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RESEARCH ARTICLE - ATMOSPHERIC & SPACE SCIENCES

Characterization of amplitude scintillation and distribution of positioning error for IRNSS/GPS/SBAS receiver

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Abstract

Indian regional navigation satellite system (IRNSS) or Navigation with Indian Constellation (NaVIC) is the satellite-based navigation system, established and controlled by the Indian Space Research Organization. It provides services of positioning, velocity, and timing for civilian and military applications. Ionospheric irregularities cause the fluctuations in the amplitude and phase of the received navigation signals; this phenomenon is known as scintillation. Scintillation can create the error in precise positioning and degrades the position accuracy of the navigation system. It varies with solar activity, geographical location, seasonal variation, day–night time, and elevation angle of satellites. The $S4$ index is one of the key parameters to estimate the amplitude scintillation to recognize the quality of the navigation signal. In this paper, amplitude scintillation characteristics are studied with IRNSS/GPS/SBAS in the Ahmedabad region which is at the average altitude of 53 m. $S4$ index is calculated and analyzed using the real-time navigation data of one week. Here, IRNSS/GPS/SBAS receiver with $L1$, $L5$, and S-band, is used to collect the data at low altitude station (IITRAM, Ahmedabad). The position error of normal sunny days is calculated using IRNSS/GPS/SBAS receiver. The probability of position error is also derived and found that it follows the gamma distribution function and validate it statistically using a chi-square test. This study also focuses on the effect of elevation of the satellite on the value of carrier to noise ratio at the location of IITRAM.

Keywords Indian Regional Navigation Satellite System · Microstrip patch antenna · Duroid · PVT-position · Velocity · Timing · IRNSS receiver · GPS

Introduction

The Indian regional navigation satellite system is now a fully developed navigation system for India to provide the services of positioning, velocity, and timing (PVT). IRNSS is designed to give accurate positioning coordinates within the error of 10 m over the Indian region and 20 m error in the surrounded area of 1500 sq.km. The space segment of IRNSS is the combination of seven satellites, from which three satellites are in geostationary earth orbit (GEO) and four satellites are in geosynchronous orbit (GSO). The three GEO satellites (1C, 1F and 1G) are positioned at 83° E, 32.5° E and 129.5° E at 5° inclinations each and four GSO satellites (1B, 1D, 1E and 1I) are positioned at55 E and 111.75° E. IRNSS offers two main services; the standard positioning services (SPS) for all users and the restricted services (RS) to authorize users. The standard position service (SPS) of IRNSS is transmitted on the $L5$ band (1164.45–1188.45 MHz) with the carrier frequency of 1.17645 GHz and S-band (2483.5–2500 MHz) with the carrier frequency of 2.492028 GHz bands (Indian Regional Navigation Satellite System 2017). The IRNSS/GPS/SBAS receiver enables us to receive $L1$, $L5$, and S band signals.

The ionosphere is the zone of an atmosphere around 60 to 1000 km of the altitude above the Earth's surface and has the ionized particles such as electrons and plasma. The propagation speed of the radio signal depends upon the electron density present in the ionosphere. The ionosphere is the most prominent source of interference in radio waves when it travels from satellite to receiver. The characteristic of the

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ionosphere is influenced by the variation in electron density which is described by total electron content (TEC). TEC is the electron number density, which represents the total number of electrons placed along 1m^2 cross-section area in the propagation path. TEC unit is often expressed as, 1 TECU = 1016 el/m^2, which is intensively dependent on sun activity (Romero and Dovis 2013). The ionosphere delays the radio signal proportional to the TEC. The ionospheric delay can be expressed by using the following equation,

$$\text{Ionodelay} = \frac{40.3}{cf^2} \times (\text{TEC}) \tag{1}$$

So,

$$\text{TEC} = \frac{\text{Iono delay} \times c \times f^2}{40.3} \tag{2}$$

Ionospheric scintillation is defined as the fluctuations in signal amplitude and phase due to signal refraction when it is passing through ionospheric plasma irregularities. Amplitude scintillation represents rapid fluctuations in signal amplitude and phase scintillation represents the deviation in the phase of the radio signal. The scintillation depends on the variation in electron density, plasma irregularities, sun radiation intensity, seasons, and geographical location (Acharya and Majumdar 2019; Acharya et al. 2007), and in turn, it causes ranging errors. At the equatorial and high latitude regions, the ionosphere is more active and very less predictable (Romero and Dovis 2013). As the signal is severely affected by scintillation, the receiver may suffer from loss of lock and the navigation system may not be able to locate a precise position. The ionospheric scintillation characterization has been investigated by Jiao and Morton (2015) at high latitude and equatorial region in the Gakona, Alaska, Jicamarca, and Peru. It shows that the navigation signal suffers from severe scintillation at the equatorial region with deeper and faster signal power fading and longer duration. The phase scintillation is more intense than amplitude scintillation at high altitude region. He et al. (2016) have analyzed the ionospheric scintillation effect on the BeiDou signal receiver. Acharya and Majumdar (2019) presented the calculation of $S4$ index and ionospheric irregularity index ROTI of GAGAN TEC Network Station. Steenburgh et al. (2008) examined amplitude scintillation data spanning 7 years from Ascension Island, UK; Ancon, Peru; and Antofagasta, Chile in the Atlantic/American longitudinal sector as well as Indonesia, and calculated the value of $S4$ index and probability of occurrence of $S4$ index. Sujimol and Shahana (2017) have studied the effect of ionospheric scintillation on IRNSS at $L5$ and S-band at New Delhi and Ahmedabad and found that the amplitude scintillation severity is more on $L5$ band than S-band, scintillation occurrence is mostly in post-sunset periods. de Oliveira Nascimento Brassarote et al. (2017) found the $S4$ index for five stations from CIGALA/CALIBRA network and by performing wavelet decomposition of scintillation $S4$ index, estimate and remove the multipath effect from it. Guo et al. (2019) have studied about ionospheric scintillation characteristics in Australia with GNSS during 2011–2015. Parmar et al. (2017) investigated the ionospheric scintillation measurement using TEC variations for IRNSS receiver at low latitude region, Surat, India. Desai and Shah (2018) have analyzed various ionospheric models to improve the position accuracy of IRNSS. Jacobsen and Dhnn (2014) have presented a strong correlation between positioning error and rate of TEC index for GNSS receiver. It is found that when the rate of the TEC index is increasing, 3D position error also increases exponentially. Rino et al. (2019) investigate that when the $S4$ index is less than 0.5 with the lower carrier frequency, the scintillation-induced errors are a small fraction of one TEC unit. TEC errors are very much small and almost negligible for weak and moderate scintillation.

