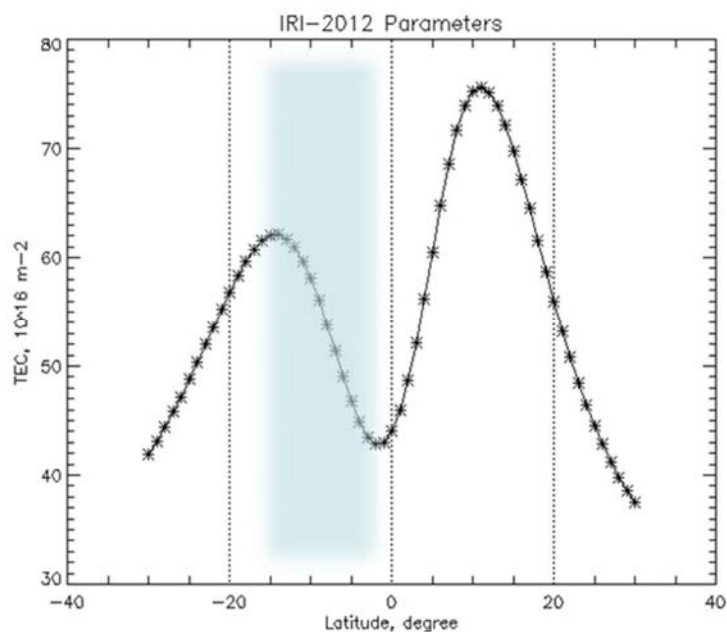


Figure 1-3 IRI-2012 TEC Model on April 2013 in Singapore

1.4. GNSS Receivers Setup and Location

Currently three receivers are logging data in three locations: S2, S2.1, and Nanyang House as shown in Figure 1-4. Our first receiver and US collaborator's receiver are located nearby in south spine academic complex. Our second receiver is located in Nanyang House which is around 1 km apart from the first receiver. The logging status of these receivers is shown in Table 1-1.

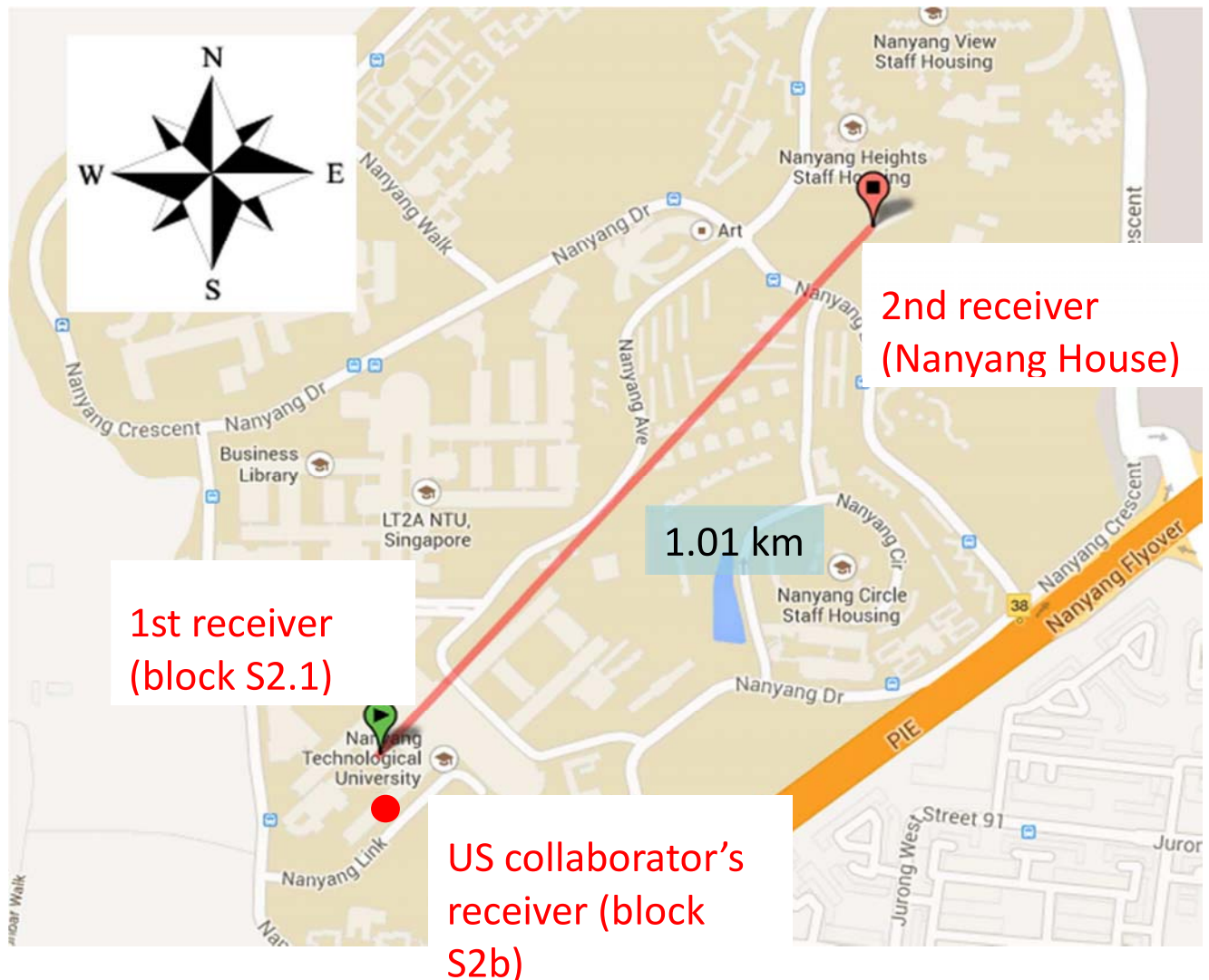


Figure 1-4 GNSS Receivers Location in NTU

Table 1-1 Data Logged by Three Receivers in NTU

S2	S2.1	Nanyang House
Logging GPS, Glonass, Galileo since 21 st of March 2012 and Beidou since 26 th of January 2013	Logging GPS, Glonass, Galileo, Beidou since 13 th of July 2013	Logging GPS, Glonass, Galileo, Beidou since 28 th of November 2013
Beidou satellites' position unavailable	Beidou satellites' position available since 22 nd of January 2014	Beidou satellites' position available since 22 nd of January 2014

Figure 1-5 and Figure 1-6 show the receiver system located on the rooftop of block S2. It is designed to be operated remotely. The detailed configuration of the receiver is shown in Figure 1-7. High capacity hard disks are attached to the PC to save the continuously recorded data. The system is connected to internet to control it remotely. Whenever power failure happens, the emergency power supply and remote power control can maintain the operability of the system. Figure 1-8 and Figure 1-9 show the receiver and antenna at block S2.1. Figure 1-10 and Figure 1-11 show the receiver and antenna at Nanyang House. An uninterrupted power supply (UPS) is also installed at Nanyang house as well as a magnetometer for local geomagnetic monitoring



Figure 1-5 Receiver System at S2



Figure 1-6 Multi Frequency GNSS Antenna at S2

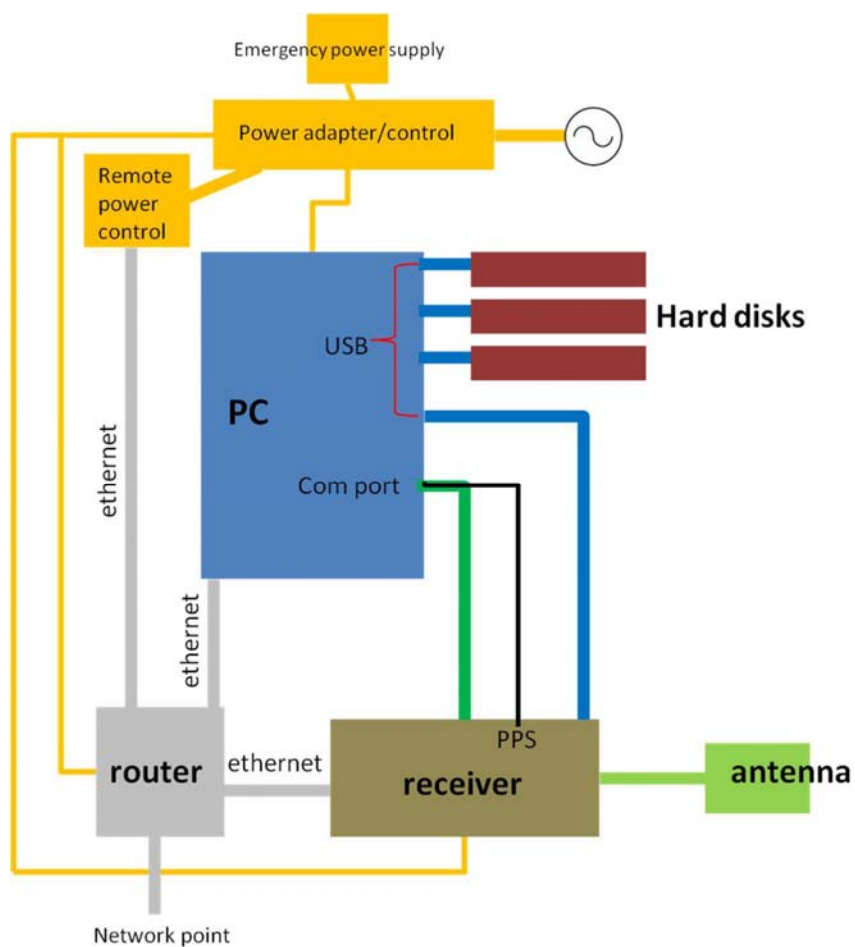


Figure 1-7 Receiver Configuration at S2



Figure 1-8 Receiver System at S2.1



Figure 1-9: Multi Frequency GNSS Antenna at S2.1



Figure 1-10 Receiver System at Nanyang House, which includes uninterrupted power supply and magnetometer.



Figure 1-11: Multi Frequency GNSS Antenna at Nanyang House

1.5. Ionospheric Scintillation Monitoring Receiver Coverage

GNSS covers a wide area of ionosphere over Singapore. Our receiver in NTU is located at 1.34°N 103.68°E in geographic coordinate. The magnetic coordinate is 8.46°S 176.10°E , which is obtained by a conversion tool provided in [7].

Collected data from GNSS are limited to a minimum elevation angle of 20° to minimize the multi path effects. To get the covered ionosphere region above Singapore the following procedure [8] is used.

Figure 1-12 shows the thin ionosphere model above earth. The green and blue dots are the receiver and satellite, respectively. This thin ionosphere model is used to obtain the coverage of the receiver.

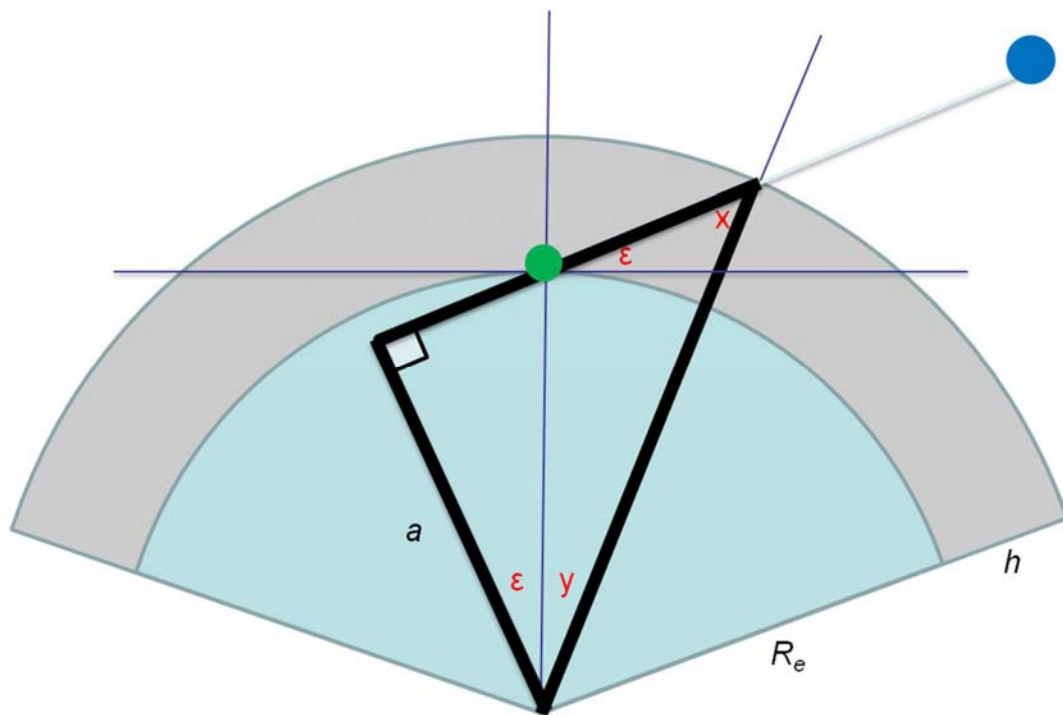


Figure 1-12 Thin Ionosphere Layer Model

The angle x can be obtained by

$$\sin(x) = \frac{a}{R_e + h} = \frac{R_e \cos \varepsilon}{R_e + h} \quad (1-1)$$

$$\cos(x) = \left(1 - \left(\frac{R_e \cos \varepsilon}{R_e + h}\right)^2\right)^{0.5} \quad (1-2)$$

where x , ε , and y are the angles shown in Figure 1-12. R_e is the earth radius which is 6371 km, h is the ionospheric height estimation at 400 km and $\varepsilon=20^\circ$ is the minimum elevation angle used. By using (1-1) or (1-2), the latitude different between receiver position and its maximum ionosphere coverage, y is calculated and obtained to be 7.85° . The receiver's coverage can be estimated by adding y to Singapore's latitude, shown by the shaded circle in Figure 1-13. This area is bounded by latitudes 9.19°N in the north and 6.51°S in the south.

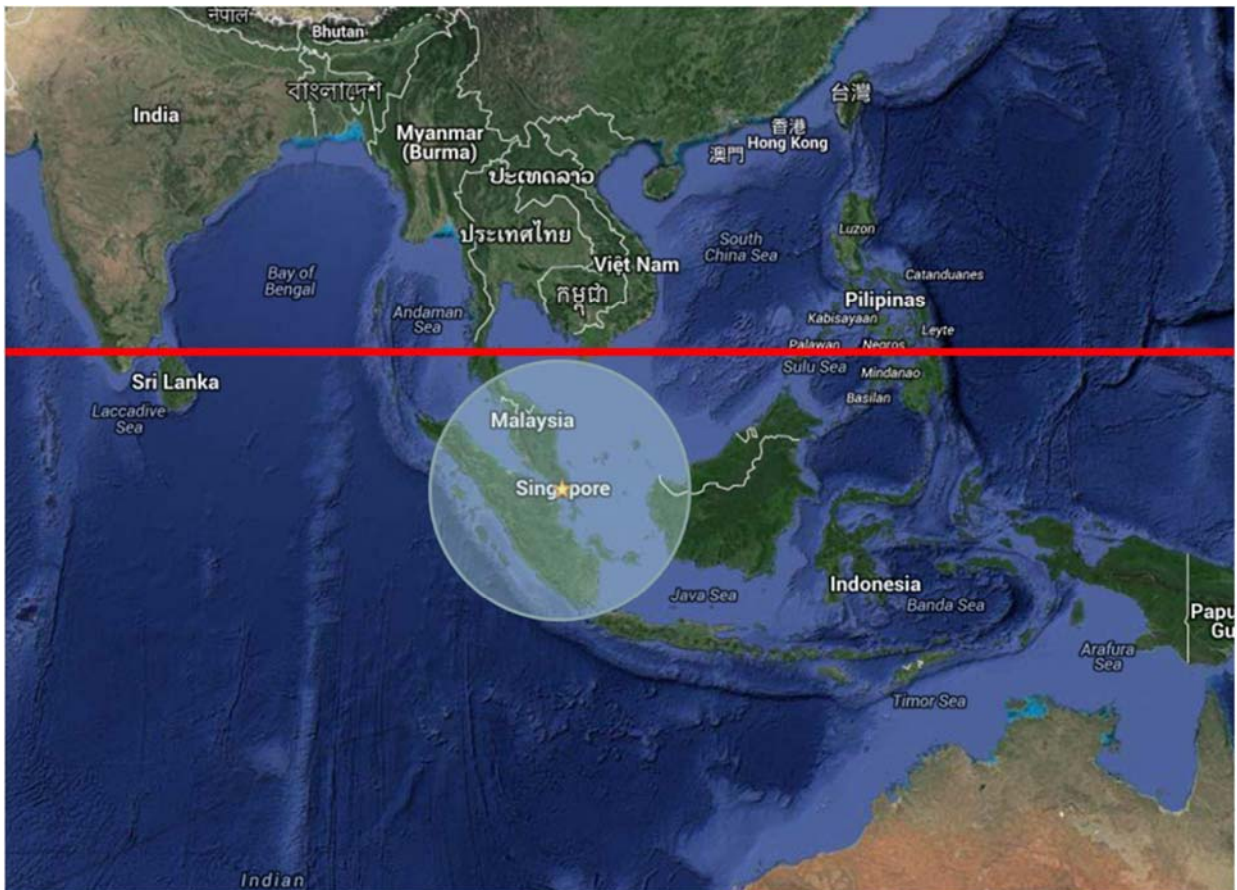


Figure 1-13 Ionosphere Region Covered by Receiver in Singapore

1.6. Ionospheric Scintillation Parameters

Ionospheric scintillation can be monitored using GNSS. GNSS including GPS, GLONASS and in the future Galileo and Compass/Beidou provide wide coverage of ionosphere to be monitored all time.

Septentrio PolaRxS receiver has the ability to obtain ionospheric scintillation parameters and record the output continuously. It covers multi frequency of GPS, GLONASS, SBAS and in the future Galileo and Compass.

Ionospheric scintillation parameters that can be monitored are:

Amplitude scintillation (S4)

Amplitude scintillation is quantified by the $S4$ parameter which is defined as the square-root of the normalized variance of signal intensity over a given interval of time [9]

$$S4 = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2}} \quad (1.3)$$

where SI is the signal intensity or power and $\langle . \rangle$ denotes the expected (or average) value over the interval of interest (60 seconds). $S4$ is a dimensionless and commonly estimated over an interval of 60 seconds.

The $S4$ defined in (1.3) can have significant values simply due to ambient noise. If the carrier-to-noise density ratio (C/N_0) is known, the predicted $S4$ due to ambient noise is

$$S4_{N_0} = \sqrt{\frac{100}{C/N_0} \left[1 + \frac{500}{19C/N_0} \right]} \quad (1.4)$$

After removing the noise, the revised value of $S4$ is

$$S4 = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2} - \frac{100}{C/N_0} \left[1 + \frac{500}{19C/N_0} \right]} \quad (1.5)$$

Phase Scintillation

Phase scintillation monitoring is traditionally accomplished by monitoring the standard deviation of detrended carrier phase from signals received from satellites given by

$$\sigma_{\phi} = \sqrt{\langle d\phi^2 \rangle - \langle d\phi \rangle^2} \quad (1.6)$$

where $d\phi$ is the detrended carrier phase and $\langle . \rangle$ denotes the expected (or average) value over the interval of interest. σ_{ϕ} calculated with 60 second interval is name phi60.

The purpose detrending is to separate scintillation from noise, multi-path and other impacts. The method used for detrending is passing the carrier phase through a high-pass filter, which removes all low frequency effects below its frequency cut-off. This method has been used in the past by ionospheric scintillation researchers [9]. The detrending method done by [10] includes a fourth order polynomial fitting and a sixth-order Butterworth filter to remove the satellite-receiver dynamics and other slowly changing errors. A sixth-order Butterworth high pass filter with 0.1-Hz cut off frequency has been used for detrending of the 50-Hz phase outputs, while a fifteenth-order Butterworth filter with 0.1-Hz cut off frequency has been used for 1,000-Hz phase outputs. Differencing between two signals from different band (such as L1 and L2) of the same satellite can also remove satellite-receiver dynamics and oscillator effects, if the same front end is used to collect and process both signals.

GLONASS satellite signals carrier phase measurements are much noisier than those of GPS satellite signals. These fluctuations make the GLONASS signals less suitable for ionosphere scintillation studies because it will be difficult to separate true scintillation events from these non-scintillation effects [10].

Scintillation Intensity Index (SII)

SII is defined as:

$$SII = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} \quad (1.7)$$

Where P_{max} is the power of the 3rd peak down from the maximum excursion shown during a scintillation occurrence, and P_{min} is the power of the 3rd peak up from the minimum excursion. These values can be readily and rapidly scaled from a calibrated chart. The SII is

expressed in decibels (dB). An SII value of 15dB corresponds to an S4 of about 0.6 [11]. Other important scintillation parameters are also given as [12]:

Code-Phase Divergence: The standard deviation of the code/carrier divergence can be used as a measure of multipath presence.

Slant TEC (sTEC): total electron content along the raypath between satellite and receiver

Vertical TEC (vTEC): the vertical component of TEC at the ionosphere piercing point

dTEC per minute is the change of TEC in 1 minute

ROT = dTEC/dt is the rate of change of the total electron content (TEC), in units of TEC/min

Reference [13] defines rate of TEC index (ROTI) based on the standard deviation of ROT as shown below

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \quad (1.8)$$

ROTI measurements can be used to predict the presence of scintillation causing irregularities. The quantitative relationship between ROTI and S4, however, varies considerably due to variations of the ionospheric projection of the satellite velocity and the ionospheric irregularity drift [14].

2. Review of Ionospheric Scintillation Models

2.1. Fremouw and Rino Model

The Fremouw and Rino model [15] is an empirical model that estimates the root mean square (rms) fluctuations of phase and amplitude of a trans-ionospheric VHF/UHF communication link under average scintillation conditions. The independent variables of the model are geomagnetic latitude, time of day, day of the year and sunspot number. The model consists of two parts. The first part describes the rms fluctuations of electron density, ΔN :

$$\Delta N = \Delta N_{eq}(R, D, t, \lambda_L) + \Delta N_{mid}(t, \lambda_L) + \Delta N_{hi}(R, t, \lambda_L) + \Delta N_{aur}(R, t, \lambda_L) \quad (2-1)$$

where

ΔN_{eq} are the contributions from equatorial region

ΔN_{mid} are the contributions from mid latitude region

ΔN_{hi} are the contributions from high latitude region

ΔN_{aur} are the contributions from auroral latitude region

Each contribution from different regions is given as follows:

$$\begin{aligned} \Delta N_{eq} = & (5.5 \times 10^9)(1 + 0.05R) \cdot \left[1 - 0.4 \cos \pi \left(\frac{D + 10}{91.25} \right) \right] \\ & \cdot \left\{ \exp \left[- \left(\frac{t}{4} \right)^2 \right] + \exp \left[- \left(\frac{t + 23.5}{3.5} \right)^2 \right] \right\} \\ & \cdot \left\{ \exp \left[- \left(\frac{\lambda_L}{12} \right)^2 \right] \right\} \text{el/m}^3 \end{aligned} \quad (2-2)$$

$$\Delta N_{mid} = (6.0 \times 10^8) \left(1 + 0.4 \cos \frac{\pi t}{12} \right) \cdot \left\{ \exp \left[- \left(\frac{\lambda_L - 32.5}{10} \right)^2 \right] \right\} \text{el/m}^3 \quad (2-3)$$

$$\Delta N_{hi} = (2.7 \times 10^9) \left\{ 1 + \text{erf} \left[\frac{\lambda_L - \lambda_b(R, t)}{0.02 \lambda_b(R, t)} \right] \right\} \text{el/m}^3 \quad (2-4)$$

$$\Delta N_{aur} = (5.0 \times 10^7) R \cdot \left\{ \exp \left[- \left(\frac{\lambda_L - 70 + 2 \cos \frac{\pi t}{12}}{0.03 R} \right)^2 \right] \right\} \text{el/m}^3 \quad (2-5)$$

where

$$\lambda_b = 79 - 0.13R - (5 + 0.04R) \cdot \cos(\pi t/12) \text{ deg} \quad (2-6)$$

In above, R is the sunspot number, D is the day of the year, t is the local time of the day in hours and λ_L is the geomagnetic latitude in degrees. Based on the contribution of fluctuation in electron density, the second part of the model gives the rms of fluctuations in phase and amplitude as:

$$\phi_0 = \pi^{1/4} r_e \lambda [(a \xi_0 \sec i)^{1/2} / \beta^{1/2}] \Delta h^{1/2} \Delta N \quad (2-7)$$

$$S_4 = 2^{1/2} \phi_0 \left[1 - (\cos u_1 \cos u_2)^{\frac{1}{2}} \cos\left(\frac{u_1 + u_2}{2}\right) \right]^{1/2} \quad (2-8)$$

where

$$\beta = (a^2 \sin^2 \psi + \cos^2 \psi)^{1/2} \quad (2-9)$$

$$u_1 = \tan^{-1}(2\lambda z / \pi \xi_0^2) \quad (2-10)$$

$$u_2 = \tan^{-1}(2\lambda z / \pi \beta^2 \xi_0^2) \quad (2-11)$$

$$z = z_1 z_2 / (z_1 + z_2) \quad (2-12)$$

In the above, r_e is electron radius, λ is wavelength, ξ_0 is transverse irregularity scale size, i is incident angle, Δh is irregularity layer thickness, a is irregularity axial ratio, ψ is angle between geomagnetic field line and propagation LOS, z_1 is distance from receiver from irregularity layer, and z_2 is distance from transmitter to irregularity layer. The two parameters in (2-7)and (2-8) are based on the formulations given in [16].

Variables i , z_1 and z_2 are related to the zenith angle θ through [16]

$$i = \sin^{-1}\{R_0 \sin \theta / (R + h)\} \quad (2-13)$$

$$z_1 = (R_0^2 \cos^2 \theta + 2R_0 h + h^2)^{1/2} - R_0 \cos \theta \quad (2-14)$$

$$z_2 = (R_0^2 \cos^2 \theta + 2R_0 H + H^2)^{1/2} - (R_0^2 \cos^2 \theta + 2R_0 h + h^2)^{1/2} \quad (2-15)$$

where R_0 is the earth radius, h is the height of irregularity layer and H is the height of the satellite.

2.2. Aarons Model

The Aarons model [17] utilizes the 15 minutes peak to peak scintillation index taken over 5 years to develop an empirical formula. The scintillation index is defined as

$$SI = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} \quad (2-16)$$

where P_{max} is the power of the 3rd peak down from the maximum excursion shown during a scintillation occurrence, and P_{min} is the power of the 3rd peak up from the minimum excursion, all in dB. The empirical formula developed has the expressions as follows:

$$SI \text{ (dB)} = 2^{q+r} \quad (2-17)$$

where

$$q = FA + FB + (-1.5FA + 0.8FB) \cdot \cos \left[\left(\frac{\pi}{12} \right) (H - 0.2 - 0.25K_p) \right] \quad (2-18)$$

$$r = FC \left\{ \cos \left[\left(\frac{\pi}{6} \right) (H + 3.3) \right] - 0.4 \cos \left[\left(\frac{\pi}{4} \right) (H + 1.5) \right] \right\} \quad (2-19)$$

$$FA = (-2.7 - 0.3FD)(S/100) \quad (2-20)$$

$$FB = 0.2 + FD + (0.1 - 0.1FD)K_p \quad (2-21)$$

$$FC = (1.6 + 0.7FD)(S/100) + 0.1K_p \quad (2-22)$$

$$FD = \cos \left(\frac{2\pi}{365} \right) (D + 1.3) - 0.6 \cos \left(\frac{4\pi}{365} \right) (D - 4) \quad (2-23)$$

Here, D is the day number, H is the local time in hours, S is the solar number in solar flux units ($1 \text{ sfu} = 10^{-22} \text{ m}^{-2} \text{ Hz}^{-1}$) and K_p is the planetary magnetic index. The empirical formula is based on LES-6 satellite signal observation made at Huancayo, Peru on the magnetic equator at 254 MHz. Therefore, the model applies to equatorial scintillation at VHF frequency.

2.3. Iyer *et. al.* Model

In this model, the scintillation occurrence, SO in percentage, as a functions of local time, latitude, season/day and solar flux value is expressed as a product of univariate normalized cubic B-splines given below [18]:

$$SO(t, d, F, \theta) = \sum_{i=1}^{17} \sum_{j=1}^{12} \sum_{k=1}^3 \sum_{l=1}^2 a_{i,j,k,l} N_{i,4}(t) N_{j,2}(d) N_{k,2}(F) N_{l,2}(\theta) \quad (2-24)$$

where

$N_{i,4}$ is cubic B-spline of order 4 with i knot span (interval)

$N_{j,2}$ is cubic B-spline of order 2 with j knot span

$N_{k,2}$ is cubic B-spline of order 2 with k knot span

$N_{l,2}$ is cubic B-spline of order 2 with l knot span

$a_{i,j,k,l}$ is monthly means of scintillation occurrence percentage for each knot span

Here, t is local time, d is day of the year, F is solar flux value and θ is latitude. The observation data is collected based on amplitude scintillation of 250 MHz signals from geostationary satellite FLEETSAT measured at Indian magnetic equatorial station, Trivandrum and anomaly crest station Rajkot. The scintillation data used during the years 1987 to 1989. The hourly percentage occurrence of scintillation of $S4 > 0.075$ from 1800 to 0600 hours local time is derived and averaged.

2.4. Franke and Liu Model

There are two parts in Franke and Liu model [19]. The first part is on ionospheric irregularities model and the second part is on propagation based on phase screen model. For the first part, a two-component model for two-dimensional ionospheric irregularities is adopted. The spectrum of the model is given by

$$S_{\Delta N}(K) = \frac{C_N}{(K_0^2 + K^2)^{p_1/2} (K_b^2 + K^2)^{(p_2-p_1)/2}} \quad (2-25)$$

where

C_N is normalization constant

$K^2 = K_x^2 + K_z^2$ where K_x and K_z are the horizontal and vertical wave number, respectively

K_0 is outer scale wave number

K_b is break scale wave number

p_1 is low frequency power law index

p_2 is high frequency power law index

The power law indices here are given by $p_1 = 2$ and $p_2 = 4$. For this case, the normalization constant C_N is given as

$$C_N = \frac{\sigma_N^2}{2\pi} \cdot \frac{K_b^2 - K_0^2}{\ln(K_b/K_0)} \quad (2-26)$$

where σ_N^2 is variance of electron density fluctuation.

The spectrum of the phase fluctuation can be derived as

$$S_{\phi}(K_x) = 2\pi\lambda^2 r_e^2 \sigma_N^2 L S_{\Delta N}(K_x, 0) \quad (2-27)$$

where λ is wavelength, r_e is classical electron radius and L is the equivalent slab thickness of the irregularity region.

Substituting (2-25) into (2-27), the spectrum of phase fluctuation is

$$S_{\phi}(K_x) = \frac{C_{\phi}}{(K_0^2 + K^2)(K_b^2 + K^2)} \quad (2-28)$$

where

$$C_{\phi} = \frac{\sigma_{\phi}^2}{\pi} \cdot K_0 K_b (K_b + K_0)$$

$$\sigma_{\phi}^2 = \pi\lambda^2 r_e^2 \sigma_N^2 L \frac{K_b - K_0}{K_b K_0} \cdot \frac{1}{\ln(K_b/K_0)}$$

For weak scintillation ($\sigma_\phi^2 \ll 1$), the S_4 index can be found as follows:

$$\begin{aligned}
S_4 &= 4 \int_{-\infty}^{\infty} S_\phi(K_x) \sin^2 \left(\frac{K_x^2 z}{2k} \right) dK_x \\
&= 2\sigma_\phi^2 \left\{ 1 - \frac{1}{1 - \frac{\alpha}{\beta}} [\cos(2\alpha^2) - \sqrt{2} \cos \left(2\alpha^2 + \frac{\pi}{4} \right) C(\sqrt{2}\alpha) \right. \\
&\quad \left. - \sqrt{2} \sin(2\alpha^2 + \pi/4) S(\sqrt{2}\alpha)] \right. \\
&\quad \left. - \frac{1}{1 - \frac{\beta}{\alpha}} [\cos(2\beta^2) - \sqrt{2} \cos \left(2\beta^2 + \frac{\pi}{4} \right) C(\sqrt{2}\beta) \right. \\
&\quad \left. - \sqrt{2} \sin(2\beta^2 + \pi/4) S(\sqrt{2}\beta)] \right\} \tag{2-29}
\end{aligned}$$

where

$$\alpha = l$$

$$\beta = lK_b$$

$$l = \left(\frac{z}{2k} \right)^{1/2}$$

z is distance from phase screen to receiver plane. $C(x)$ and $S(x)$ are Fresnel integral given as

$$S(x) = (2/\pi)^{1/2} \int_0^x \sin t^2 dt$$

$$C(x) = (2/\pi)^{1/2} \int_0^x \cos t^2 dt$$

2.5. More Advanced and Global Model

2.5.1. Wideband Model (WBMOD)

The WBMOD (WideBand Model) [20], [21] consists of an ionosphere model, which provides the global distribution and synoptic behavior of the electron density irregularities that cause the scintillations, and a propagation model that calculates the effects that these irregularities will have on a given system. The outputs that the model returns are the phase scintillation

spectrum spectral index p , the spectral strength parameter (the spectral power at 1 Hz) T , the intensity scintillation index S_4 , and rms phase, σ_ϕ .

The WBMOD consists of two parts: the electron density irregularities model and the propagation model. The electron density model was developed based on a large collection of scintillation observations taken during the Wideband, HiLat, and Polar Bear experiments and from the USAF Phillips Laboratory equatorial scintillation monitoring network. The most important parameter returned by the model is the height-integrated irregularity strength $C_k L$, i.e., the product of the turbulence strength parameter C_k and the irregularity layer thickness L . The propagation model employed in WBMOD is the phase screen model. The phase spectrum is characterized by the power law with two-dimensional spectral index p and phase spectral power at 1 Hz, T given as

$$p \approx q + 1 \quad (2-30)$$

$$T = N(q) \lambda^2 C_k L \sec \theta G V_e^q \quad (2-31)$$

where q is the one-dimensional spectral index of electron density fluctuations as measured in situ onboard a satellite, G is geometrical enhancement factor and V_e is effective scan speed across contour of plasma density, λ is radio wavelength and N is normalization factor.

The phase variance σ_ϕ^2 is then given as

$$\sigma_\phi^2 = \int_{f_c}^{\infty} P_\phi(f) df = 2 \int_{f_c}^{\infty} \frac{T}{f_0^2 + f^2} df \approx \frac{2T}{q f_c^q} \quad (2-32)$$

where $P_\phi(f)$ is the phase spectrum, $f_0 = V_e/2\pi r_0$ and r_0 is outer scale size, f_c is cut-off at low frequency. The corresponding S_4 index for weak scintillation is found as

$$S_4^2 = \frac{M(q)}{N(q)} T \frac{F z^{q/2}}{G V_e^q} \quad (2-33)$$

where F is the Fresnel filter factor, z is Fresnel zone size and M/N is another normalization factor.

