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Key Points:
- Decorrelated C/N_0 fluctuations on same SV link observed from two receivers
- Calculation of north-south spatial displacement rate of L band scintillation pattern
- Large receiver position deviations correspond to high irregularity characteristic velocities

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Relation of decorrelated transionospheric GPS signal fluctuations from two stations in the northern anomaly crest region with equatorial ionospheric dynamics

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Abstract The ionosphere around the northern crest of the equatorial ionization anomaly (EIA) and beyond exhibits rapid temporal as well as spatial development of ionization density irregularities during postsunset hours. A GPS campaign was conducted during September 2012 and April 2013 from the Institute of Radio Physics and Electronics, Calcutta (22.58°N, 88.38°E geographic; magnetic dip: 32°N), and North Bengal University (NBU), Siliguri (26.72°N, 88.39°E geographic, magnetic dip: 39.49°N) in India in order to assess and quantify differences, if any, in the nature of carrier to noise ratio (C/N_0) fluctuations observed on the same satellite link around the same time interval from these stations. Significant decorrelation of the received signals was found when tracking the same satellite vehicle (SV) link from these stations during periods of scintillations. Low values of correlation coefficient of C/N_0 at L1 frequency recorded on the same SV link at these two stations were found to correspond with high irregularity characteristic velocities. North-south spatial displacement rates of the impact of ionospheric irregularities were calculated based on coordinated GPS observations which followed an increasing trend with irregularity characteristic velocities measured at VHF. Values of characteristic velocities in excess of 36 m/s were also found to result in large receiver position deviations ~3.5–4.0 m during periods of scintillations. Information related to time lag associated with occurrence of scintillations on the same SV link observed from two stations could be useful for improving performance of transionospheric satellite-based position determination techniques.

1. Introduction

The morphology of the ionosphere in the region around the northern crest of the equatorial ionization anomaly (EIA) is influenced by the magnetic field alignment, which is nearly parallel to the Earth surface in this region. Observations of dark bands in 6300 Å airglow intensity measurements aligned along the north-south direction have been reported in literature [*Weber et al.*, 1980]. *Dyson and Benson* [1978] found by using topside sounder data from Alouette-2 and Isis-1 that the bubbles extend for greater distances along geomagnetic field lines. The movement of depleted magnetic flux tubes in the equatorial ionosphere has been studied in details [*Anderson and Haerendel*, 1979].

Equatorial ionospheric scintillations at locations around the anomaly crest region are mainly caused by these irregularities generated over the magnetic equator in the early evening hours which elongate along the highly conducting magnetic field lines to off-equatorial locations. The equatorial ionospheric irregularities in the postsunset hours often exhibit rapid development over a short period of time and across spatial distances of the order of 400–500 km. Intense, often saturated L band scintillations occur in the northern anomaly crest region even under magnetic quiet conditions [*Ray and DasGupta*, 2007].

Amplitude scintillation observations and cycle slips at Calcutta located in the northern anomaly crest region have been extensively reported in literature [*Ray and DasGupta*, 2007; *Roy and Paul*, 2013] and also from locations beyond the northern crest of the EIA [*A. Das et al.*, 2014].

Yet scintillation characteristics are not identical over these distances, even for receivers whose raypaths sample the same elongated depletion. It has been observed from GPS phase scintillation observations conducted during a multistation campaign in 2011 and 2012 that GPS cycle slip characteristics show marked difference from two locations, with a subionospheric latitude separation of about 4°–5° [*Roy and Paul*, 2013].

In the postsunset hours, ionospheric scintillations play a major detrimental role in degrading the performance of satellite-based systems through fast, intense, and random fluctuations of signal amplitude and cycle slips in the phase often resulting in complete loss of lock of the signal. It is necessary to develop a causative understanding of such variations even across base lines ~500 km in view of the stringent requirement of precision approach for aircrafts and high dynamic platform as stipulated by the International Civil Aviation Organization.

Study of the effects of the dynamic evolution of irregularities will provide new information for SBAS (Satellite Based Augmentation System), as this effect will be superposed on the already existing high spatial gradient of ionization in this geophysically sensitive region from the northern crest toward the midlatitudes [*A. Das et al.*, 2014]. Information related to the time interval between the onset or occurrence of scintillations on the same SV link observed from the two stations could be used for designing satellite-based position determination algorithms where such satellite links which are tracked from both stations and are affected by scintillations could be excluded from position calculations.

The emphasis of the present paper is to understand the possible reasons behind different levels of impact of equatorial ionospheric irregularities on the same GPS SV link over the same time interval for sites spanning the anomaly crest region and beyond. The effect of randomness of the medium of propagation, measured in terms of characteristic velocity, contributes significantly toward decorrelating transionospheric satellite signals and degrading the performance and accuracy of satellite-based communication and navigation systems operational in this region. The characteristic velocity is taken as a measure of randomness of the medium of propagation through which transionospheric satellite signals propagate to ground-based receivers.

Irregularity dynamical information including characteristic velocity has been obtained using simple and inexpensive VHF spaced aerial measurements [*Bhattacharyya et al.*, 1989, 2001]. These measurements of zonal drift and characteristic velocity could serve as an indicator of L band scintillations and GPS position accuracy parameters such as position dilution of precision (PDOP) [*Das et al.*, 2014b].

In this study, the correlation between amplitude scintillations is examined, as quantified by the carrier to noise density ratio C/N_0, for two sites spanning the anomaly crest, as a function of the characteristic velocity derived from VHF measurements. The characteristic velocity is compared to the time differences between the onset and occurrence of scintillations on the same SV link from a chain of GPS stations, which correspond to a "spatial displacement rate." Receiver position deviations are also estimated during the period of scintillations to correlate randomness of the medium of propagation with navigation accuracy.

The practical intent is to find out whether quantitative specification of the effects of diverse satellite signal fluctuations across baselines of the order of 500 km when traversing through ionospheric irregularities could be used for satellite-based services and application, e.g., planning satellite selection in development of algorithms to improve the accuracy of position fixing.

2. Data and Methodology

In the present paper, to study the dynamic behaviour of equatorial ionosphere across a spatial extent of 450 km (~equivalent to 4° latitude separation at 350 km subionospheric height), GPS carrier to noise ratios (C/N_0) have been recorded from two stations Calcutta and Siliguri on the same satellite link over the same time interval during September 2012 and April 2013. In order to quantify the differences observed in C/N_0 fluctuations from these two stations on the same SV link, correlations of C/N_0 have been calculated and from the associated time lags a north-south displacement rate of the impact of irregularities has been estimated. Irregularity characteristic velocities at VHF represent the randomness in the medium of propagation which has been calculated to develop a causal understanding for diverse C/N_0 fluctuations over spatial extents ~500 km.

A multistation GPS campaign was conducted from the Institute of Radio Physics and Electronics (IRPE), University of Calcutta, Calcutta (22.58°N, 88.38°E geographic; 33.82°N magnetic dip), and Department of Physics, North Bengal University (NBU), Siliguri (26.72°N, 88.39°E geographic, 39.49°N magnetic dip), during the equinoctial periods of September 2012 and April 2013. C/N_0 and S_4 variations were measured for the above period from two dual-frequency GPS receivers, one at Calcutta situated in the anomaly crest region and the other beyond the northern crest of the EIA at Siliguri, almost along the same geographic longitude (~88.5°E).

The station at Calcutta, operated by the IRPE is part of the international SCINDA (SCIntillation Network Decision Aid) program of the U.S. Air Force since November 2006 whereby a dual-frequency ionospheric scintillation and total electron content (TEC) monitor is operational continuously providing C/N_0 at a sampling frequency of 50 Hz, diurnal TEC and scintillation index S_4 at 1 min interval and polar plots corresponding to different satellites observed during the whole day. These data may be accessed in a postprocessed format by authorized users. Receiver position information is also available in terms of latitude and longitude at 1 s sampling interval from this receiver.

Amplitude scintillation index (S_4), and TEC were recorded at 1 minute sampling interval while C/N_0 was recorded at 50 Hz sampling frequency from the dual-frequency GPS receiver operational at NBU. The location of this station is important, being situated in the geophysically sensitive region poleward from the northern crest of the Equatorial Ionization Anomaly (EIA). TEC deviations were calculated by estimating the differences from the 90 min moving average values.

In order to understand the location of the northern crest of the equatorial ionization anomaly (EIA) in relation to the stations at Calcutta and Siliguri, TEC maps have been made using measured Slant TEC above an elevation angle of 50° combining data from the IGS stations located at Port Blair (11.64°N, 92.71°E geographic; magnetic dip 9.72°N), Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69°N), and Hyderabad 17.44°N, 78.47°E geographic; magnetic dip 21.9°N) with that recorded at Calcutta and Siliguri.