This paper focuses on the study of amplitude scintillation in the Gujarat region particularly in Ahmedabad city, to evaluate the performance of IRNSS/GPS/SBAS positioning services. The $S4$ index is calculated for seven days from June 10, 2019 to June 16, 2019, which are the moderate sunny days in Ahmedabad. The $S4$ index for seven days with $L1$, $L5$, and S-band is calculated, plotted, and analyzed. The probability distribution of positioning error for a week is determined and the effect of variation in elevation angle on the ionospheric delay at IITRAM, Ahmedabad station is also determined.

Ionospheric scintillation effect on IRNSS: theoretical study

The Ionosphere delay is inversely proportional to the square of the frequency, so for a higher frequency, the delay is less. In the case of IRNSS receiver, the S-band will suffer from less amount of delay compared to $L5$ and $L1$. The ionospheric delay is directly proportional to TEC. The variation in the electron density at the ionosphere causes curvature in the propagation path of navigation signal which increases the pseudo-range for satellite positioning. The pseudo-range or first-order ionospheric free range for dual-frequency IRNSS user can be defined as

$$\rho = \left(\rho_{L5} - \gamma \rho_S\right)/(1 - \gamma) \tag{3}$$

where $L5$ and S are the center frequency of IRNSS

$$\gamma = \left(f_S^2/f_{L5}^2\right) \ldots \tag{4}$$

ρ = pseudo-range corrected for first-order ionospheric effects

ρ_{L5}, ρ_S = pseudo-range measured on the channel indicated by the subscript.

For navigation system, two measurements pseudo-range and carrier phase measurements are very important. The navigation receiver measures the time difference between the transmitted signal by using a satellite clock and received signal by using the receiver clock. When the satellite clock and receiver clocks are synchronized, the measured range is called true range otherwise it is pseudo-range. Generally, pseudo-range measurement is used for the civilian purpose where high accuracy is not required. In the carrier phase measurement technique, the receiver measures the range between a satellite and receiver in terms of cycles of the carrier frequency. It gives a very high precision measurement in the millimeter range. In the day time, the ionization activity is more severe compared to night time so the ionospheric delay is more at day time (Brahmanandam et al. 2012). This ionospheric activity will fluctuate the amplitude and phase of navigation signal which induce the scintillation event. The dilution of precision (DOP) is a measure of the error caused by the relative position of navigation satellites. The one value of DOP represents the ideal condition means negligible error and high value of DOP indicates the more error. The low elevation angle gives more scintillation due to the reduction of GDOP (Jianjun et al. 2006). The $S4$ index is used to investigate the amplitude scintillation for navigation system (de Oliveira Nascimento Brassarote et al. 2017). It is the ratio of the standard deviation of the received carrier power to the average carrier power by considering the data stability of 1 minute and can be expressed as, (Chen et al. 2017; Chakraborty et al. 2017)

$$S_4 = \left[\frac{\langle s_i^2 \rangle - \langle s_i \rangle^2}{\langle s_i \rangle^2} \right]^{1/2} \tag{5}$$

where S_i is the detrending of the carrier-to-noise ratio (C/N_0) to construct the time series of received navigation signal for estimating the trend. C/N_0 is the ratio of carrier power to noise power per unit bandwidth and expressed in terms of dB-Hz. S_i is a linear scaled C/N_0, and S_i indicates the average value of signal intensity for 60 s. If the value of the $S4$ index is less than 0.3, the navigation signal will not be affected. When the value of the $S4$ index is within 0.3 to 0.6, it shows moderate scintillation and if the $S4$ index is greater than 0.6, the navigation signal will suffer from strong scintillation (Jianjun et al. 2006; de Oliveira Nascimento Brassarote et al. 2017).

Due to the dispersive characteristics of the ionosphere, the different frequencies will have different amounts of time delay. The time delay for a higher carrier frequency is less than the lower carrier frequency wave. This is the main reason to select the dual-frequency for navigation receiver to achieve a better result compare to a single-frequency receiver. As $S4$ is highly sensitive to the Fresnel scale (Carrano et al. 2019), the effect of amplitude scintillation for the navigation signals can be derived by the effect of Fresnel diffraction caused by ionospheric irregularities. The Fresnel diffraction (D_f) can be described by the following equation

$$D_f = \sqrt{2\lambda h} \dots \tag{6}$$

where λ represents the wavelength of the carrier wave and h is the height of the irregularities (typically 300–400 km). The amplitude will fluctuate at the Fresnel frequency is given by,

$$f_F = V/D_f \tag{7}$$

where V is the drift velocity of the irregularities.

Here, the drift velocity of plasma irregularities (V) is typically 100–200 m/s. So, for $L5$ band $\lambda = 0.25$ m, and the scale range of Fresnel diffraction will be 387.2–447.2 m and the amplitude will fluctuate at 0.25–0.51 Hz. According to the sampling theory, the sampling rate should be at least twice as fast as the Fresnel frequency, i.e., 0.5–1.02 Hz and sometimes more than this. Amplitude scintillation directly reduces the value of the carrier-to-noise ratio (C/N_0) of navigation signals in the receiver. The receiver tracking threshold value for the signal-to-noise ratio is 32 dB for IRNSS receiver and if the signal intensity degrades from this threshold, the receiver will suffer from loss of lock on that satellite and the acquisition of signal is required within few seconds. The tracking will be lost for this time duration. This will reduce the accuracy and may have a loss of data for a particular time. The strong scintillation will lead to an error in positioning accuracy. There is no direct relation between ionospheric scintillation and position error but 3D position error increases exponentially with increasing Rate of change of TEC index (ROTI) (Carrano et al. 2019). The ionospheric delay can be overcome by using the efficient ionospheric delay correction algorithm. Here, grid model is selected to minimize the effect of ionospheric delay to improve the performance of IRNSS/GPS/SBAS receiver.