2.5.2. Global Ionospheric Scintillation Model (GISM)

The Global Ionospheric Scintillation Model (GISM) [22] is another global scintillation model that also consists of two parts. The first part gives the electron density calculated by NeQuick model and the second part is based on multiple phase screen technique. The locations of transmitter and receiver are arbitrary. The radio link's angle of incidence is arbitrary with respect to the ionosphere layers and to the magnetic field vector orientation. It can either cross the entire ionosphere or a small part of it. At each screen location along the line of sight, the parabolic equation (PE) is solved for estimating the complex amplitude. The ionospheric electron density at any point inside the medium, required for this calculation, is provided by the NeQuick model. Mean errors are related to the total electron content (TEC) value. The results are presented in the form of maps of scintillation index using geographic coordinates.

3. Singapore Ionospheric Scintillation Analysis

3.1. Monthly Ionospheric Scintillation Average

The monthly S4 average of GPS satellites obtained from receiver at block S2 are computed where the S4 is averaged over all visible GPS satellites in every minute. The visible satellites are only limited to those having elevation angle more than 20 degrees to filter out fluctuation due to multipath effects. Although Singapore has no seasons, the months are categorized into equinox, 'winter', and 'summer' months, following the earth northern hemisphere. The equinox months consist of March, April, September and October, 'winter' months consist of January, February, November and December and lastly, 'summer' months consist of May, June, July and August. These GPS based results and analysis have been presented and published in [1*]. Note that the analysis can also be performed for other GNSS constellation such as Beidou, and they have also been presented and published in [2*].

Figure 3-1 shows the monthly S4 average of visible GPS satellites during the equinox months of March, April, September and October 2013. The y and x axes for each subplot represent the day (1st to 30th or 31st) and local time (8 a.m. to 8 a.m. next day) in each month. It can be observed that in equinox months, relatively high S4 average of larger than 0.2 is present in reasonably high number of days. This indicates high number of scintillation events during these months, which may be attributed to the close alignment of the solar terminator with magnetic meridian [23]. This result agrees with previous study done in India which was conducted in low latitude zone [24].

Diurnally, these scintillation events occur mostly around local time of 8 p.m. to 12 a.m, which is during the post sunset period. This is attributed to the eastward prereversal enhancement (PRE) electric field. PRE is the enhancement of the eastward electric field that happen right after sunset due to atmosphere activity [25]. The enhanced eastward electric field is coupled with the earth's geomagnetic field to produce stronger upward vertical force derived from $\mathbf{E} \times \mathbf{B}$. The upward vertical force results in steep gradient of ion and electron densities between upper and lower layer, thereby producing plasma bubble irregularities arising from Rayleigh-Taylor instability process.

Figure 3-2 plots the monthly S4 average of visible GPS satellites during the 'winter' months of January, February, November and December 2013. The S4 average is relatively low in these months, indicating fewer scintillation events. Nevertheless, there exist certain days in

which some day time scintillation events can be observed, occurring mostly before 6 p.m. Figure 3-3 plots the monthly S4 average of visible GPS satellites during the ‘summer’ months of May, June, July and August 2013. These months are also relatively quiet with fewer scintillation events. Overall, the observations here are quite consistent with the observations derived from nearby countries around equatorial region such as Malaysia [26] and Indonesia [27].

Figure 3-4 and Figure 3-5 show the same plot for ϕ_{60} and ROTI respectively during equinox months of year 2013. They show the same pattern as the S4 which has high magnitude at night after sunset. This suggests that in Singapore S4, ϕ_{60} , and ROTI generally happen concurrently, which differs with some observations done in high latitude region. In high latitude near polar region, phase fluctuation is more likely to occur compared to amplitude scintillation [28], [29]. This is caused by improper phase detrending process that was used on those high latitude ionospheric scintillation observations [30]. At high latitude, typical values of ionospheric irregularity drift are higher compared to those in equatorial region, especially during geomagnetic storm. This causes higher Fresnel frequency which requires higher detrending cut off frequency. Neglecting this factor will lead to overestimated phase scintillation which sometimes observed as phase scintillation without amplitude scintillation [30].

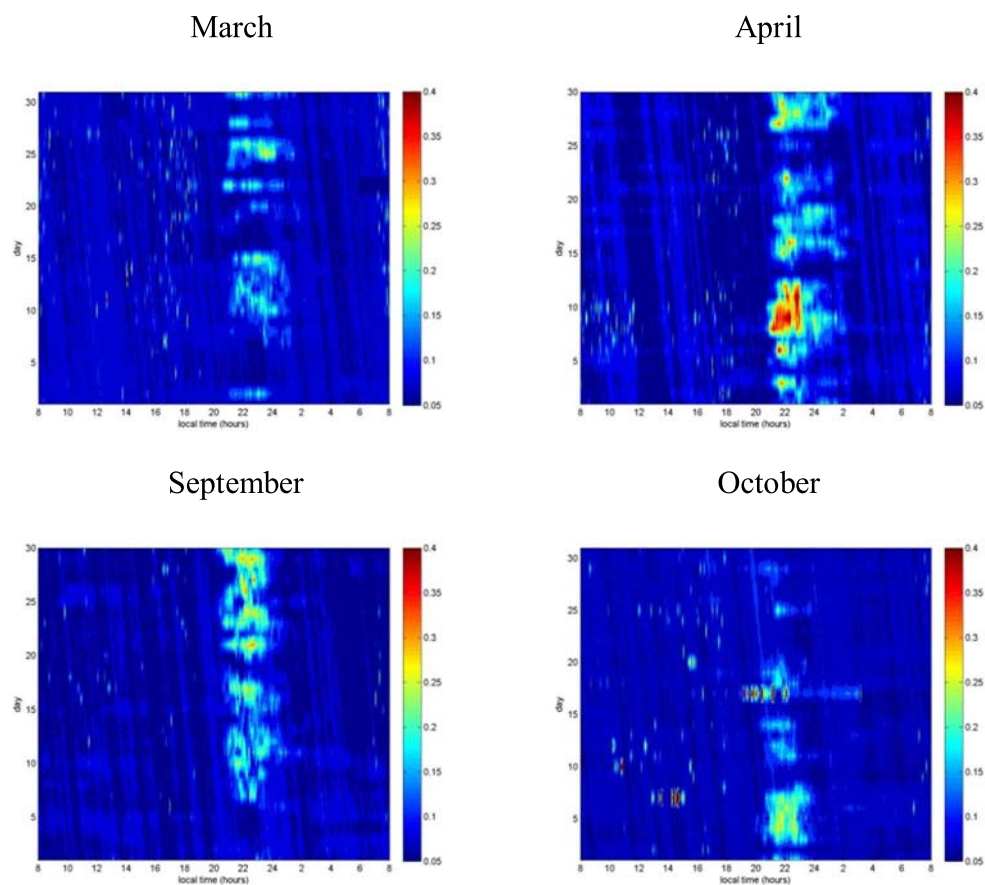


Figure 3-1 Monthly S4 average during equinox months of year 2013

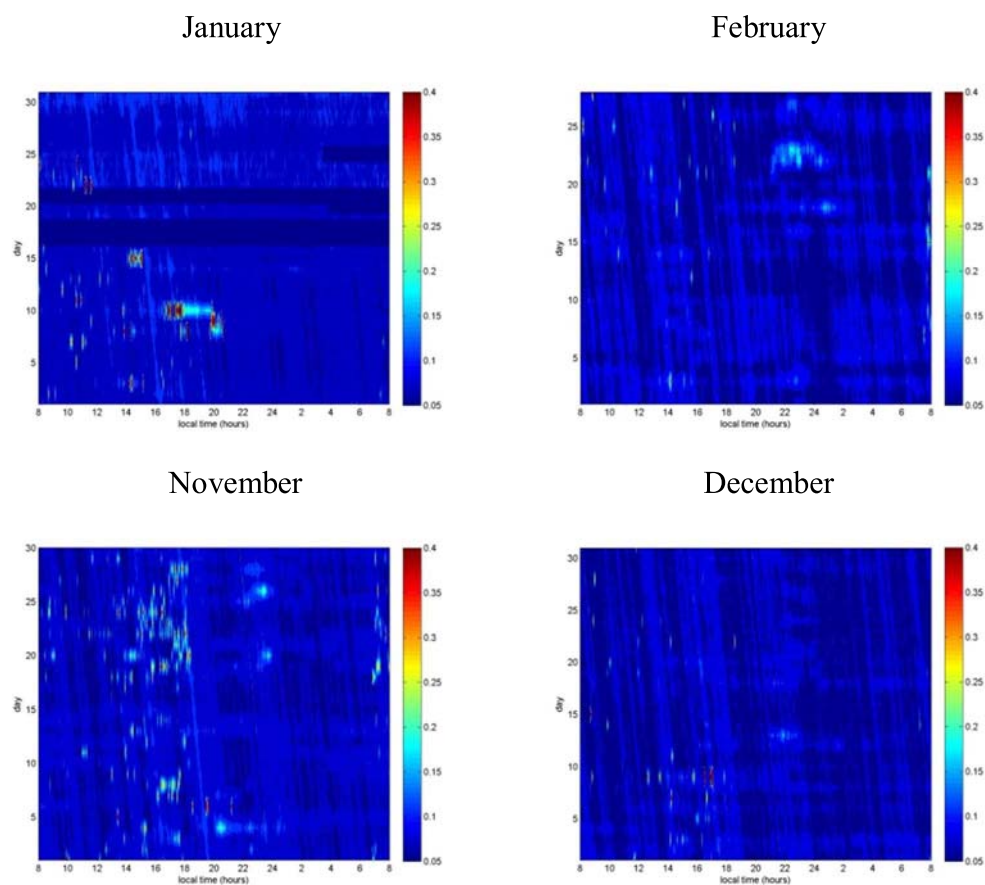


Figure 3-2 Monthly S4 average during winter months of year 2013

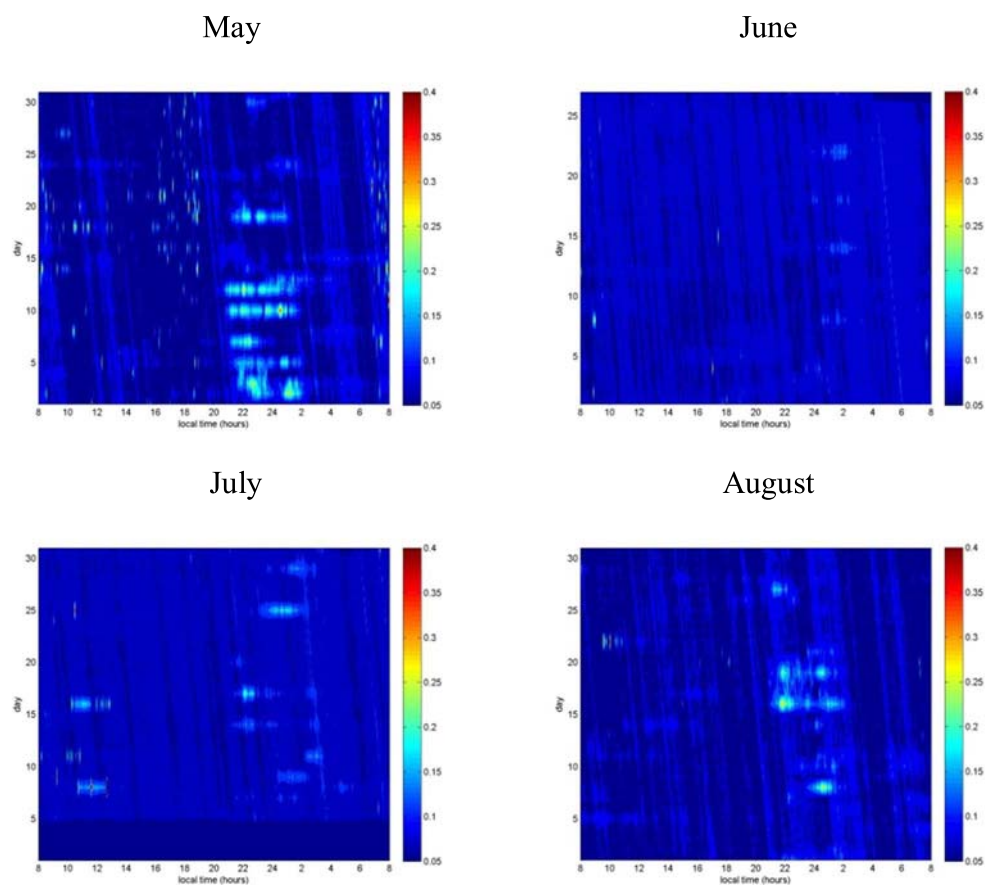


Figure 3-3 Monthly S4 average during summer months of year 2013

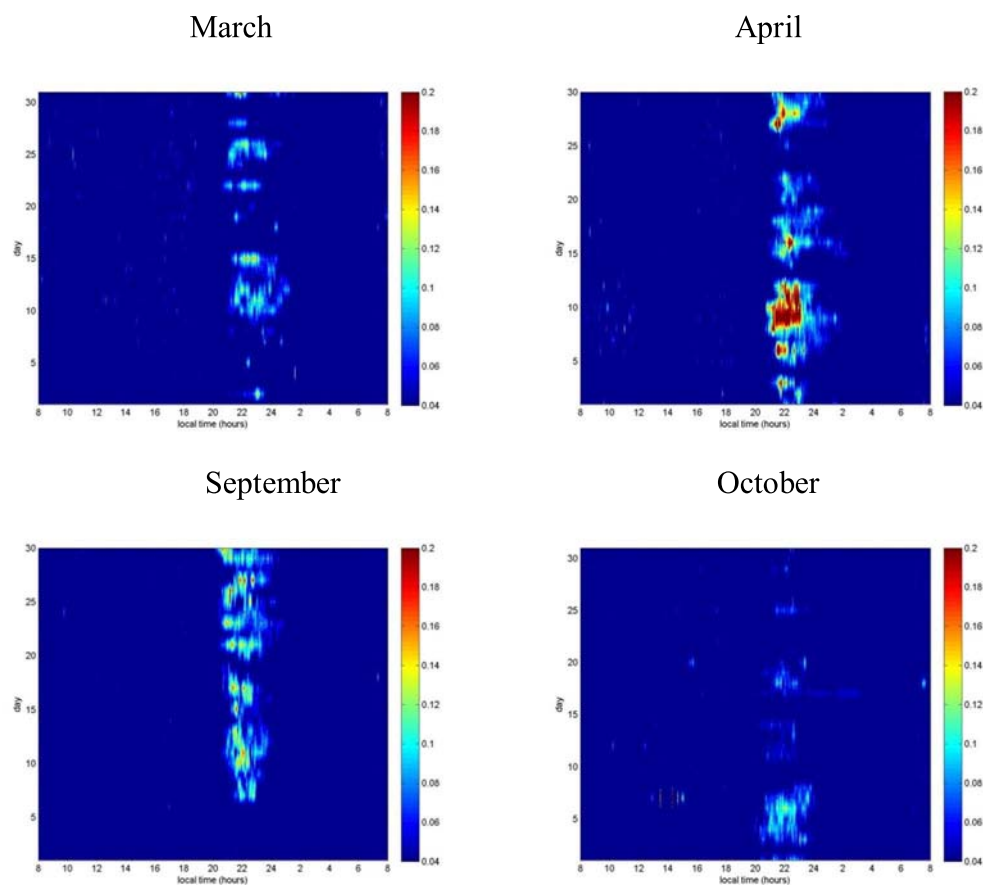


Figure 3-4 Monthly Phi60 average during equinox months of year 2013

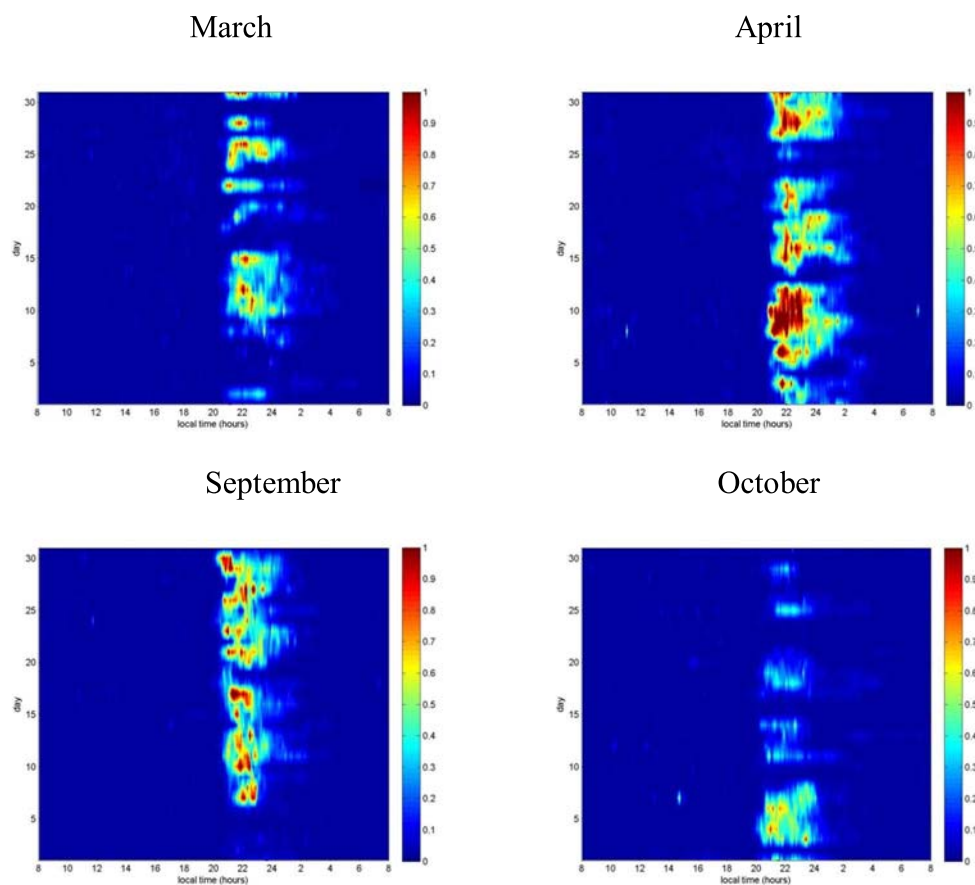


Figure 3-5 Monthly ROTI average during equinox months of year 2013

3.2. Selected Ionospheric Scintillation Events

For closer analysis, selected GPS scintillation events during the equinox months in year 2013 are done. The events of S4 values larger than 0.2 with considerably long duration are first identified. It is then plotted along with other scintillation parameters such as phi60 and ROTI for the same duration and PRN. Also plotted are the vTEC, C/N₀ of the signal, satellite elevation angle, and the rate of change of TEC (ROT). Figure 3-6 and Figure 3-7 show the plots of various scintillation parameters, on 31 March 2013 of satellite PRN 23 and 9 April 2013 of satellite PRN 20. It can be seen that high S4 is generally accompanied by high phi60, indicating that amplitude and phase scintillations usually occur concurrently. Besides that, we also observe fluctuations in the ROT and high ROTI during this period, which shows the presence of plasma bubble irregularities in the ionospheric layer. Evidently, both signal intensity and the carrier phase of the GPS signal exhibit fluctuations during this period, which signifies propagation through the plasma bubble irregularities of the ionosphere layer.

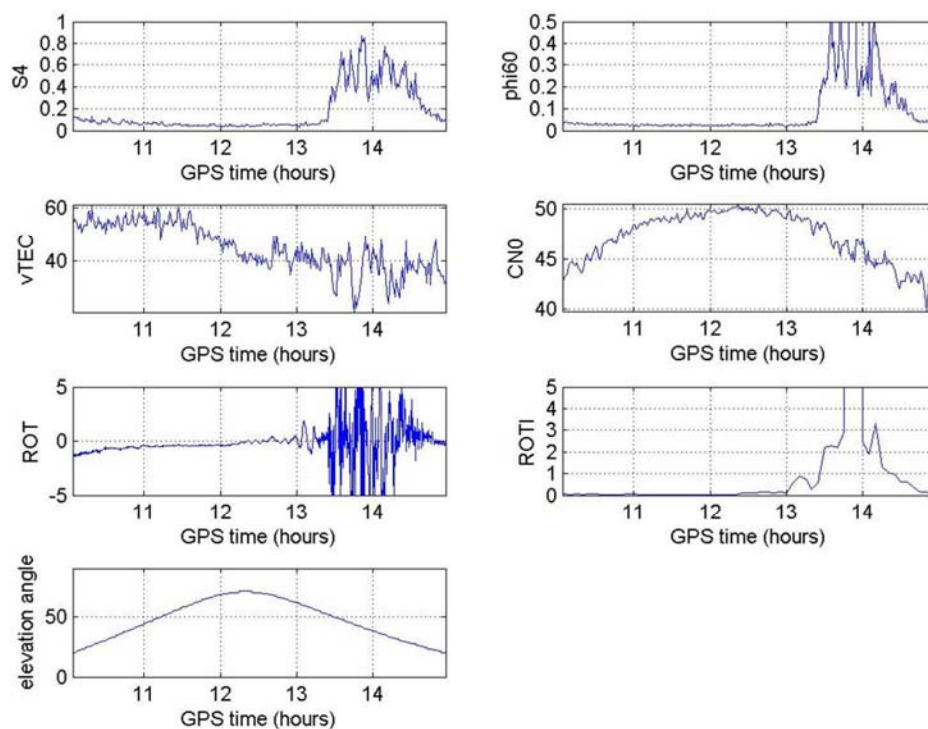


Figure 3-6 Scintillation parameters on 31 March 2013 of PRN 23

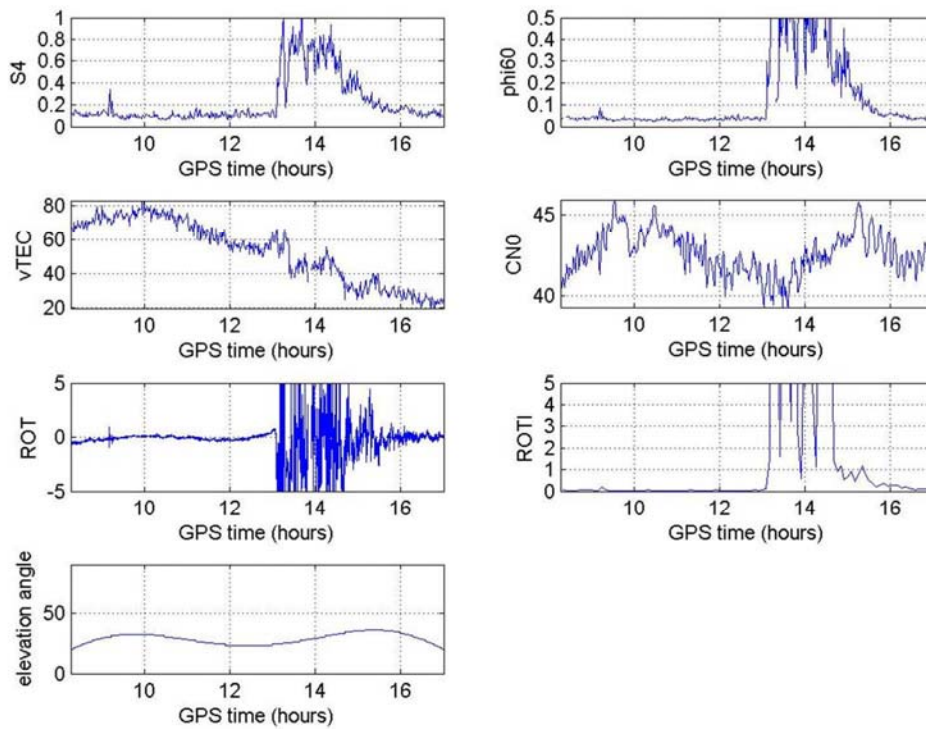


Figure 3-7 Scintillation parameters on 9 April 2013 of PRN 20

3.3. Number of Occurrence of GPS Scintillation Events

In this section we identify the number of occurrence of scintillation events throughout years 2012 and 2013 based on GPS scintillation parameters S4, phi60, and ROTI separately. An amplitude scintillation event is identified if S4 value is higher than 0.2 for at least 10 minutes. Separately for phi60, a phase scintillation event is identified if its value is larger than 0.1 for at least 10 minutes. Lastly, scintillation is identified if ROTI is larger than 0.5 as used in [31] for the same amount of time. Ten minutes minimum length is used to exclude false observation or insignificant scintillation from our analysis. Recorded data with satellite's elevation angle less than 20 degree are also excluded to minimize false scintillation event caused by multi path effect.

32 GPS satellites are used here. Data available from the receiver in S2 is starting from March 21st 2012 until end of 2013. If the scintillation parameters of any of the 32 GPS satellites meet the aforementioned conditions, it is counted as one scintillation event. Note that the counting will be performed for each S4, phi60, and ROTI separately.

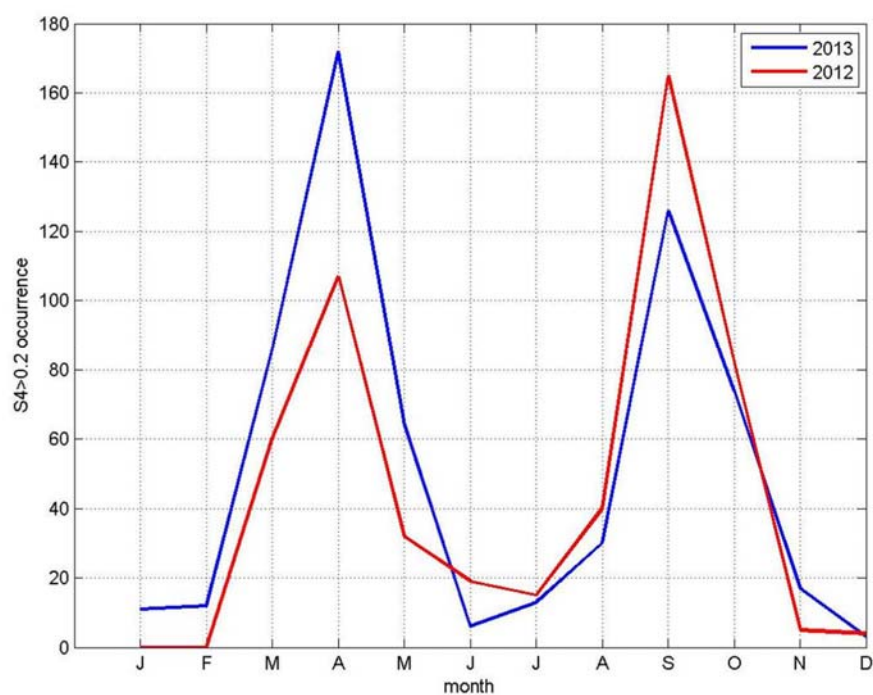


Figure 3-8 Monthly occurrence of $S_4 > 0.2$

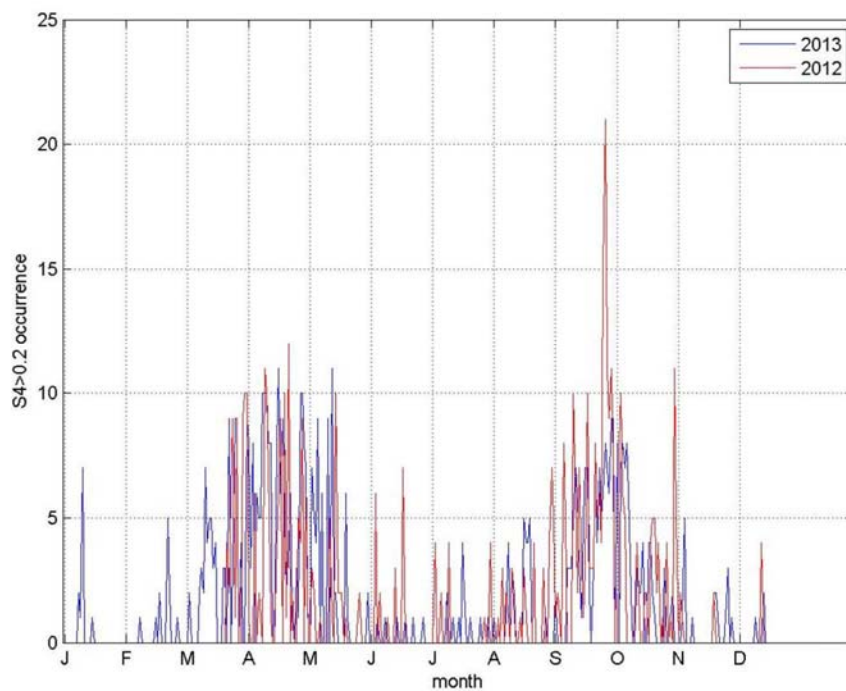


Figure 3-9 Daily occurrence of $S_4 > 0.2$

Figure 3-8 shows the monthly occurrence of amplitude scintillations identified by S4 larger than 0.2 throughout years 2012 and 2013. It can be seen that for both years, the months April and September exhibit the highest number of occurrence of amplitude scintillations. On the other hand, Figure 3-9 shows the daily occurrence of S4 larger than 0.2 for the same period. Similarly, we also observe high occurrence of amplitude scintillations congregating around the months of April/May and September/October.

Table 3-1 S4>0.2 occurrence in 2012

2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	total
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	6	9	1	9	0	0	9	10	10	60
April	1	0	0	6	0	2	1	0	11	10	7	1	0	0	4	6	9	0	10	1	12	0	2	0	0	5	4	9	0	6	0	107
May	0	3	2	0	0	1	0	0	0	0	5	1	0	10	2	2	2	0	1	0	0	0	0	0	1	2	0	0	0	0	0	32
June	0	0	6	0	2	0	0	0	1	0	0	0	3	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19
July	0	4	0	0	2	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	15
August	0	0	1	0	3	0	2	1	0	3	2	0	0	1	0	3	1	0	0	0	4	0	0	0	0	3	0	0	4	7	5	40
September	1	2	1	0	8	5	0	0	0	10	6	2	7	3	1	3	10	3	3	3	8	5	6	4	15	21	11	9	11	7	0	165
October	0	8	10	6	5	0	0	0	0	1	4	2	0	0	2	2	0	4	5	5	2	4	0	1	0	4	0	1	0	11	5	82
November	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	5
December	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4

Table 3-2 S4>0.2 occurrence in 2013

2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	total
January	0	0	0	0	0	0	0	2	1	7	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
February	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	2	0	0	0	5	2	0	0	0	1	0	0	0	0	12
March	0	2	0	0	0	0	2	3	2	7	4	5	5	3	4	0	0	0	3	3	0	9	0	3	9	9	0	4	0	0	9	86
April	8	3	8	0	6	5	5	10	10	10	8	8	0	0	8	11	6	9	5	2	4	6	1	0	3	1	10	10	8	7	0	172
May	0	7	5	4	9	0	6	0	0	9	0	11	2	2	0	0	0	0	6	1	0	0	0	0	0	0	0	0	0	2	0	64
June	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	6
July	0	0	0	0	0	0	0	2	0	0	1	0	0	1	0	4	2	0	0	1	0	0	0	0	1	0	0	0	1	0	0	13
August	1	0	0	0	0	0	1	4	0	3	1	0	0	1	0	5	4	4	5	0	0	0	0	0	0	0	0	1	0	0	0	30
September	2	0	0	0	0	0	3	3	3	5	7	6	3	1	5	7	7	2	0	3	8	4	7	5	6	8	7	6	9	9	0	126
October	8	0	7	8	7	8	6	2	0	0	3	2	2	4	0	0	4	4	2	1	0	0	0	0	3	0	0	1	2	0	0	74
November	0	0	1	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	2	1	0	0	0	1	3	0	1	0	0	0	17
December	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3

Table 3-1 and Table 3-2 show a more detailed number of occurrences of S4 larger than 0.2 for years 2012 and 2013, respectively. For both years, highest occurrences of amplitude scintillations are observed in months April and September.

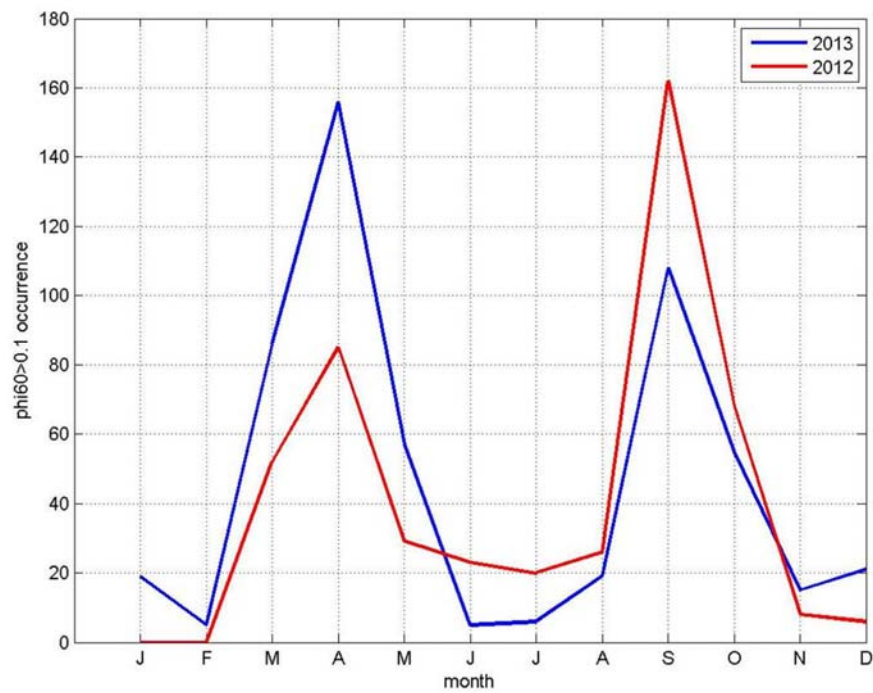


Figure 3-10 Monthly occurrence of Phi60>0.1

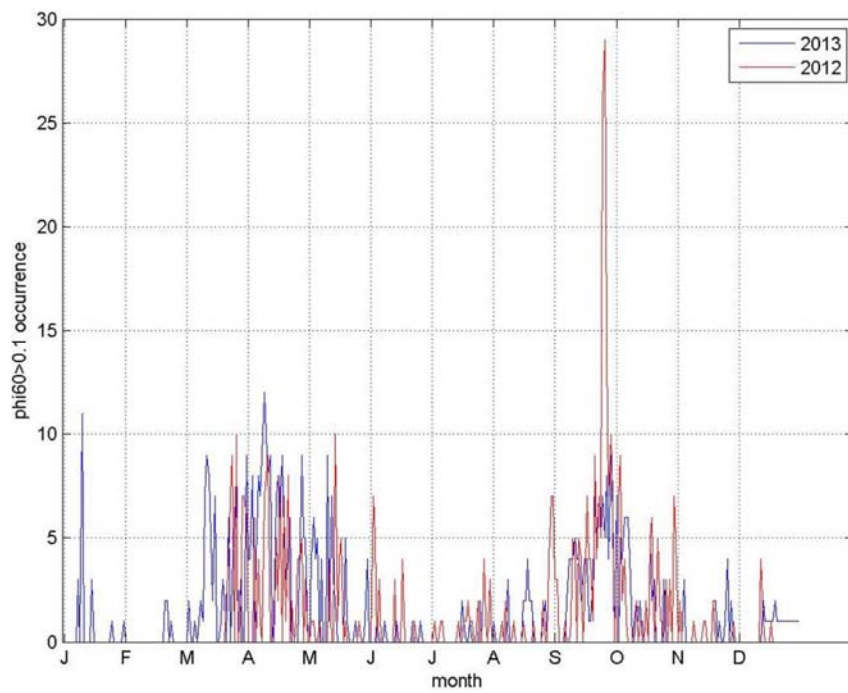


Figure 3-11 Daily occurrence of Phi60>0.1

Figure 3-10 and Figure 3-11 now show the monthly and daily occurrence of ϕ_{60} larger than 0.1 for years 2012 and 2013. Similar to amplitude scintillation, the months of April and September of both years also exhibit the highest occurrences of phase scintillations.