In the present paper, efforts have been made to identify the cases when both the receivers at Calcutta and Siliguri recorded scintillations over the same time interval on the same satellite link. The occurrence of scintillation in the satellite track has been considered only when the corresponding S_4 index recorded by the receiver shows value greater than 0.2 for at least 3 min time interval or more. Scintillation index (S_4) has been categorized into three sections, namely, (i) mild scintillation ($0.2 \le S_4 < 0.4$), (ii) moderate scintillation ($0.4 \le S_4 < 0.6$), (iii) and intense scintillation ($S_4 \ge 0.6$), respectively. During analysis of the data for September 2012 and April 2013, periods of common scintillation observation from the two stations were found on 1, 3, 4, and 25 September 2012 and 2, 5, 10, 11, 13, and 27 April 2013. Detailed descriptions of solar and magnetic activities during these periods are listed in Table 1. During the months of September 2012 and April 2013, one moderate geomagnetic storm occurred during 3–4 September 2012 having maximum negative *Dst* of −74 nT. Correlation was performed on samples of C/N_0 deviations of 3 min duration simultaneously observed from Calcutta and Siliguri on the same SV link for September 2012 and April 2013 and expressed in the form of correlation coefficient. C/N_0 deviations have been calculated by subtracting the moving averaged values, calculated over a running time interval of 10 min, from the in situ measurement of C/N_0. As the two stations are situated along the same meridian, the time lag associated with cross correlation of C/N_0 deviations recorded on a particular satellite link would provide an estimate of the north-south displacement rate of the impact of the irregularities on the same SV link.

A parameter, spatial displacement rate, has been calculated to understand the north-south rate of movement of the impact of GPS L band irregularities on the same SV link observed from Calcutta and Siliguri around the same time. To obtain this parameter, the component of the ionospheric pierce point (IPP) separation along the north-south direction for the satellite link observed from the two stations at Calcutta and Siliguri over the same time interval has been taken into account. This separation was converted into equivalent distance. The time lag obtained from the cross-correlation plot between the C/N_0-L1 deviations recorded from Calcutta and Siliguri was considered as the difference between the time of impact of the irregularity with the two transionospheric links. Finally, the spatial displacement rate was obtained by dividing the north-south component of the calculated distance by the time lag. The spatial displacement rates have been calculated corresponding to cross-correlation coefficients of C/N_0-L1 deviations greater than 0.2 in order to avoid the cases of strong scattering.

It is defined as

$$\text{Spatial Displacement Rate} = \frac{\left(\Delta\text{lat}^2 + \Delta\text{lon}^2\right)^{1/2}}{\tau \times 60} \sin\left(\tan^{-1}\frac{\Delta\text{lat}}{\Delta\text{lon}}\right)\ (\text{km/s}) \tag{1}$$

where Δlat is (subionospheric latitude of satellite link_{NBU}) − (subionospheric latitude of satellite $\text{link}_{\text{IRPE}}$) in kilometers, Δlon is (subionospheric longitude of satellite link $_{\text{NBU}}$) − (subionospheric longitude of satellite

Table 1. List of SV Numbers, Times of Occurrence, Ionospheric Pierce Points (IPP), Geophysical Parameters, Namely, Sunspot Number, *Dst* Index and *Kp* Index, and IPP Separation for the Same GPS Satellite From the Two Stations, Calcutta and Siliguri, Corresponding to the Start and End Times of Common Scintillation Observation for the Two Periods of Observation, Namely, September 2012 and April 2013

						Ionospheric Pierce Point (IPP)											
						Subionospheric Latitude (°N)				Subionospheric Longitude (°E)				IPP Separations			
	Geophysical Parameters					Initial		Final		Initial		Final		ΔLatitude (°N) (km)		ΔLongitude (°E) (km)	
Campaign Period	Daily sun Spot No.	Minimum *Dst* Index (nT)	Maximum *Kp* Index	SV No.	Time (LT)	Cal	Sil	Cal	Sil	Cal	Sil	Cal	Sil	Initial	Final	Initial	Final
1 Sept 2012	145	−20	2	SV9	21:23–21:26	17.88	21.29	18.12	21.57	92.99	93.55	92.93	93.47	3.41 (375.1)	3.37 (370.7)	0.56 (61.6)	0.54 (59.4)
3 Sept 2012	171	−74	6−	SV14	22:12–22:15	18.1	21.79	18.35	22.06	84.38	84.06	84.48	84.18	3.6 (396)	3.71 (408.1)	0.32 (35.2)	0.3 (33)
					22:56–23:02	20.74	24.66	21.0	24.93	85.43	85.29	85.52	85.4	3.92 (431.2)	3.93 (432.3)	0.14 (15.4)	0.12 (13.2)
					23:04–23:07	21.08	25.02	21.2	25.14	85.55	85.44	85.59	85.49	3.94 (433.4)	3.94 (433.4)	0.11 (12.1)	0.1 (11)
					23:16–23:20	21.54	25.49	21.69	25.64	85.72	85.64	85.78	85.7	3.95 (434.5)	3.95 (434.5)	0.08 (8.8)	0.08 (8.8)
4 Sept 2012	159	−63	4+	SV16	03:35–03:38	17.05	20.54	17.32	20.85	87.95	87.96	87.99	88.01	3.49 (383.9)	3.53 (388.3)	0.01 (1.1)	0.02 (2.2)
25 Sept 2012	136	−6	1−	SV27	19:42–19:49	19.5	23.19	19.97	23.71	93.7	94.17	93.55	93.96	3.69 (405.9)	3.74 (411.4)	0.47 (51.7)	0.41 (45.1)
12 April 2013	98	−19	2	SV4	21:46–21:52	16.29	19.18	16.9	20.07	85.99	85.62	86.19	85.92	2.89 (317.9)	3.17 (348.7)	0.37 (40.7)	0.27 (29.7)
15 April 2013	114	−15	1+	SV4	21:34–21:51	16.29	19.18	17.85	21.12	85.99	85.62	86.49	86.25	2.89 (317.9)	3.27 (359.7)	0.37 (40.7)	0.24 (26.4)
				SV7	22:00–22:03	18.11	21.43	17.96	21.24	90.23	90.48	90.27	90.54	3.32 (365.2)	3.28 (360.8)	0.25 (27.5)	0.27 (29.7)
				SV8	22:53–22:58	18.4	21.78	18.02	21.33	89.17	89.28	89.23	89.36	3.38 (371.8)	3.31 (364.1)	0.11 (12.1)	0.13 (14.3)
10 April 2013	139	−2	2+	SV2	22:28–22:36	17.13	20.25	17.86	21.15	84.25	83.67	84.57	84.09	3.12 (343.2)	3.29 (361.9)	0.58 (63.8)	0.48 (52.8)
					22:45–22:51	18.56	21.98	18.97	22.47	84.87	84.47	85.04	84.69	3.42 (376.2)	3.5 (385)	0.4 (44)	0.35 (38.5)
					22:57–23:00	19.34	22.9	19.46	23.04	85.19	84.87	85.24	84.93	3.56 (391.6)	3.58 (393.8)	0.32 (35.2)	0.31 (34.1)
				SV9	23:06–23:13	21.09	24.88	20.83	24.58	86.39	86.27	86.35	86.21	3.79 (416.9)	3.75 (412.5)	0.12 (13.2)	0.23 (25.3)
					23:15–23:18	20.74	24.49	20.62	24.36	86.34	86.2	86.32	86.17	3.75 (412.5)	3.74 (411.4)	0.14 (15.4)	0.15 (16.5)
					23.24–23.27	20.36	24.07	20.27	23.97	86.29	86.13	86.28	86.11	3.71 (408.1)	3.7 (407)	0.16 (17.6)	0.17 (18.7)
11 April 2013	126	−8	2	SV5	00:42–00:49	17.41	20.57	17.96	21.25	87.53	87.41	87.65	87.56	3.16 (347.6)	3.29 (361.9)	0.12 (13.2)	0.09 (9.9)
					00:56–01:03	18.44	21.84	18.88	22.36	87.74	87.65	87.82	87.77	3.4 (374)	3.48 (382.8)	0.09 (9.9)	0.05 (5.5)
				SV9	00:00–00:08	18.42	21.81	17.85	21.13	86.06	85.8	86.04	85.74	3.39 (372.9)	3.28 (360.8)	0.26 (28.6)	0.3 (33)
					00:19–00:27	16.96	20.02	16.22	19.08	86.01	85.66	86.02	85.63	3.06 (336.6)	2.86 (314.6)	0.35 (38.5)	0.39 (42.9)
13 April 2013	117	−5	3	SV2	22:17–22:22	17.26	20.41	17.72	20.97	84.31	83.75	84.52	84.02	3.15 (346.5)	3.25 (357.5)	0.56 (61.6)	0.5 (55)
					22:38–22:49	18.93	22.42	19.59	23.2	85.03	84.67	85.3	85.01	3.49 (383.9)	3.61 (397.1)	0.36 (39.6)	0.3 (33)
				SV9	23:20–23:27	19.89	23.53	19.53	23.13	86.29	86.1	86.24	86.04	3.7 (407)	3.63 (399.3)	0.1 (11)	0.2 (22)
					23:49–23:57	18.2	21.55	17.91	21.2	86.13	85.86	86.11	85.82	3.35 (368.5)	3.29 (361.9)	0.27 (29.7)	0.29 (31.9)
27 April 2013	107	−26	2+	SV10	22:00–22:03	17.43	20.47	17.74	20.84	90.07	90.27	90.09	90.28	3 (330)	3.1 (341)	0.2 (22)	0.19 (20.9)

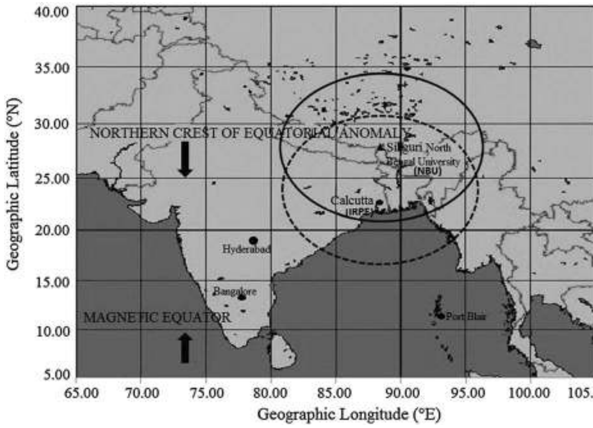

Figure 1. The 20° zone of reception from the stations Calcutta (IRPE) and Siliguri (NBU) situated along the same meridian (88.5°E). Locations of the IGS stations at Bangalore, Port Blair, and Hyderabad are also shown.