Instrumental setup and data processing

Two IGS receivers A314 and A315 (IRNSS/GPS/SBAS) are installed in the laboratory at the Institute of Infrastructure Technology Research and Management (IITRAM) at Ahmedabad, Gujarat, India. The antenna is set on the rooftop of the building to receive the navigation signal; the receiver is connected with the computer which enables us to log the real-time navigation data using the GUI interface. The real-time data have been extracted in the form of an excel file that further processed using IRDAS. For this study, the data are extracted from June 10–16, 2019 from IGS receiver and processed by IRDAS and MATLAB to get a resultant plot. Figure 1 shows the basic experimental setup to collect real-time navigation data from IRNSS satellites.

The $L1$, $L5$, and S-band data for this study are received by IRNSS receiver and further processed as follows:

1. The IRNSS receiver is connected with the computer to log the data. The data is logged in the form of a raw data file.
2. The raw data is extracted in the form excel file. The 8 folders are created for one day with an interval of 3 h.
3. Position data are logged into the system in the form of x position, y position and z position. These x, y, and z position data are taken from the POSB file.
4. To find the position error, the x, y, and position data are subtracted from reference data X, Y, and Z. X = 1754426 m, Y = 5605814.42 m and Z = 2477176.59 m.
5. Position error and its occurrence probability are found by MATLAB.
6. The C/N_0 is taken from the SATB file. Here, C/N_0 is taken for $L1$, $L5$, and S-band.
7. The average value of C/N_0 is taken every 60 s to find the $S4$ index (Ya'acob et al. 2010).
8. The standard deviation of C/N_0 is calculated.
9. The mean of C/N_0 is calculated.
10. $S4$ index is calculated by the ratio of standard deviation by mean of C/N_0.
11. Here, the $S4$ index is found for Satellite B for $L1$, $L5$, and S, with the data of seven days.
12. $S4$ index is plotted with MATLAB 2017

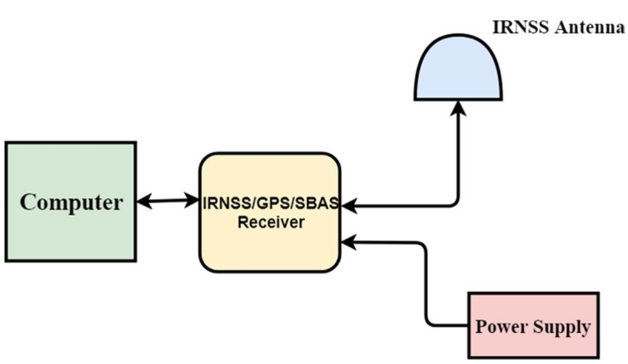


Fig. 1 Experimental setup to collect real-time navigation data from IRNSS Satellites

Results and discussion

The performance of IRNSS can be evaluated in terms of carrier-to-noise ratio, elevation angle, positioning error, distribution probability of positioning error, and amplitude scintillation. Here, IRNSS/GPS/SBAS receiver receives $L1$, $L5$, and S-band signals, so these signals are processed to find ionospheric delay, position error, distribution probability of positioning error, and $S4$ index. We also analyzed the carrier-to-noise ratio and ionospheric delay w.r.t elevation angle of IRNSS satellites.

Distribution of position error

The position error can be found by the difference between the reference position and the measured position. IRNSS receiver gives the position data in the form of X, Y, and Z position. The reference position (golden reference) for IITRAM is X = 1754426 m, Y = 5605814.42 m, and Z = 2477176.59 m. The error in positioning data can be calculated by the following equation

$$\text{Pos. error} = \sqrt{(X - x1)^2 + (Y - y1)^2 + (Z - z1)^2} \ldots \quad (8)$$

where X, Y, Z are reference positions of IITRAM, and $x1$, $x2$, $x3$ are the observed position of IITRAM using IRNSS receiver. Here, positioning error per second for seven days are calculated to estimate the maximum positioning error of the days and to plot the distribution function.

Figure 2 shows the probability of a position error of seven days from June 10, 2019 to June 16, 2019. The maximum, minimum and average value of position error belongs to a day for a week is mentioned in Table 1. It includes maximum, minimum and average positioning error with the value of $S4$ index on the same time with three different bands. Maximum positioning error during the week is 7.850121187 m on 3.55 pm, June 15, 2019 and at this time the scintillation is strong in $L1$ band only. It is clear that positioning error is within the 10 m always so IRNSS is operating well at our location. The estimated coefficients decide the expected distribution of positioning error. Hence, we can find that the probability distribution of positioning error follows the gamma distribution as shown in Fig. 2. To validate the gamma distribution model, the chi-square goodness of fit test is conducted. Here, there are seven data sets, i.e., $n = 7$. So we assure the sum of the square of n numbers of errors which are normalized by $n-1$ value, called a degree of freedom. The chi-square test gives the value 1 to validate the distribution in MATLAB.

The location coordinates of IITRAM which are 23.00439687° N and 72.62182262° E, 80 m altitude have been considered as a golden reference (Rawat et al. 2019).