Table 3-3 $\phi_{60}>0.1$ occurrence in 2012

2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	total
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	7	9	0	10	0	0	7	7	6	52
April	0	0	0	6	0	4	1	0	7	8	9	0	0	0	5	2	8	0	7	1	8	0	2	0	1	4	4	5	0	3	0	85
May	0	1	1	0	0	1	0	0	0	0	4	0	0	10	1	4	5	0	1	0	0	0	0	0	0	1	0	0	0	0	0	29
June	0	7	5	0	3	0	0	0	0	0	0	0	3	0	0	0	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	23
July	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	2	1	1	0	0	2	0	0	4	1	0	3	0	20
August	0	0	0	0	1	0	2	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	2	0	0	4	7	7	26
September	3	3	0	0	0	1	0	0	1	5	4	0	5	4	0	2	7	4	4	1	9	4	7	5	26	29	14	7	10	7	0	162
October	0	7	9	2	4	1	0	0	0	1	2	0	1	1	0	2	0	5	6	0	2	5	1	1	0	3	0	3	0	7	5	68
November	0	2	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0	8
December	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6

Table 3-4 $\phi_{60}>0.1$ occurrences in 2013

2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	total
January	0	0	0	0	0	0	0	3	0	11	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	19
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	1	0	0	0	0	0	0	0	5
March	0	2	0	0	1	0	1	2	1	7	9	8	5	2	7	0	0	1	3	2	0	6	0	3	6	8	0	3	0	0	9	86
April	4	4	8	0	4	8	7	9	12	10	8	9	0	1	7	8	6	9	5	3	4	6	0	0	0	0	5	9	5	5	0	156
May	0	4	6	4	5	0	4	0	0	9	1	7	3	2	0	0	0	0	5	1	0	0	0	1	0	0	0	0	1	4	0	57
June	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	5
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	6
August	1	0	0	0	0	0	0	3	0	0	0	0	0	0	2	2	4	2	2	0	0	0	0	0	0	1	2	0	0	0	0	19
September	0	0	0	0	0	0	2	4	4	4	5	4	4	2	3	4	4	1	1	3	7	5	7	5	7	5	8	4	9	6	0	108
October	7	0	5	4	6	6	6	3	0	0	2	1	2	0	0	0	0	5	2	3	0	0	0	0	3	0	0	0	0	0	0	55
November	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	1	0	0	1	4	0	2	0	0	0	15
December	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	21

Table 3-3 and Table 3-4 show a more detailed number of occurrence of ϕ_{60} larger than 0.1 for years 2012 and 2013, respectively. For both years, highest occurrences of phase scintillations are again observed in equinox months April and September.

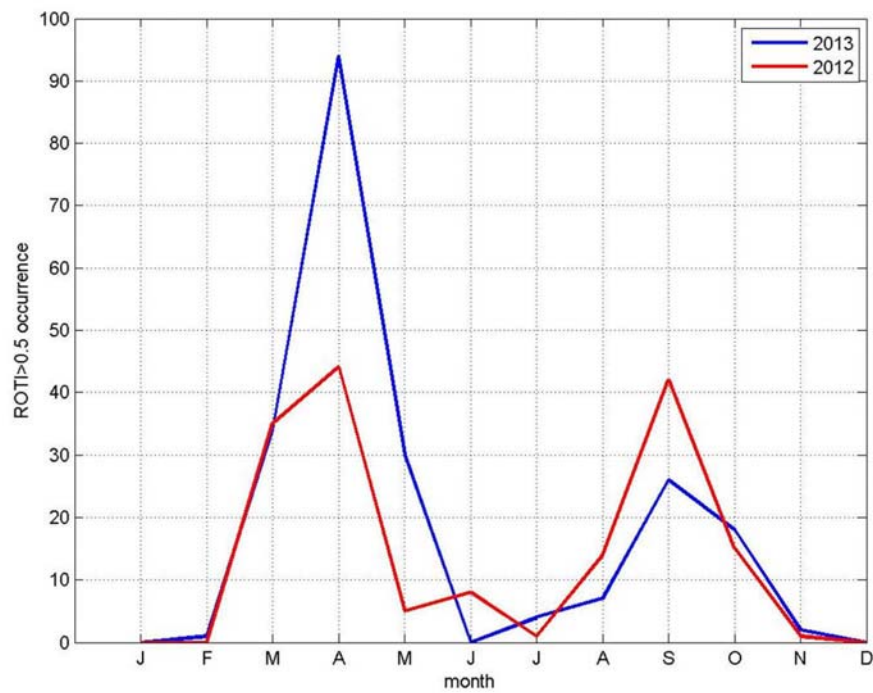


Figure 3-12 Monthly occurrence of ROTI>0.5

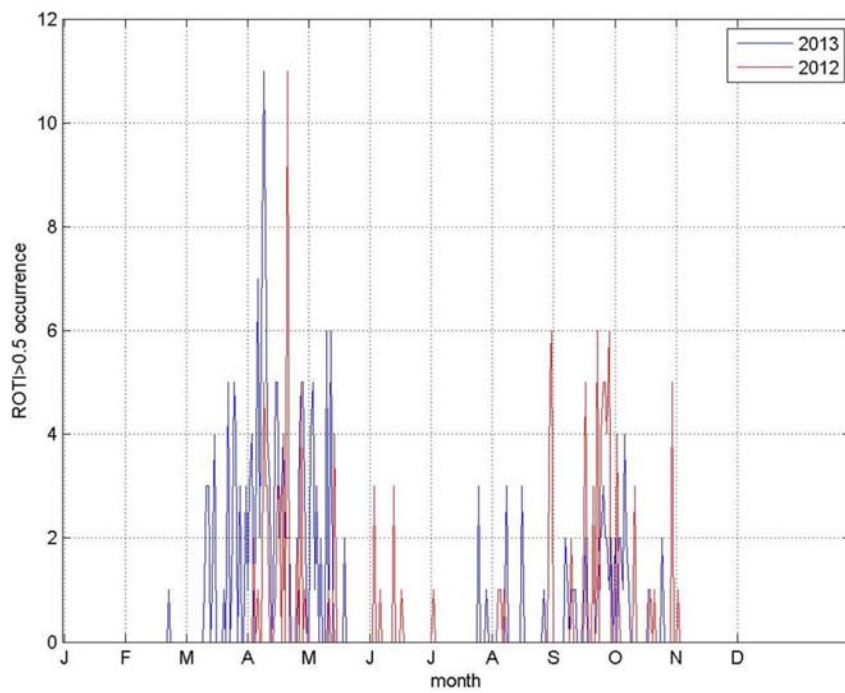


Figure 3-13 Daily occurrence of ROTI>0.5

Figure 3-12 and Figure 3-13 now show the monthly and daily occurrences of ROTI larger than 0.5 for years 2012 and 2013. Similar to amplitude and phase scintillation, the equinox months of April and September of both years exhibit the highest number of high ROTI occurrences which indicate high TEC fluctuation.

Table 3-5 ROTI>0.5 occurrence in 2012

2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	total
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	2	0	1	0	0	5	3	3	0	0	0	1	3	3	0	4	0	11	0	0	0	0	2	0	5	0	1	0	44
May	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
June	0	0	3	0	0	1	0	0	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
July	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
August	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	14
September	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	5	1	0	0	3	0	6	0	4	5	5	4	6	0	0	42
October	0	4	1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	5	0	15
November	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3-6 ROTI>0.5 occurrence in 2013

2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	total
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
March	0	0	0	0	0	0	0	0	0	1	3	3	0	1	4	0	0	0	0	1	0	5	0	1	5	4	0	3	0	0	3	34
April	1	3	4	0	2	7	2	6	11	8	4	3	0	1	5	5	2	3	4	2	2	2	0	0	0	0	4	5	5	3	0	94
May	0	4	5	1	3	0	2	0	0	6	0	6	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	30
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1	0	4
August	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	7
September	0	0	0	0	0	0	2	1	0	1	1	1	0	0	0	0	2	0	0	0	3	0	1	2	2	3	2	2	1	2	0	26
October	2	0	2	2	1	4	2	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	2	0	0	0	0	0	0	18
November	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3-5 and Table 3-6 show a more detailed number of occurrence of ROTI larger than 0.5 for years 2012 and 2013, respectively. For both years, highest occurrence of TEC fluctuation is again observed in months April and September.

To conclude for this section, ionospheric scintillation peak usually happen in around April and September (equinox) for both years 2012 and 2013, which is indicated by high S4, phi60, and ROTI.

3.4. Histogram of the GPS Satellites with Scintillation at Night

Ionospheric scintillation can reduce the accuracy of GNSS positioning and can even prevent the receiver from locking into satellites. At least four visible satellites are needed to obtain position information by GPS. Severe ionospheric scintillation that affects too many satellites will leave not enough number of usable satellites for position calculation. Based on our observation, in Singapore typically around six GPS satellites are always visible all the time. This means that when more than two satellites are suffering from severe ionospheric scintillation at a time, it is likely that GPS receiver cannot obtain position solution due to lacking of satellites number.

In this section the histogram of the number of GPS satellites suffering from scintillation is presented. This analysis gives us the probability estimation of the number of satellites that suffer from scintillation every time. This analysis is done for night time during equinox months when scintillations commonly happen. $S4 > 0.2$ is used to determine that ionospheric scintillation is happening. $S4$ is obtained every minute. For each minute the number of satellites with $S4 > 0.2$ is counted.

Figure 3-14 and Figure 3-15 show the histogram of the occurrence percentage of concurrently scintillation afflicted GPS satellites at night during equinox months in year 2012 and 2013. Night is defined as time period begins at 6 pm and ends at 6 am the next day. Night scintillation is expected to be more frequent than day scintillation. Equinox months is chosen as ionospheric scintillation is most severe in this period. Besides that, the same data from June and July 2013 which are non equinox month are also presented as comparison in Figure 3-16.

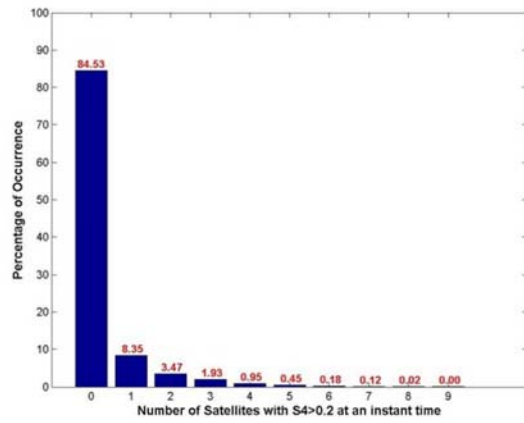
Among those presented equinox months, the April 2013 data shows the highest percentage of more than two satellites suffering from scintillation. The receiver sees all satellites without scintillation for 73.8 % of the time. The occurrence of only one satellite affected by scintillation is 11.88% of the time. Two satellites are seen with scintillation at 6.35% of the time. Subsequently, three, four, five, six, seven, and eight concurrently afflicted satellites happen at 3.81%, 2.40%, 1.16%, 0.43%, 0.13%, and 0.04% of the time respectively. Hence, the occurrence of more than two satellites affected by scintillation is 7.93% of the time.

In April 2012, the occurrence of more than two satellites affected by scintillation is lower, only 3.65%. This is because in year 2012 the solar activity is still ascending and hasn't reached its peak in around year 2013 or 2014. Higher solar activity increases the possibility of ionospheric scintillation. Nevertheless, this occurrence in April 2012 is still much higher compared to the non equinox data shown in Figure 3-16. In June and July 2013, the occurrence of more than two satellites affected by scintillation is nearly zero, only 0.01% and 0.07%. The effect solar activity and solar cycle will be further analyzed in chapter three of this thesis.

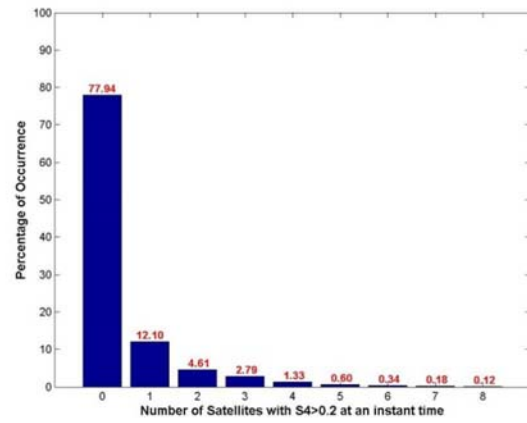
For closer analysis, Figure 3-17 shows the histogram of the occurrence percentage of concurrently scintillation afflicted GPS satellites at 20.00-02.00 local time during April 2013. High ionospheric scintillation is typically concentrated in this time span. The occurrence of only one satellite affected by scintillation is 19.63% of the time. Two satellites are seen with scintillation at 12.45% of the time. Subsequently, three, four, five, six, seven, and eight concurrently afflicted satellites happen at 7.56%, 4.75%, 2.28%, 0.83%, 0.25%, and 0.06% of the time respectively. Hence, the occurrence of more than two satellites affected by scintillation is 15.73% of the time.

In conclusion, it has been shown that at 20.00-02.00 local time, the occurrence concurrently scintillation afflicted GPS satellites can reach 15.73%. This result shows that during this time span the GPS applications, especially those which need continuous tracking are likely to be affected by ionospheric scintillation. Further analysis involving tracking and positioning performance of GPS receiver during scintillation is needed to comprehensively study the adverse effect of such scintillation.

April 2012



September 2012



October 2012

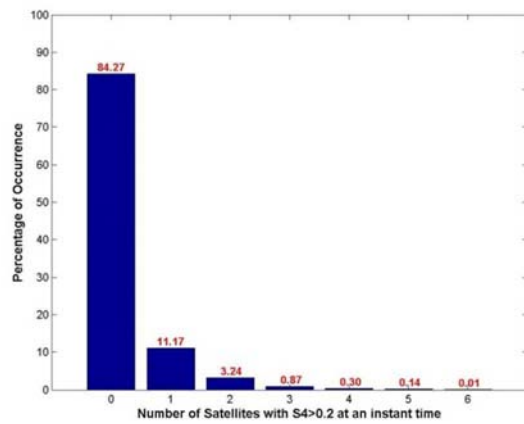
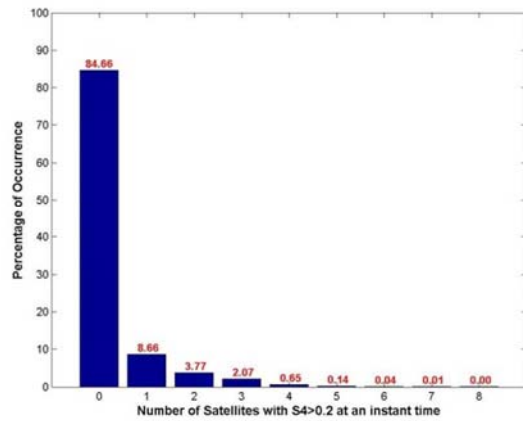
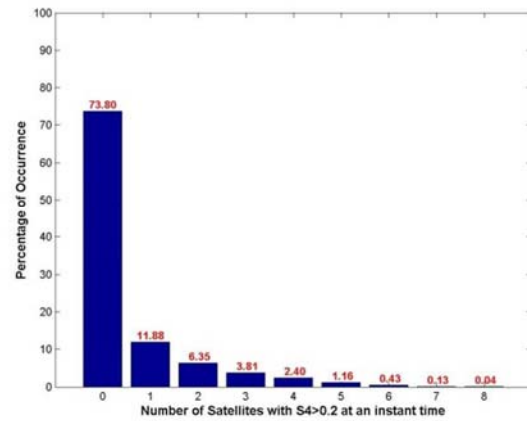


Figure 3-14 Distribution of the number of concurrently scintillation affected GPS satellites at night during equinox months of year 2012

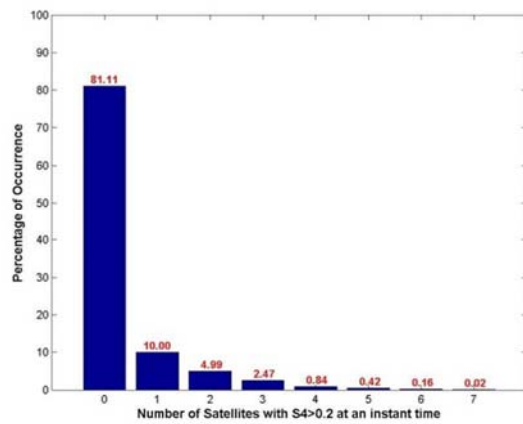
March 2013



April 2013



September 2013



October 2013

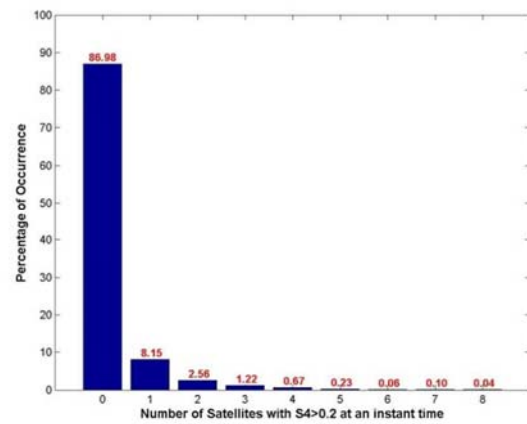


Figure 3-15 Distribution of the number of concurrently scintillation affected GPS satellites at night during equinox months of year 2013

June 2013

July 2013

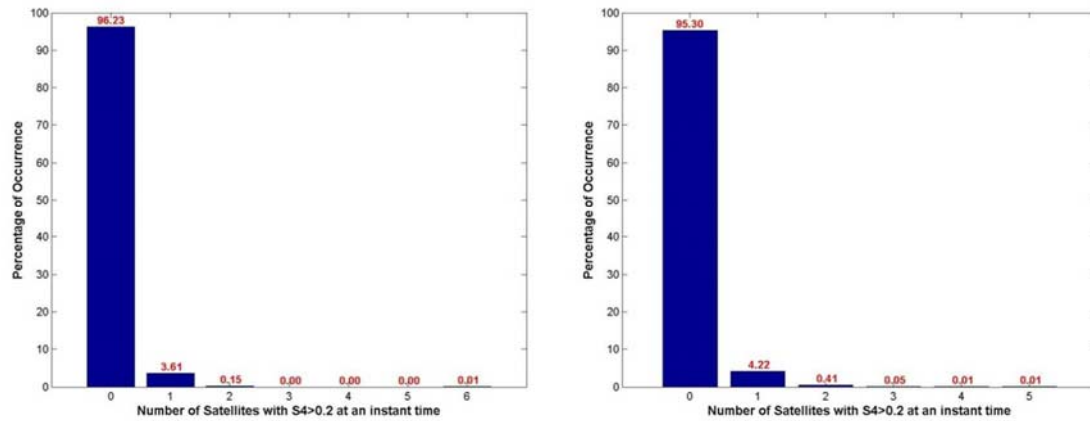


Figure 3-16 Distribution of the number of concurrently scintillation affected GPS satellites at night during non equinox months of year 2013

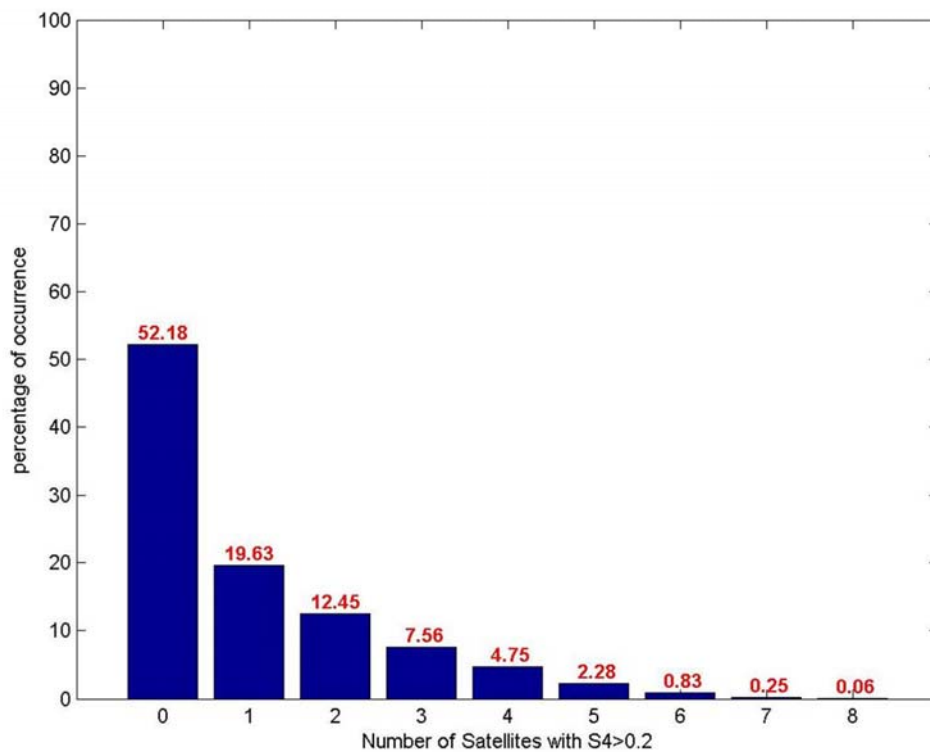


Figure 3-17 Distribution of the number of concurrently scintillation affected GPS satellites at 20.00-02.00 local time during April 2013

4. Scintillation Models For Singapore Equatorial Region and Their Validation with Scintillation Data

4.1. Frequency Dependence Scintillation model

Reference [32] has predicted the frequency dependence model on ionospheric scintillation as follows:

$$S4(f) = S4_{L1} \left(\frac{f_{L1}}{f} \right)^{1.5} \quad (4-1)$$

$$\text{phi60}(f) = \text{phi60}_{L1} \frac{f_{L1}}{f} \quad (4-2)$$

where f is any frequency targeted.

These equations are applied to S4 and phi60 of L1 and L2 frequencies. To further study the relation between L1 and L2 frequency, S4 of L2 frequency is plotted against S4 of L1 for all satellites in Figure 4-1 to Figure 4-3. The fitted line of each figure is then plotted using robust least square method performed by Matlab which is shown by the green lines. Only S4 higher than 0.2 are used for the fitted line computation to minimize the noise effect. The same method is also done for phi60 in Figure 4-4 to Figure 4-6. For phi60, only those higher than 0.1 are used for the fitted line computation, except that GLONASS uses 0.2 as the limit due to higher phase noise.

It can be seen that the phi60 fitting lines from GPS, GLONASS, and BeiDou closely follow the aforementioned models. Therefore, the frequency dependence models in [32] are found to be applicable to Singapore equatorial region. However, apparent differences are shown between the obtained S4 fitting lines and models in [32]. Based on the new fitting line, for GPS, the following modified frequency dependence model which is applicable for Singapore equatorial region is obtained as follows:

$$S4_{L2} = S4_{L1} \left(\frac{f_{L1}}{f_{L2}} \right)^{1.1193} \quad (4-3)$$

For GLONASS the modified frequency dependence model is given as:

$$S4_{L2} = S4_{L1} \left(\frac{f_{L1}}{f_{L2}} \right)^{1.3443} \quad (4-4)$$

For BeiDou the modified frequency dependence model is given as:

$$S4_{L2} = S4_{L1} \left(\frac{f_{L1}}{f_{L2}} \right)^{1.0236} \quad (4-5)$$

In average, the modified frequency dependence model is:

$$S4_{L2} = S4_{L1} \left(\frac{f_{L1}}{f_{L2}} \right)^{1.1624} \quad (4-6)$$

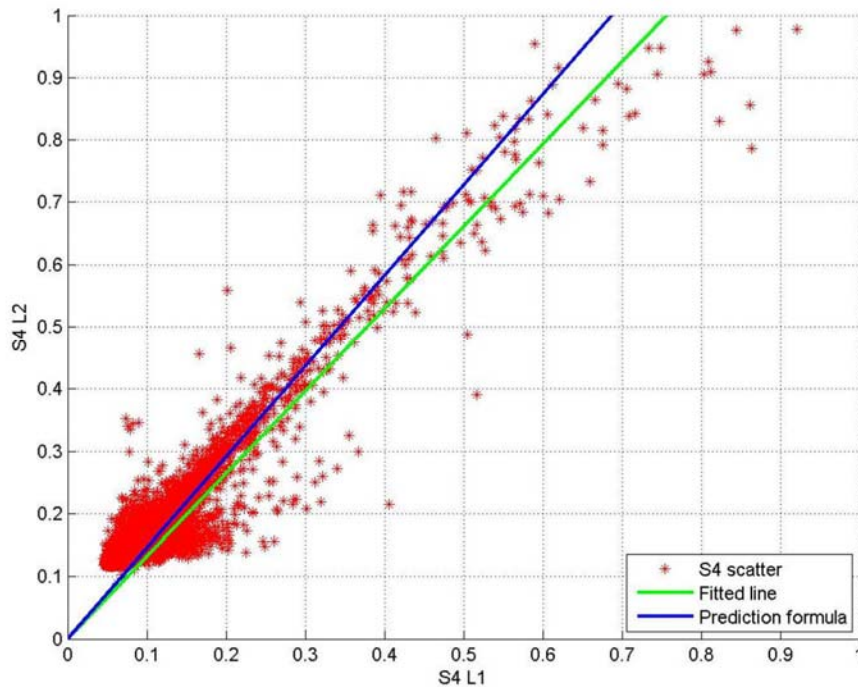


Figure 4-1 Scatter plot of GPS S4 L1 and L2

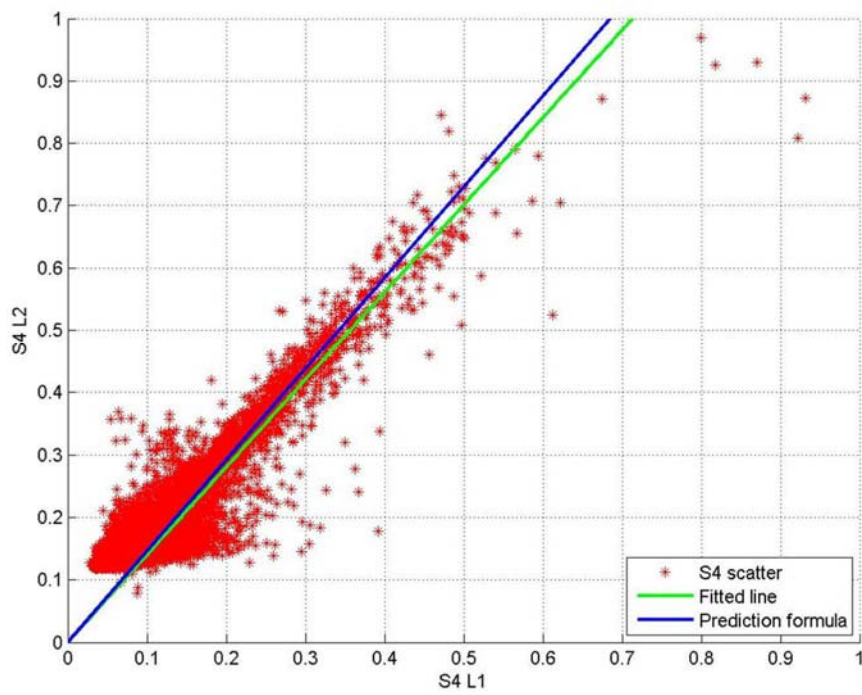


Figure 4-2 Scatter plot of GLONASS S4 L1 and L2

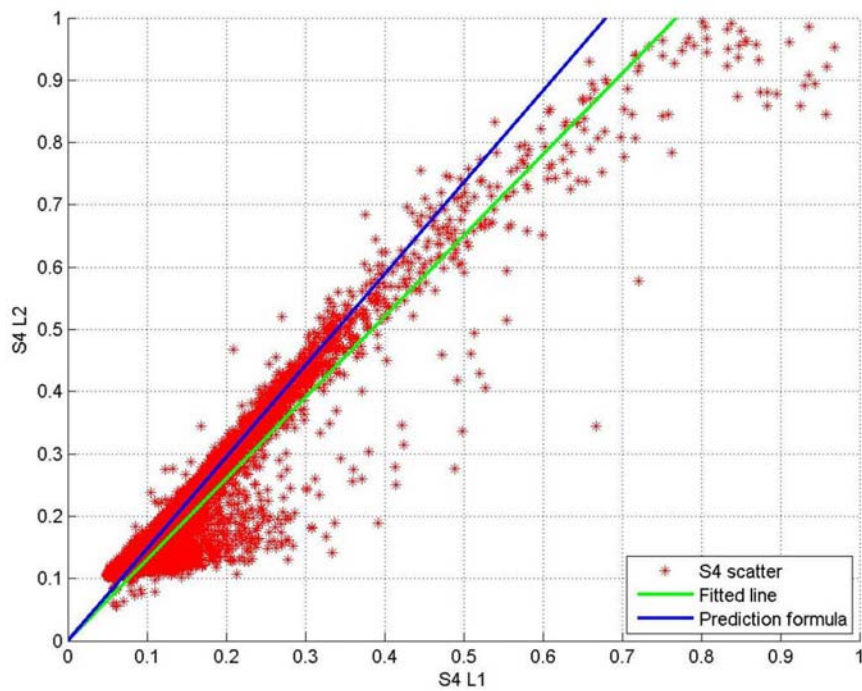


Figure 4-3 Scatter plot of BeiDou S4 L1 and L2

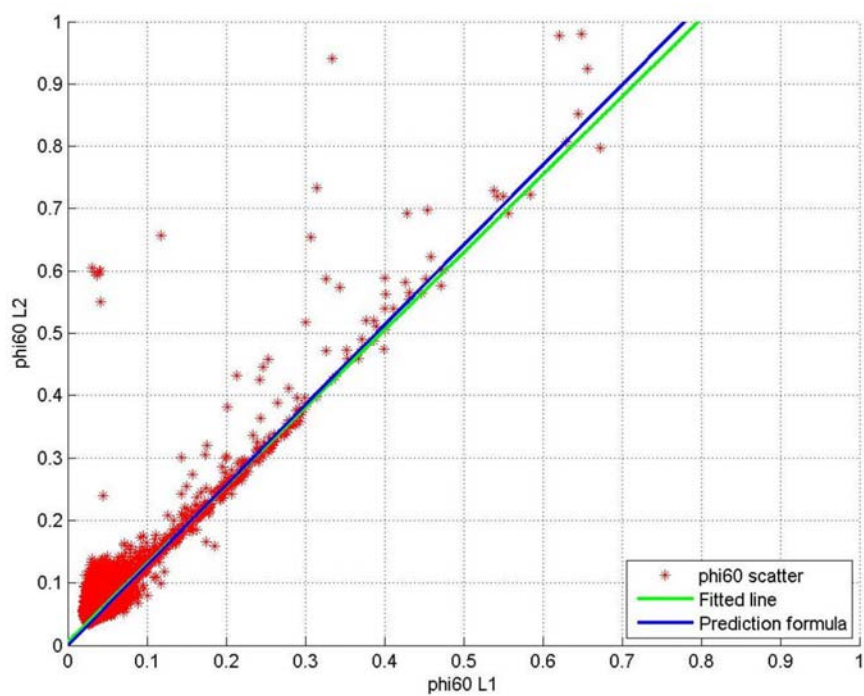


Figure 4-4 Scatter plot of GPS Phi60 L1 and L2

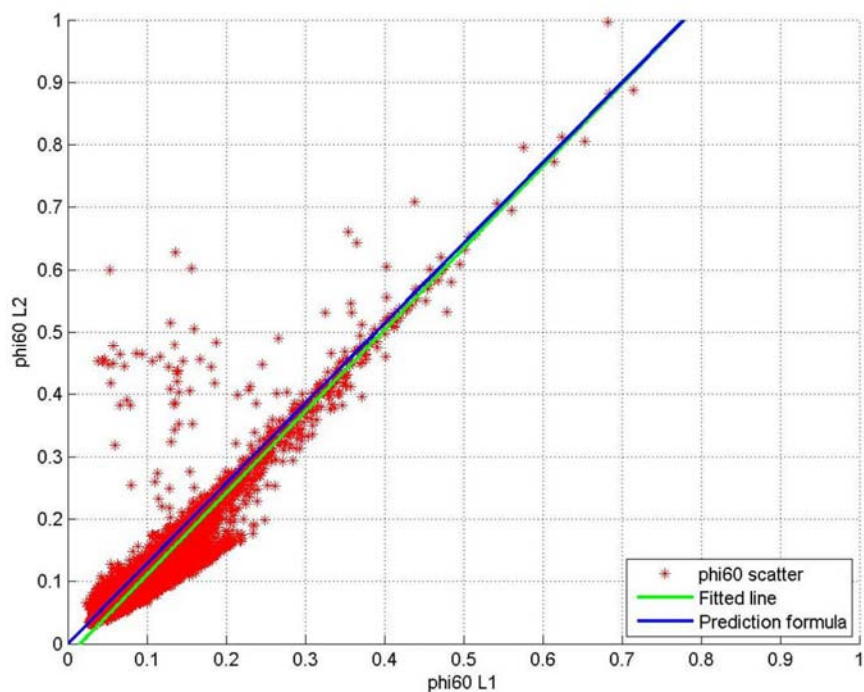


Figure 4-5 Scatter plot of GLONASS Phi60 L1 and L2

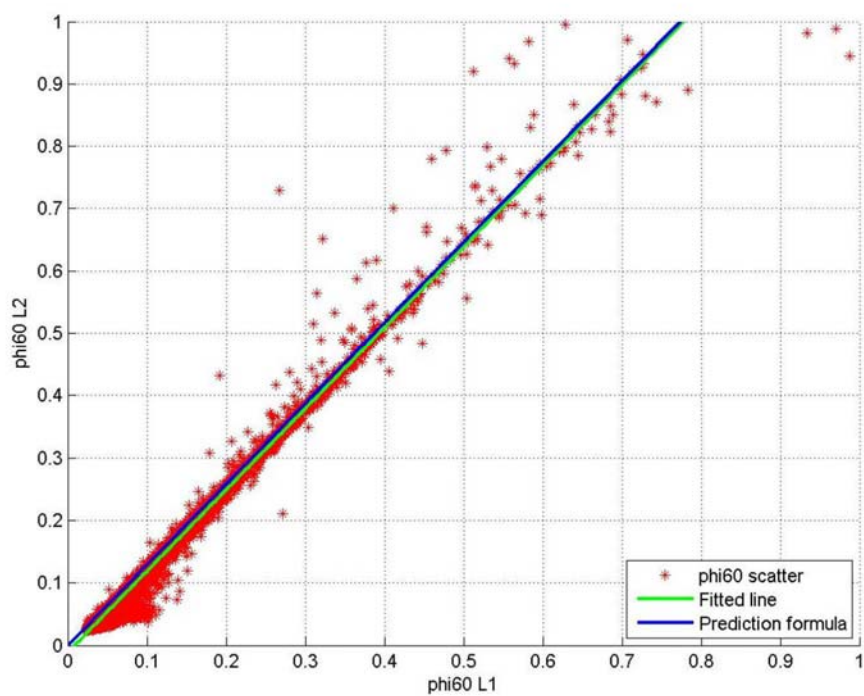


Figure 4-6 Scatter plot of BeiDou Phi60 L1 and L2

4.2. Fremouw and Rino Scintillation model

The Fremouw and Rino scintillation model described in Section 2.1 is first applied to GPS L1 frequency and Singapore equatorial region to ascertain its applicability in this region. For convenience the rms of fluctuations in phase and amplitude in the scintillation model are rewritten as:

$$\phi_0 = \pi^{1/4} r_e \lambda [(a \xi_0 \sec i)^{1/2} / \beta^{1/2}] \Delta h^{1/2} \Delta N \quad (4-7)$$

$$S_4 = 2^{1/2} \phi_0 \left[1 - (\cos u_1 \cos u_2)^{\frac{1}{2}} \cos\left(\frac{u_1 + u_2}{2}\right) \right]^{1/2} \quad (4-8)$$

where

$$\beta = (a^2 \sin^2 \psi + \cos^2 \psi)^{1/2} \quad (4-9)$$

$$u_1 = \tan^{-1}(2\lambda z / \pi \xi_0^2) \quad (4-10)$$

$$u_2 = \tan^{-1}(2\lambda z / \pi \beta^2 \xi_0^2) \quad (4-11)$$

$$z = z_1 z_2 / (z_1 + z_2) \quad (4-12)$$

In the above, r_e is electron radius, λ is wavelength, ξ_0 is transverse irregularity scale size, i is incident angle, Δh is irregularity layer thickness, a is irregularity axial ratio, ψ is angle between geomagnetic field line and propagation LOS, z_1 is distance from receiver from irregularity layer, and z_2 is distance from transmitter to irregularity layer. The two parameters in (4-7) and (4-8) are based on the formulations given in [16].