$link_{IRPE}$) in kilometers, for the same satellite link observed from the two stations, and, τ is the time lag of peak correlation in minutes between the GPS C/N_0-L1 observed from Calcutta and Siliguri on the same satellite link.

The parameter spatial displacement rate may give an idea about the different propagation environment associated with distribution of ionization density irregularities between the two stations having small subionospheric latitude difference (~4°–5°) and time differences between onset or occurrence of scintillations on the same satellite link observed from the two stations. This information obtained apriori will be useful in planning satellite selections for position determination.

Spaced aerial measurements are one of the most accepted procedures for studying the dynamical characteristics of ionospheric irregularities. The nonfrozen aspect of the irregularities can be observed from the estimation of the drift velocity of the ground diffraction pattern. VHF spaced aerial measurements using satellite beacon from the geostationary FLEETSATCOM (FSC, 250 MHz, 73°E) are being routinely conducted from Calcutta. The irregularity drift and characteristic velocities have been calculated during the equinoctial periods of September 2012 and April 2013. Using the method of "Full Correlation Analysis" [*Briggs et al.*, 1950; *Vacchione et al.*, 1987; *Bhattacharyya et al.*, 1989], the characteristic velocity is calculated, which is a measure of the temporal rate of change of the medium of propagation. High values of characteristic velocities indicate rapidly changing background ionospheric conditions as presented to a particular satellite link. Assuming that the amplitude space-time correlation function $C_A(x, t)$ is of the type

$$C_A(x,t) = f\left[(x–V_O t)^2 + {V_C}^2 t^2\right] \tag{2}$$

where V_O and V_C represents the irregularity drift velocity and characteristic velocity, respectively; the peak value method shows that the irregularity drift velocity (V_O) and characteristic velocity (V_C) can be calculated by using the formulas

$$V_O = \Delta x \tau_m / \left({\tau_m}^2 + {\tau_p}^2\right) \tag{3}$$

$${V_C}^2 = \Delta x V_o / \tau_m – {V_o}^2 \tag{4}$$

where Δx is the spacing between the two aerials aligned along geomagnetic east west direction, τ_p is the time lag for which the autocorrelation function of the amplitude equals the peak value of the cross correlation function for the signal amplitudes recorded at the two VHF receivers, and τ_m is the time lag for which the cross-correlation function is maximum. *Spartz et al.* [1988] discusses the above equations and methods in details. In the present study, the calculation of characteristic velocities at VHF have been done after 20:00 LT to eliminate any contamination due to vertical movement of structure during the early phase of irregularity generation [*Kudeki and Bhattacharyya*, 1999; *Das et al.*, 2014b].

Figure 1 shows the zone of reception of GPS satellite signals from the two stations Calcutta and Siliguri above an elevation of 20° on a map of India. Combining the data for two stations Calcutta and Siliguri lying almost along the same meridian (~88.5°E) within 20° zone of reception, the ionosphere can be tracked from 15.59°N, south of Calcutta (IRPE) to 33.71°N, north of Siliguri (NBU). Locations of IGS stations at Bangalore, Port Blair, and Hyderabad used for generating TEC maps are also indicated in this figure.

The present paper reports seven cases during the month of September 2012 and 19 cases in April 2013 of decorrelated C/N_0 fluctuations on the same GPS SV link recorded from the two stations and tries to understand the observed phenomena from the perspective of VHF irregularity characteristic velocities. During September 2012, total duration of GPS scintillations observed from Calcutta and Siliguri is

	$0.2 < S_4 < 0.6$	$S_4 > 0.6$
Calcutta	987 min	314 min
Siliguri	284 min	185 min

Out of this, during September 2012, common duration of scintillation observation was

	$0.2 < S_4 < 0.6$	$S_4 > 0.6$
Calcutta	29 min	7 min
Siliguri	30 min	6 min

During April 2013, the durations were

	$0.2 < S_4 < 0.6$	$S_4 > 0.6$
Calcutta	2159 min	1020 min
Siliguri	1027 min	289 min

The periods of common scintillation observation from Calcutta and Siliguri during April 2013 are

	$0.2 < S_4 < 0.6$	$S_4 > 0.6$
Calcutta	102 min	41 min
Siliguri	109 min	34 min

Receiver position deviations calculated at 1 s sampling and expressed in terms of latitude and longitude in meters have been used to correlate randomness of the medium of propagation with navigation performance during periods of scintillations. The position deviations were calculated taking the nominal receiver position at 06:00 LT as reference when ionospheric effects are minimal. Representative cases of 1 September 2012 and 3 April 2013 have been highlighted in the paper. Overall statistics for the whole months of September 2012 and April 2013 have also been presented in this paper.

3. Results

During analysis of the data for September 2012 from Calcutta and Siliguri, amplitude scintillations with $S_4 > 0.2$ at elevation angle in excess of 20° were observed on same SV link on 1, 3 , 4, and 25 September. Common period of scintillation observations from Calcutta and Siliguri on the same satellite link occurred on

	SV#	Time Interval
1 September 2012	9	21:23–21:26 LT
3 September 2012	14	22:12–22:15 LT
		22:56–23:02 LT
		23:04–23:07 LT
		23:16–23:20 LT
4 September 2012	16	03:35–03:38 LT
25 September 2012	27	19:42–19:49 LT

VHF spaced aerial measurements at Calcutta also recorded amplitude scintillations on all the above dates. A detailed case study of 1 September 2012 has been reported in this paper to describe the phenomenon of diverse multistation GPS scintillations and its possible relation with equatorial ionospheric dynamics. On

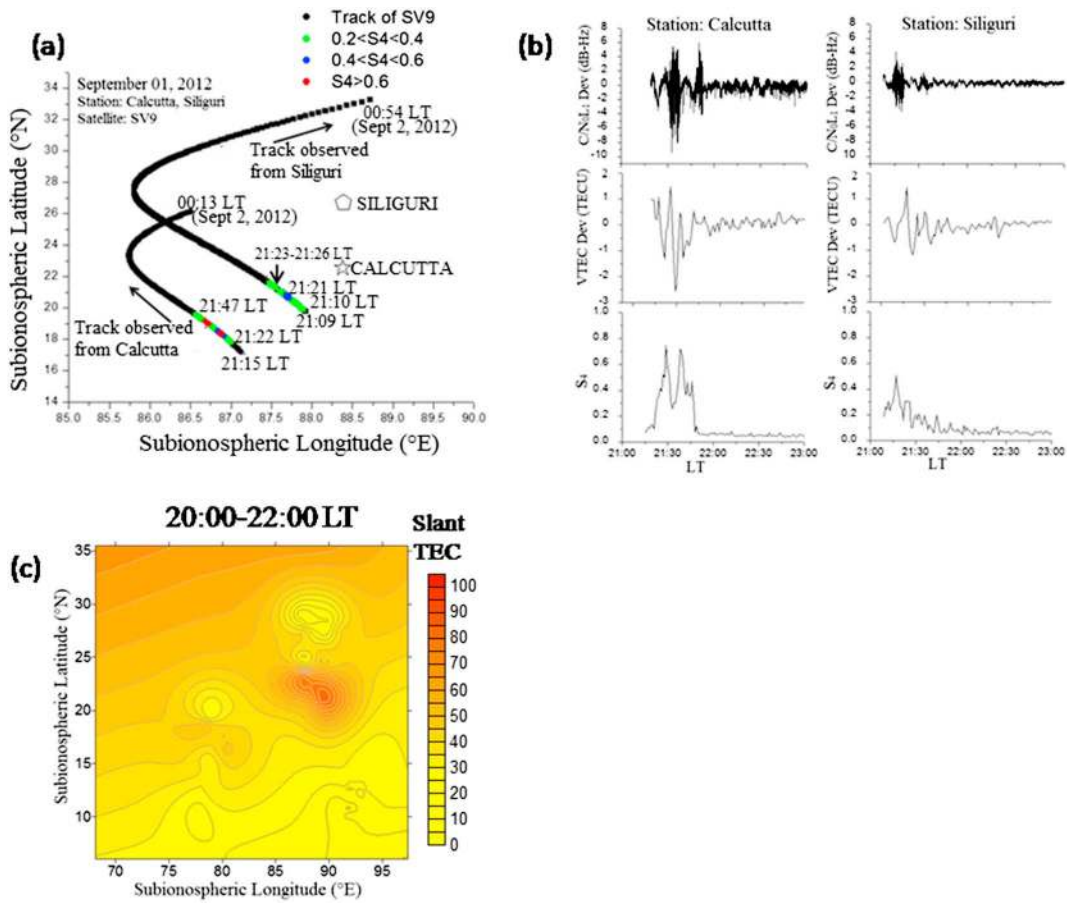

Figure 2. Case study of 1 September 2012. (a) Plot of 350 km subionospheric tracks of GPS SV9 link above an elevation of 20°, observed from Calcutta (IRPE) and Siliguri (NBU), on 1 September 2012. S_4 values and the time of occurrence of scintillations are indicated on the track. (b) Plot of C/N_0 deviations in L1, VTEC deviations, and S_4 indices of GPS SV9 link observed from Calcutta and Siliguri on 1 September 2012. (c) TEC map for 1 September 2012 for 20:00–22:00 LT above an elevation of 50° recorded from Bangalore, Port Blair, Hyderabad, Calcutta, and Siliguri.