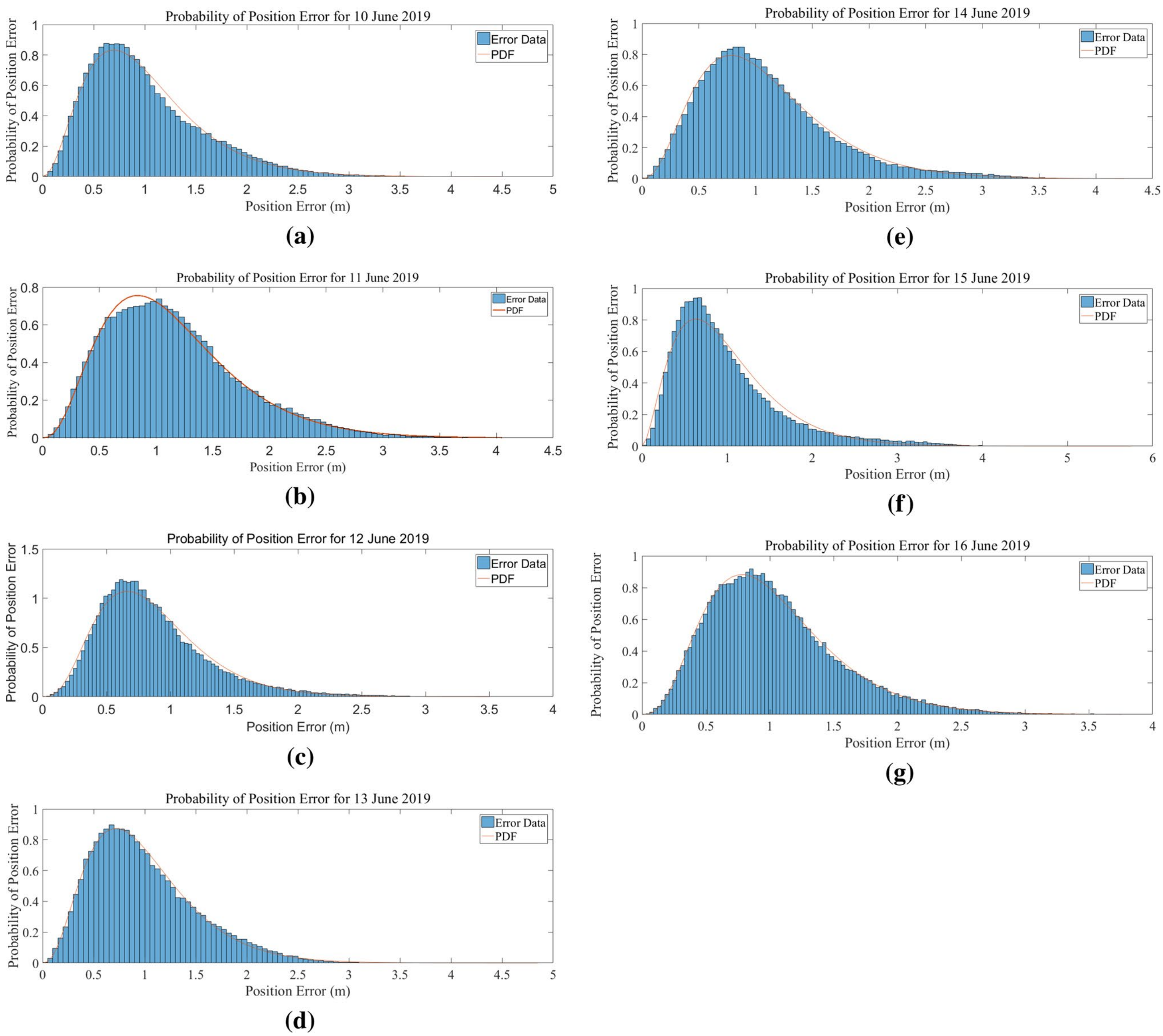


Fig. 2 Probability of position error for **a** June 10, 2019, **b** June 11, 2019, **c** June 12, 2019, **d** June 13, 2019, **e** June 14, 2019, **f** June 15, 2019, **g** June 16, 2019

Table 1 Position error and scintillation effect during 7 days

Date	Maximum position error during the day (meter)	Minimum position error during the day (meter)	Average position error during the day (meter)	Scintillation effect and *S*4 value		
				*L*1 band	*L*5 band	*S* band
June 10, 2019	4.520687877	0.008706882	1.005781005	Strong 6.208951	Weak 0.153425	Weak 0.082996
June 11, 2019	3.939897583	0.010645815	1.10346843	Strong 7.166093	Weak 0.346017	Strong 1.162300
June 12, 2019	3.53665228	0.020780165	0.860768438	Strong 7.228055	Weak 0.258122	Strong 0.715059
June 13, 2019	4.861034833	0.01660597	0.989546067	Strong 3.388511	Weak 0.278801	Strong 0.865200
June 14, 2019	4.271728885	0.021466451	1.052917505	Strong 4.942313	Weak 0.229814	Moderate 0.541158
June 15, 2019	7.850121187	0.02687701	1.23769472	Strong 5.484095	Weak 0.235113	Moderate 0.604400
June 16, 2019	5.978445517	0.193510838	1.342709765	Strong 4.367337	Weak 0.221881	Weak 0.483628

The 3DRMS position error is 1.16 m, and circular error probability (CEP) is 0.46 m for the location of IITRAM by using IRNSS/GPS/SBAS receiver. It is also observed that maximum ionospheric delay is nearly 19 m at *L*5 band and 4 m for *S* band, i.e., at a higher frequency the ionospheric delay is less compared to a lower frequency. Figure 3 shows the position error plot generated by IRDAS software.

*S*4 Index

The data of C/N_0 are logged into the computer and converted into the excel file. Here, the amplitude scintillation index *S*4 is calculated using C/N_0 from SATB files of a particular band for PRN 2. The presented results are capable to visualize the effect of scintillation on repeatedly and randomly. The *S*4 index represents the variation in the power level of navigation signal over one minute interval (de Oliveira Nascimento Brassarote et al. 2017; Ya'acob et al. 2010). IRNSS receiver's ability for positioning and tracking the location is highly dependent on the value of C/N_0. Lower the value of C/N_0, greater the possibility of error in positioning (Sharma et al. 2019). Here, the *S*4 index of June 10, 2019 to June 16, 2019, (7 days) is calculated and plotted using the MATLAB. Figures 4, 5 and 6 represents the plots of *S*4 index of *L*5, *S* and *L*1 band, respectively, for the duration of seven days. Figures 4, 5, and 6 shows the *S*4 value by blue spikes with respect to minutes. *L*5 band does not show strong scintillation but there is a rapid variation in *S*4 index in this band. *S* band and *L*1 band gives *S*4 value higher than