Variables i , z_1 and z_2 are related to the zenith angle θ through [16]

$$i = \sin^{-1}\{R_0 \sin \theta / (R_0 + h)\} \quad (4-13)$$

$$z_1 = (R_0^2 \cos^2 \theta + 2R_0 h + h^2)^{1/2} - R_0 \cos \theta \quad (4-14)$$

$$z_2 = (R_0^2 \cos^2 \theta + 2R_0 H + H^2)^{1/2} - (R_0^2 \cos^2 \theta + 2R_0 h + h^2)^{1/2} \quad (4-15)$$

where R_0 is the earth radius, h is the height of irregularity layer and H is the height of the satellite.

The rms of fluctuations in phase and amplitude in (4-7) and (4-8) are dependent on the rms fluctuations of electron density, ΔN :

$$\Delta N = \Delta N_{eq}(R, D, t, \lambda_L) + \Delta N_{mid}(t, \lambda_L) + \Delta N_{hi}(R, t, \lambda_L) + \Delta N_{aur}(R, t, \lambda_L) \quad (4-16)$$

where

$$\begin{aligned} \Delta N_{eq} = & (5.5 \times 10^9)(1 + 0.05R) \cdot \left[1 - 0.4 \cos \pi \left(\frac{D + 10}{91.25} \right) \right] \\ & \cdot \left\{ \exp \left[- \left(\frac{t}{4} \right)^2 \right] + \exp \left[- \left(\frac{t + 23.5}{3.5} \right)^2 \right] \right\} \\ & \cdot \left\{ \exp \left[- \left(\frac{\lambda_L}{12} \right)^2 \right] \right\} \text{el/m}^3 \end{aligned} \quad (4-17)$$

$$\Delta N_{mid} = (6.0 \times 10^8) \left(1 + 0.4 \cos \frac{\pi t}{12} \right) \cdot \left\{ \exp \left[- \left(\frac{\lambda_L - 32.5}{10} \right)^2 \right] \right\} \text{el/m}^3 \quad (4-18)$$

$$\Delta N_{hi} = (2.7 \times 10^9) \left\{ 1 + \text{erf} \left[\frac{\lambda_L - \lambda_b(R, t)}{0.02 \lambda_b(R, t)} \right] \right\} \text{el/m}^3 \quad (4-19)$$

$$\Delta N_{aur} = (5.0 \times 10^7) R \cdot \left\{ \exp \left[- \left(\frac{\lambda_L - 70 + 2 \cos \frac{\pi t}{12}}{0.03 R} \right)^2 \right] \right\} \text{el/m}^3 \quad (4-20)$$

$$\lambda_b = 79 - 0.13R - (5 + 0.04R) \cdot \cos(\pi t/12) \text{ deg} \quad (4-21)$$

In above, R is the sunspot number, D is the day of the year, t is the local time of the day in hours and λ_L is the geomagnetic latitude in degrees.

We shall first plot $\emptyset_0$ and S_4 with GPS L1 frequency 1575.42 MHz with its corresponding wavelength $\lambda = 0.1904$ m and Singapore geomagnetic latitude $\lambda_L = -8.4$ degree (8.4 degree South). The two parameters are plotted for the period of year 2014, and the corresponding daily sunspot number is adopted from [33]. The irregularity parameters are set accordingly to those in [1] and are given as $a = 10$; $\Delta h = 100$ km; $h = 350$ km. ξ_0 is modeled as

$$\begin{aligned} \xi_0 = & 300 + 600\{1 + \text{erf}[(\lambda_L - 12)/3]\} - 450\{1 + \text{erf}[(\lambda_L - 62)/3]\} \\ & + 200\{1 + \text{erf}[(\lambda_L - 69)/3]\} \text{ m} \end{aligned} \quad (4-22)$$

For the geometric parameters, it is assumed here that θ and ψ are both averaged at 45 degrees, $H = 20200$ km (altitude of GPS satellites) and $R_0 = 6371$ km.

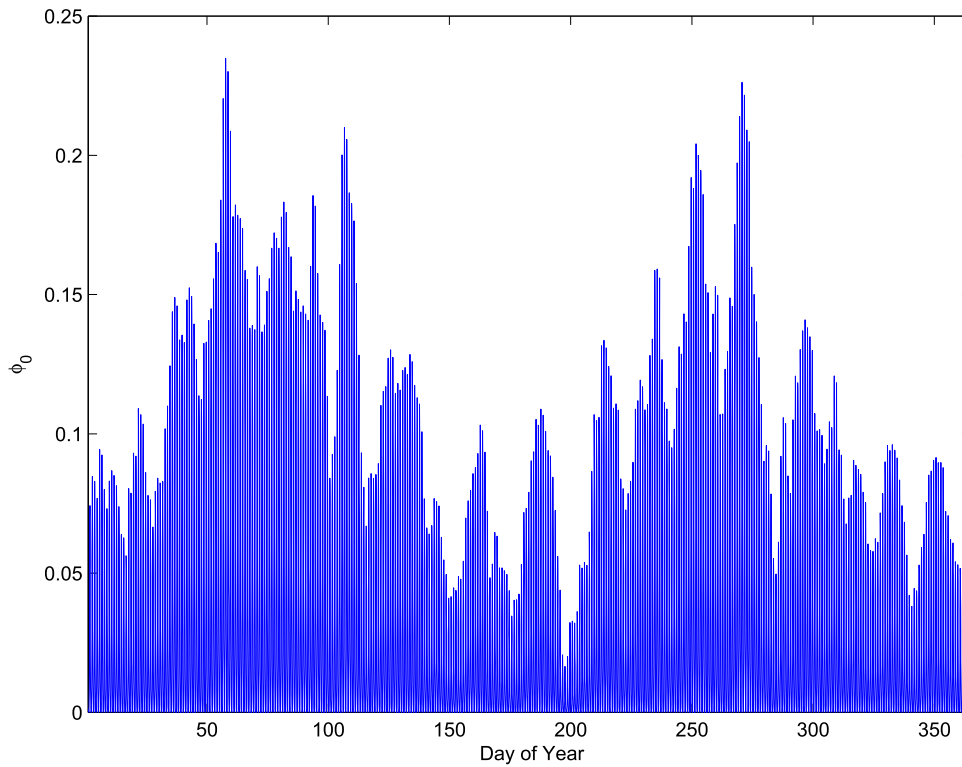


Figure 4-7 Plot of ϕ_0 versus day of year for year 2014 using Fremouw and Rino model

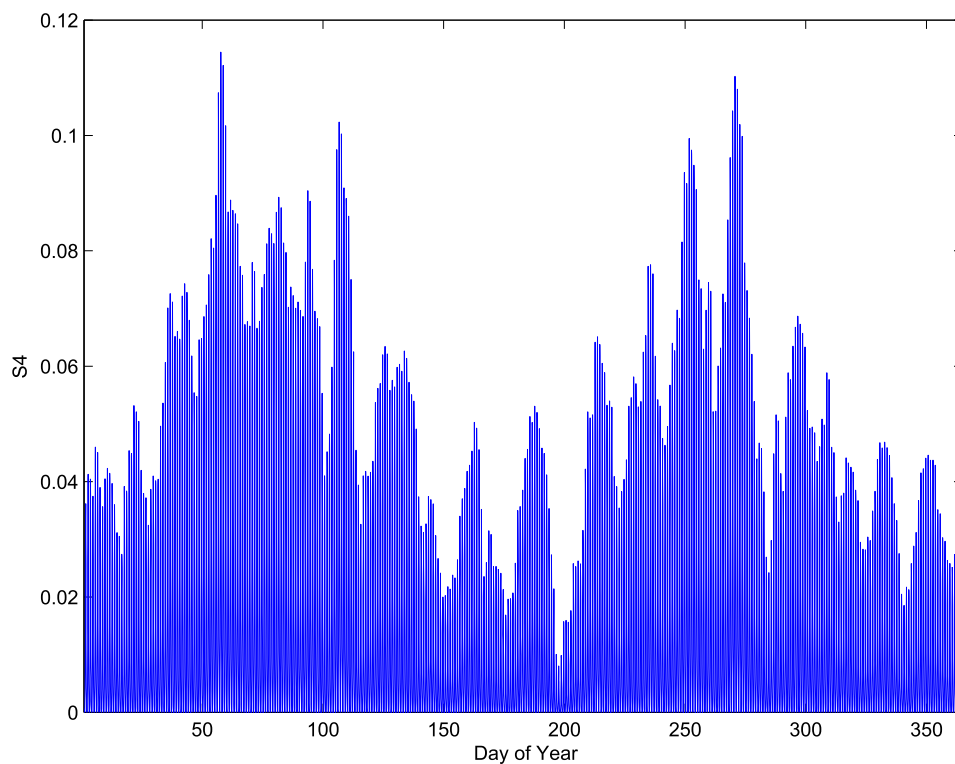


Figure 4-8 Plot of S_4 versus day of year for year 2014 using Fremouw and Rino model

Figure 4-7 and Figure 4-8 show the $\emptyset_0$ and S_4 versus day of year for year 2014 using Fremouw and Rino model. It is first observed that the model shows the correct seasonal peaks for the two scintillation parameters at around equinox months of March, April, September and October. However, the values of $\emptyset_0$ and S_4 are deemed too low for scintillation event at GPS L1 frequency. Moreover, the value of S_4 is lower than $\emptyset_0$, which is unexpected based on the general observed scintillation data in Singapore region. As the original Fremouw and Rino model are mostly formulated based on VHF experimental data, the model is found to be inaccurate at GPS L1 frequency.

4.3. Proposed Modified Fremouw and Rino Scintillation Model

We now propose to make the following modifications to the original Fremouw and Rino model:

$$\begin{aligned} \Delta N_{eq} = & 8 \times (5.5 \times 10^9)(1 + 0.05R) \cdot \left[1 - 0.6 \cos \pi \left(\frac{D + 10}{91.25} \right) \right] \\ & \cdot \left\{ \exp \left[- \left(\frac{t}{4} \right)^2 \right] + \exp \left[- \left(\frac{t + 23.5}{3.5} \right)^2 \right] \right\} \\ & \cdot \left\{ \exp \left[- \left(\frac{\lambda_L}{12} \right)^2 \right] \right\} \text{el/m}^3 \end{aligned} \quad (4-23)$$

$$\begin{aligned} \xi_0 = & 30 + 600\{1 + \text{erf}[(\lambda_L - 12)/3]\} - 450\{1 + \text{erf}[(\lambda_L - 62)/3]\} \\ & + 200\{1 + \text{erf}[(\lambda_L - 69)/3]\} m \end{aligned} \quad (4-24)$$

The above modifications are made such that the rms fluctuation of electron density at equatorial region ΔN_{eq} is scaled at 8 times larger than the original model and the coefficient for seasonal variation is changed from 0.4 to 0.6 to accentuate the scintillation peaks during equinox months. The irregularity scale size ξ_0 at near geomagnetic equator is also proposed to be 10 times smaller at 30 m instead of the original 300 m.

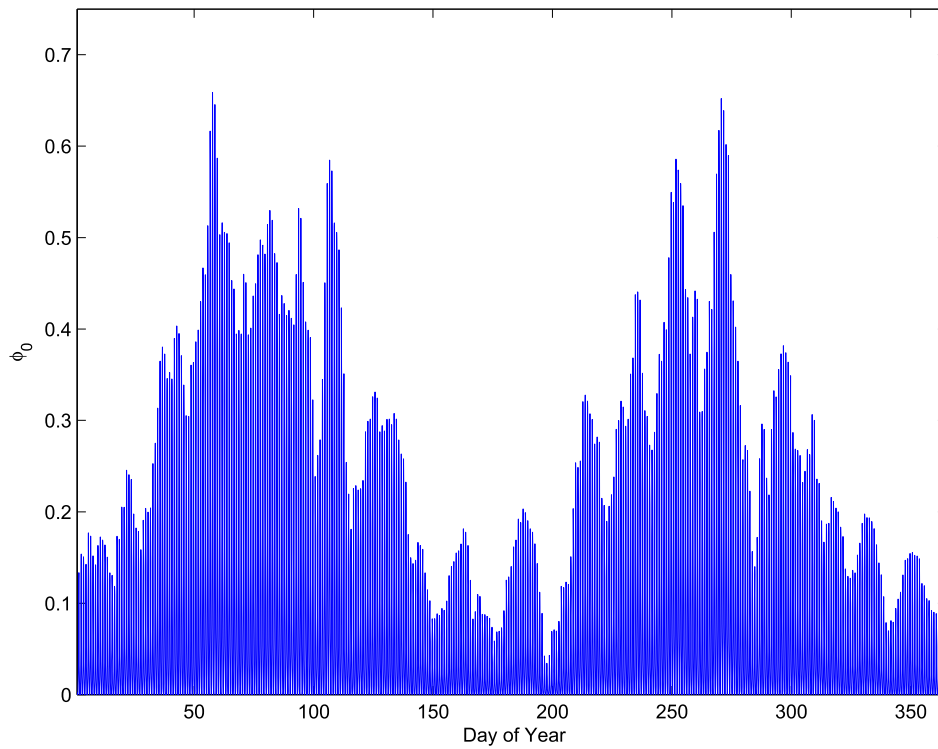


Figure 4-9 Plot of ϕ_0 versus day of year for year 2014 using the proposed modified Fremouw and Rino model

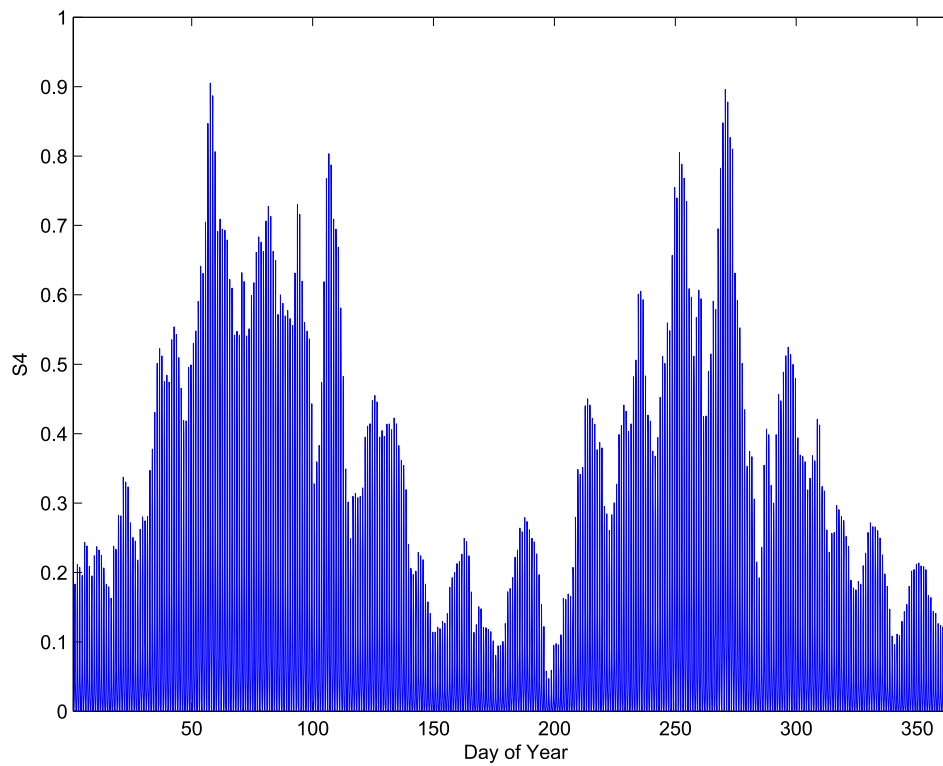


Figure 4-10 Plot of S_4 versus day of year for year 2014 using the proposed modified Fremouw and Rino model

Figure 4-9 and Figure 4-10 now show the $\emptyset_0$ and S_4 versus day of year for year 2014 using the proposed modified Fremouw and Rino model. It is observed that the values of $\emptyset_0$ and S_4 are higher to appropriately reflect scintillation events in GPS L1 frequency. The value of S_4 is also higher than $\emptyset_0$, which is the general case based on the observation data in Singapore. They shall now be compared in more detail with the ionosphere scintillation data collected in Singapore.

The proposed modified Fremouw and Rino scintillation model will be validated with the ionosphere scintillation data collected in Singapore. The scintillation data used to compare are S_4 and ϕ_{60} output from Septentrio receiver at GPS L1 frequency. Note that the rms fluctuation of phase $\emptyset_0$ in the model will be compared against the ϕ_{60} of scintillation data. The scintillation parameters S_4 and ϕ_{60} are calculated below as

$$S_4 = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2}} \quad (4.25)$$

where SI is the signal intensity or power and $\langle . \rangle$ denotes the expected (or average) value over the interval of interest (60 seconds). S_4 is a dimensionless and commonly estimated over an interval of 60 seconds.

$$\phi_{60} = \sigma_{\emptyset} = \sqrt{\langle d\emptyset^2 \rangle - \langle d\emptyset \rangle^2} \quad (4.26)$$

where $d\emptyset$ is the detrended carrier phase and $\langle . \rangle$ denotes the expected (or average) value over the interval of interest. $\sigma_{\emptyset}$ calculated with 60 second interval is name ϕ_{60} .

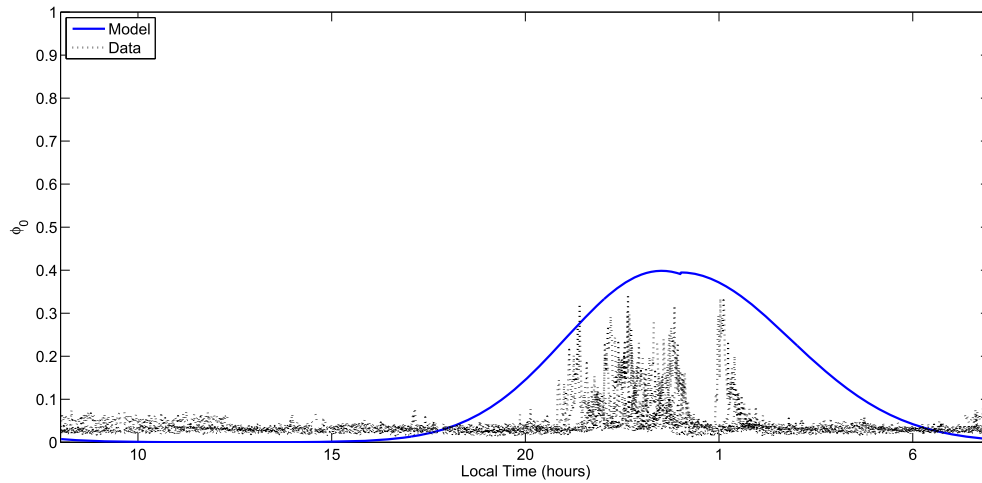


Figure 4-11 Comparison between model and scintillation data for ϕ_0 versus local time from DOY 69 8am to DOY 70 8am.

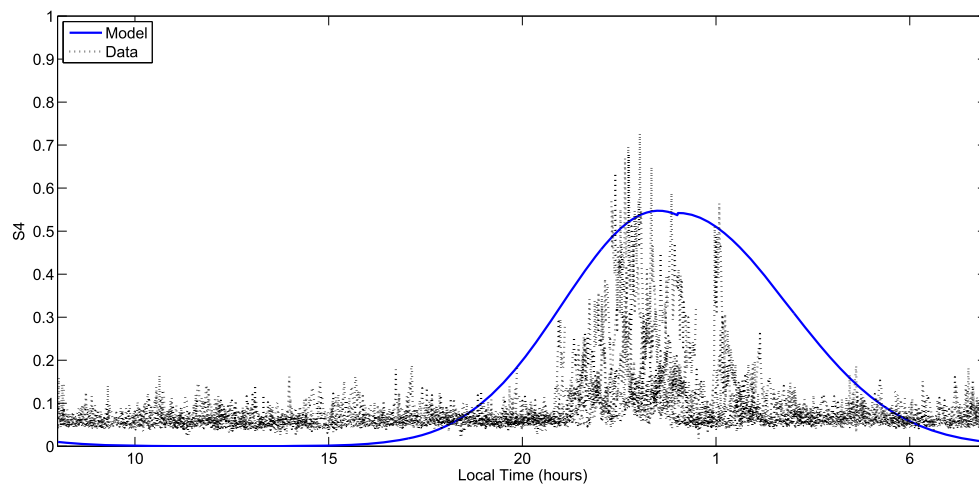


Figure 4-12 Comparison between model and scintillation data for S_4 versus local time from DOY 69 8am to DOY 70 8am.

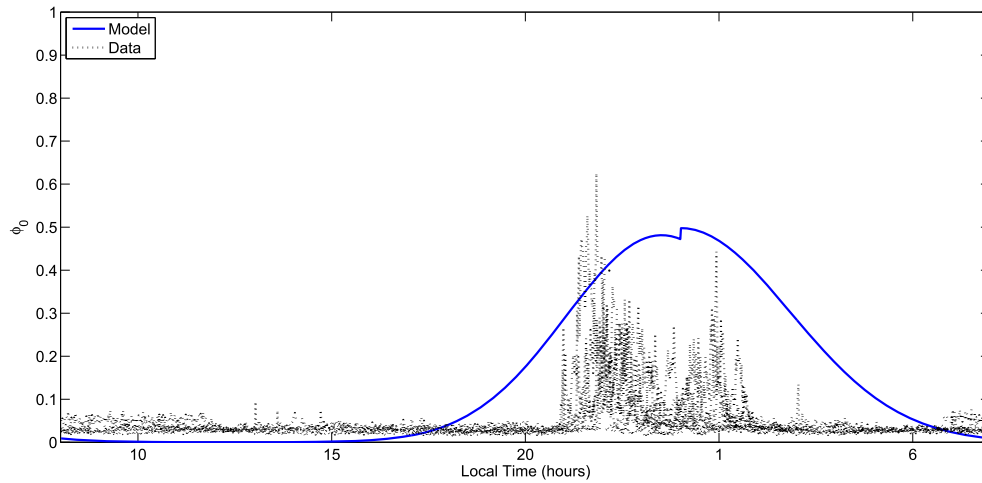


Figure 4-13 Comparison between model and scintillation data for ϕ_0 versus local time from DOY 77 8am to DOY 78 8am.

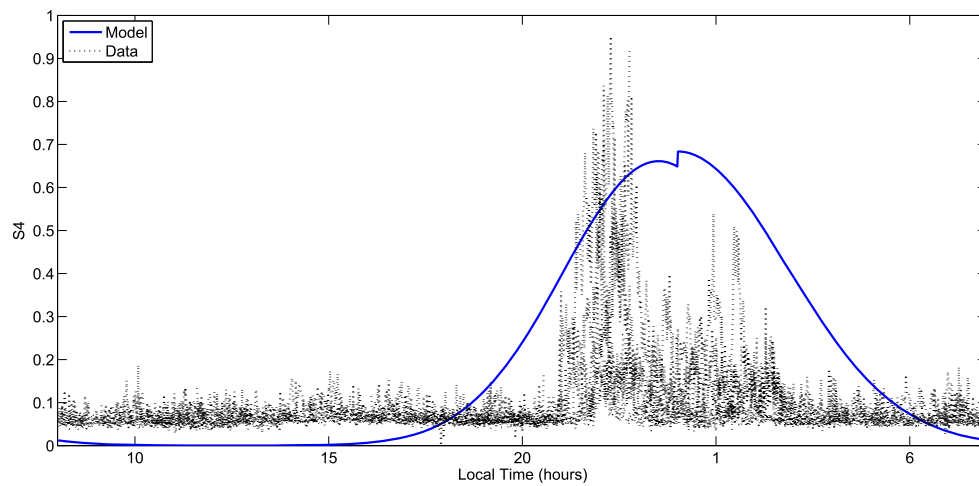


Figure 4-14 Comparison between model and scintillation data for S_4 versus local time from DOY 77 8am to DOY 78 8am.

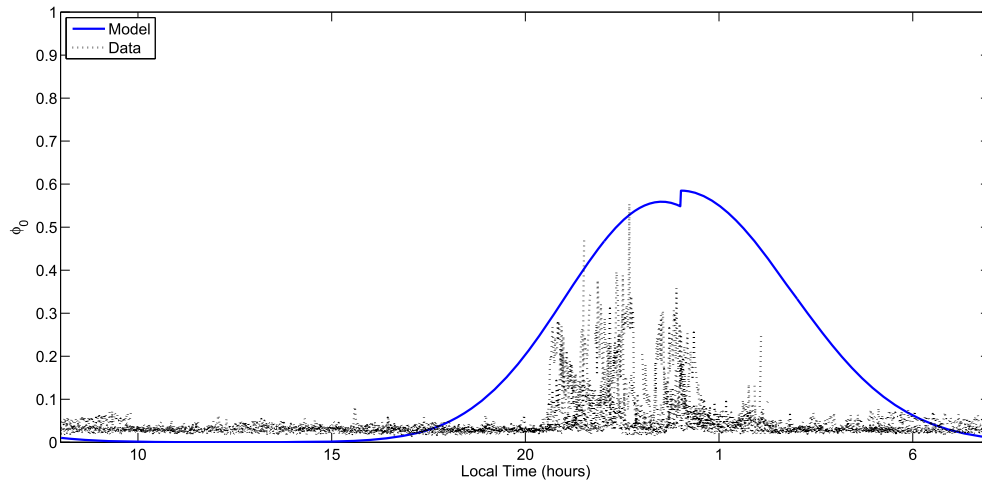


Figure 4-15 Comparison between model and scintillation data for ϕ_0 versus local time from DOY 106 8am to DOY 107 8am.

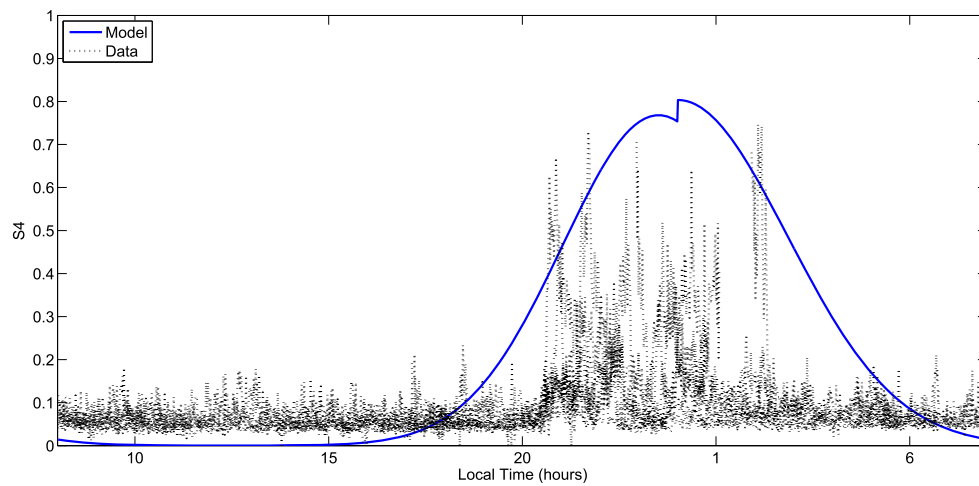


Figure 4-16 Comparison between model and scintillation data for S_4 versus local time from DOY 106 8am to DOY 107 8am.

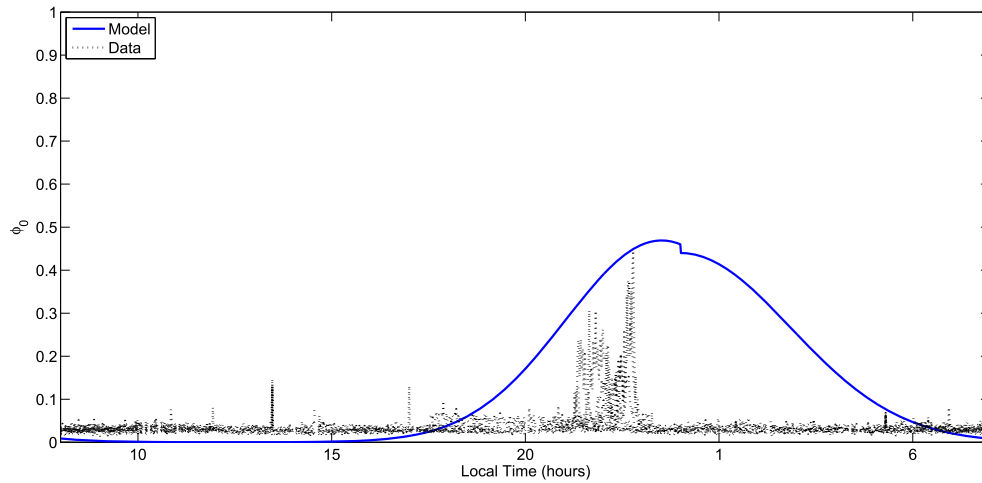


Figure 4-17 Comparison between model and scintillation data for ϕ_0 versus local time from DOY 274 8am to DOY 275 8am.

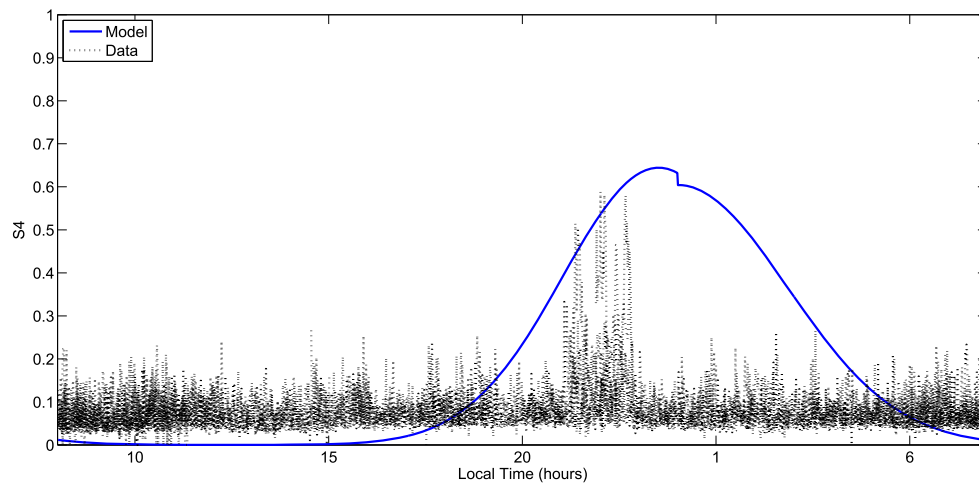


Figure 4-18 Comparison between model and scintillation data for S_4 versus local time from DOY 274 8am to DOY 275 8am.

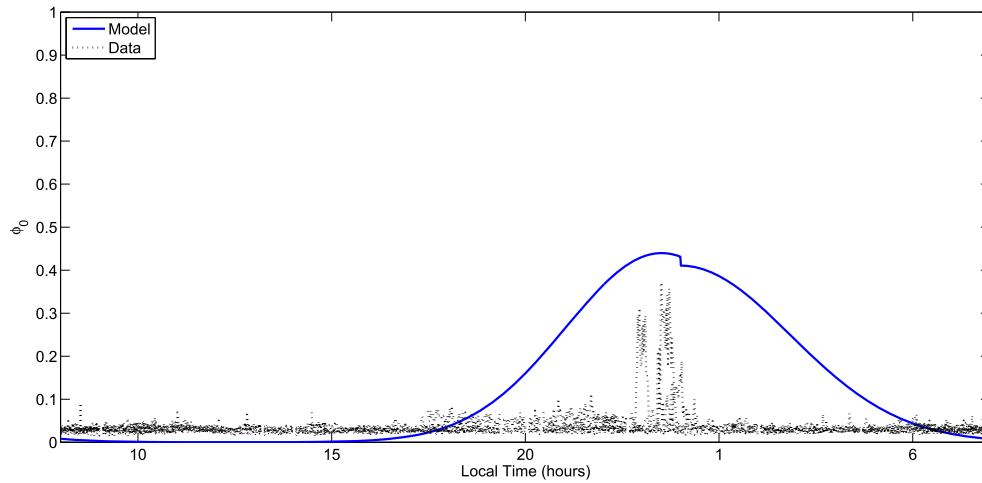


Figure 4-19 Comparison between model and scintillation data for ϕ_0 versus local time from DOY 275 8am to DOY 276 8am.