1 September 2012, the case of SV9 during the time interval of 21:23–21:26 LT has been demonstrated as a representative case.

Figure 2a describes the track of SV9 observed from Calcutta and Siliguri simultaneously. The position of Calcutta (IRPE) is represented by the star and the corresponding track of SV9 recorded from Calcutta during 21:15 LT of 1 September to 00:13 LT of 2 September 2012 is shown by the black filled circles in the figure. The position of Siliguri is represented by a pentagon mark and corresponding subionospheric track of SV9 during 21:09 LT of 1 September to 00:54 LT of 2 September is represented by pentagons. From Figure 2a, it could be seen that common periods of scintillation was observed on SV9 link during 21:23–21:26 LT from Calcutta and Siliguri, respectively. The track recorded from Calcutta during 21:23–21:26 LT shows moderate to intense scintillations ($0.2 < S_4 < 0.7$) around 17.88°–18.13°N subionospheric latitude whereas from Siliguri mild ($0.2 \leq S_4 < 0.4$) scintillations around 21.29°–21.57°N subionospheric latitude were noted. This phenomenon indicates that the ionization density irregularities in the propagating medium may have changed over the subionospheric latitude separation of ~3.4° (by taking the difference of subionospheric latitudes measured from Calcutta and Siliguri). To study this effect in details, the corresponding recorded C/N_0s at L1 on the SV9 link from the two stations have been taken into account. Figure 2b represents C/N_0 deviations at L1 frequency, vertical total electron content (VTEC) deviations, and S_4 index measured from both stations on the SV9 link during the time interval of 21:00–23:00 LT of 1 September. VTEC deviation of 3.88 TEC unit (TECU, 1 TECU = 10^{16} el m^{-2}) could be observed from Calcutta during 21:30–21:50 LT whereas from Siliguri the deviation in VTEC of 2.58 TECU was recorded during 21:20–21:30 LT. It can also be observed from Figure 2b that during the time interval 21:09–21:26 LT, the C/N_0 deviations recorded from Siliguri is ~7 dB Hz

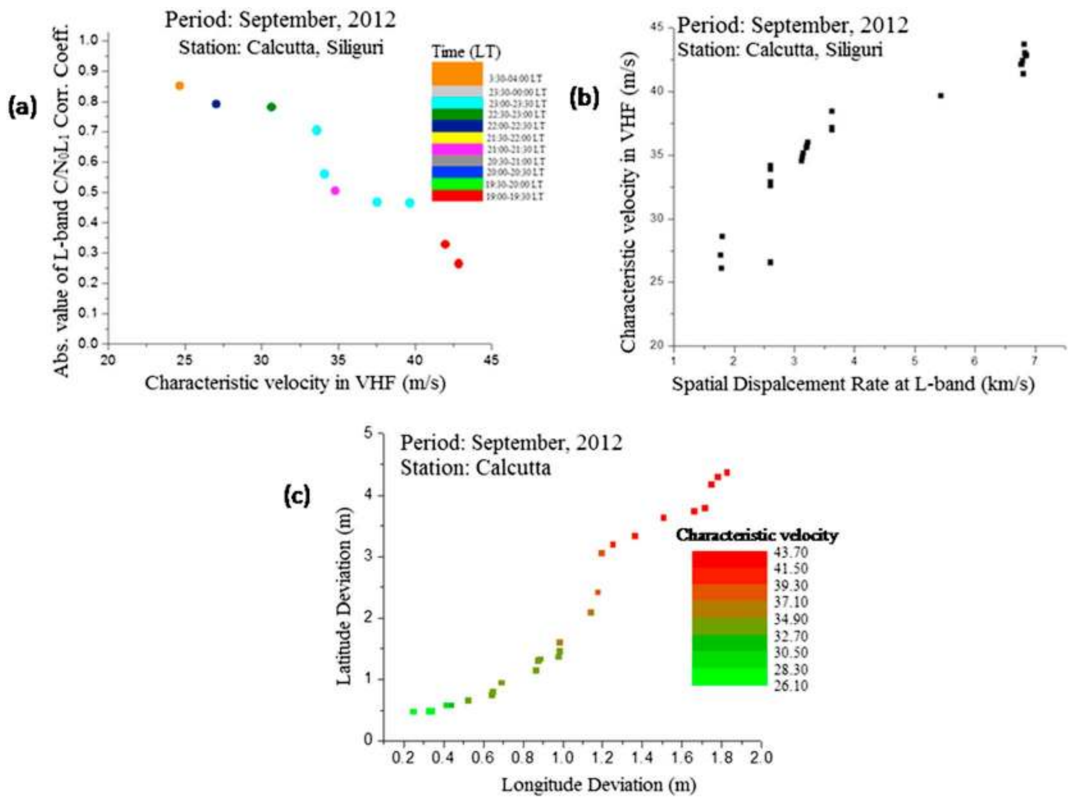

Figure 3. (a) Plot for correlation coefficient of L band C/N_0 deviations measured at Calcutta and Siliguri and the measured characteristic velocities (V_C) of VHF from Calcutta during the month of September 2012. (b) Plots for spatial displacement rates of the impact of L band irregularities with the characteristic velocities of the propagating ionospheric medium during September 2012. (c) Latitude and longitude deviations of the receiver measured in meters with characteristic velocities associated with the irregularities in the medium for the month of September 2012 from Calcutta.

whereas the recorded C/N_0 deviations from Calcutta during 21:23–21:53 LT are more intense ~13 dB Hz on the SV9 link. This indicates the existence of a dynamic medium of propagation.

During periods of common scintillation observations on the same satellite link from the two stations, correlation was performed on samples of C/N_0 deviations of 3 min interval. Correlation of C/N_0 deviations recorded from the two stations calculated during the time interval of 21:23–21:26 LT has been discussed. It is important to note that throughout this interval, scintillation was observed in the tracks of SV9 recorded from Calcutta and Siliguri as mentioned above. For the particular case of 1 September 2012, the value of spatial displacement rate along north-south direction of SV9 for the 3 min time interval 21:23–21:26 LT was found to be 3.1 km/s. Similar analyses have been done for all the cases of September 2012, and the spatial displacement rates have been calculated.

In order to understand the ambient ionization around this time, TEC maps have been generated for the period 20:00–22:00 LT of 1 September 2012, combining Slant TEC data above an elevation of 50° from the IGS stations located at Bangalore, Port Blair, and Hyderabad with the present stations at Calcutta and Siliguri. From Figure 2c, it is found that the crest of EIA at this time lies around a subionospheric latitude of 21.69°N which is south of Calcutta. The high elevation mask was selected in order to avoid the sharp spatial gradients of ionization occurring in the equatorial anomaly crest location.

VHF spaced aerial measurements using satellite beacon from the geostationary FLEETSATCOM (FSC, 250 MHz, 73°E) are available from Calcutta for the period of observation. To understand the level of randomness in the medium of propagation, the characteristic velocities have been calculated for the time interval when GPS scintillations were observed from Calcutta and Siliguri. Zonal drift and characteristic velocities were calculated for each 1 min sample of amplitude scintillation observed on the FSC link for each night of the period of observation using the method of full correlation analysis. Similar calculations have been done for all the cases of September 2012 for each 1 min sample of VHF amplitude scintillations.

Figure 3a shows the absolute values of the cross-correlation coefficients of L band C/N_0 deviations measured on the same satellite link from the two stations, and the measured characteristic velocities (V_C) from VHF spaced aerial measurement at Calcutta at different local times for all the cases of amplitude scintillations recorded during the month of September 2012. It can be observed from the plot that weak correlation of C/N_0 deviations at L band recorded from two stations for the same SV link correspond to high values of characteristic velocities. Figure 3b shows the calculated spatial displacement rates of the impact of irregularities affecting transionospheric L band signals and the characteristic velocities of the ionospheric medium of propagation for all the recorded cases of September 2012 having cross-correlation coefficients of C/N_0-L1 deviations greater than 0.2. This procedure has been followed since weakly correlated signals during periods of scintillations may result from strong scattering. It can be observed from the plot that the spatial displacement rate increases linearly with V_C.

To estimate the impact of a highly random medium of propagation on the performance of a GPS receiver, the receiver position deviations given in terms of latitude and longitude deviations in meters every second were estimated by taking the receiver position at 06:00 LT in the early morning hour as reference when ionospheric activities are normally minimal. Instantaneous position deviations were calculated by taking the difference from this reference value. Figure 3c shows the latitude and longitude deviations of the receiver measured in meters and the characteristic velocities associated with the irregularities in the medium for the month of September 2012. It is interesting to note that high values of characteristic velocities ~43.7 m/s are associated with larger (1.83 m along longitude and 4.36 m along latitude) position deviations.

During April 2013, amplitude scintillations ($S_4 > 0.2$) were recorded from Calcutta and Siliguri on 2, 5, 10, 11, 13, and 27 April on same SV link above an elevation of 20°.