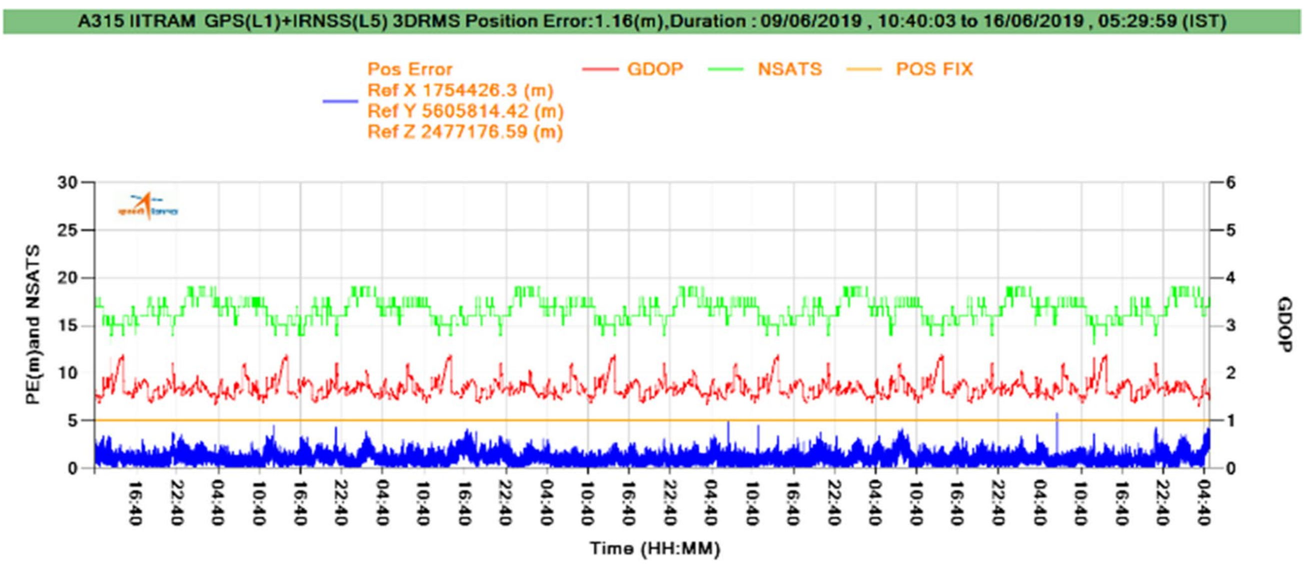
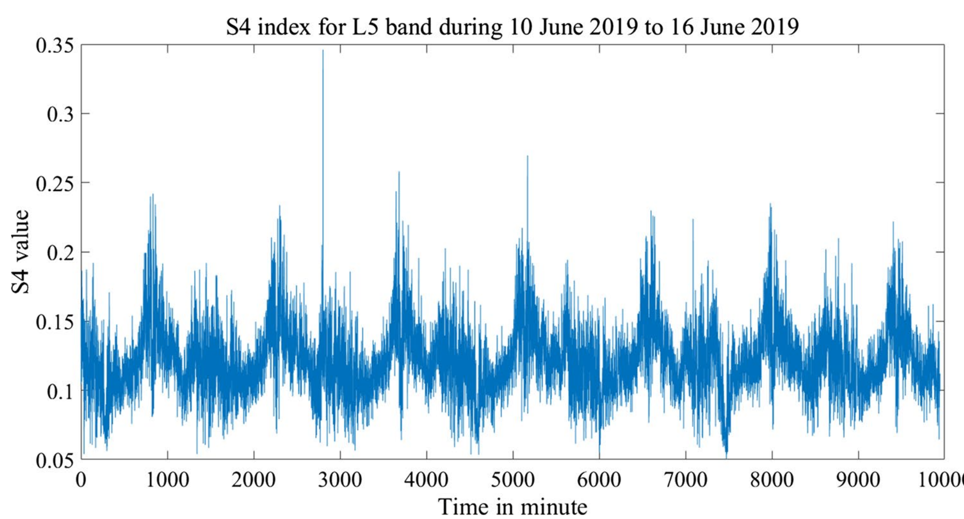


Fig. 3 Position error plot

Fig. 4 *S*4 index of *L*5 band from June 10, 2019 to June 16, 2019



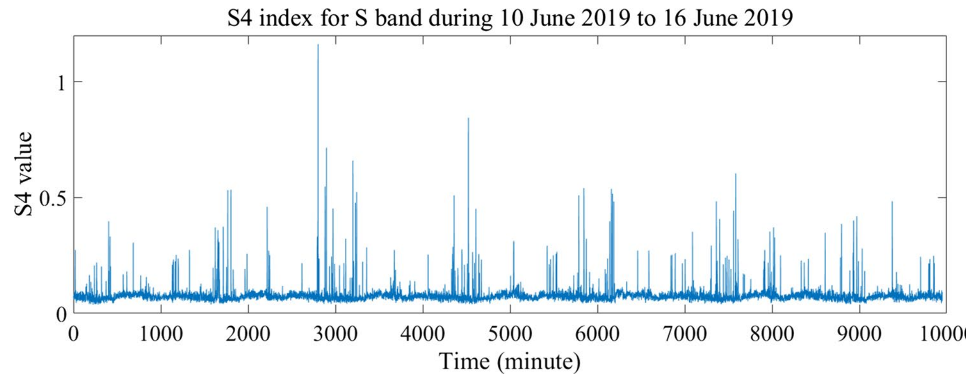


Fig. 5 *S*4 index of *S* band from June 10, 2019 to June 16, 2019

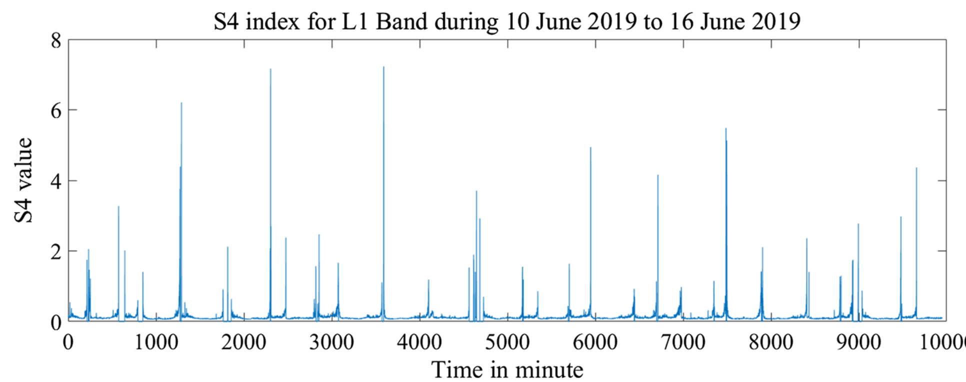


Fig. 6 *S*4 index of *L*1 band from June 10, 2019 to June 16, 2019

0.6 many times in a day but it is just for the interval of 1 minute only. So, loss of lock with satellite never occurs and data are not blocked during these periods and error will not be more than 10 m.