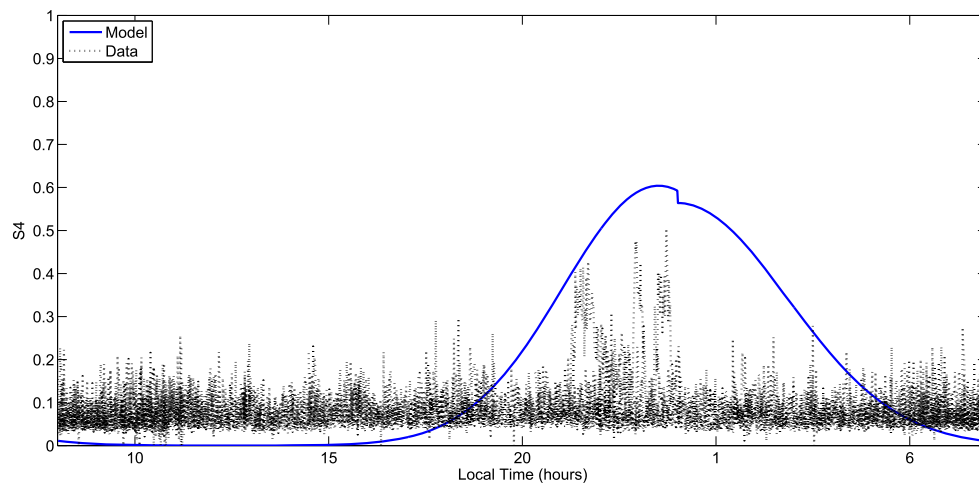


Figure 4-20 Comparison between model and scintillation data for S_4 versus local time from DOY 275 8am to DOY 276 8am.

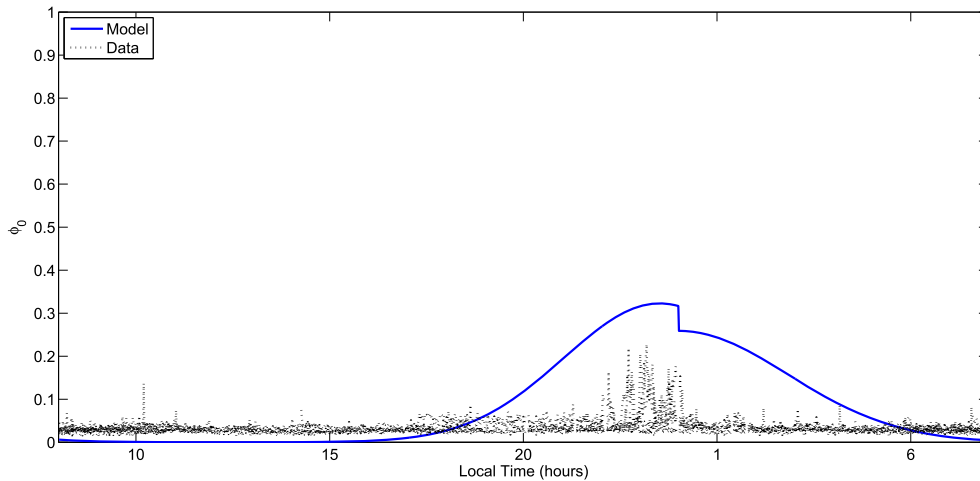


Figure 4-21 Comparison between model and scintillation data for ϕ_0 versus local time from DOY 278 8am to DOY 279 8am.

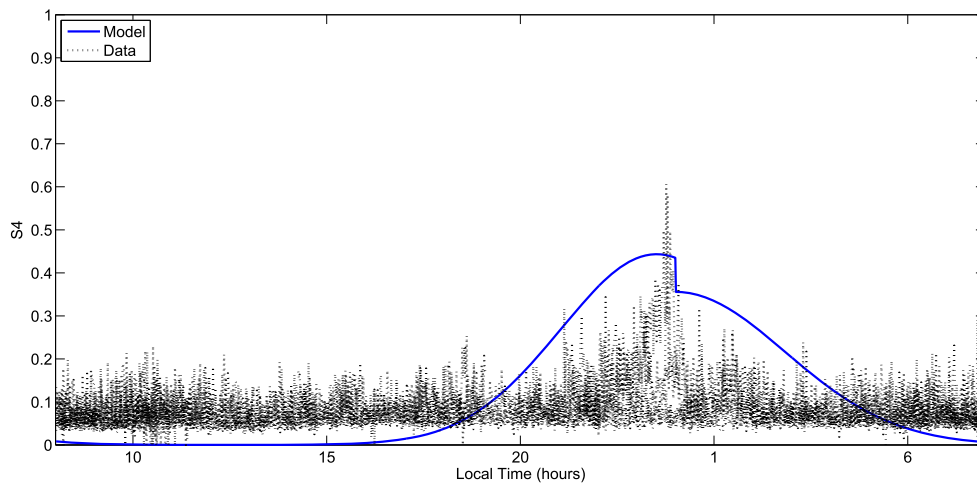


Figure 4-22 Comparison between model and scintillation data for S_4 versus local time from DOY 278 8am to DOY 279 8am.

Figure 4-11 to Figure 4-22 plot the comparison between the proposed modified model and scintillation data ϕ_0 and S_4 versus local time for several different days in equinox months (March, April, September and October) of year 2014. Year 2014 data is first compared as it represents the solar maximum period with the most number of sunspot number and scintillation activity. It can be seen that the proposed modified model agrees with the scintillation data generally well during these days in equinox months. As predicted,

scintillation events in equinox months generally occur during post sunset period around local time from 8pm to 2am of the next day.

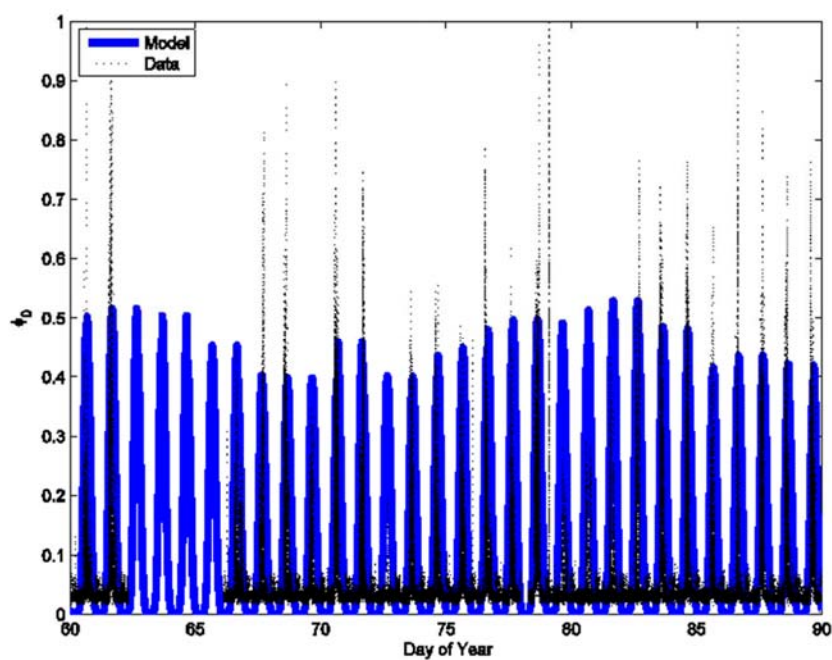


Figure 4-23 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 60 to 90 (March 2014).

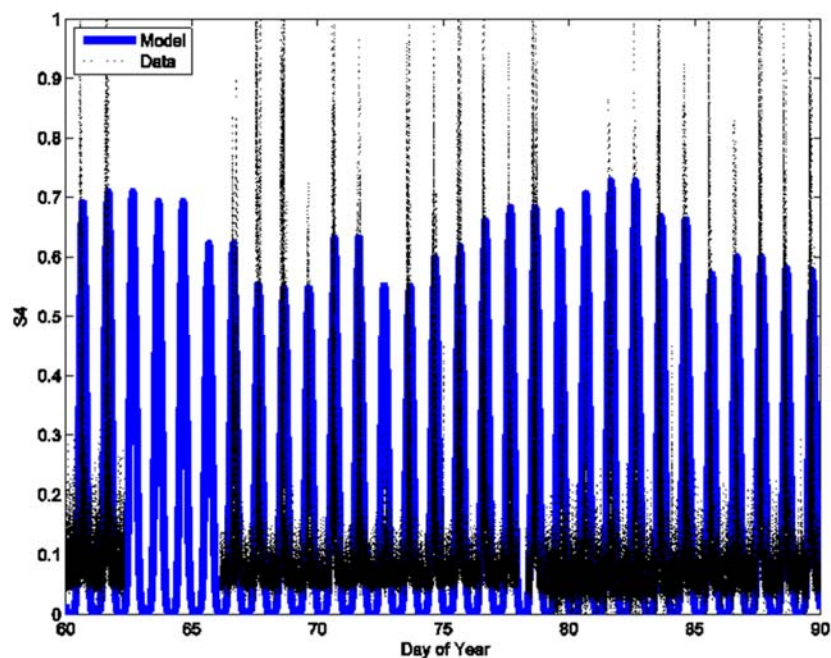


Figure 4-24 Comparison between model and scintillation data for S_4 versus day of year from DOY 60 to 90 (March 2014).

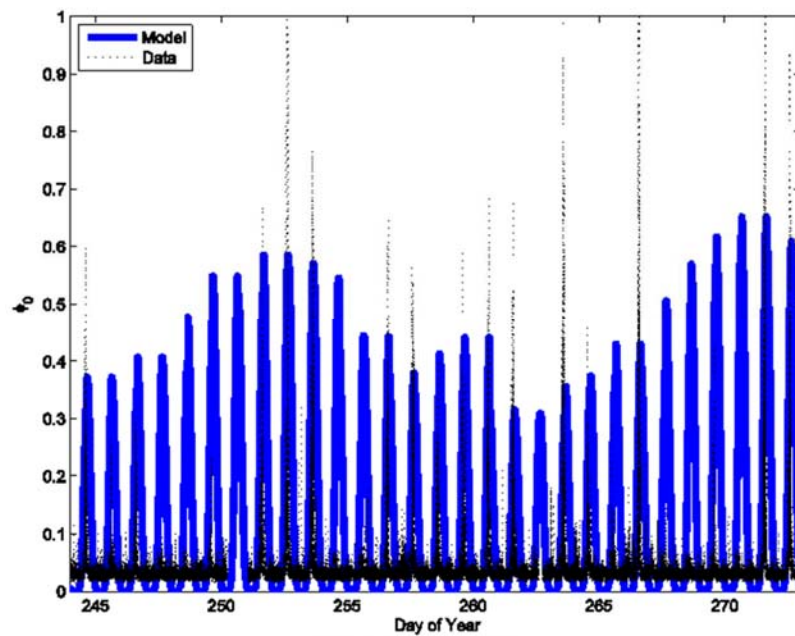


Figure 4-25 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 244 to 273 (September 2014).

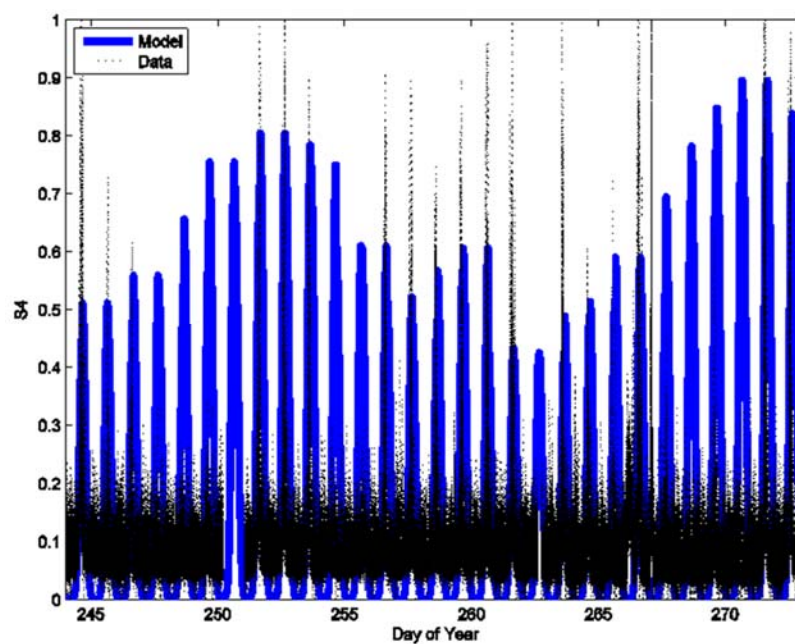


Figure 4-26 Comparison between model and scintillation data for S_4 versus day of year from DOY 244 to 273 (September 2014).

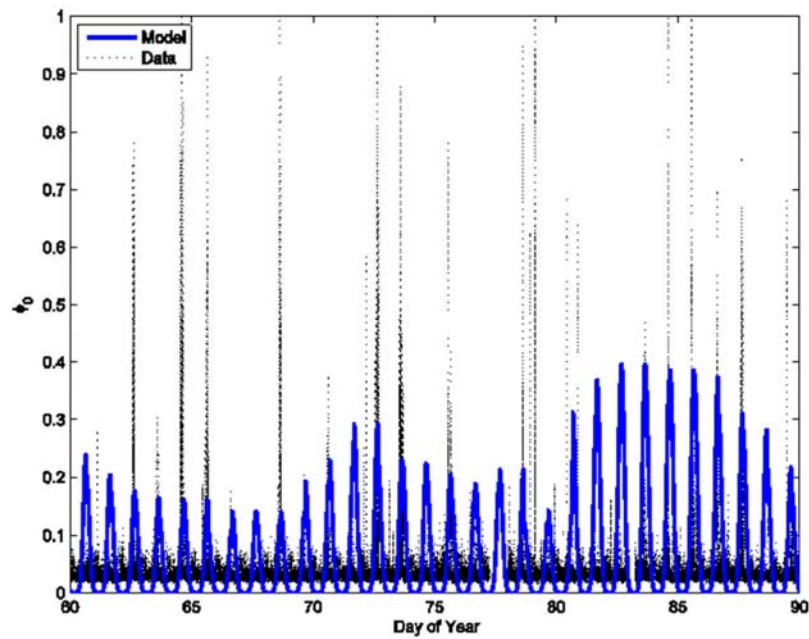


Figure 4-27 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 60 to 90 (March 2015).

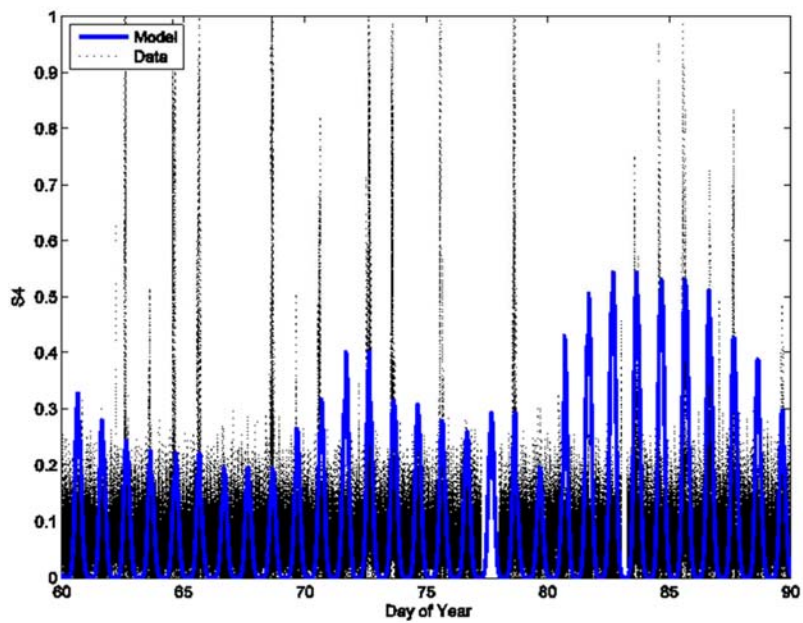


Figure 4-28 Comparison between model and scintillation data for S_4 versus day of year from DOY 60 to 90 (March 2015).

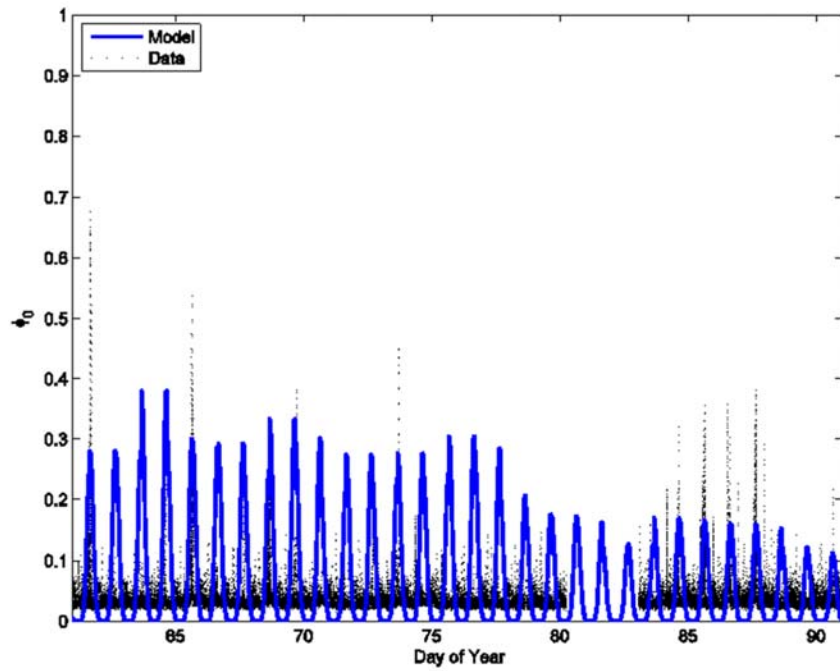


Figure 4-29 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 61 to 91 (March 2016).

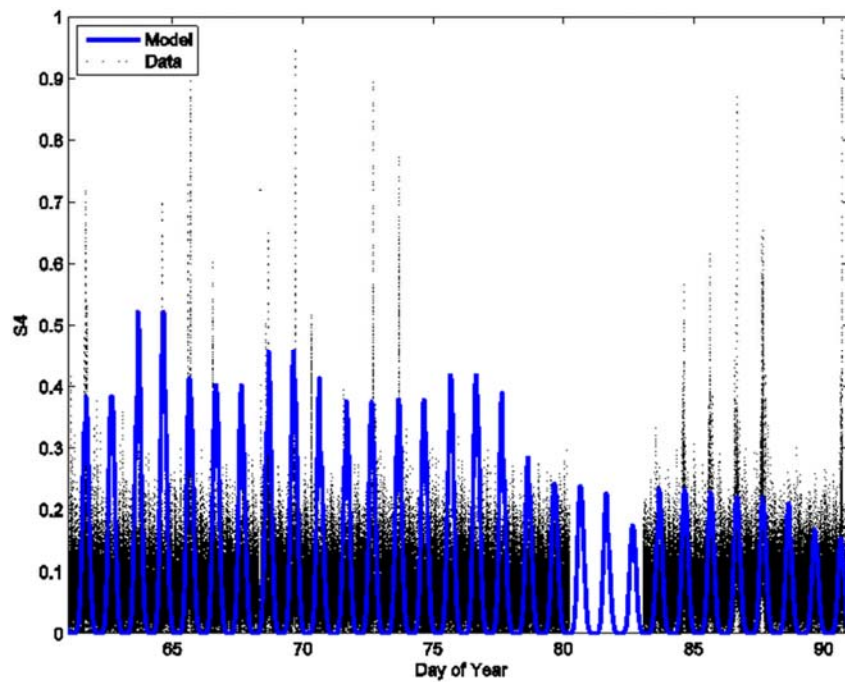


Figure 4-30 Comparison between model and scintillation data for S_4 versus day of year from DOY 61 to 91 (March 2016).

To further assess the accuracy of the proposed modified model across the equinox months, Figure 4-23 to Figure 4-26 compare the model and scintillation data across all days in March

and September 2014. For more recent data, Figure 4-27 to Figure 4-30 compare the model and scintillation data across all days in March 2015 and 2016. For the gaps shown in some of the figures, scintillation data is not available due to system malfunction and maintenance. It can be seen that the model predicts the scintillation pattern well diurnally, with scintillation events occurring during the post sunset period. In year 2016, less scintillation activity is also observed in equinox months as it has passed the solar maximum period. However, as scintillation is still a random process which are difficult to model, there are some discrepancies between the model and scintillation data in terms of scintillation level, especially at high scintillation level. This also coincides with the limitation of the model, under which the weak scatter condition is assumed [15]. Therefore, the model would not be able to predict scintillation level very accurately, more so during strong scintillation.

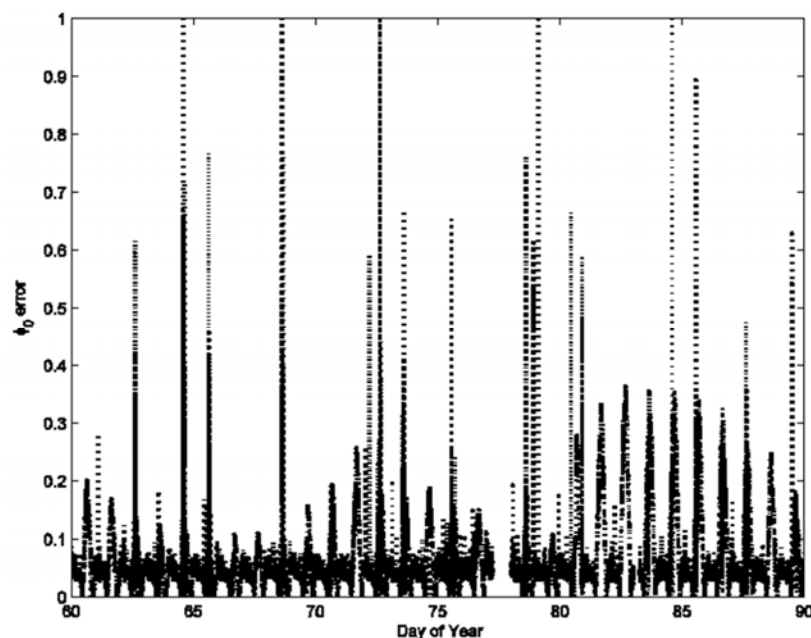


Figure 4-31 Plot of ϕ_0 error versus day of year from DOY 60 to 90 (March 2015).

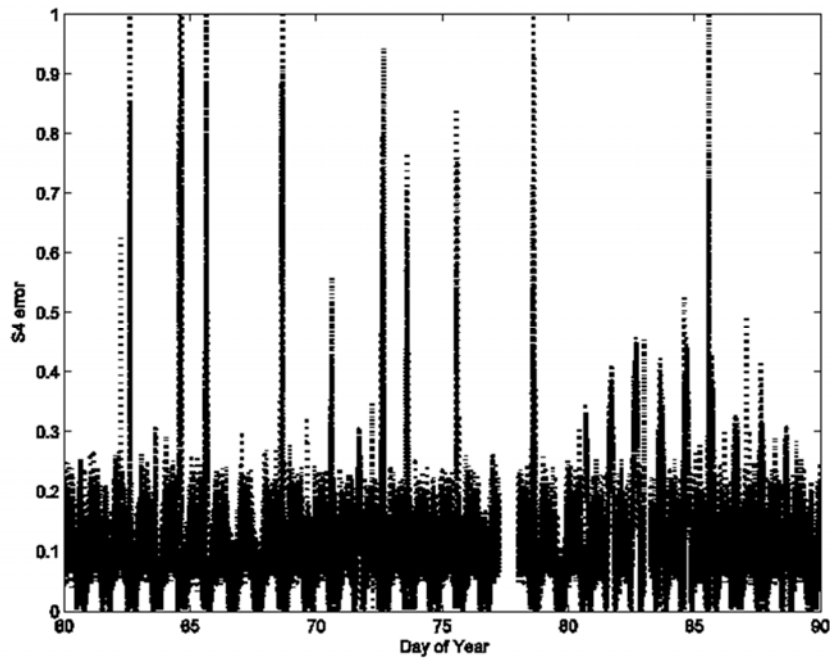


Figure 4-32 Plot of S_4 error versus day of year from DOY 60 to 90 (March 2015).

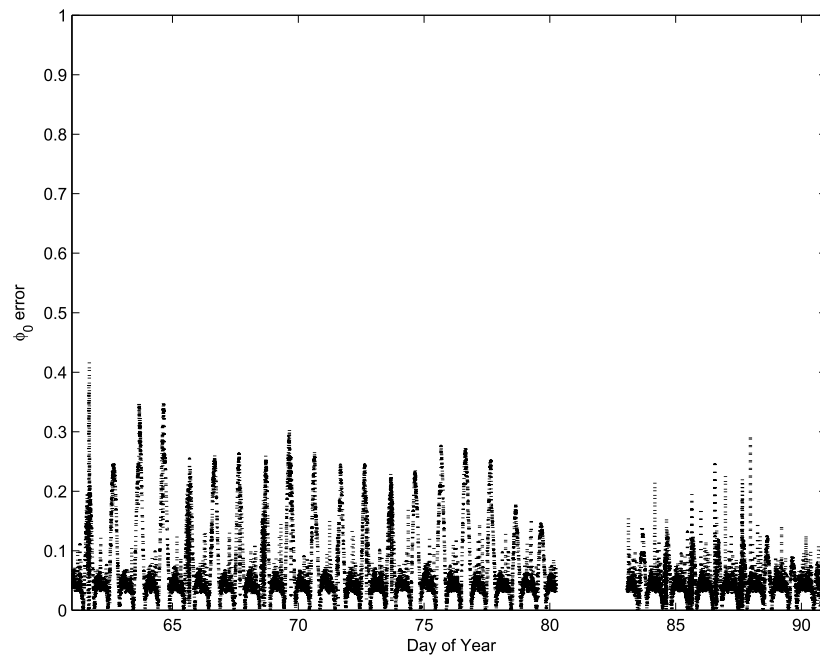


Figure 4-33 Plot of ϕ_0 error versus day of year from DOY 61 to 91 (March 2016).

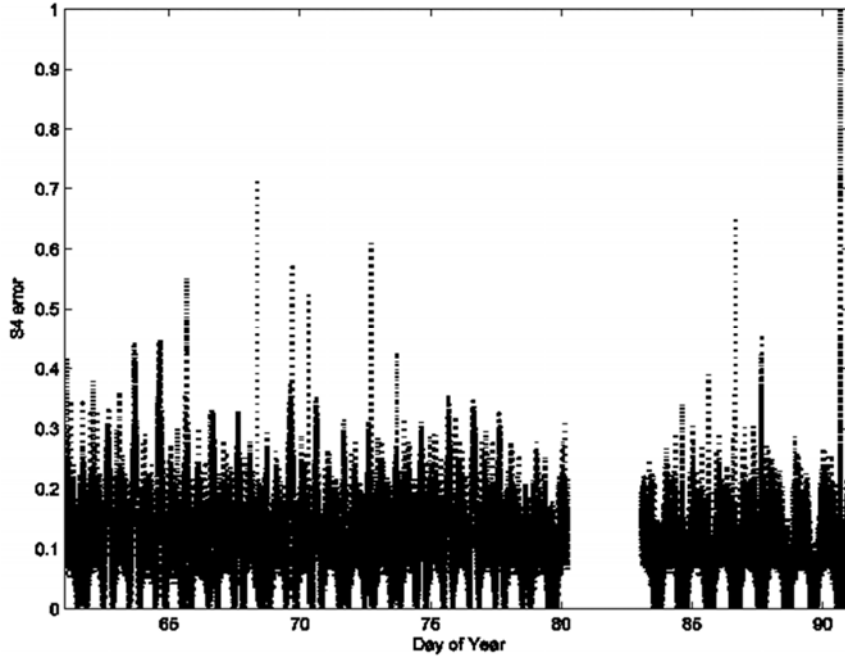


Figure 4-34 Plot of S_4 error versus day of year from DOY 61 to 91 (March 2016).

To quantify the errors of the model, We define the errors of ϕ_0 and S_4 of the model as

$$\phi_0 \text{ error} = |\phi_0 \text{ data} - \phi_0| \quad (4-27)$$

$$S_4 \text{ error} = |S_4 \text{ data} - S_4| \quad (4-28)$$

where $\phi_0 \text{ data}$ and $S_4 \text{ data}$ are ϕ_0 and S_4 obtained from Septentrio data, respectively, while ϕ_0 and S_4 are generated from the model. Figure 4-31 to Figure 4-34 plot the $\phi_0 \text{ error}$ and $S_4 \text{ error}$ in equinox month of March 2015 and 2016. It is first observed that there is a threshold error floor which results from the fact that the model is not able to capture the ϕ_0 and S_4 noise from the receiver. For S_4 the level is around 0.2 while for ϕ_0 the level is around 0.1. As mentioned before, the model would not be able to predict scintillation level very accurately, more so during strong scintillation. This results in several error peaks observed during scintillation event. Furthermore, as evident from Figure 4-11 to Figure 4-22, the model generally only predicts the slow varying envelope of scintillation pattern (trend) and not the fast fluctuation of scintillation event. All these contribute to the difference between the model and data in (4-27) and (4-28).

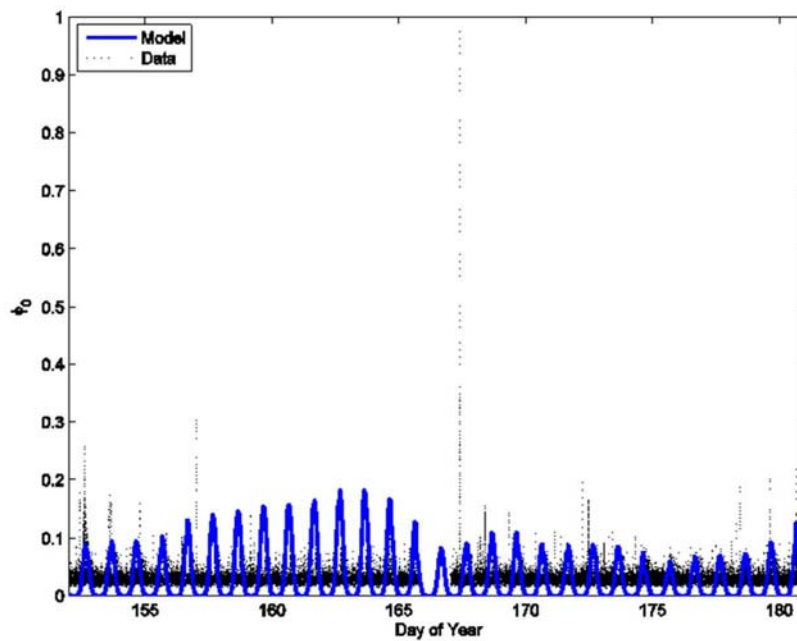


Figure 4-35 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 152 to 181 (June 2014).

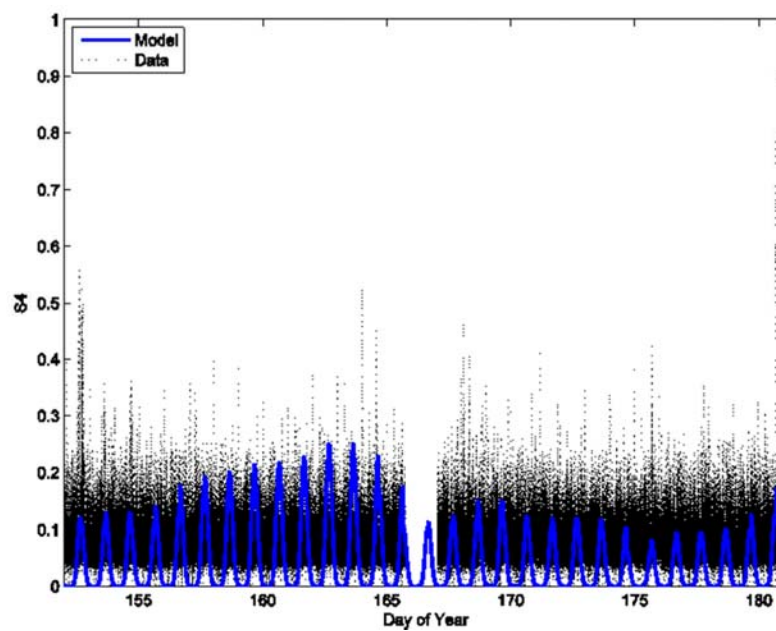


Figure 4-36 Comparison between model and scintillation data for S_4 versus day of year from DOY 152 to 181 (June 2014).

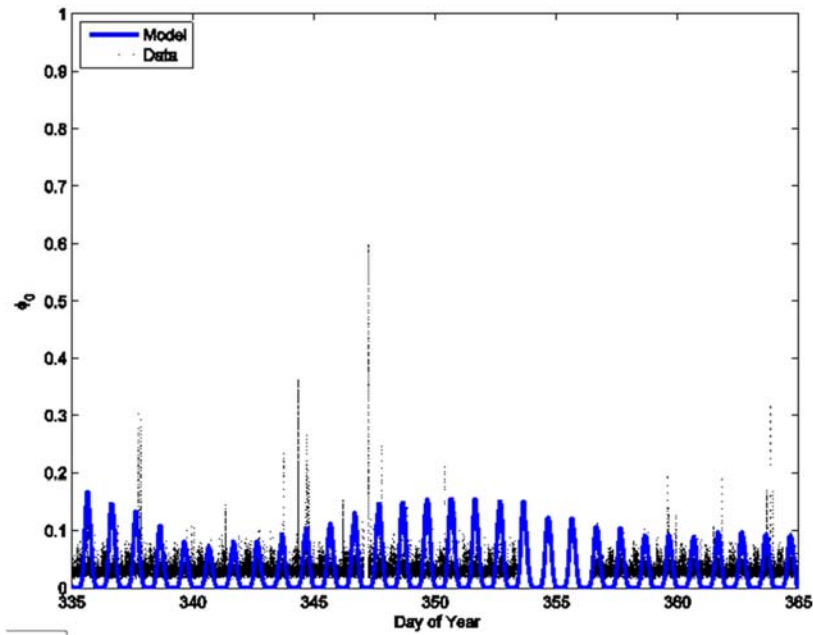


Figure 4-37 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 335 to 365 (December 2014).

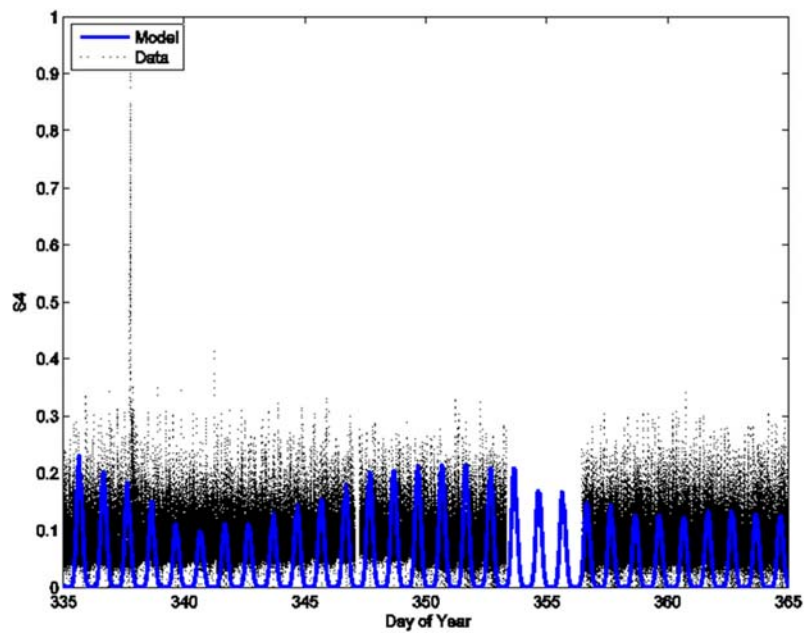


Figure 4-38 Comparison between model and scintillation data for S_4 versus day of year from DOY 335 to 365 (December 2014).