L band scintillation observations on same satellite link over the same time interval occurred on

	SV#	Time Interval
2 April 2013	4	21:46–21:52 LT
5 April 2013	4	21:34–21:51 LT
	7	22:00–22:03 LT
	8	22:53–22:58 LT
10 April 2013	2	22:28–22:36 LT
		22:45–22:51 LT
		22:57–23:00 LT
	9	23:06–23:13 LT
		23:15–23:18 LT
		23:24–23:27 LT
11 April 2013	5	00:42–00:49 LT
		00:5601:03 LT
	9	00:19–00:27 LT
13 April 2013	2	22:17–22:22 LT
		22:38–22:49 LT
	9	23:20–23:27 LT
		23:49–23:57 LT
27 April 2013	10	22:00–22:03 LT

It should be mentioned that on 11 April, postmidnight amplitude scintillations have been observed in GPS as well as VHF from Calcutta and Siliguri.

The case on 13 April 2013 is being discussed as a representative one for the month of April 2013. On 13 April 2013, two SV links recorded common scintillation observations from both the stations, of which only the case of SV9 during the time interval 23:24–23:27 LT has been highlighted in the paper. Figure 4a shows the track of SV9 link observed from Calcutta and Siliguri simultaneously. The positions of Calcutta and Siliguri are indicated in the plot and the corresponding tracks of SV9 recorded from Calcutta (IRPE) during 19:58–00:28 LT of 14 April 2013 and during 19:49–00:17 LT of 14 April 2013 from Siliguri are shown. It is seen from the

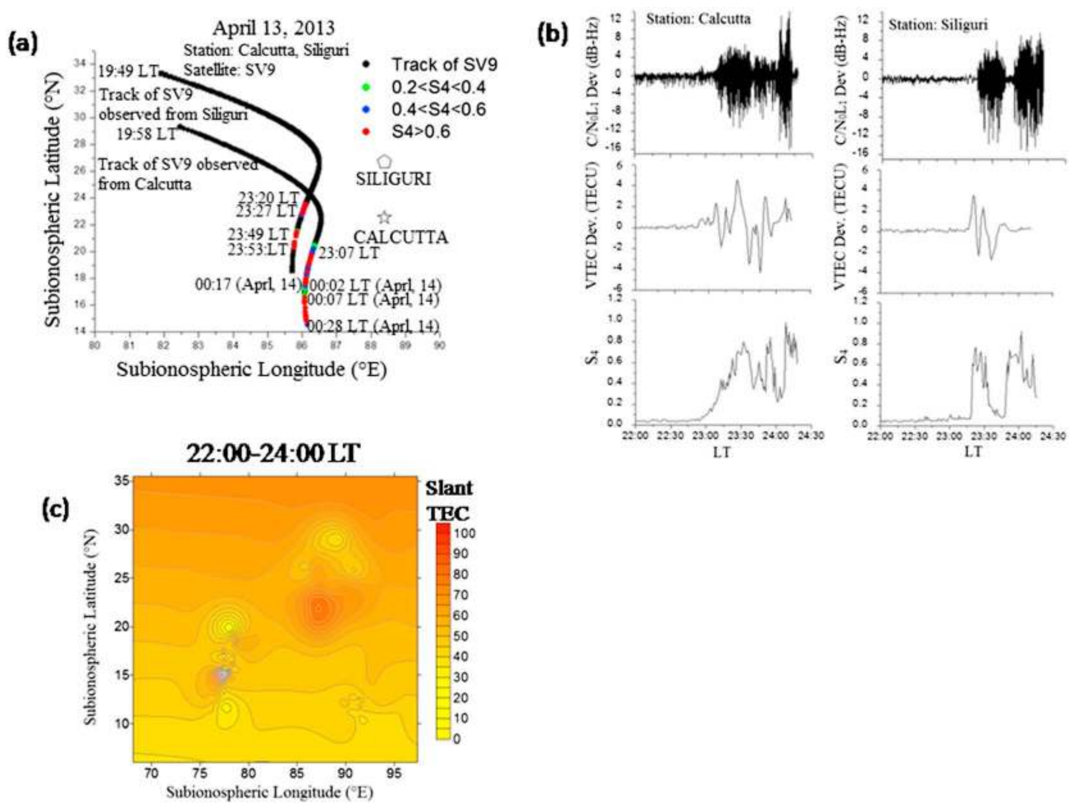

Figure 4. Case study of 13 April 2013. (a) Plot of 350 km subionospheric tracks of GPS SV9 satellite link above an elevation of 20°, observed from Calcutta (IRPE) and Siliguri (NBU), on 13 April 2013. S_4 values and the time of occurrence of scintillations are indicated on the track. (b) Plot of C/N$_0$-L1 deviations, VTEC deviations and S_4 indices of SV8 satellite link observed from Bangalore, Port Blair, Hyderabad, Calcutta, and Siliguri on 13 April 2013. (c) TEC map for 13 April 2013 for 22:00–24:00 LT above an elevation of 50° recorded from Calcutta and Siliguri.

figure that during 23:24–23:27 LT, the SV9 satellite link recorded from Calcutta exhibits moderate and intense L band scintillation patches around 19.69°–19.53°N subionospheric latitude whereas from Siliguri, the SV9 link at the same time shows intense scintillation patches around 23.31°–23.13°N subionospheric latitude. This event also indicates that the ionization density irregularities in the medium of propagation may have changed over the subionospheric latitude separation of ~3.6° (by taking the difference of subionospheric latitudes measured from Calcutta and Siliguri). Figure 4b presents C/N$_0$-L1 deviations, VTEC deviations, and S_4 indices recorded on the SV9 link from Calcutta and Siliguri, respectively. From the figure, maximum VTEC deviation of 8 TECU could be found from Calcutta and 6 TECU from Siliguri. It can also be observed from the figure that during 23:24–23:27 LT, the C/N$_0$-L1 deviations observed from Siliguri is ~17 dB Hz while that recorded from Calcutta ~13 dB Hz. An interesting point to note from the 350 km subionospheric track of SV9 as observed from Calcutta is the occurrence of intense scintillations ($S_4 > 0.6$) around 15°−20°N subionospheric latitude along 86°–86.5°E longitude around midnight and postmidnight hours. This region corresponds to the zone of maximum propagation angle for GPS observations from Calcutta as a result of which even weak irregularities when viewed over a longer propagation path due to field alignment with magnetic field lines cause intense scintillations during midnight or postmidnight hours [*DasGupta et al.*, 2004; *Paul et al.*, 2011; *Ray et al.*, 2015]. Spatial displacement rate has been calculated to understand the north-south rate of movement of the impact of ionization density irregularities with the same SV link observed from Calcutta and Siliguri for every 1 min interval of the corresponding time period. For the case of 13 April 2013, on the SV9 link, the value of spatial displacement rate along north-south direction for the 3 min time interval 23:24–23:27 LT was measured as 3.3 km/s. Similar analyses have been done for all the cases of April 2013, and the corresponding spatial displacement rate and C/N$_0$ deviation correlation coefficients have been calculated.

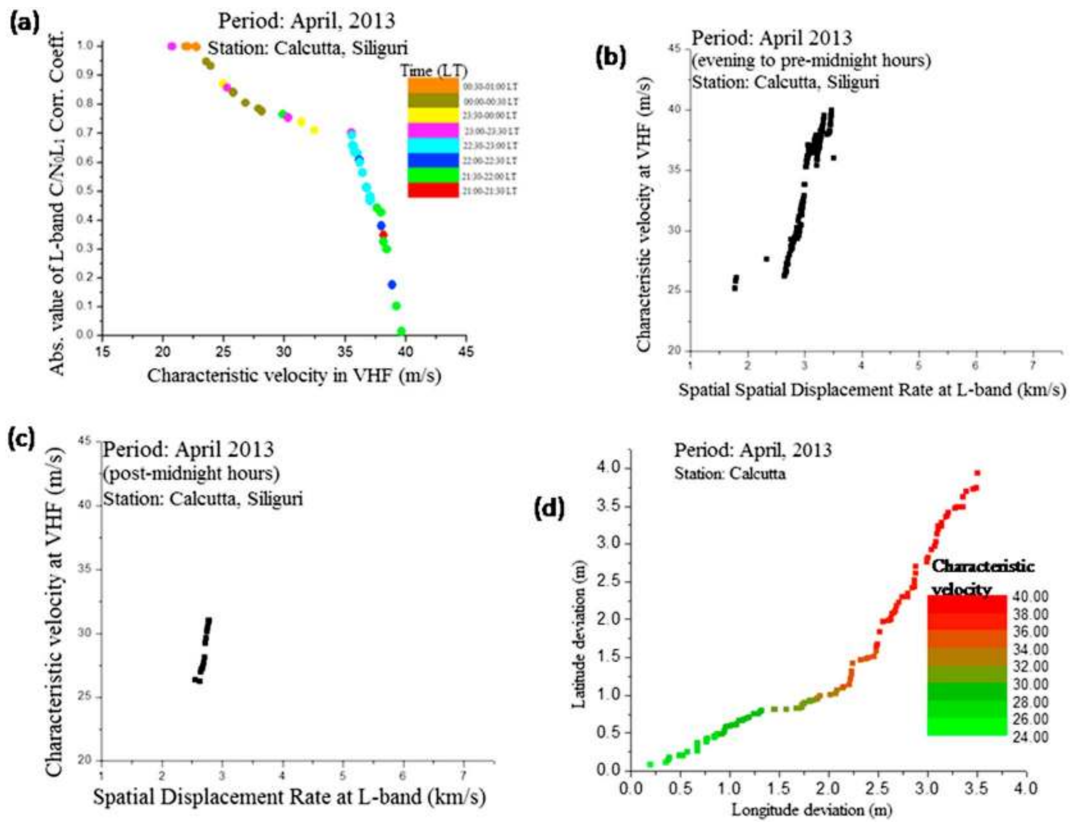

Figure 5. (a) Plot for correlation coefficient of L band C/N_0 deviations measured at Calcutta and Siliguri and the measured characteristic velocities (V_C) of VHF from Calcutta during the month of April 2013. (b) Plots for spatial displacement rates of the impact of L band irregularities with the characteristic velocities of the propagating ionospheric medium during premidnight hours of April 2013. (c) Plots for spatial displacement rates of L band irregularities with the characteristic velocities of the propagating ionospheric medium during postmidnight hours of April 2013. (d) Latitude and longitude deviations of the receiver measured in meters with characteristic velocities associated with the irregularities in the medium for the month of April 2013 from Calcutta.