Figure 4 show that there is a rapid variation in the *S*4 index for the *L*5 band and it never increases more than 0.35. Figure 5 shows that the *S*4 index for *S*-band is 1.1623 for day 2, 0.715059 for day 3, and 0.865200 for day 4 which represents strong scintillation, and Fig. 6 shows *S*4 value for *L*1 band reaches greater than 1, every day, so on that particular time the strong scintillation occurs. Figure 7 shows the graph of *S*4 index for *L*1, *L*5 and *S* band for seven days. In this graphs, red line indicates *S*4 value for *L*1 band, blue line indicates *S*4 value for *L*5 band and black line indicates *S*4 value for *S* band. It is found that most of the time, in *L*1 band, strong scintillation occurs from 5:00 to 6 am. Most of the time, weak scintillation event is found in *L*5 band but rapid variation in *S*4 value is stated here with no scintillation event. Strong scintillation events are found from 12:00 to 9 am in *S* band. Mostly moderate/strong scintillation occurs after mid night and remains up to 9:00 o'clock in the morning. These observations are found during normal sunny days in Ahmedabad to analyze the characteristics of amplitude scintillation. These results can be used for further research.

Carrier-noise ratio and ionospheric delay w.r.t elevation angle of satellite

The observed elevation angle of IRNSS Satellite 1B is 16° for 3 hours (i.e., 9:00 am–12 pm) at the day time on June 11, 2019, which induces strong scintillation for *S*-band. Ionospheric delay attains maximum value during 12:00–3:00 pm and minimum during 12:00–3:00 am. The variation of ionospheric delay concerning the elevation angle is presented in Fig. 8. Initially, C/N_0 increases when the elevation angle of satellite increases, and it will saturate above 45° and below 20° as shown in Fig. 9. The signals reach to low elevation angles, suffer from more scintillation and may have a poor value of C/N_0. C/N_0 degrades at lower elevation angles, below 20 degree as shown in Fig. 9. To consider the IRNSS publicly usable, the Indian users must have at least one satellite above 60° and at least two satellites above 50°. This is also observed by Santra

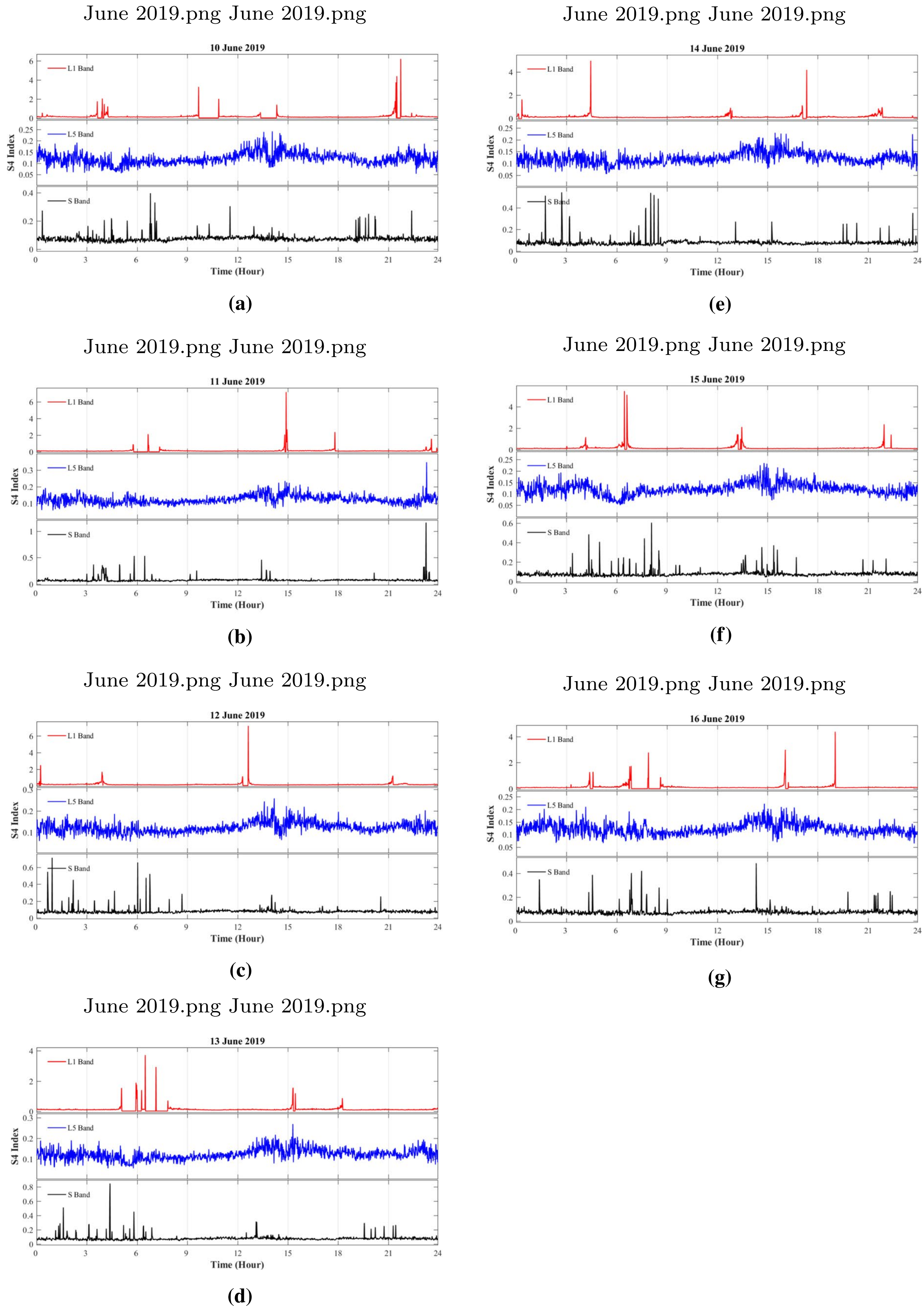


Fig. 7 *S*4 index of *L*1, *L*5, and *S*-band for **a** June 10, 2019, **b** June 11, 2019, **c** June 12, 2019, **d** June 13, 2019, **e** June 14, 2019, **f** June 15, 2019, **g** June 16, 2019