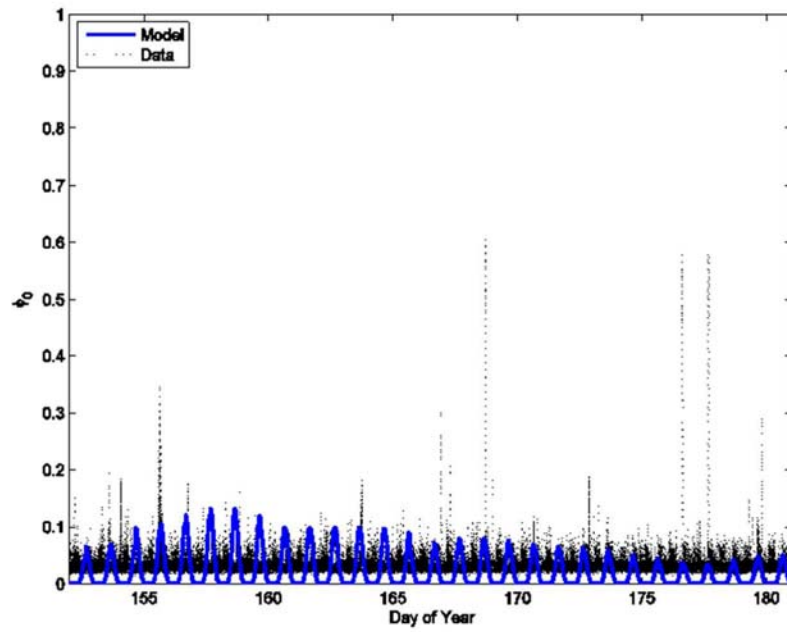


Figure 4-39 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 152 to 181 (June 2015).

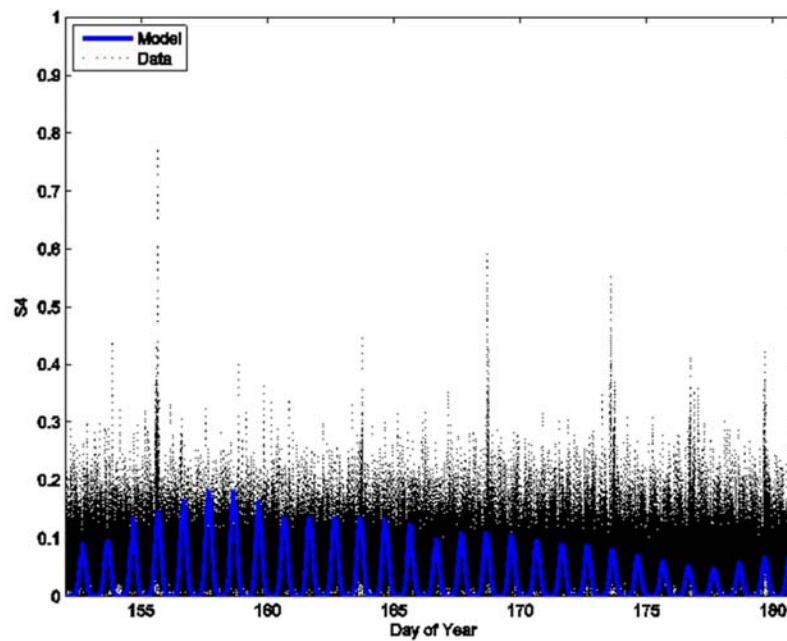


Figure 4-40 Comparison between model and scintillation data for S_4 versus day of year from DOY 152 to 181 (June 2015).

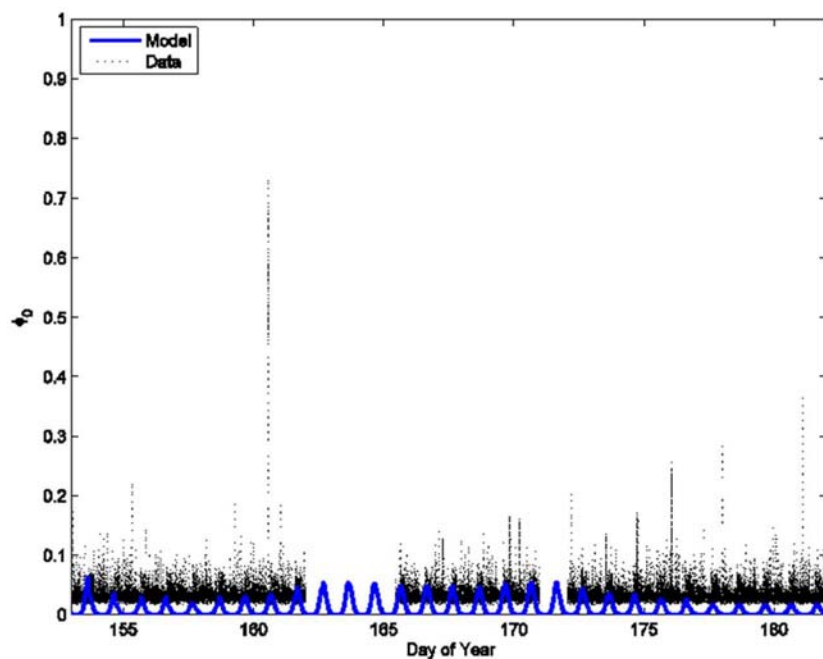


Figure 4-41 Comparison between model and scintillation data for ϕ_0 versus day of year from DOY 153 to 182 (June 2016).

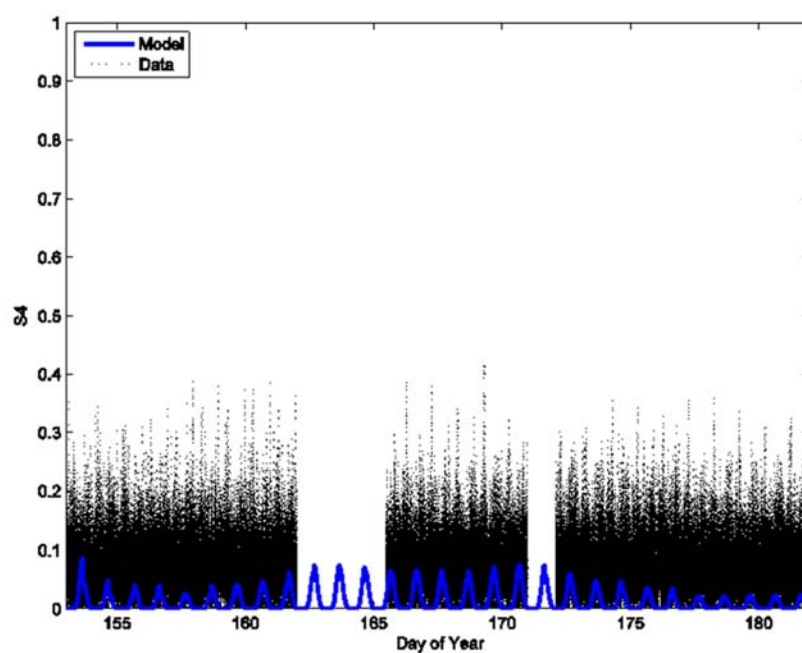


Figure 4-42 Comparison between model and scintillation data for S_4 versus day of year from DOY 153 to 182 (June 2016).

We also assess the accuracy of the proposed modified model across the summer (June 2014) and winter (December 2014) months, in which the ionosphere is generally quite during these period, shown in Figure 4-35 to Figure 4-38. For more recent data, Figure 4-39 to Figure 4-42

plot the model and scintillation data in June 2015 and 2016. It can be seen that the model is generally in good agreement with the scintillation data, depicting minimal scintillation events during these period. However, it again can be observed that the model is not able to capture the ϕ_0 and S_4 noise from the receiver, which results in model showing lower ϕ_0 and S_4 than the receiver data during quiet periods.

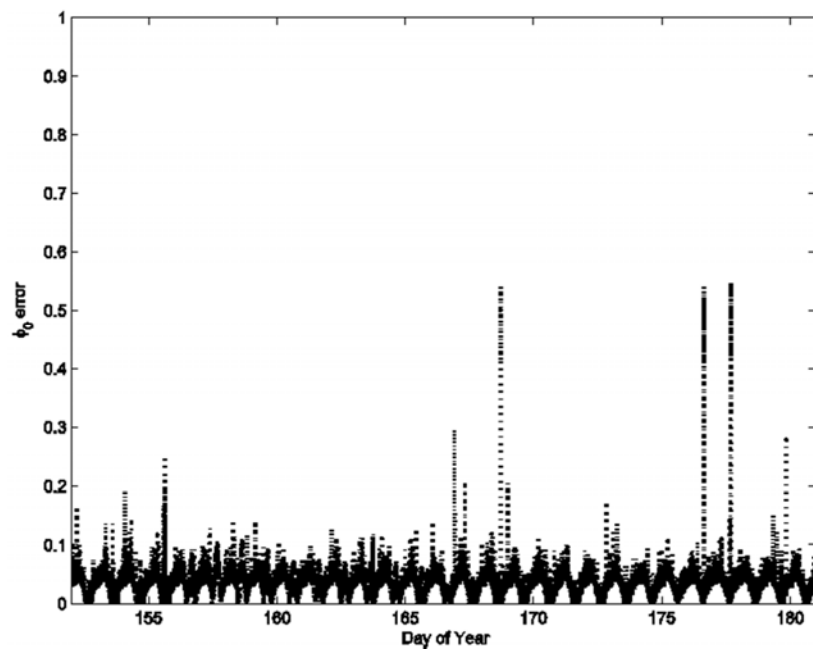


Figure 4-43 Plot of ϕ_0 error versus day of year from DOY 152 to 181 (June 2015).

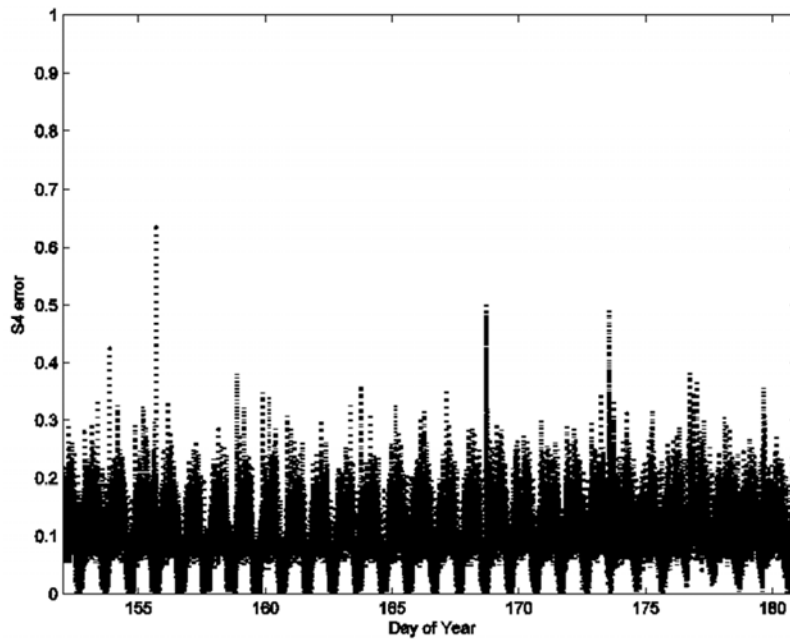


Figure 4-44 Plot of S_4 error versus day of year from DOY 152 to 181 (June 2015).

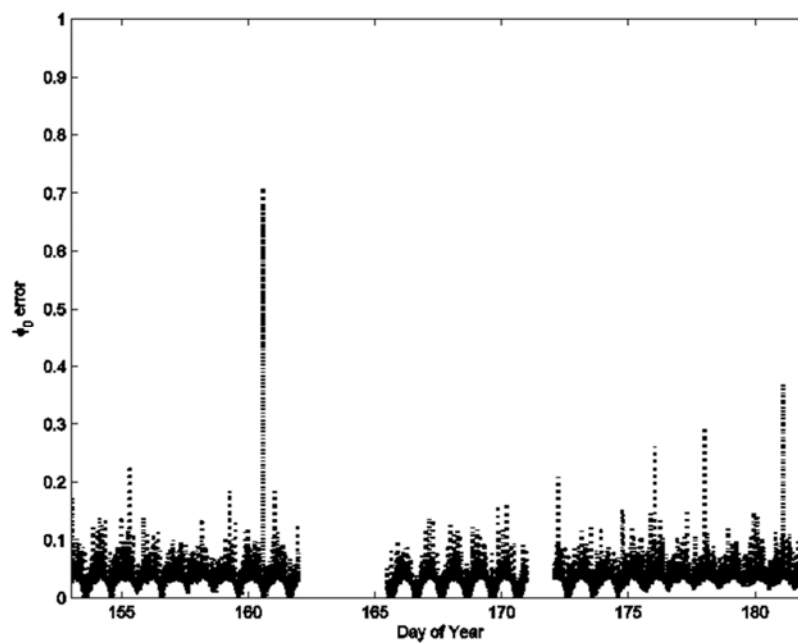


Figure 4-45 Plot of ϕ_0 error versus day of year from DOY 153 to 182 (June 2016).

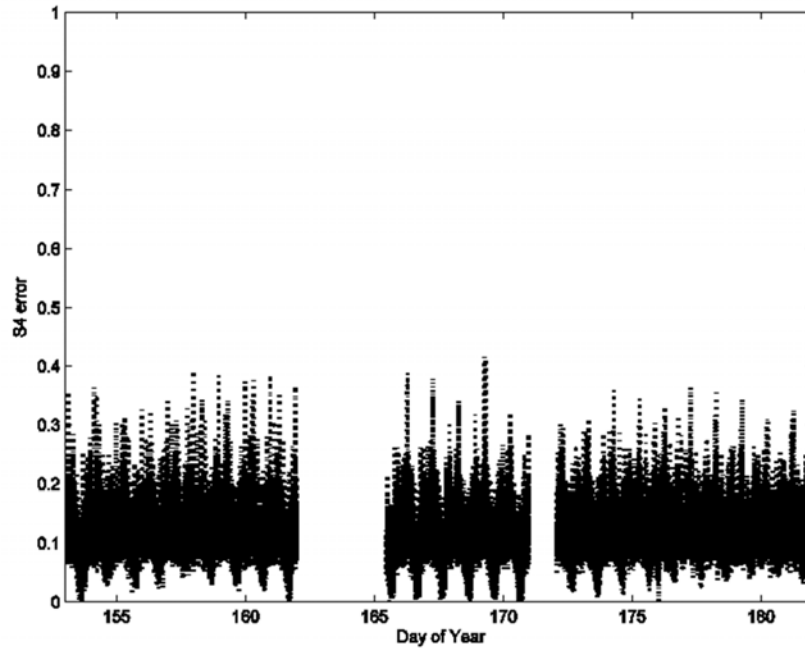


Figure 4-46 Plot of S_4 error versus day of year from DOY 153 to 182 (June 2016).

Figure 4-43 to Figure 4-46 now plot the ϕ_0 error and S_4 error in June 2015 and 2016. The threshold error floors of 0.2 for S_4 and 0.1 for ϕ_0 are again observable. There are also fewer error peaks observed during this period compared to equinox months.

Overall, the proposed scintillation model is useful to predict the seasonal and diurnal trend of the scintillation for GPS L1 frequency in Singapore equatorial region. It is able to describe the temporal occurrence of scintillation during seasonal peaks of equinox months, i.e., March, April, September and October and during post sunset periods of around 8pm to 2am. Nevertheless, there are several limitations on the model. As scintillation is a random process which is difficult to model, the exact scintillation levels could not be predicted very accurately, more so during strong scintillation. This is also partly due to the fact that the model is generally based on weak scatter assumption. The daytime scintillation is also not taken into consideration and assumed to be negligible compared to post sunset scintillation.

4.4. Gaussian Model

In this subsection, we shall make use of direct curve fitting to model the scintillation data in Singapore region for better accuracy. To this end, we let S4 to be represented by a simple multi term Gaussian model as follows:

$$S4 = \sum_{i=1}^N a_i \exp\left(-\frac{(t - b_i)^2}{c_i^2}\right) \quad (4-29)$$

where t is the local time. The coefficients a_i , b_i and c_i are to be determined as well as the number of Gaussian term N . These coefficients are determined based on the 90th percentile of S4 scintillation data collected for the months of March (equinox), June (summer), September (equinox) and December (winter) in the years of 2014, 2015 and 2016. For each day, the local time ranges from 8 to 32 (24+8) hour.

For year 2014, the coefficients and number of Gaussian term for various months are listed below as:

March 2014

$$N = 2$$

$$a_1 = 0.3141, b_1 = 22.48, c_1 = 1.826$$

$$a_2 = 0.1588, b_2 = 125.7, c_2 = 137.1$$

June 2014

$$N = 2$$

$$a_1 = 0.01414, b_1 = 26.72, c_1 = 3.765$$

$$a_2 = 0.1184, b_2 = -281, c_2 = 1171$$

September 2014

$$N = 2$$

$$a_1 = 0.2443, b_1 = 22.16, c_1 = 1.502$$

$$a_2 = 0.1206, b_2 = 17.8, c_2 = 46.63$$

December 2014

$$N = 2$$

$$a_1 = 0.1186, b_1 = 15.16, c_1 = 21.69$$

$$a_2 = 0.05109, b_2 = 32.63, c_2 = 7.906$$

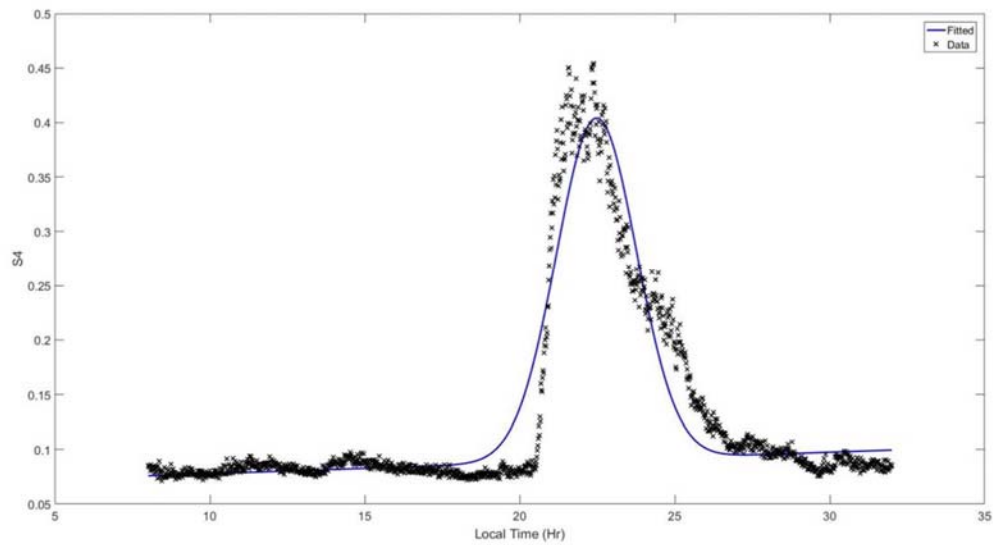


Figure 4-47 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for March 2014.

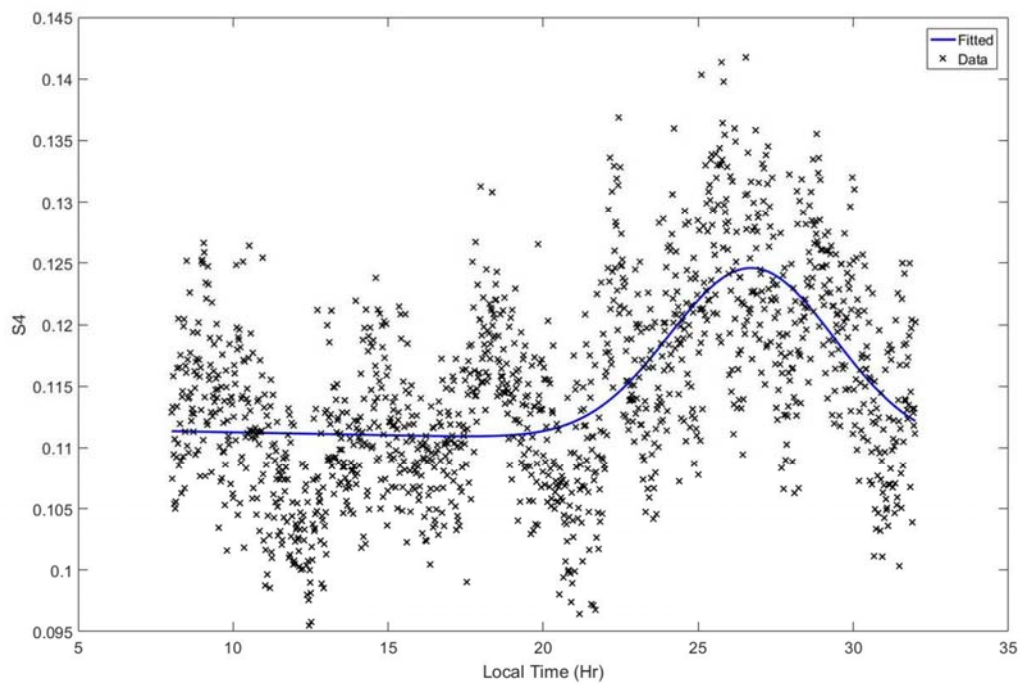


Figure 4-48 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for June 2014.

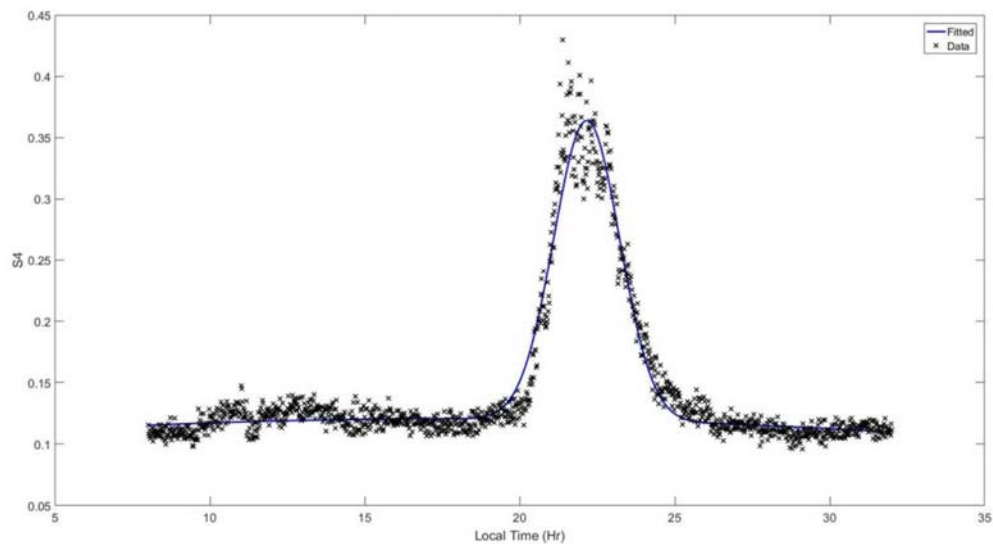


Figure 4-49 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for September 2014.

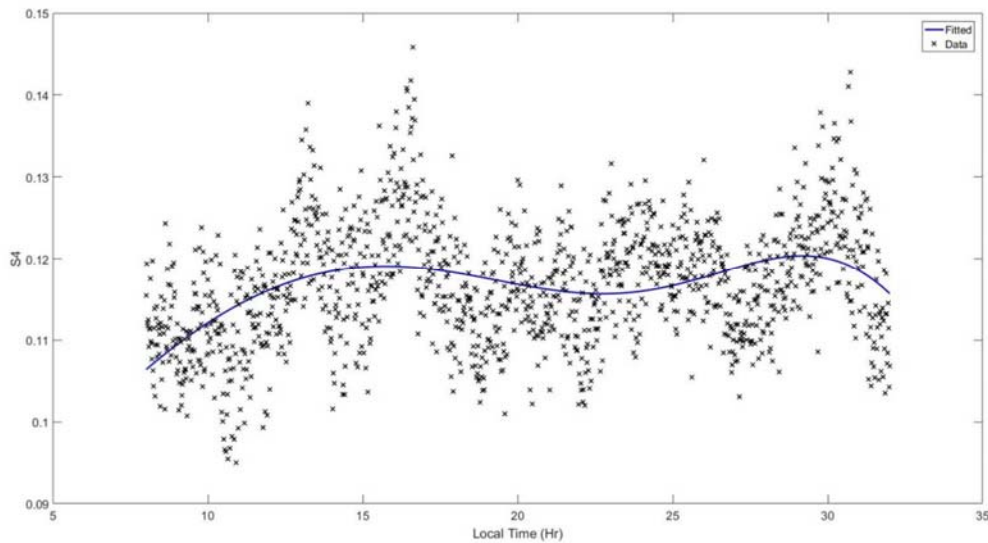


Figure 4-50 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for December 2014.

Figure 4-47 to Figure 4-50 show the comparison between the fitted Gaussian model and the 90th percentile S_4 scintillation data versus local time in March, June, September and December 2014, respectively. It is observed that the fitted model agrees well with the scintillation data. Generally, two Gaussian terms are needed for acceptable fitting accuracy. In the equinox months of March and September, the scintillation levels are higher as expected, reflected in the high coefficient a_i of these months compared to June and December. Scintillation peaks are also more obvious in these equinox months compared to June and December. Also as expected, the scintillation peaks occur around 20 to 25 (24+1) post sunset period.

For more recent data of year 2015 and 2016, the coefficients and number of Gaussian term for various months are listed below as:

March 2015

$$N = 3$$

$$a_1 = 0.09327, b_1 = 22.89, c_1 = 1.726$$

$$a_2 = 0.6493, b_2 = -466.7, c_2 = 362.1$$

$$a_3 = 0.01408, b_3 = 30.64, c_3 = 3.815$$

June 2015

$$N = 2$$

$$a_1 = 0.01701, b_1 = 27.39, c_1 = 3.958$$

$$a_2 = 0.1122, b_2 = 18.55, c_2 = 40.67$$

September 2015

$$N = 2$$

$$a_1 = 0.05078, b_1 = 22.32, c_1 = 1.226$$

$$a_2 = 0.08174, b_2 = 12.71, c_2 = 75.48$$

December 2015

$$N = 2$$

$$a_1 = 0.08122, b_1 = 14.86, c_1 = 21.72$$

$$a_2 = 0.03391, b_2 = 30.46, c_2 = 5.197$$

March 2016

$$N = 3$$

$$a_1 = 45.9, b_1 = 27.34, c_1 = 4.006$$

$$a_2 = 0.1139, b_2 = 7.347, c_2 = 23.72$$

$$a_3 = -45.86, b_3 = 27.34, c_3 = 4$$

June 2016

$$N = 2$$

$$a_1 = 0.04811, b_1 = 29.4, c_1 = 5.453$$

$$a_2 = 0.09938, b_2 = 15.04, c_2 = 19.26$$

September 2016

$$N = 2$$

$$a_1 = 0.02367, b_1 = 9.989, c_1 = 3.097$$

$$a_2 = 0.1228, b_2 = 21.84, c_2 = 30.93$$

December 2016

$$N = 1$$

$$a_1 = 0.07778, b_1 = 24.2, c_1 = 103.1$$

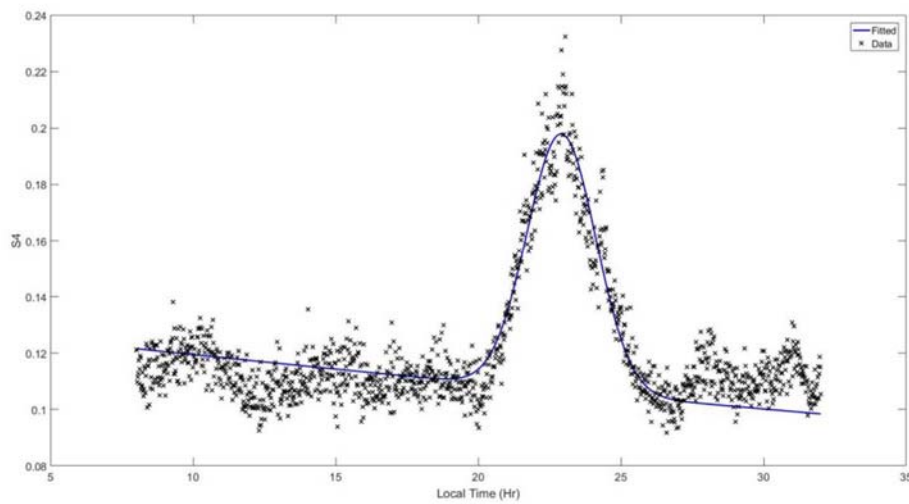


Figure 4-51 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for March 2015.

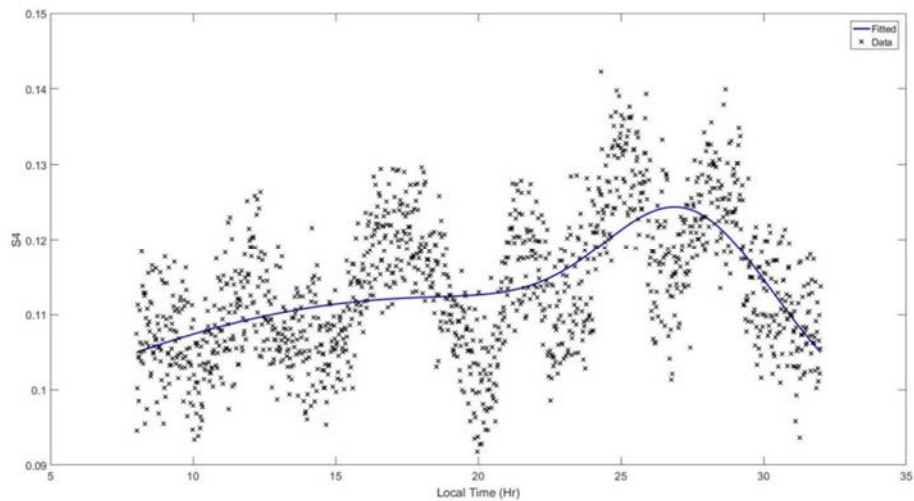


Figure 4-52 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for June 2015.

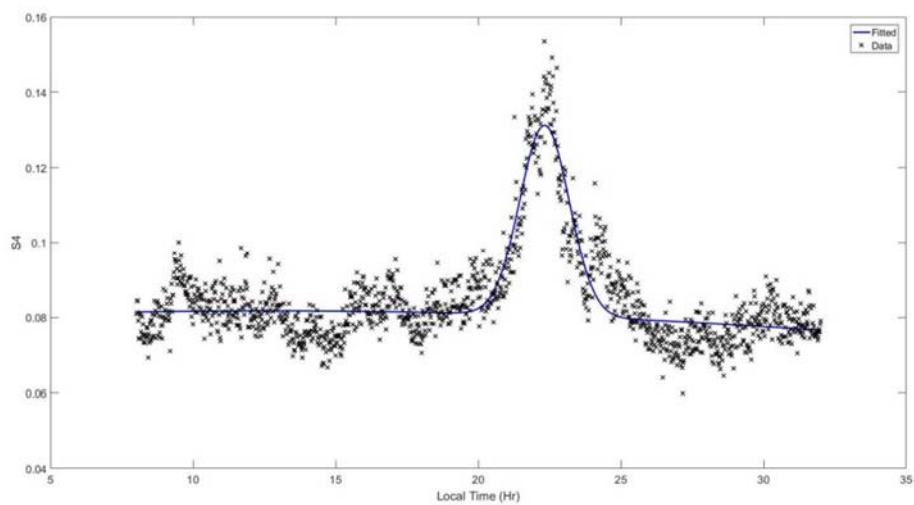


Figure 4-53 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for September 2015.

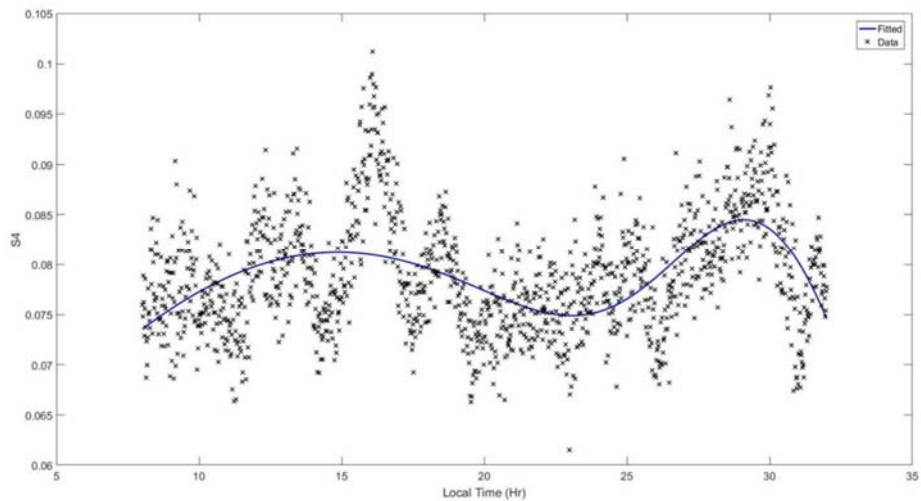


Figure 4-54 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for December 2015.

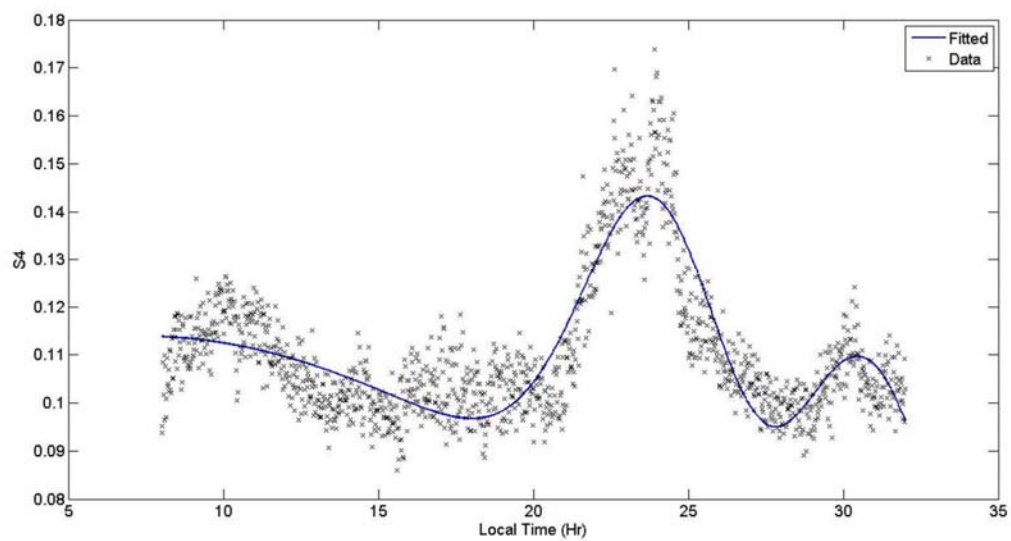


Figure 4-55 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for March 2016.