Figure 4c shows the TEC plots for 13 April 2013 combining Slant TEC above an elevation of 50° from the IGS stations at Port Blair, Bangalore, and Hyderabad with those from Calcutta and Siliguri for the period 22:00–24:00 LT. The location of the EIA crest at this time is found to lie south of Calcutta at 21.82°N.

Figure 5a shows the absolute values of the cross-correlation coefficients of L band C/N_0 deviations measured on the same SV link from the two stations, and the measured characteristic velocities (V_C) from VHF spaced aerial measurement at Calcutta for all cases of amplitude scintillations recorded during April 2013 at different local times. It can be observed from the plot that the weakly correlated C/N_0 deviations at L band observed from Calcutta and Siliguri for the same SV link correspond to high values of characteristic velocities measured at VHF. Figure 5b shows the calculated spatial displacement rates of irregularities impacting transionospheric L band signals and the characteristic velocities of the propagating ionospheric medium for all the premidnight cases of April 2013 which correspond to cross-correlation coefficients of C/N_0-L1 deviations greater than 0.2. It can be observed from the plot that the north-south spatial displacement rate measured at L band between Calcutta and Siliguri increases with characteristic velocities at VHF. Figure 5c represents spatial displacement rate versus characteristic velocities for four postmidnight cases of April 2013. *Bhattacharyya et al.* [1989] observed that the characteristic velocity shows a gradual decrease during postmidnight period and provides minima around 01:00 LT. For that reason, the study between spatial displacement rates and characteristic velocities has been divided into two sections to obtain more accurate results. In this figure, it is observed that the L band spatial displacement rate increases with characteristic velocities.

The receiver position deviations in terms of latitude and longitude for every second were calculated for all cases of April 2013 by considering the receiver position at 06:00 LT as a reference. Figure 5d shows the

Table 2. Values of Maximum Displacement Rates, Maximum Latitude and Longitude Deviations Along With Maximum Characteristic Velocity, Maximum C/N_0 Deviations and Maximum S_4 Measured From Calcutta for the Periods September 2012 and April 2013

	Date	SV No.	Time Interval (LT)	Maximum Spatial Displacement Rate (km/s)	Maximum Longitude Deviation (m)	Maximum Latitude Deviation (m)	Maximum Characteristic Velocity (m/s)	Maximum C/N_0 Deviation (dB Hz)	Maximum S_4
September 2012	Sept 1	SV9	21:23–21:26	3.15	0.98	1.59	35.11	13	0.48
	Sept 3	SV14	22:12–22:15	1.80	0.42	0.58	28.63	9	0.40
			22:56–23:02	2.60	0.53	0.65	32.60	5.8	0.34
			23:04–23:07	5.43	1.25	3.19	39.65	16	0.77
			23:16–23:20	1.80	0.25	0.47	26.12	6	0.39
	Sept 4	SV16	03:35–03:38	2.60	0.53	0.65	32.79	5.6	0.33
	Sept 25	SV27	19:42–19:49	6.81	1.83	4.36	43.70	19	0.82
April 2013	Apr 2	SV4	21:46–21:52	3.34	3.46	3.72	39.54	17.3	0.82
	Apr 5	SV4	21:34–21:51	3.46	3.50	3.93	39.97	21	1.15
		SV7	22:00–22:03	1.80	0.32	0.14	26.11	10	0.34
		SV8	22:53–22:58	3.27	2.80	2.31	37.75	10.5	0.45
	Apr 10	SV2	22:28–22:36	2.99	0.84	0.46	27.68	12	0.48
			22:45–22:51	3.20	2.23	1.27	36.41	13	0.50
			22:57–23:00	3.08	2.15	1.11	35.27	10.7	0.35
		SV9	23:06–23:13	2.33	0.67	0.26	26.78	11	0.41
			23:15–23:18	2.86	1.57	0.82	30.23	14	0.51
			23:24–23:27	1.77	0.19	0.09	25.22	10.6	0.30
	Apr 11	SV5	00:42–00:49	3.43	3.18	3.35	38.65	18.2	0.89
			00:56–01:03	3.51	3.50	3.93	39.97	21.7	1.23
		SV9	00:00–00:08	3.07	2.49	1.67	36.16	14.8	0.59
			00:19–00:27	3.31	2.99	2.78	37.93	16	0.65
	Apr 13	SV2	22:17–22:22	3.30	3.09	3.13	38.23	19	0.88
			22:38–22:49	3.16	2.86	2.44	37.16	12.8	0.55
		SV9	23:20–23:27	3.28	3.46	3.72	37.86	13	0.64
			23:49–23:57	3.06	2.64	1.99	36.45	12.7	0.62
	Apr 27	SV10	22:00–22:03	2.8	1.03	0.60	29.05	13	0.48

latitude and longitude deviations of the receiver measured in meters and the characteristic velocities associated with the irregularities in the medium for the month of April 2013. It is observed from the figure that larger position deviations (~3.5 m along longitude and 3.93 m along latitude) correspond to high values of characteristic velocities (39.97 m/s).

Table 1 lists the SV number, time of occurrence, ionospheric pierce points (IPP), geophysical parameters, namely, sunspot number, *Dst* index, and *Kp* index, and IPP separation for the same satellite from the two stations corresponding to the start and end times of common scintillation observation on a particular GPS satellite from the two stations for the two periods of observation, namely, September 2012 and April 2013. Typical IPP separation of 350–370 km in terms of latitude and 30–50 km in terms of longitude are noted during the 2 months of observation. Table 2 shows the maximum displacement rates, maximum latitude and longitude deviations along with maximum characteristic velocity, and maximum C/N_0 deviations and maximum S_4 from Calcutta. It should be borne in mind that irregularity dynamic properties like characteristic velocities have been measured at Calcutta.

4. Discussions

The dynamic nature of the equatorial ionosphere is not only exhibited over large spatial extent but exhibits variability in transionospheric signal perturbations even across base lines with ground separation around 500 km and subionospheric spacing of 4°–5°. The phenomena of post sunset ionospheric scintillations introduces random, fast, and intense fluctuations of the carrier amplitude and causes cycle slips on the phase of transionospheric satellite links which intersect the plasma bubbles typically drifting from west to east. It is commonly understood that the structures of the ionospheric irregularities change with the progress of time from early evening to late night hours.

In the present paper, efforts have been made to calculate the north-south propagation velocity of the impact of the ionospheric irregularity. It is important to note that this velocity should not be interpreted as the north-south velocity of the irregularities. Since the cross section of the bubble decreases as it moves away from the equator and becomes very narrow around the anomaly crests [*Weber et al.*, 1978; *Sobral et al.*, 1985], the lack of correspondence between the C/N_0 fluctuations observed on the same satellite link from the two stations may be predominantly contributed by different propagation medium conditions rather than the geometry of the two satellite links with respect to the longitudinally elongated irregularity structure. The spatial displacement rate is influenced by the irregularity N-S movement. However, relative motion between the moving GPS satellite and the receiver also plays a part.

The temporal scales or fading times of the amplitude fluctuations are important to understand the response of GPS receivers during periods of scintillations. *Kintner et al.* [2007] measured the fading time in terms of Fresnel length and the scintillation pattern velocity by employing four spaced scintillation GPS receivers. *Kintner et al.* [2007] discusses fading rates associated with amplitude scintillation patterns using four GPS receivers aligned along magnetic east-west direction in the Brazilian longitude sector. Although this configuration of receiver is different from the one presented in the paper, the issue that relative motion between the moving GPS satellites and the receiver plays an important role in determining the observed duration of scintillation patches is important from the perspective of the present work.

Correlation between the fading rates of VHF scintillations and GPS S_4 has been studied by *Das et al.* [2010]. The scale size of irregularities causing GPS L band scintillations are of the order of 300–400 m. It has been observed from GPS scintillation records at Calcutta and Siliguri that the durations of scintillation patches on different satellite links recorded from Calcutta and Siliguri are often 25–30 min, which in turn indicates a spatial zonal extent of the irregularity cloud of 300–400 km, assuming a nominal zonal drift velocity of 200 m/s [*Bhattacharyya et al.*, 1989, 2001]. Variations in C/N_0 fluctuations observed from Calcutta and Siliguri on the same satellite link over the same interval of time could be attributed primarily to randomness of the medium of propagation. Values of IPP separation of about 350 km in terms of latitude and 30 km in terms of longitude have been obtained for the same satellite observed from the two stations at Calcutta and Siliguri from Table 1. However, this separation may not be the actual irregularity dimension. For estimating the irregularity dimension along north-south direction, tracking from the magnetic equator to locations beyond the northern crest of the equatorial ionization anomaly (EIA) along a magnetic field line is necessary. In the present case, the station at Calcutta is located in the anomaly crest region, while Siliguri is situated beyond the northern crest of the EIA.