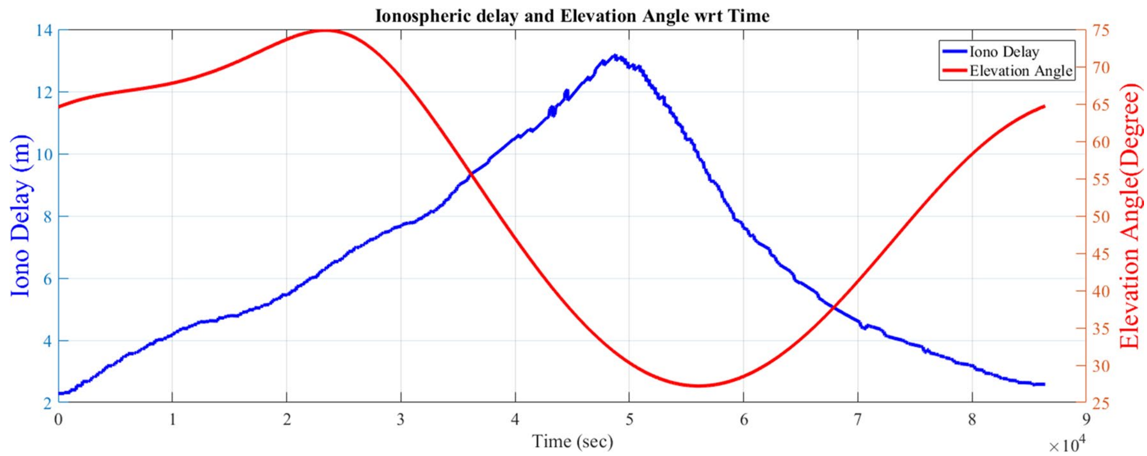


Fig. 8 Ionospheric delay and elevation angle variations for satellite 1B throughout the day (June 11, 2019)

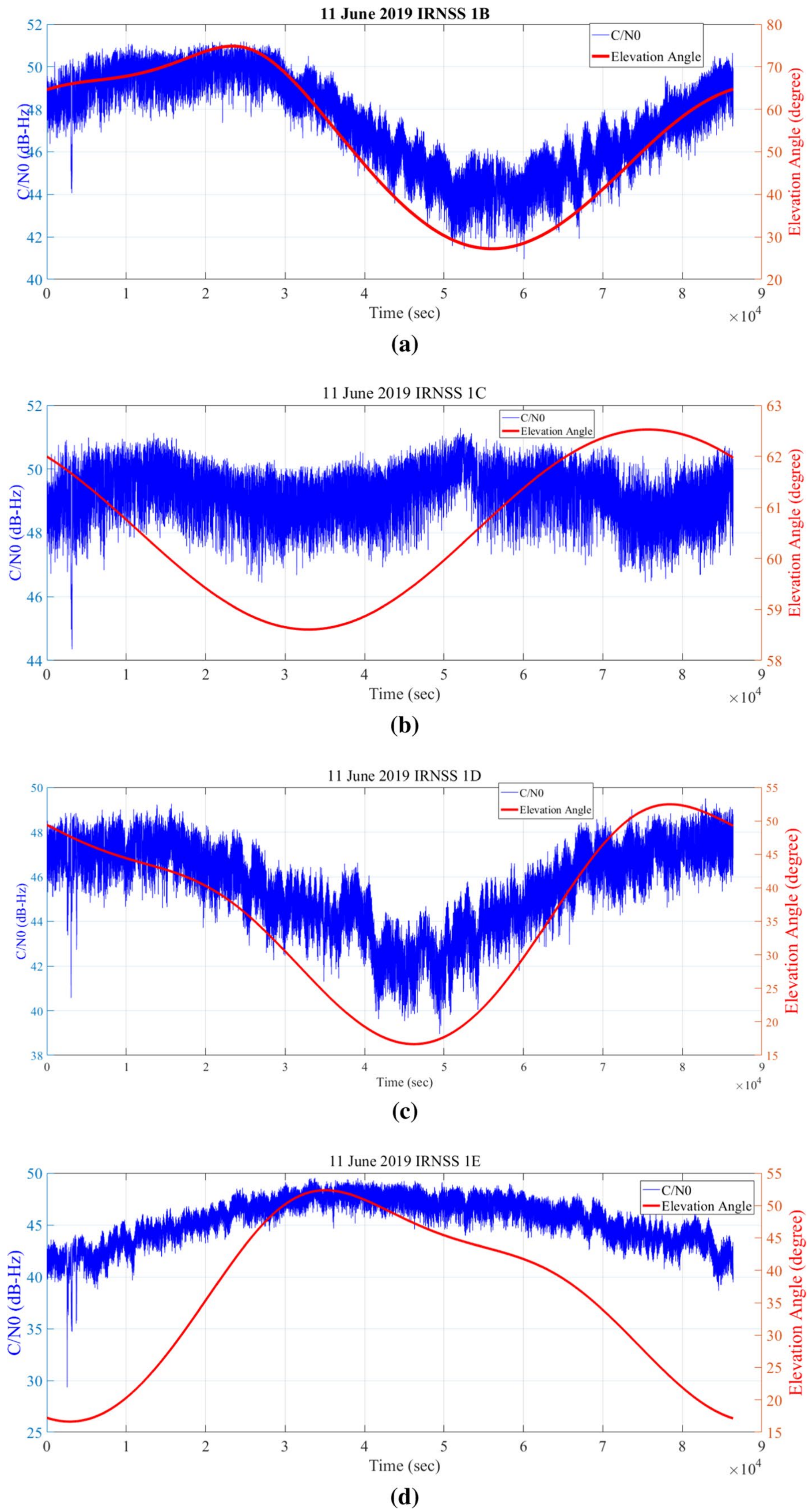
et al. in 2019. We found that the minimum elevation angle reaches to 27.21286° at 3.57 pm over which maximum positioning error is found on June 15, 2019. From evening 4.42 pm, elevation angle is increased, and reaches its maximum value of 74.8625° from 6:69 to 6.499 am, then it is started decreasing gradually and reaches to its minimum value of 27.21286° at 3.57 pm.