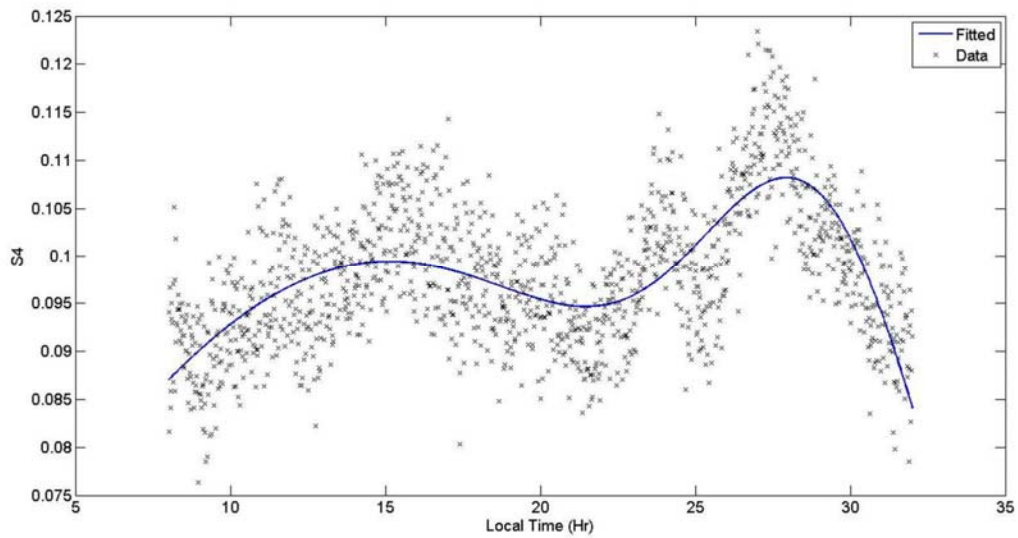


Figure 4-56 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for June 2016.

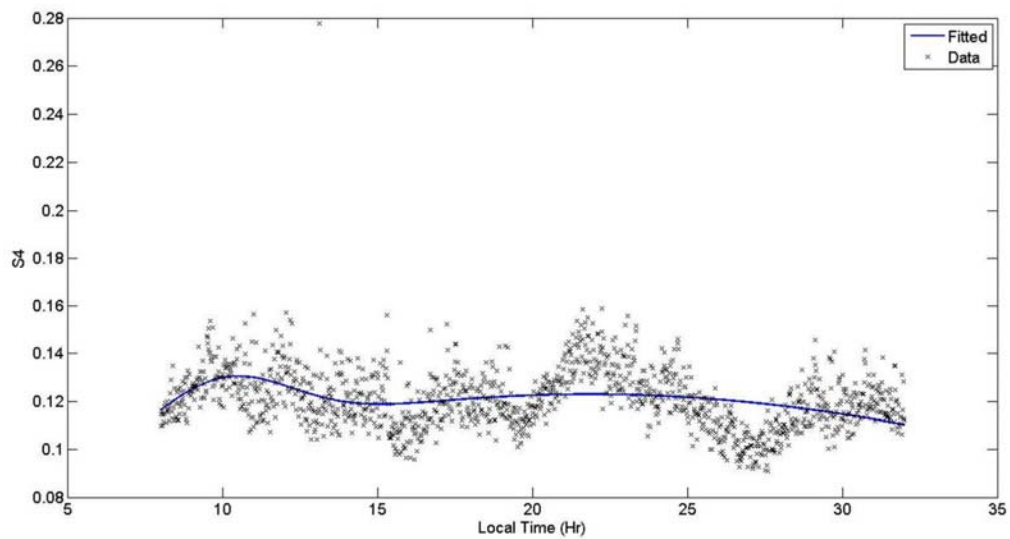


Figure 4-57 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for September 2016.

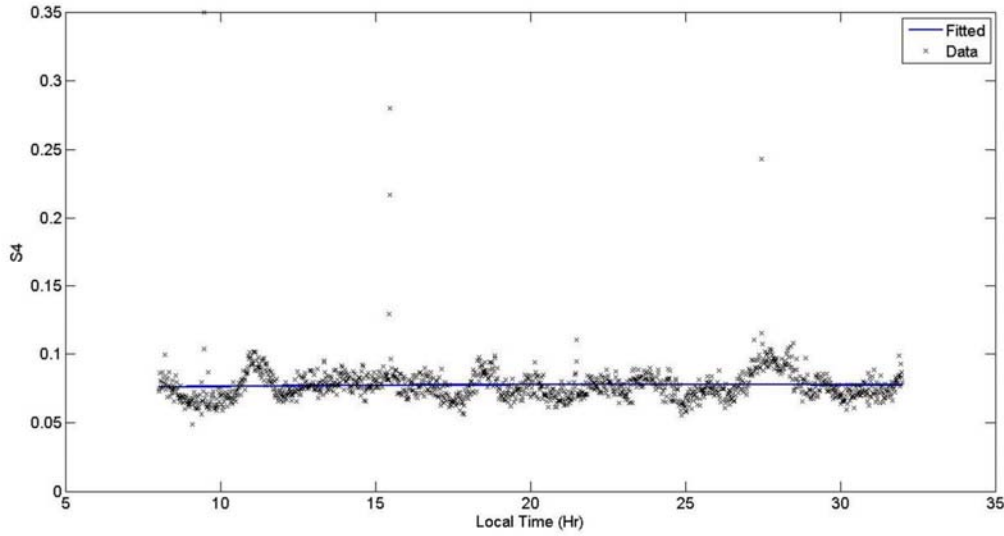


Figure 4-58 Comparison between fitted model and 90th percentile scintillation data for S_4 versus local time for December 2016.

Figure 4-51 to Figure 4-58 show the comparison between the fitted Gaussian model and the 90th percentile S_4 scintillation data versus local time in March, June, September, December 2015 and March, June, September, December 2016, respectively. Again, the fitted model agrees well with the scintillation data. In equinox months of March and September of both years, scintillation level is also higher compared to other months. Comparing the equinox months across years 2014 to 2016, one important observation is that the scintillation level decreases gradually from year 2014 to 2016. This is due to the fact that the solar cycle is transitioning towards solar minimum. This can be seen clearly in the equinox month of September 2016, c.f. Figure 4-57, where the scintillation level in this month no longer shows clear scintillation peak.

Instead of multi-term Gaussian model used earlier, we shall now simplify the Gaussian model with only one Gaussian term and a constant as follows, which also includes the sunspot number as the input:

$$S_4(t, SN) = \frac{SN}{SN_0} a_1 \exp\left(-\frac{(t - b_1)^2}{c_1^2}\right) + d_1 \quad (4-30)$$

where t is the local time and SN is the sunspot number. SN_0 is the reference sunspot number and a_1 , b_1 , c_1 and d_1 are Gaussian coefficients. These values are again to be determined based on fitting of 90th percentile of scintillation data.

For high scintillation activity months such as the equinox months, the model parameters are determined as follows:

$$SN_0 = 123.7, a_1 = 0.3078, b_1 = 22.46, c_1 = 1.738, d_1 = 0.1$$

We shall now compare the model with the scintillation data collected in Singapore for equinox months. The monthly sunspot numbers are obtained from [33].

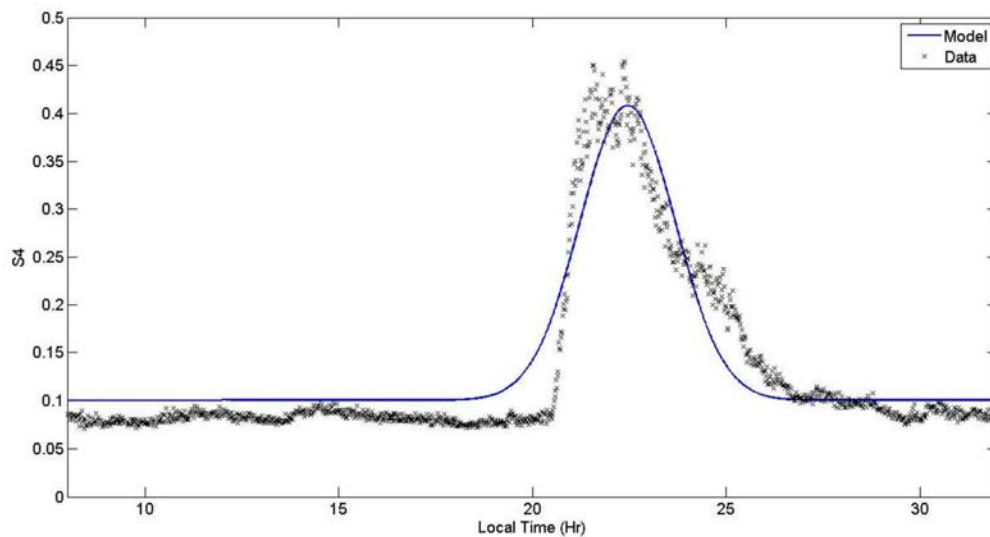


Figure 4-59 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for March 2014. Monthly sunspot number is 123.7.

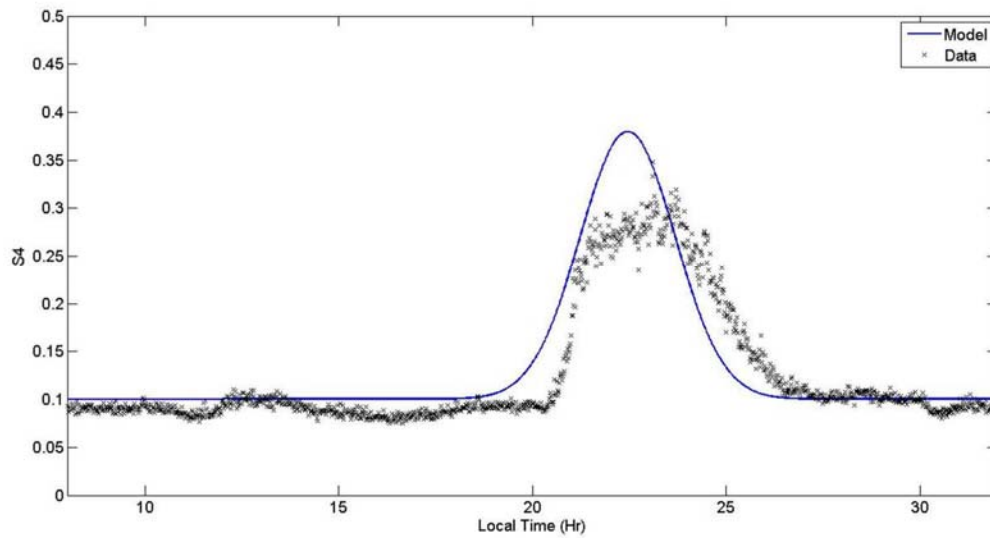


Figure 4-60 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for April 2014. Monthly sunspot number is 112.5.

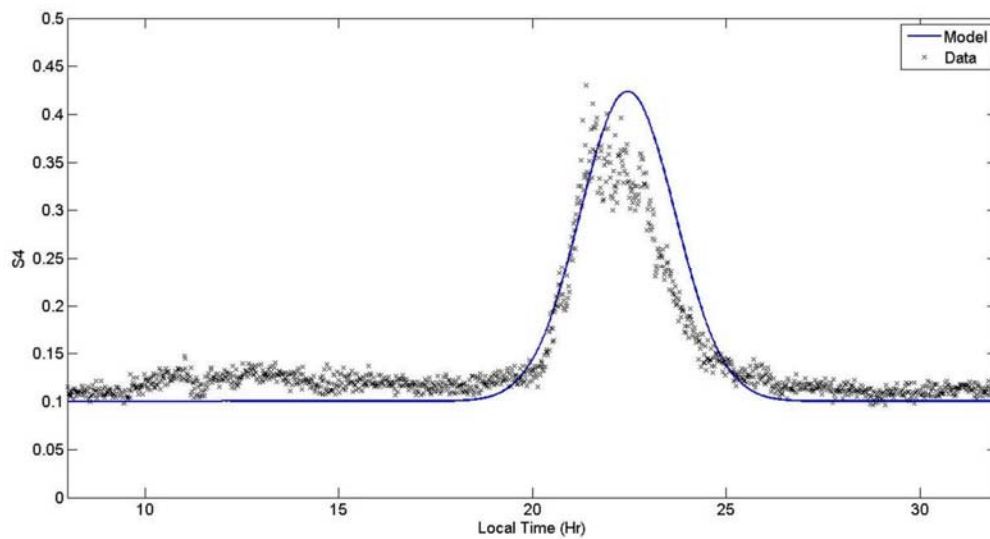


Figure 4-61 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for September 2014. Monthly sunspot number is 130.

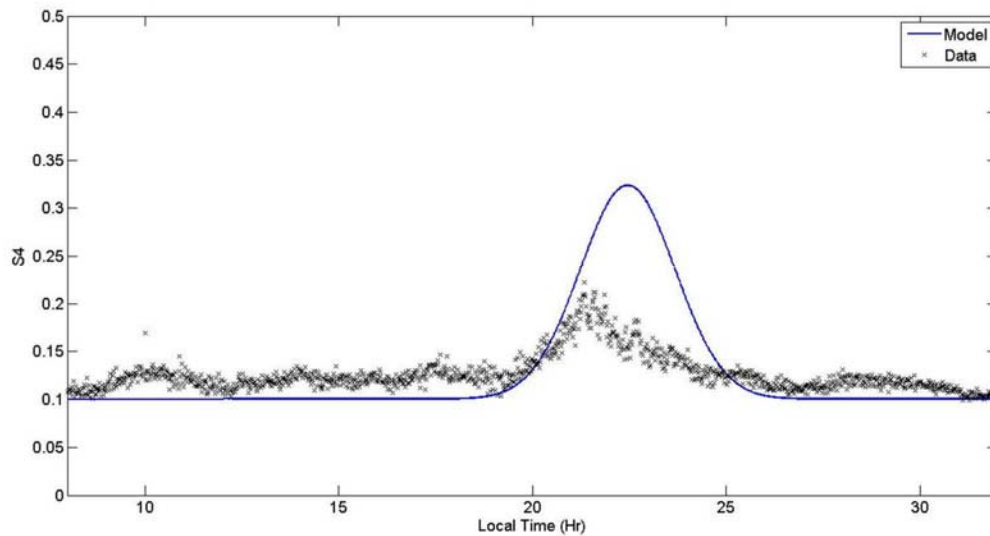


Figure 4-62 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for October 2014. Monthly sunspot number is 90.

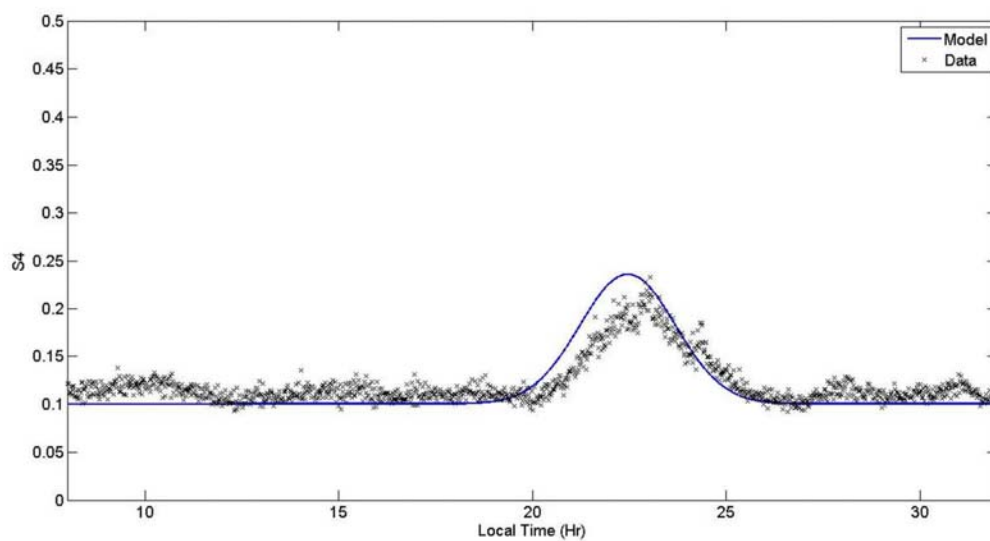


Figure 4-63 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for March 2015. Monthly sunspot number is 54.5.

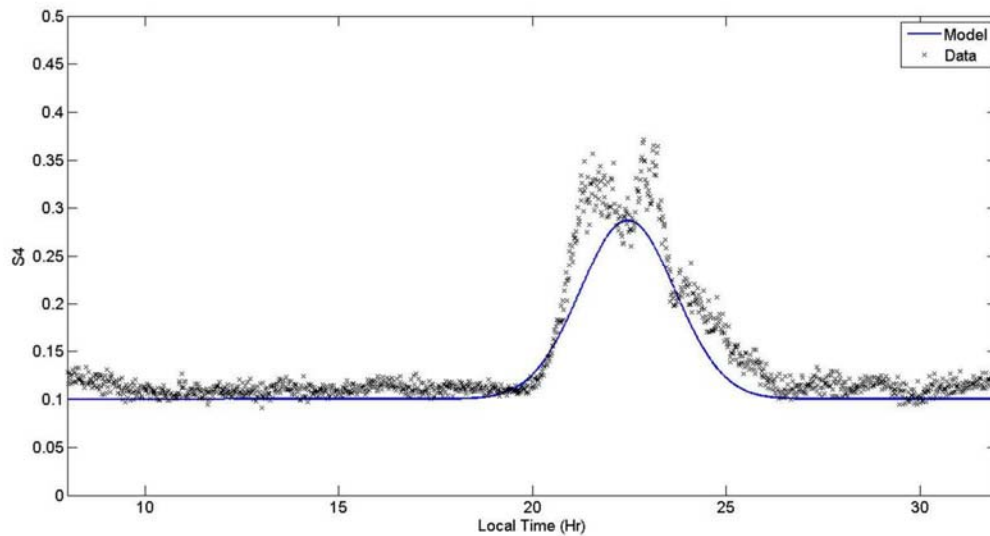


Figure 4-64 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for April 2015. Monthly sunspot number is 75.3.

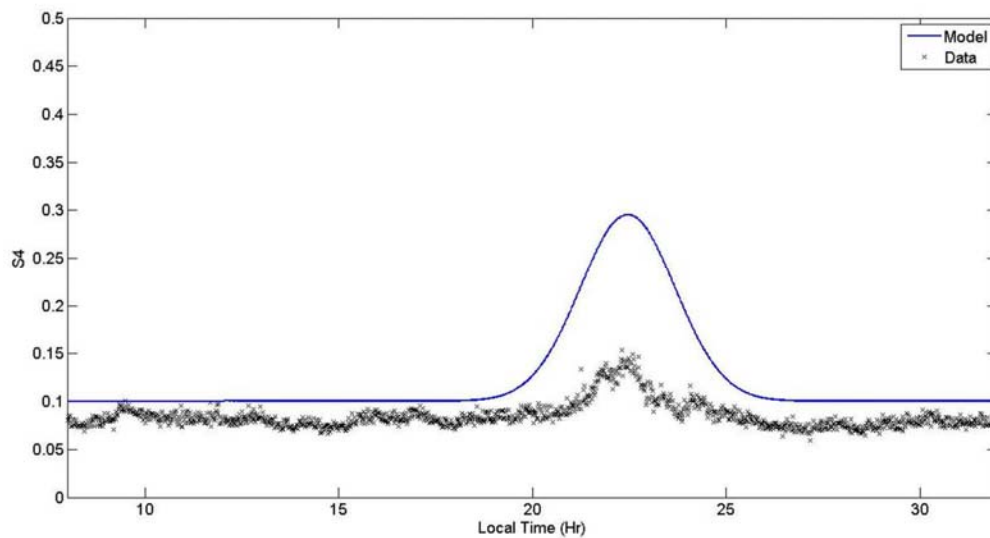


Figure 4-65 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for September 2015. Monthly sunspot number is 78.6.

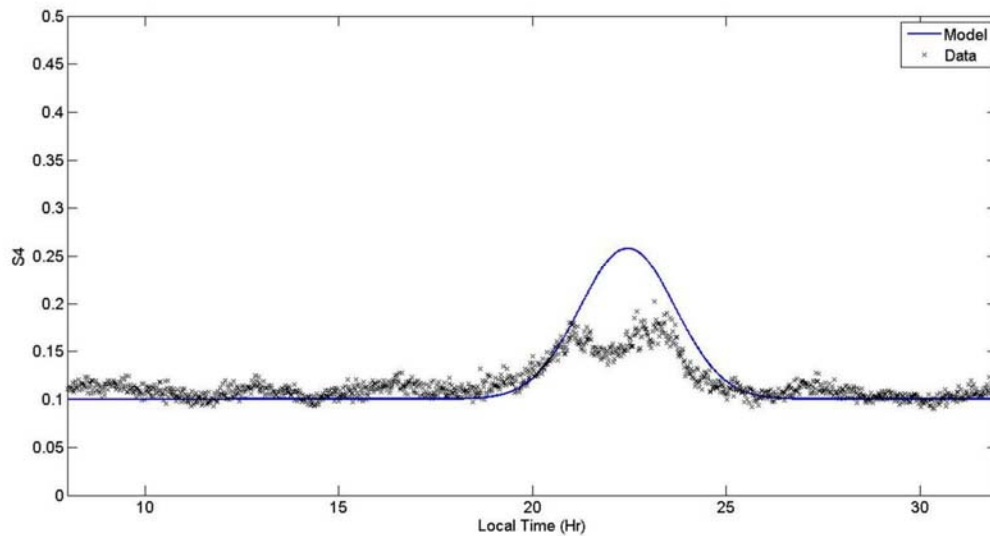


Figure 4-66 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for October 2015. Monthly sunspot number is 63.6.

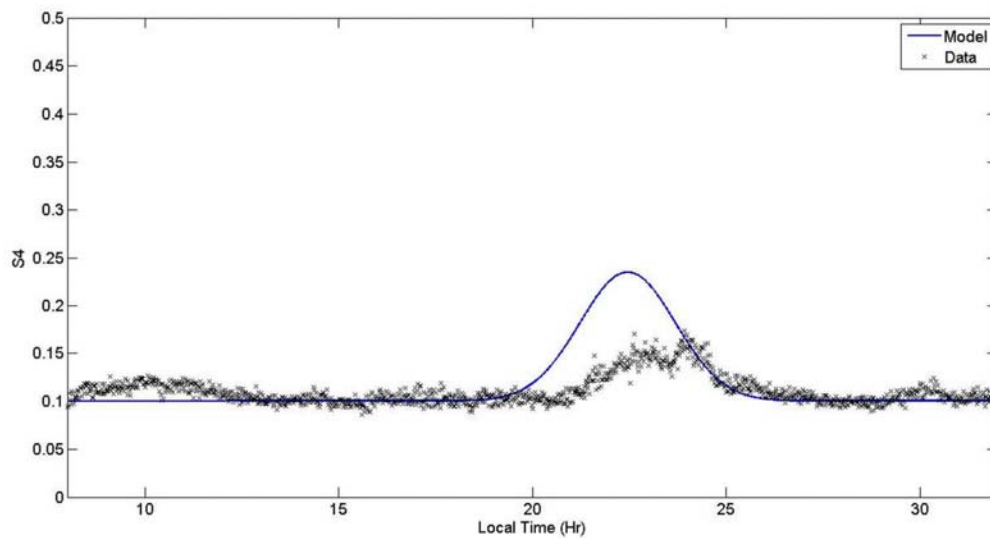


Figure 4-67 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for March 2016. Monthly sunspot number is 54.1.

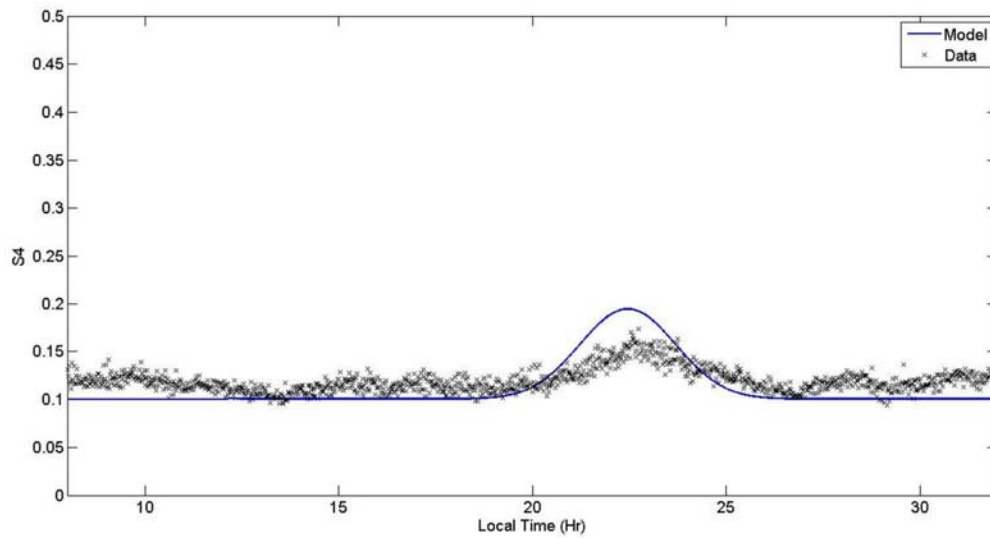


Figure 4-68 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for April 2016. Monthly sunspot number is 37.9.

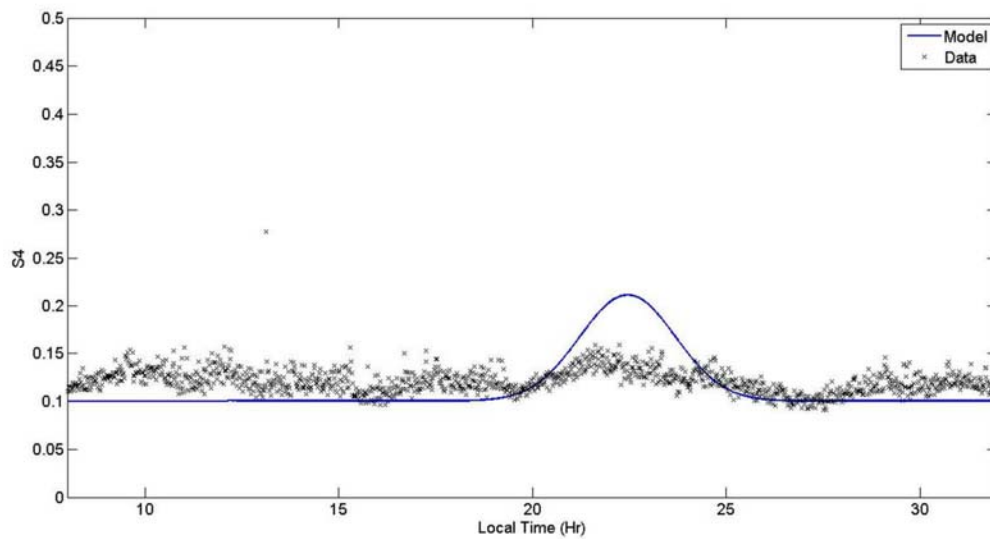


Figure 4-69 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for September 2016. Monthly sunspot number is 44.6.

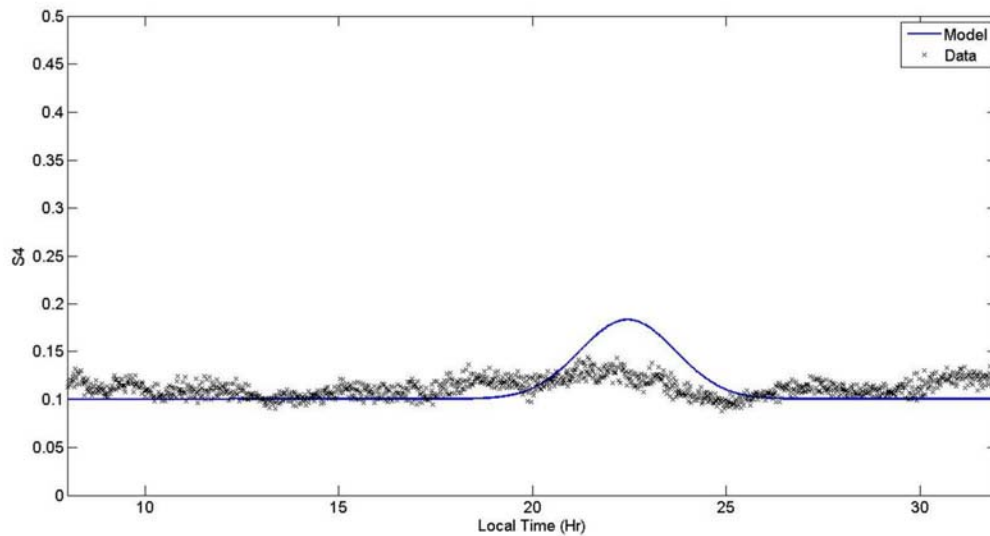


Figure 4-70 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for October 2016. Monthly sunspot number is 33.4.

Figure 4-59 to Figure 4-70 plots the comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for equinox months of March, April, September and October in year 2014, 2015 and 2016. Overall, it can be seen that the one term Gaussian model predicts the scintillation relatively well for the equinox months. Scintillation is predicted to center around 10pm and the scintillation level are also predicted relatively well by the Gaussian model.

For low scintillation activity months such as the summer and winter months, the model parameters are determined as follows:

$$SN_0 = 102.9, a_1 = 0.0195, b_1 = 33.8, c_1 = 27.23, d_1 = 0.1$$

We shall now compare the model with the scintillation data collected in Singapore for summer and winter months.

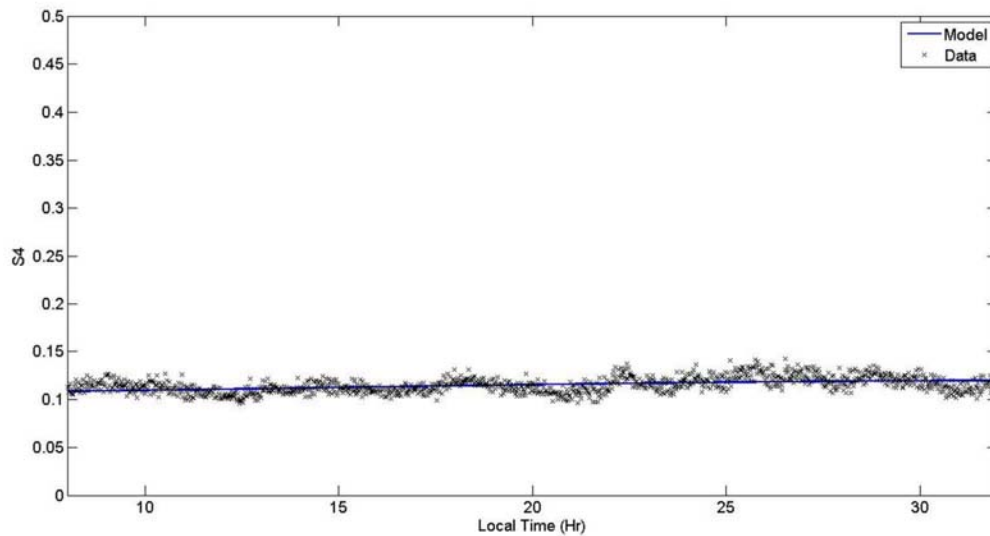


Figure 4-71 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for June 2014. Monthly sunspot number is 102.9.

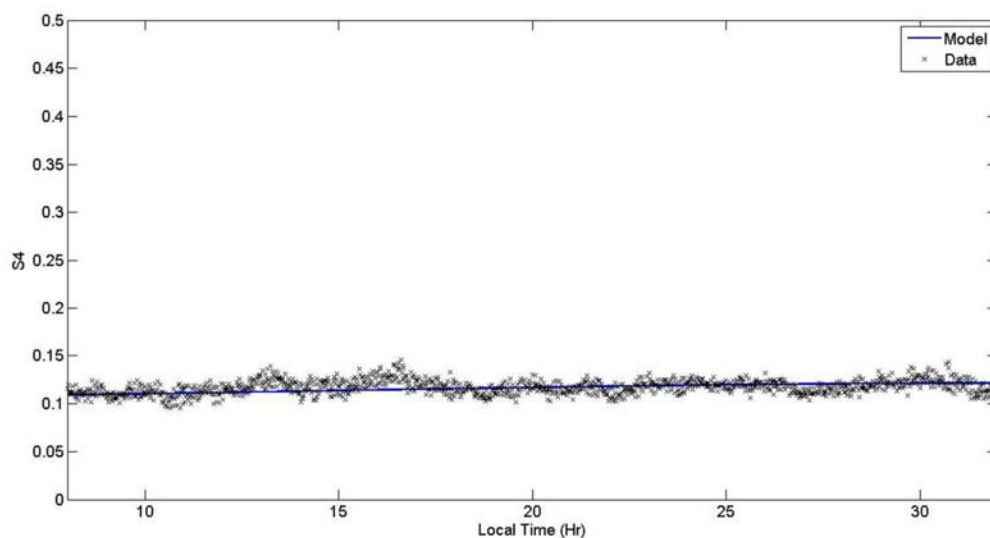


Figure 4-72 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for December 2014. Monthly sunspot number is 112.9.

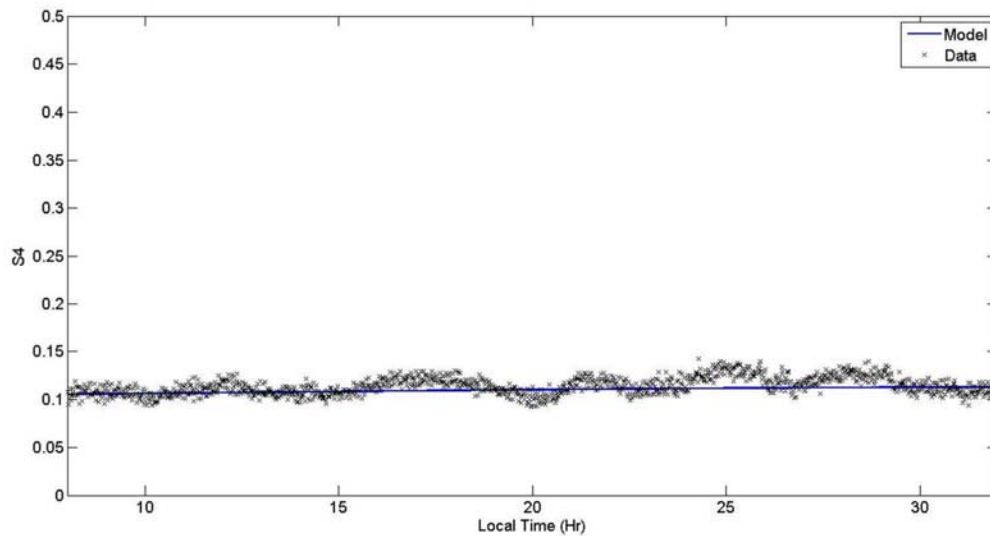


Figure 4-73 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for June 2015. Monthly sunspot number is 66.5.