From Figures 3a and 5a it has been observed that the low values of correlation coefficients of L band C/N_0 deviations from two stations are associated with high values of characteristic velocities. The issue of scintillation occurrences when satellite links pass end-on through field-aligned plasma bubbles as observed from Calcutta has been extensively discussed in literature [*DasGupta et al.*, 2004; *Paul et al.*, 2011; *Ray et al.*, 2015]. The maximum propagation angle for a GPS satellite link observed from Calcutta occurs over the range 14.09°–16.87°N, 86.93°–89.40°E geographic [*Ray et al.*, 2015]. The intense scintillations ($S_4 > 0.6$) observed on SV9 on 13 April 2013 from Calcutta during local postmidnight hours may be attributed to field-aligned geometry enhancement. The present paper reports different nature of C/N_0 fluctuations observed when tracking the same GPS satellite from two stations in the anomaly crest region over the same time interval and tries to understand this observed difference in terms of randomness of the medium of propagation, measured in terms of the irregularity characteristic velocity at VHF. During April 2013, premidnight and postmidnight cases have been separately presented in Figures 5b and 5c, respectively.

Differences in values of spatial displacement rates may be related to equinoctial asymmetry of occurrence of equatorial ionization density and ionospheric irregularities as illustrated in literature. It has been observed that TEC at vernal equinox is higher than autumnal equinox. This phenomenon is called equinoctial asymmetry [*Titheridge*, 1973; *Titheridge and Buonsanto*, 1983; *Maruyama and Matuura*, 1984; *Balan et al.*, 1997, 1998; *Kawamura et al.*, 2002; *Liu et al.*, 2010, 2011; *Paul and DasGupta*, 2010; *Akala et al.*, 2013]. This asymmetry intensifies near EIA crest [*Balan et al.*, 2000]. From *Balan et al.* [1997, 1998], the effects of neutral winds on this asymmetry can be explained. Seasonal variability of TEC in the Indian longitude sector has been documented by *Rama Rao et al.* [1977], *Rama Rao et al.* [2006], *Bhuyan and Borah* [2007] and *Bagiya et al.* [2009]. The equinoctial asymmetry of ionization has also been observed using incoherent scatter radar observations from Jicamarca Radio Observatory [*Fejer et al.*, 1981, 1985, 1989]. *Sripathi et al.* [2011, and references therein] had shown asymmetry in occurrence of scintillations over the Indian longitudes using GPS L band amplitude scintillation and rate of TEC index. Their occurrences have been found to be greater during vernal equinox than autumnal equinox. Since irregularity occurrence is dependent on the ambient ionization, the above mentioned factors may influence north-south movement of the zone of impact of scintillation observation on a common GPS satellite link observed from two stations located in the anomaly crest region.

It is important to note that around midnight and postmidnight period, cases of occurrence of GPS L band scintillations have been reported from Indian longitude sector [*Das et al.*, 2014a; *Paul et al.*, 2015]. *Das et al.* [2014a and references therein] suggested that during postmidnight hours, some fresh locally generated bubbles or irregularities generated in the midlatitudes may move to higher equatorial latitudes and affect the transionospheric satellite link operating in this region. Fossil bubbles may also contribute in the occurrence of scintillations at high equatorial latitudes during postmidnight period. From Figures 3 and 5, it is found that characteristic velocities are less, about 20–25 m/s, during postmidnight hours compared to premidnight, when their values are around 40–45 m/s. It should be noted that during the period of study covering September 2012 and April 2013, there was one geomagnetic storm during 3–4 September 2012. However, this storm being moderate, having maximum *Dst* of −74 nT, has not been separately classified. The values of characteristic velocity on 3–4 September 2012 were measured to be between 26 and 40 m/s, while the values on 1 and 25 September 2012 were between 35 and 43 m/s.

Since the spatial displacement rates have been calculated from differences in C/N_0 deviations observed on the same satellite link at almost the same time from two stations in the anomaly crest region, different values of the above are contributed by different propagation medium conditions, i.e., geophysical effects. Spatial displacement rates are found to be higher about 4–6 km/s during premidnight hours and low with values around 2 km/s during postmidnight hours. This indicates relatively slower movement of the impact of L band irregularities along a meridional slice during postmidnight hours compared to premidnight cases. Irregularity occurrence has a pronounced seasonal asymmetry in the Indian longitude sector as reported and explained in several earlier work [*Zhang et al.*, 2011; *Sur et al.*, 2015, and references therein].

Characteristic velocities greater than 39 m/s result in maximum latitude and longitude deviations of 4.36 m and 1.83 m, respectively, for September 2012. The corresponding figures for April 2013 are 3.93 m and 3.5 m, respectively. It should be borne in mind that kinematic positioning tests based on code and carrier phase-smoothed code measurements using the between-receiver single-difference technique had shown 1 m and 50 cm root-mean-square accuracies [*Cannon and Lachapelle*, 1992].

Thus, the irregularity characteristic velocity measured using simple inexpensive VHF spaced aerial measurement could be used to understand the receiver position deviation for GPS under condition of ionospheric scintillation. Results of correlation of GPS S_4 with VHF irregularity characteristic velocities from Calcutta for the period February–April 2011 are available in literature [*Das et al.*, 2014b]. Thus, significant improvement in the present understanding of the origin, evolution, and consequent effects of equatorial ionospheric irregularities on transionospheric satellite links needs to be developed. As SBAS grid sizes are nominally of the order of 5° × 5°, there may be serious implications for air-borne users operating in the equatorial anomaly crest region when carrier to noise ratios of GPS signals are significantly decorrelated over spatial extents of 4°–5° under adverse ionospheric conditions. Thus, the present paper makes an attempt to develop an understanding of decorrelated C/N_0 fluctuations on same satellite link observed from two GPS receivers having midrange separation located in the anomaly crest region with associated large position errors and suggests dynamic evolution of equatorial ionospheric irregularity as a possible cause for the same. Study of such cases would help improve algorithms for satellite-based position determination by indicating the satellites sharing a common ionospheric volume and showing scintillations from two stations.

5. Conclusions

The present paper reports the results of multistation GPS measurements conducted from Calcutta and Siliguri over the months of September 2012 and April 2013. The analysis done for this paper is based on seven cases for September 2012 and 19 cases for April 2013 of observations of C/N_0 fluctuations on the same SV link around the same time from the two stations. Quantitative relations have been established between the decorrelated C/N_0 fluctuations (for decorrelation coefficient > 0.2) on the same GPS SV link recorded at the same time interval from Calcutta and Siliguri, and efforts have been made to develop an understanding of the observed phenomena from the perspective of VHF irregularity characteristic velocities. It has been found that low values of correlation coefficients of L band C/N_0 deviations from two stations are associated with high values of characteristic velocities at VHF and resulting high receiver position errors. Spatial displacement rate, which corresponds to the north-south propagation velocity of the impact of the ionospheric irregularity on ground-based GPS receivers located at Calcutta and Siliguri, has been calculated which could be used for predicting satellite signal outages at stations along the same meridian.

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References

Akala, A. O., G. K. Seemala, P. H. Doherty, C. E. Valladares, C. S. Carrano, J. Espinoza, and S. Oluyo (2013), Comparison of equatorial GPS-TEC observations over an African station and an American station during the minimum and ascending phases of solar cycle 24, *Ann. Geophys.*, *31*, 2085–2096, doi:10.5194/angeo-31-2085-2013.

Anderson, D. N., and G. Haerendel (1979), The motion of depleted plasma regions in the equatorial ionosphere, *J. Geophys. Res.*, *84*, 4251–4256, doi:10.1029/JA084iA08p04251.

Bagiya, M. S., H. P. Joshi, K. N. Iyer, M. Aggarwal, S. Ravindran, and B. M. Pathan (2009), TEC variations during low solar activity period (2005–2007) near the equatorial ionospheric anomaly crest region in India, *Ann. Geophys.*, *27*, 1047–1057.

Balan, N., Y. Otsuka, and S. Fukao (1997), New aspects in the annual variation of the ionosphere observed by the MU radar, *Geophys. Res. Lett.*, *24*, 2287–2290, doi:10.1029/97GL02184.

Balan, N., Y. Otsuka, G. J. Bailey, and S. Fukao (1998), Equinoctial asymmetries in the ionosphere and thermosphere observed by the MU radar, *J. Geophys. Res.*, *103*, 9481–9495, doi:10.1029/97JA03137.

Balan, N., Y. Otsuka, S. Fukao, M. A. Abdu, and G. J. Bailey (2000), Annual variations of the ionosphere: A review based on MU radar observations, *Adv. Space Res.*, *25*(1), 153–162, doi:10.1016/S0273-1177(99)00913-8.

Bhattacharyya, A., S. J. Franke, and K. C. Yeh (1989), Characteristic velocity of equatorial *F* region irregularities determined from spaced receiver scintillation data, *J. Geophys. Res.*, *94*, 11,959–11,969, doi:10.1029/JA094iA09p11959.