Conclusions

In this paper, the characterization of amplitude scintillation index and distribution of positioning error for IRNSS/GPS/SBAS receiver is realized at IITRAM, Ahmedabad, Gujarat. Amplitude scintillation is analyzed using the $S4$ index for $L1$, $L5$, and S band which estimate the performance of IRNSS and GPS for seven days June 10, 2019 to June 16, 2019. Amplitude scintillation is more on the S band compare to the $L5$ band and maximum on the $L1$ band. Results show that the distribution of positioning error follows the gamma distribution and validated by the chi-square goodness of fit test. It also found that the scintillation effect is more significant at a low elevation angle for a particular satellite. The ionospheric delay and elevation angle variation are found and the result shows that the Satellite 1B gives more ionospheric delay compare to other satellites, as it may contain a minimum elevation angle at a certain time. The average position error of one week is 1.16 m for IRNSS and GPS combined at our location. The following are the main findings of this research work:

(1) $L1$ band suffers from more scintillation compare to $L5$ and S band at the location of IITRAM, Ahmedabad, India.
(2) IRNSS Satellite 1B is having elevation angle of 16° for 3 h (i.e., 9:00 am–12 pm) at the day time on June 11, 2019, which induces strong scintillation for S-band. Elevation angle of Satellite 1B reaches to 27.21286°, nearly around 4pm on June 15, 2019 over which positioning error is 7.850121187m.
(3) The highest elevation angle is 74.8625° and it is between morning 6:00 to 7:00 am for all satellites.
(4) Maximum ionospheric delay is nearly 19 m at $L5$ band and 4 m for S-band during the observation.
(5) The 3DRMS position error is 1.16 m, and circular error probability (CEP) is 0.46 m for the location of IITRAM.
(6) Positioning error is within the 10 m for all seven days, so it is clear that IRNSS fulfill its objectives at our location.

Fig. 9 Variation of C/N_0 with elevation angle for **a** Satellite 1B, **b** Satellite 1C, **c** Satellite 1D, **d** Satellite 1E



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Compliance with ethical standards

Conflict of interest The authors hereby confirm that there is no conflict of interest with respect to the current manuscript.

References

Acharya R, Majumdar S (2019) Statistical relation of scintillation index *S*4 with ionospheric irregularity index ROTI over Indian equatorial region. Adv Space Res 64(5):1019–1033

Acharya R, Nagori N, Jain N, Sunda S, Regar S, Sivaraman M, Bandopadhyay K (2007) Ionospheric studies for the implementation of GAGAN. Indian J Radio Space Phys 36:394–404

Brahmanandam PS, Uma G, Liu JY, Chu YH, Latha Devi NSMP, Kakinami Y (2012) Global S4 index variations observed using FORMOSAT-3/COSMIC GPS RO technique during a solar minimum year. J Geophys Res 117:1–31. https://doi.org/10.1029/2012JA017966

Carrano CS, Groves KM, Rino CL (2019) On the relationship between the rate of change of total electron content index (ROTI), irregularity strength (C k L), and the scintillation index (*S*4). J Geophys Res Space Phys 124:2099–2112. https://doi.org/10.1029/2018JA026353

Chakraborty S, Chatterjee S, Jana D (2017) A study on multifrequency scintillations near the EIA crest of the Indian zone. Adv Space Res 60(8):1670–1687

Chen S, Bilitza D, Liu J, Caton R, Chang L, Yeh W (2017) An empirical model of *L*-band scintillation *S*4 index constructed by using FORMOSAT-3/COSMIC data. Adv Space Res 60(5):1015–1028

de Oliveira Nascimento Brassarote G, de Souza E, Monico J (2017) *S* 4 index: does it only measure ionospheric scintillation? GPS Solut. https://doi.org/10.1007/s10291-017-0666-x

Desai M, Shah S (2018) The GIVE ionospheric delay correction approach to improve positional accuracy of Navic/IRNSS single-frequency receiver. Current Sci 114(08):1665

Guo K, Aquino M, Veettil SV (2019) Ionospheric scintillation intensity fading characteristics and GPS receiver tracking performance at low latitudes. GPS Solutions 23(2)

He Z, Zhao H, Feng W (2016) The ionospheric scintillation effects on the beidou signal receiver. Sensors 16 (11):1883

Indian Regional Navigation Satellite System (2017) Signal in space ICD for standard positioning service, version-1.1, ISRO-IRNSS-ICD-SPS-1.1

Jacobsen K, Dhnn M (2014) Statistics of ionospheric disturbances and their correlation with GNSS positioning errors at high latitudes. J Space Weather Space Clim 4:A27

Jianjun H, Cheng C, Li H, Qiusheng H (2006) Effect of ionosphere refraction on satellite navigation precision. In: 2006 7th international symposium on antennas, propagation and EM theory

Jiao Y, Morton Y (2015) Comparison of the effect of high latitude and equatorial ionospheric scintillation on GPS signals during the maximum of solar cycle 24. Radio Sci 50(9):886–903

Parmar S et al (2017) A comparative analysis of ionospheric effects on Indian Regional Navigation Satellite System (IRNSS) signals at low latitude region, Surat, India using GDF and Nakagami-m Distribution. In: International conference on future internet technologies and trends ICFITT 2017: future internet technologies and trends, pp 126–136. https://doi.org/10.1007/978-3-319-73712-6_13

Rawat A, Savaliya J, Chhabhaya D (2019) Field trial of IRNSS receiver. Microw Opt Technol Lett 61(5):1149–1153

Rino C, Morton Y, Breitsch B, Carrano C (2019) Stochastic TEC structure characterization. J Geophys Res Space Phys 124:10571–10579. https://doi.org/10.1029/2019JA026958

Romero R, Dovis F (2013) Effect of interference in the calculation of the amplitude scintillation index *S*4. In: 2013 international conference on localization and GNSS (ICL-GNSS)

Shahana K (2017) Ionospheric scintillation characteristics in IRNSS L5 and S-band signals. Indian J Radio Space Phys. https://www.researchgate.net/publication/324006991_Ionospheric_scintillation_characteristics_in_IRNSS_L5_and_S-band_signals

Sharma A, Gurav O, Bose A, Gaikwad H, Chavan G, Santra A, Kamble S, Vhatkar R (2019) Potential Of IRNSS/Navic *L*5 signals for ionospheric studies. Adv Space Res 63(10):3131–3138

Steenburgh RA, Smithtro CG, Groves KM (2008) Ionospheric scintillation effects on single frequency GPS. Space Weather 6:1–12. https://doi.org/10.1029/2007SW000340

Ya'acob N, Abdullah M, Ismail M (2010) GPS total electron content (TEC) prediction at ionosphere layer over the equatorial region. Trends Telecommun Technol. https://doi.org/10.5772/8474. https://www.intechopen.com/books/trends-in-telecommunications-technologies/gps-total-electron-content-tec-prediction-at-ionosphere-layer-over-the-equatorial-region