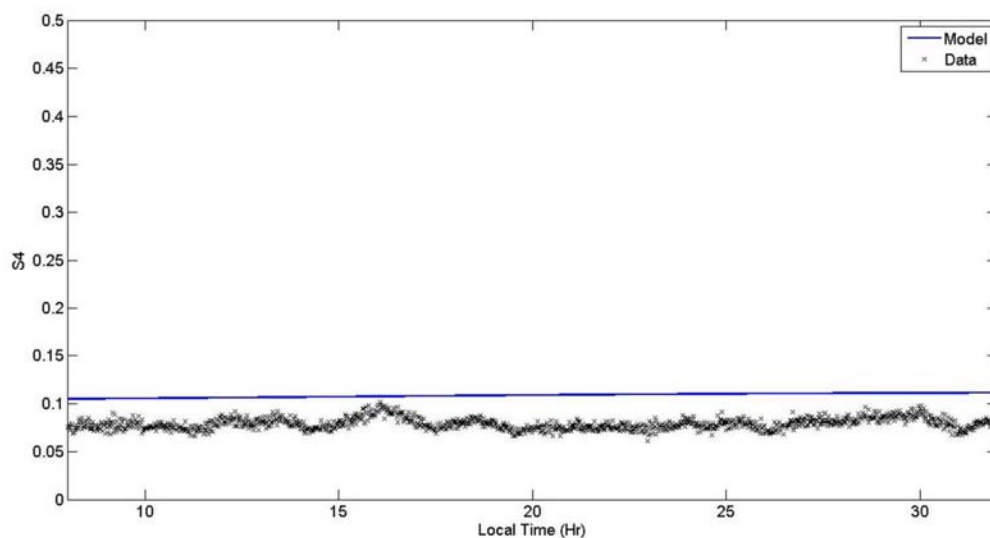


Figure 4-74 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for December 2015. Monthly sunspot number is 58.

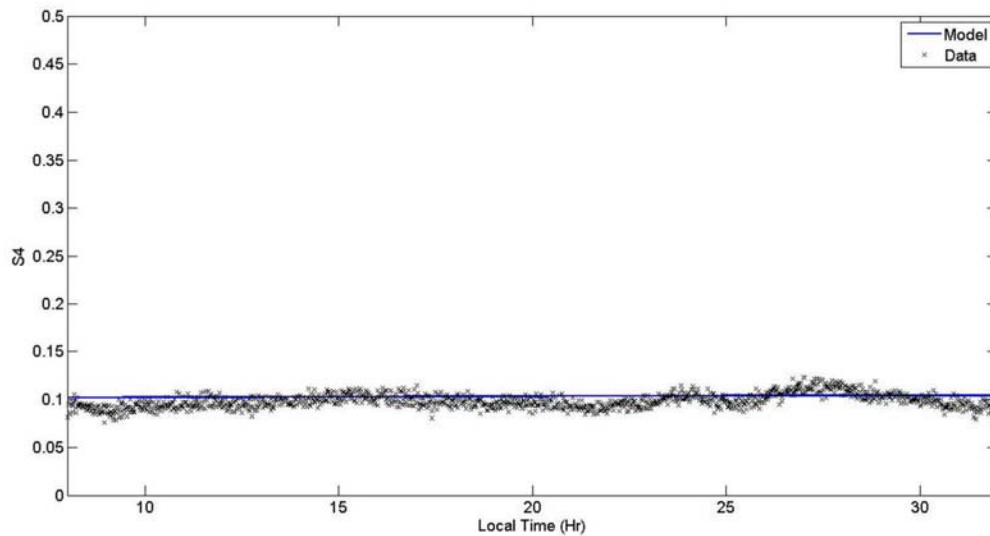


Figure 4-75 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for June 2016. Monthly sunspot number is 20.5.

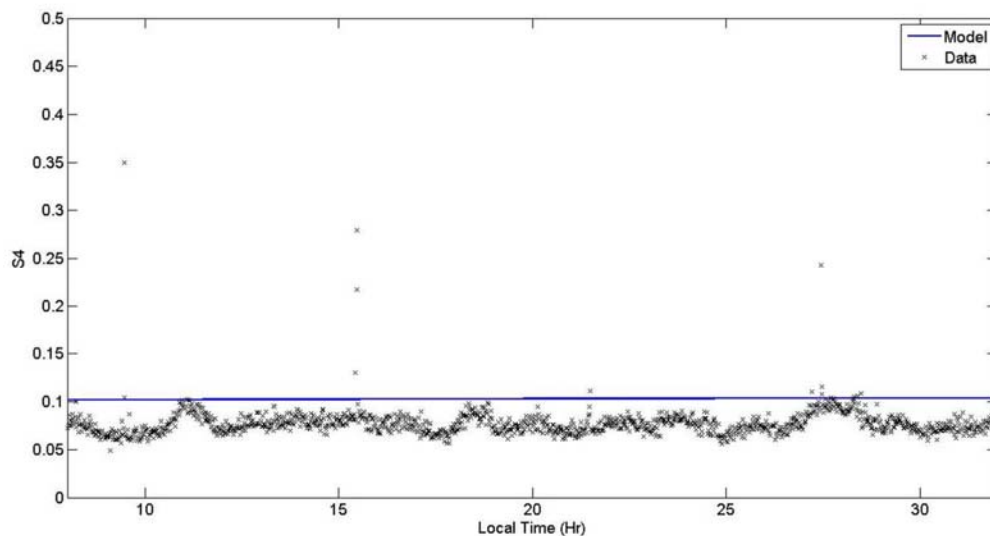


Figure 4-76 Comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for December 2016. Monthly sunspot number is 18.

Figure 4-71 to Figure 4-76 shows the comparison between one term Gaussian model and 90th percentile scintillation data for S_4 versus local time for summer and winter months of June and December in the year of 2014, 2015 and 2016. It can be seen that in these quiet months,

the model and the scintillation data also agrees relatively well. The model predicts low level of scintillation activity during these quiet months. Overall, the one term Gaussian model predicts relatively well the scintillation activity in Singapore equatorial region.

5. Technical Collaborations with AFRL

This project is also partly in collaboration with AFRL and university counterparts Prof. Jade Morton from Colorado State University and Prof. Frank van Graas from Ohio University. The project is tasked to investigate the ionospheric scintillation patterns and events in Singapore equatorial region. Some of the results and analysis have been shown in Section 3 of this report. For the most recent task, the US team comprising Mr. Neeraj Pujara from AFRL, Prof. Jade Morton from Colorado State University and Prof. Frank van Graas from Ohio University visited Singapore from 14 to 18 March 2016 for technical discussions on recording of scintillation data using a high gain mesh antenna. It is intended to investigate the scintillation indices calculated from high gain antenna raw data and compare them with those provided by Septentrio receiver. The antenna is a 1.9 m mesh antenna from RF Hamdesign with a L band LHCP helix dish feed and a controllable rotor. The gain and -3 dB angle specifications are provided as follows:

Frequency	Gain dB	-3dB angle (dgr)
1296 MHz	24.2	9.1
2320 MHz	29.2	5.1
3456 MHz	32.4	3.4
5760 MHz	35.9	2.0



Figure 5-1 Skeleton of the mesh antenna

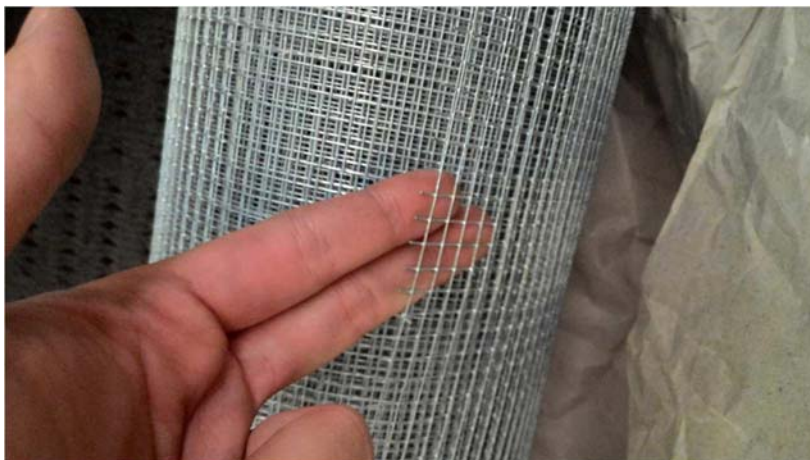


Figure 5-2 Wire mesh

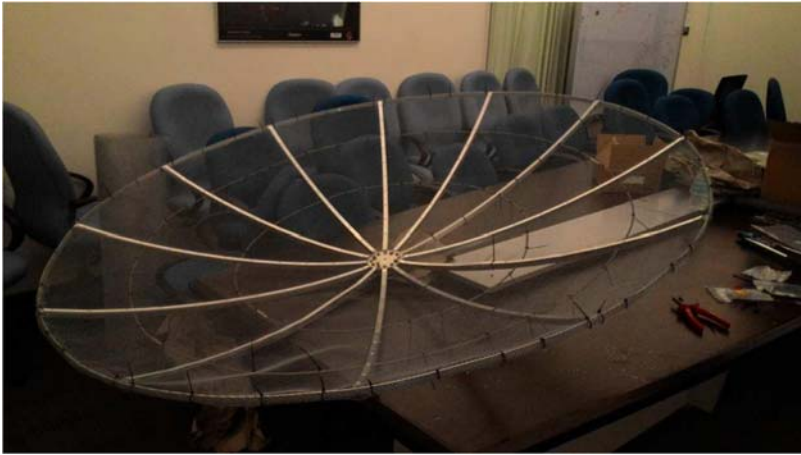


Figure 5-3 Wire mesh fitted onto the skeleton

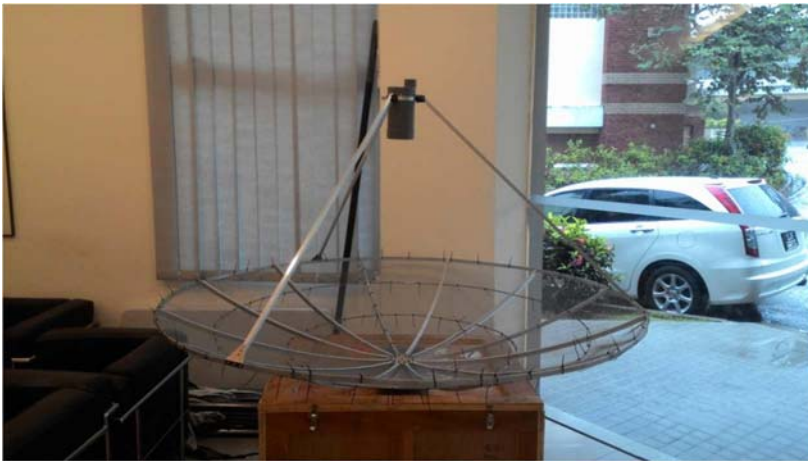


Figure 5-4 Mesh antenna with LHCP helix dish feed



Figure 5-5 Completed mesh antenna with rotor and base structure

Figure 5-1-Figure 5-5 show the process of assembling the 1.9 m mesh antenna from its individual components such as the skeleton, wire mesh, helix dish feed and base structure. The mesh antenna is assembled and fixed at the rooftop of NUS SWIFT building. The mesh antenna can be rotated in azimuthal and elevation angles via a controlled rotor, with the rotor and the corresponding controller shown in Figure 5-6 and Figure 5-7.



Figure 5-6 Rotor used to rotate the mesh antenna in both azimuthal and elevation direction



Figure 5-7 Rotor controller

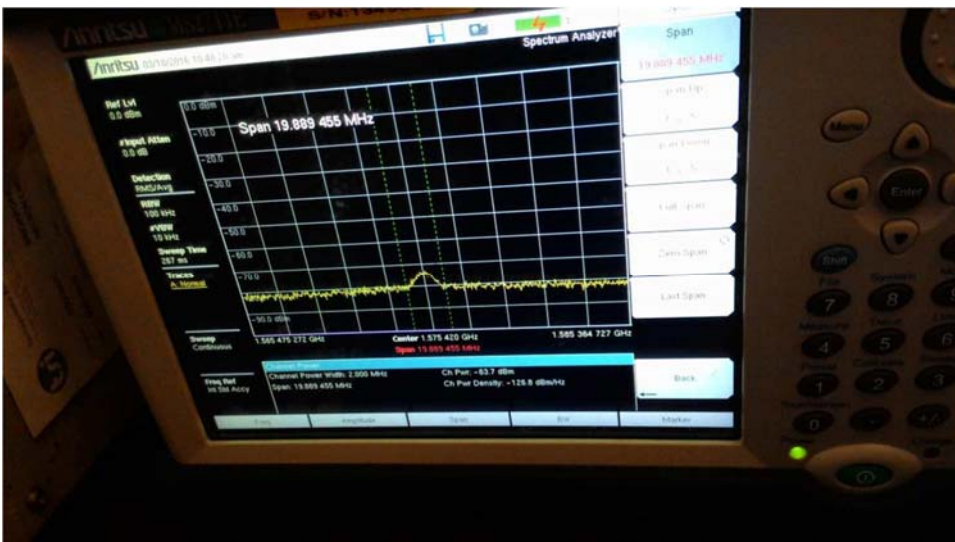


Figure 5-8 Snapshot of the frequency spectrum of L1 GPS signal as shown by the spectrum analyzer

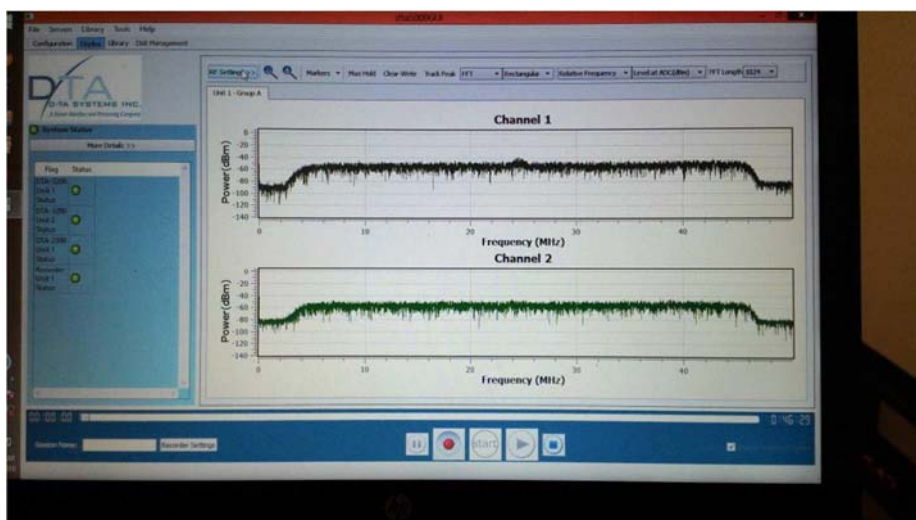


Figure 5-9 Snapshot of the frequency spectrum of L1 GPS signal as shown by the spectrum analyzer within the DTA system

A matlab program is used to direct the mesh antenna to point at a particular GPS satellite on the sky and maintain the physical tracking of the satellite. The DTA system is used to record the raw data collected by the mesh antenna. The mesh antenna and DTA system is connected via a 30 m RF cable. A 30 dB pre amplifier is also fixed after the helix feed stage, and another 30 dB amplifier is fixed after the 30 m RF cable before being fed into the DTA system. A spectrum analyzer is also used to monitor the RF signal. Figure 5-8 shows the snapshot of the frequency spectrum of L1 GPS signal as shown by the spectrum analyzer. A L1 GPS signal is clearly visible. The signal is also visible through channel 1 spectrum analyzer in the DTA system depicted in Figure 5-9. Concurrently, the signal received by an omnidirectional Septentrio antenna is also connected via channel 2 of DTA system.

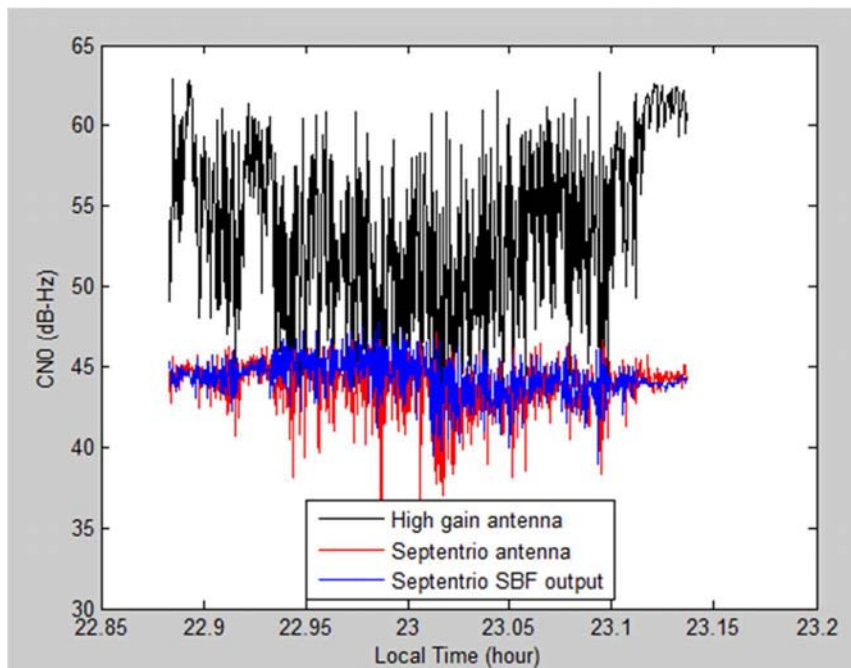


Figure 5-10 Comparison of C/N_0 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 28, 29 April 2016.

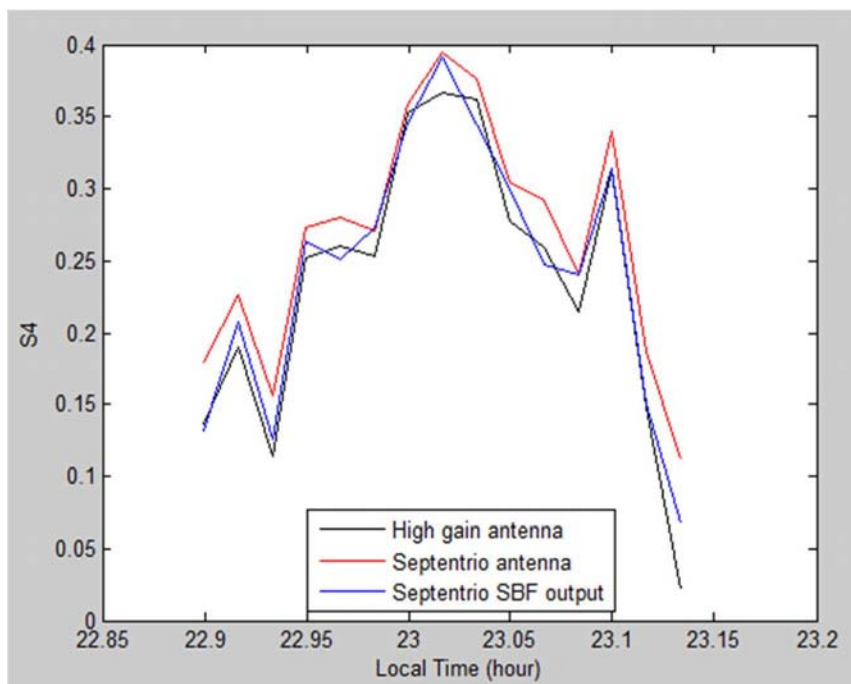


Figure 5-11 Comparison of S4 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 28, 29 April 2016.

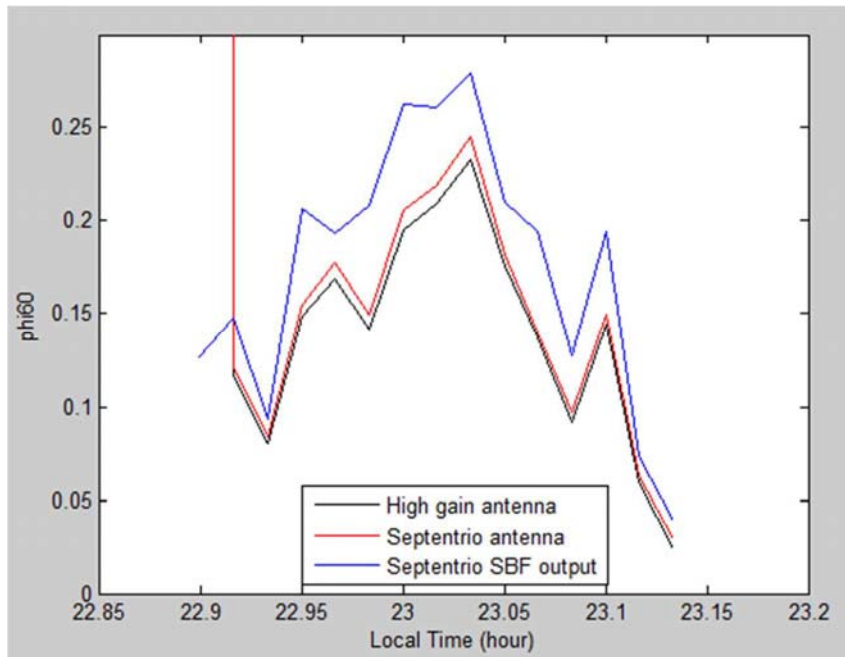


Figure 5-12 Comparison of phi60 between high gain antenna, Septentrio antenna and direct SBF output. PRN 28, 29 April 2016.

Scintillation indices S4 and phi60 are monitored by Septentrio receiver during the post sunset period (8 pm to 2 am) in April 2016. If scintillation event is detected, for e.g. $S4 > 0.2$ or $\text{phi60} > 0.1$, the mesh antenna is directed at the particular scintillating GPS satellite and the recording with DTA system is initiated. The experiment is performed by the Singapore team at NUS SWIFT. The raw data collected via mesh antenna and Septentrio are processed, and the scintillation indices are calculated. The following results and analysis have been discussed with US counterparts via teleconference on 19 July 2016. Figure 5-10 shows the plot of carrier to noise density ratio C/N_0 of PRN 28 on 29 April 2016. The black curve indicates those calculated from raw data of high gain mesh antenna. The red curve indicates those calculated from raw data of Septentrio antenna and the blue curve is the direct Septentrio output, extracted from Septentrio SBF file. It can be seen that the calculated C/N_0 of Septentrio antenna has relatively the same levels with direct Septentrio output. As expected, the high gain dish antenna has higher C/N_0 levels. Next, Figure 5-11 plots the S4 index of the same satellite and duration. We can see that high gain antenna has relatively the same S4 index as the Septentrio antenna, and their levels are generally agreeable to the direct Septentrio output. Figure 5-12 plots the phi60 of the same satellite and duration, and it is seen again that the high gain antenna has relatively same level of phi60 as the Septentrio antenna. Some discrepancies exist between the calculated phi60 and the direct Septentrio output, probably due to phase detrending.

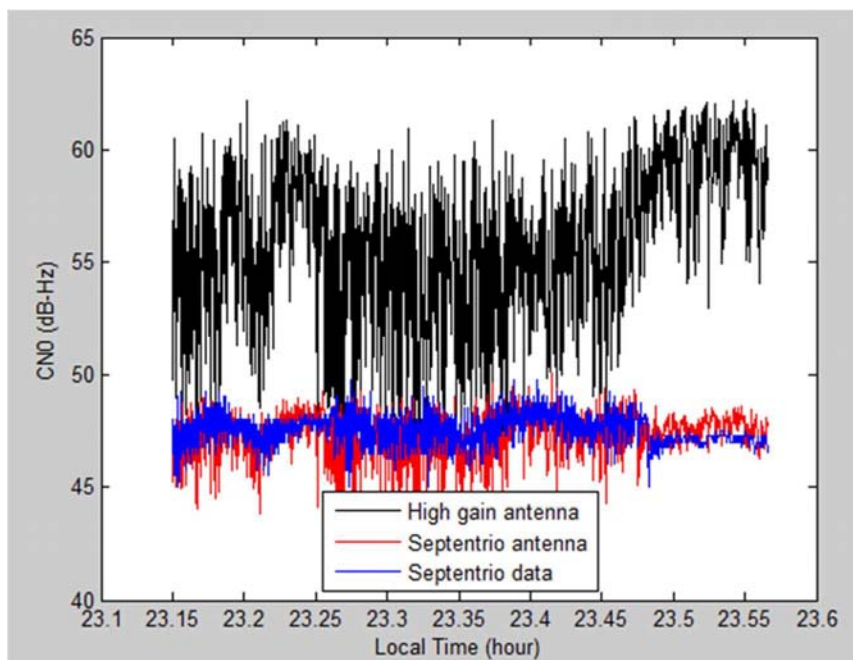


Figure 5-13 Comparison of C/N_0 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 5, 29 April 2016.

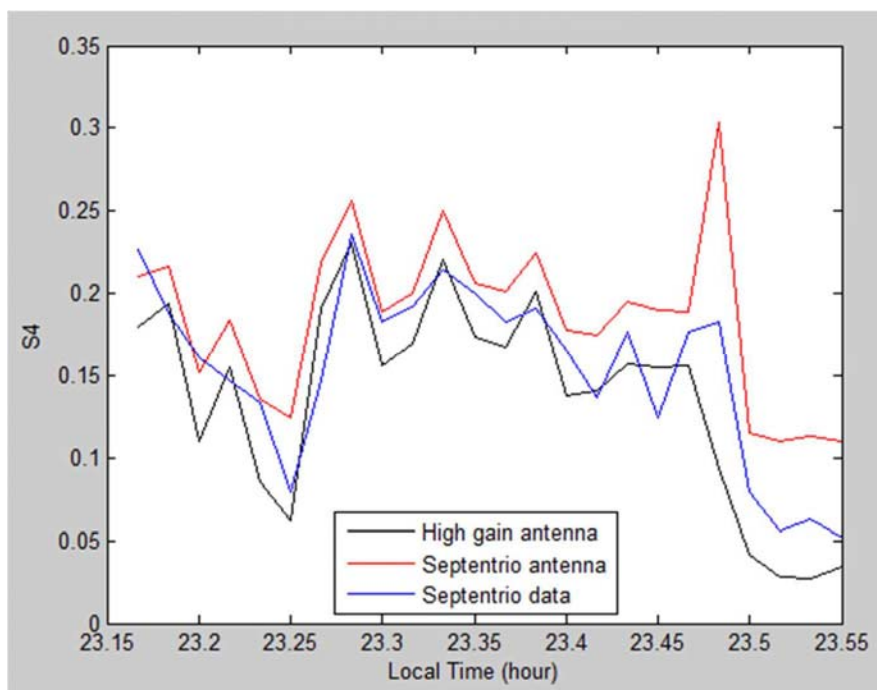


Figure 5-14 Comparison of S4 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 5, 29 April 2016.

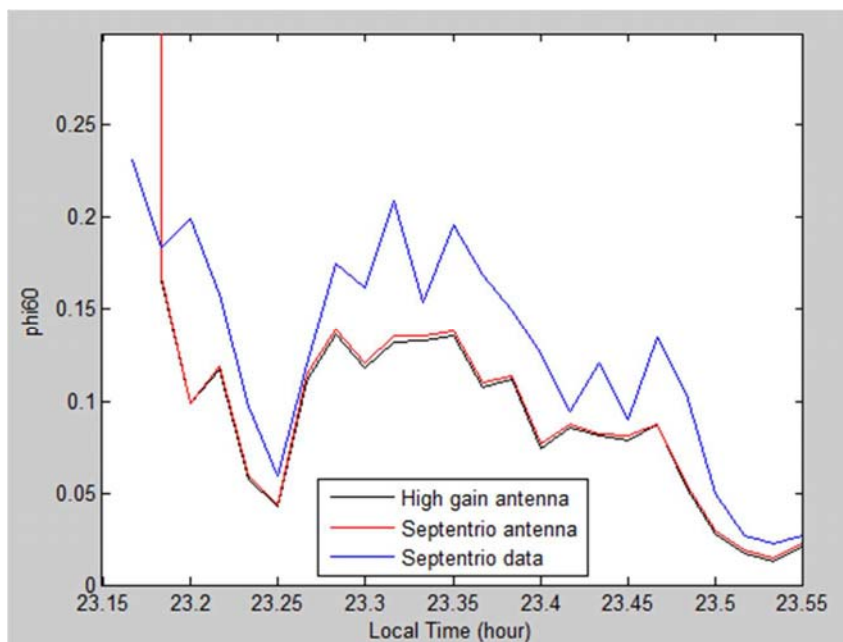


Figure 5-15 Comparison of ϕ_{60} between high gain antenna, Septentrio antenna and direct SBF output.
PRN 5, 29 April 2016.

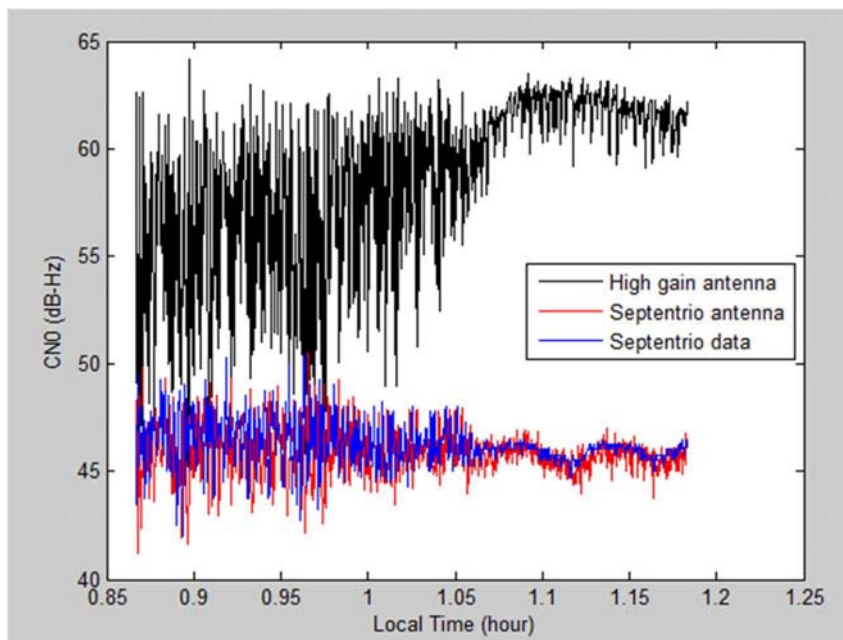


Figure 5-16 Comparison of C/N_0 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 5, 30 April 2016.

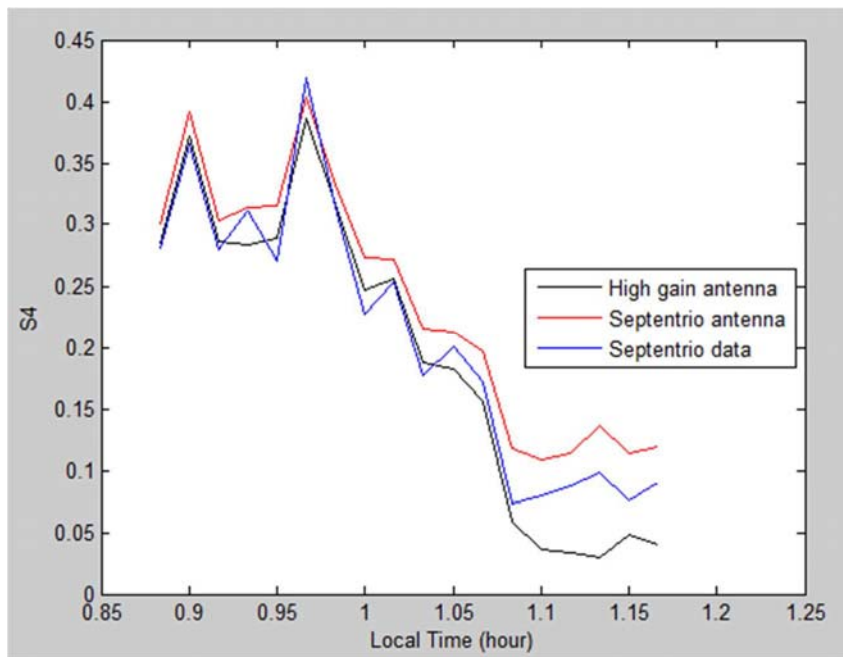


Figure 5-17 Comparison of S4 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 5, 30 April 2016.

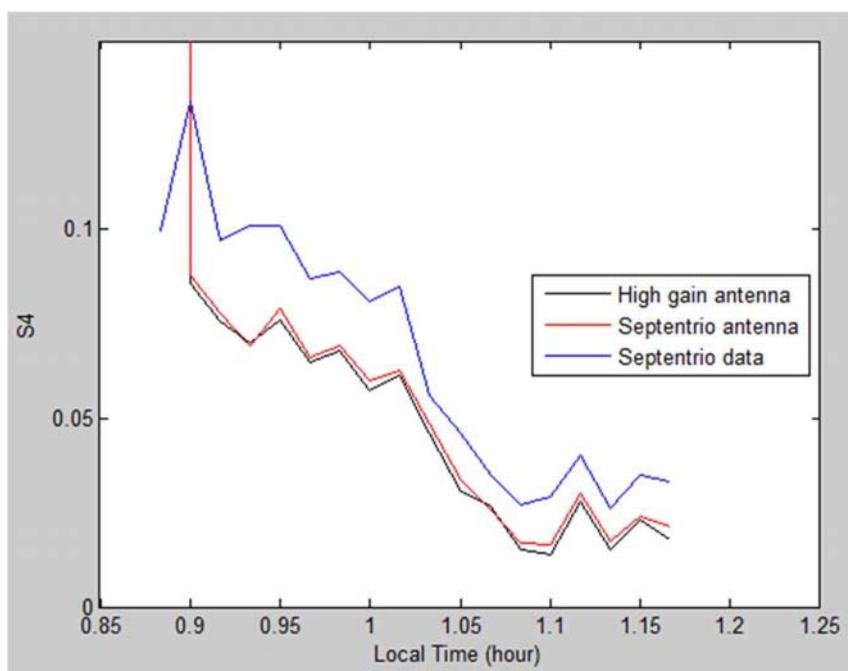


Figure 5-18 Comparison of phi60 between high gain antenna, Septentrio antenna and direct SBF output.
PRN 5, 30 April 2016.

Figure 5-13-Figure 5-18 show the same scintillation parameters of different PRN and duration for PRN 5 and 30 April 2016. The observations are consistent with the first analyzed case. In conclusion, by using high gain mesh dish antenna, the C/N_0 is improved, but no significant improvement in scintillation levels (S4, phi60) over Septentrio antenna. The high gain mesh antenna will also be useful for GNSS under foliage and weak signal processing for subsequent project collaborations with the AFRL.

List of Publications

- [1*] D. Y. Heh, D. S. Murti, E. L. Tan, E. K. Poh, K. V. Ling and Y. L. Guan, "Ionospheric scintillation of GPS microwave signals in Singapore," in *Proc. Asia Pac. Microwave Conf.*, Sendai, Nov. 2014, pp. 1390-1392.
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(Note: For some of the publications, the research works have been carried out since before AOARD grant, under local support from Ministry of Defense)

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