Bhattacharyya, A., S. Basu, K. M. Groves, C. E. Valladares, and R. Sheehan (2001), Dynamics of equatorial *F* region irregularities from spaced receiver scintillation observations, *Geophys. Res. Lett.*, *28*, 119–122, doi:10.1029/2000GL012288.

Bhuyan, P. K., and R. R. Borah (2007), TEC derived from GPS network in India and comparison with the IRI, *Adv. Space Res.*, *39*, 830–840, doi:10.1016/j.asr.2006.12.042.

Briggs, B. H., G. L. Phillips, and D. H. Shinn (1950), The analysis of observations on spaced receivers of the fading of radio signals, *Proc. Phys. Soc. B*, *63*, 106, doi:10.1088/0370-1301/63/2/305.

Cannon, M. E., and G. Lachapelle (1992), Analysis of a high-performance C/A-code GPS receiver in kinematic mode, *Navigation*, *39*(3), 285–300.

Das, A., A. DasGupta, and S. Ray (2010), Characteristics of L-band (1.5 GHz) and VHF (244MHz) amplitude scintillations recorded at Kolkata during 1996–2006 and development of models of occurrence probability of scintillations using neural network, *J. Atmos. Sol. Terr. Phys.*, *72*(9–10), 685–704.

Das, A., K. S. Paul, S. Haldar, K. Basu, and A. Paul (2014), Characteristics of equatorial ionization anomaly (EIA) in relation to transionospheric satellite links around the northern crest in the Indian longitudinal sector, *Ann. Geophys.*, *32*, 91–97.

Das, T., K. S. Paul, and A. Paul (2014a), Observation of ionospheric irregularities around midnight and post-midnight near the northern crest of the equatorial ionization anomaly in the Indian longitude sector: Case studies, *J. Atmos. Sol. Terr. Phys.*, *121*, 188–195.

Das, T., B. Roy, and A. Paul (2014b), Effects of transionospheric signal decorrelation on Global Navigation Satellite System (GNSS) performance studied from irregularity dynamics around the northern crest of EIA, *Radio Sci.*, *49*, 851–860, doi:10.1002/2014RS005406.

DasGupta, A., S. Ray, A. Paul, P. Banerjee, and A. Bose (2004), Errors in position-fixing by GPS in an environment of strong equatorial scintillations in the Indian zone, *Radio Sci.*, *39*, RS1S30, doi:10.1029/2002RS002822.

Dyson, P. L., and R. F. Benson (1978), Topside sounder observations of equatorial bubbles, *Geophys. Res. Lett.*, *5*, 795–798, doi:10.1029/GL005i009p00795.

Fejer, B. G., D. T. Farley, C. A. Gonzales, R. F. Woodman, and C. Calderon (1981), F region east-west drifts at Jicamarca, *J. Geophys. Res.*, *86*, 215–218, doi:10.1029/JA086iA01p00215.

Fejer, B. G., E. Kudeki, and D. T. Farley (1985), Equatorial F region zonal plasma drifts, *J. Geophys. Res.*, *90*, 12,249–12,255, doi:10.1029/JA090iA12p12249.

Fejer, B. G., E. R. de Paula, I. S. Batista, E. Bonelli, and R. F. Woodman (1989), Equatorial *F* region vertical plasma drifts during solar maxima, *J. Geophys. Res.*, *94*, 12,049–12,054, doi:10.1029/JA094iA09p12049.

Kawamura, S., N. Balan, Y. Otsuka, and S. Fukao (2002), Annual and semiannual variations of the midlatitude ionosphere under low solar activity, *J. Geophys. Res.*, *107*(A8), 1166, doi:10.1029/2001JA000267.

Kintner, P. M., B. M. Ledvina, and E. R. de Paula (2007), GPS and ionospheric scintillations, *Space Weather*, *5*, S09003, doi:10.1029/2006SW000260.

Kudeki, E., and S. Bhattacharyya (1999), Post-sunset vortex in equatorial *F* region plasma drifts and implication for bottom side spread *F*, *J. Geophys. Res.*, *104*, 28,163–28,170, doi:10.1029/1998JA900111.

Liu, L., M. He, X. Yue, B. Ning, and W. Wan (2010), Ionosphere around equinoxes during low solar activity, *J. Geophys. Res.*, *115*, A09307, doi:10.1029/2010JA015318.

Liu, L., H. Le, Y. Chen, M. He, W. Wan, and X. Yue (2011), Features of the middle- and low-latitude ionosphere during solar minimum as revealed from COSMIC radio occultation measurements, *J. Geophys. Res.*, *116*, A09307, doi:10.1029/2011JA016691.

Maruyama, T., and N. Matuura (1984), Longitudinal variability of annual changes in activity of equatorial spread-*F* and plasma bubbles, *J. Geophys. Res.*, *89*, 10,903–10,912, doi:10.1029/JA089iA12p10903.

Paul, A., and A. DasGupta (2010), Characteristics of the equatorial ionization anomaly in relation to the day-to-day variability of ionospheric irregularities around the postsunset period, *Radio Sci.*, *45*, RS6001, doi:10.1029/2009RS004329.

Paul, A., B. Roy, S. Ray, A. Das, and A. DasGupta (2011), Characteristics of intense space weather events as observed from a low latitude station during solar minimum, *J. Geophys. Res.*, *116*, A10307, doi:10.1029/2010JA016330.

Paul, A., H. Haralambous, and C. Oikonomou (2015), Characteristics of post-midnight L band scintillation in the transition region from the equatorial to mid-latitudes over the Indian longitude sector using COSMIC, C/NOFS and GPS measurements, *Radio Sci.*, *50*, 1246–1255, doi:10.1002/2015RS005807.

Rama Rao, P. V. S., M. Srirama Rao, and M. Satyam (1977), Diurnal and seasonal trends in TEC values observed at Waltair, *Indian J. Radio Space Phys.*, *6*, 233–235.

Rama Rao, P. V. S., S. Gopi Krishna, K. Niranjan, and D. S. V. V. D. Prasad (2006), Temporal and spatial variations in TEC using simultaneous measurements from the Indian GPS network of receivers during the low solar activity period of 2004–2005, *Ann. Geophys.*, *24*, 3279–3292.

Ray, S., and A. DasGupta (2007), Geostationary L-band signal scintillation observations near the crest of equatorial anomaly in the Indian zone, *J. Atmos. Sol. Terr. Phys.*, *69*(4–5), 500–514.

Ray, S., A. Paul, and B. Chandel (2015), GPS scintillation effects as observed from a location beyond the anomaly crest in the Indian longitude sector, Ionos. Effects Symp. (IES-2015), Alexandria, Va.

Roy, B., and A. Paul (2013), Impact of space weather events on satellite-based navigation, *Space Weather*, *11*, 680–686, doi:10.1002/2013SW001001.

Sobral, J. H. A., M. A. Abdu, and Y. Sahai (1985), Equatorial plasma bubble eastward velocity characteristics from scanning airglow photometer measurements over Cachoeira Paulista, *J. Atmos. Terr. Phys.*, *47*, 895–900, doi:10.1016/0021-9169(85)90064-9.

Spartz, D. E., S. J. Franke, and K. C. Yeh (1988), Analysis and interpretation of spaced receiver scintillation data recorded at an equatorial station, *Radio Sci.*, *23*, 347–361, doi:10.1029/RS023i003p00347.

Sripathi, S., B. Kakad, and A. Bhattacharyya (2011), Study of equinoctial asymmetry in the equatorial spread F (ESF) irregularities over Indian region using multi-instrument observations in the descending phase of solar cycle 23, *J. Geophys. Res.*, *116*, A11302, doi:10.1029/2011JA016625.

Sur, D., S. Ray, and A. Paul (2015), Role of neutral wind in the performance of artificial neural-network based TEC models at diverse longitudes in the low latitudes, *J. Geophys. Res. Space Physics*, *120*, 2316–2332, doi:10.1002/2014JA020594.

Titheridge, J. E. (1973), The electron content of the southern mid-latitude ionosphere, 1965–1971, *J. Atmos. Terr. Phys.*, *35*, 981–1001, doi:10.1016/0021-9169(73)90077-9.

Titheridge, J. E., and M. J. Buonsanto (1983), Annual variations in the electron content and height of the *F* layer in the northern and southern hemispheres, related to neutral composition, *J. Atmos. Terr. Phys.*, *45*, 683–696, doi:10.1016/S0021-9169(83)80027-0.

Vacchione, J. D., S. J. Franke, and K. C. Yeh (1987), A new analysis technique for estimating zonal irregularity drifts and variability in the equatorial F region using spaced receiver scintillation data, *Radio Sci.*, *22*, 347–361, doi:10.1029/RS022i005p00745.

Weber, E. J., J. Buchau, H. Eather, and S. B. Mende (1978), North-south aligned equatorial airglow depletions, *J. Geophys. Res.*, *83*, 712–716, doi:10.1029/JA083iA02p00712.

Weber, E. J., J. Buchau, and J. G. Moore (1980), Airborne studies of equatorial *F* layer ionospheric irregularities, *J. Geophys. Res.*, *85*, 4631–4641, doi:10.1029/JA085iA09p04631.

Zhang, S., J. C. Foster, A. J. Coster, and P. J. Erickson (2011), East-west coast differences in total electron content over the continental U.S, *Geophys. Res. Lett.*, *38*, L19101, doi:10.1029/2011GL049116.