Features of ionospheric irregularities observed using multi-technique investigations from a low latitude station

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- Equatorial and low latitude ionospheric irregularities impact transionospheric radio signals over a wide spectrum of frequencies ranging from HF to L-band and sometimes even S-band.

- Since these frequency bands host majority of satellite-based communication and navigation links and other systems, impairment of these signals implies partial or sometimes complete outage of associated services to a vast panoply of modern society.

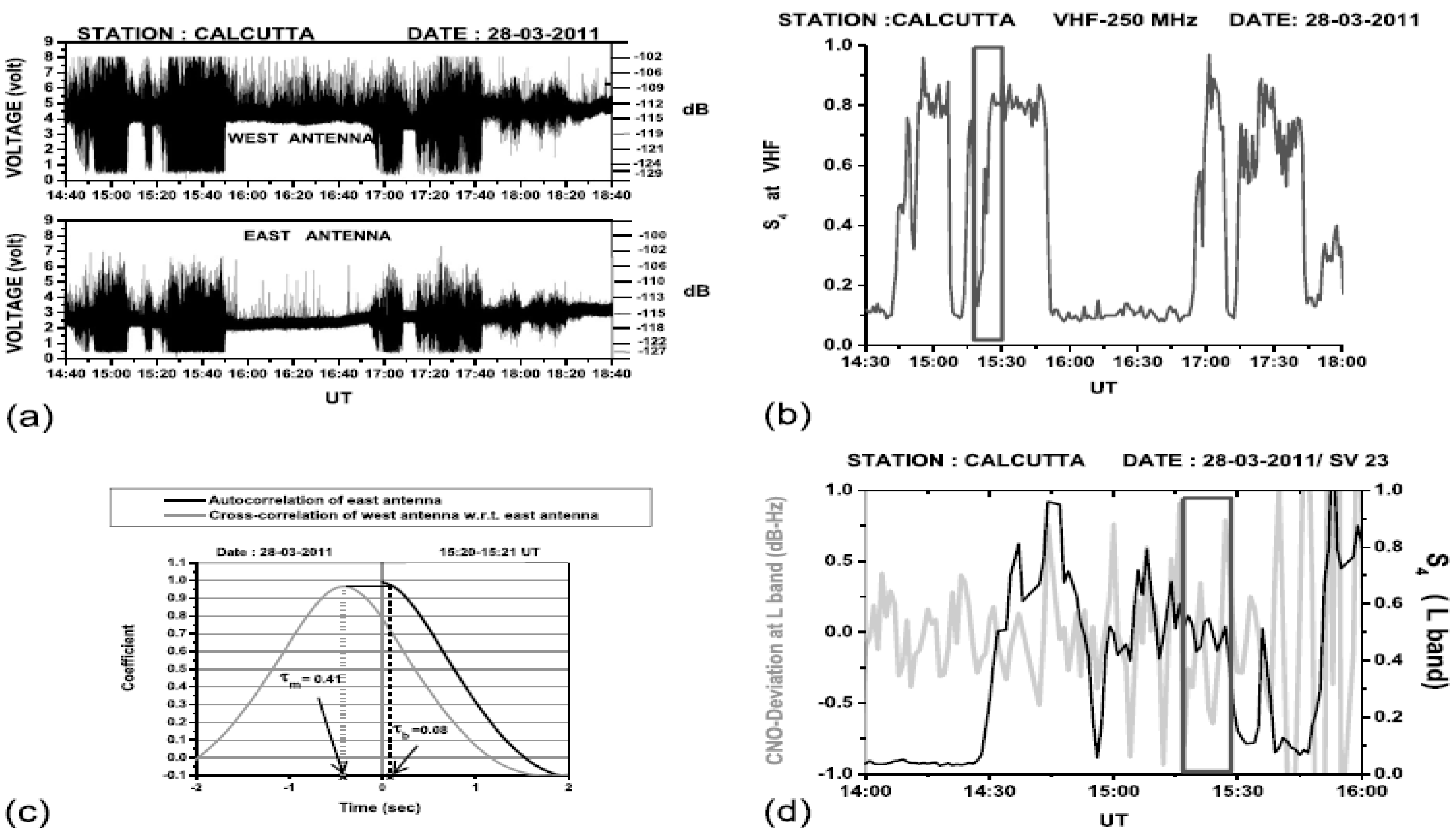
- Characterization and diagnostics of such effects are necessary for advancement of the present understanding of the basic physics of ionospheric irregularity dynamics and its applications.

- Institute of Radio Physics and Electronics, University of Calcutta operates a number of active and passive radio systems around the northern crest of Equatorial Ionization Anomaly (EIA) in the Indian longitude sector.

Systems operational at University of Calcutta

System	Frequency (MHz)	Wavelength (m)
VHF Radar	53	5.66
LEO	150	2
GEO	250	1.2
LEO	400	0.75
GPS	1575.42	0.2

Measurement of VHF irregularity dynamics



- Intense, often saturated, amplitude scintillations have been observed at VHF on the 250MHz geostationary satellite beacon from Ionosphere Field Station, Haringhata of University of Calcutta (22.93°N, 88.37°E; 32°N magnetic dip) during 2011-2012

- GPS L1 signal (1575.42MHz) from a link situated within a common ionospheric volume around the GEO link also showed amplitude scintillations at the same time

- While the irregularity scale sizes affecting transionospheric VHF signals are ~800-1000m, the corresponding Fresnel scale size for GPS is around 300-400m

Das et al., *Radio Sci.*, 49, 851–860, doi:10.1002/2014RS005406, 2014

Correlation of VHF irregularity dynamics with GPS scintillation indices

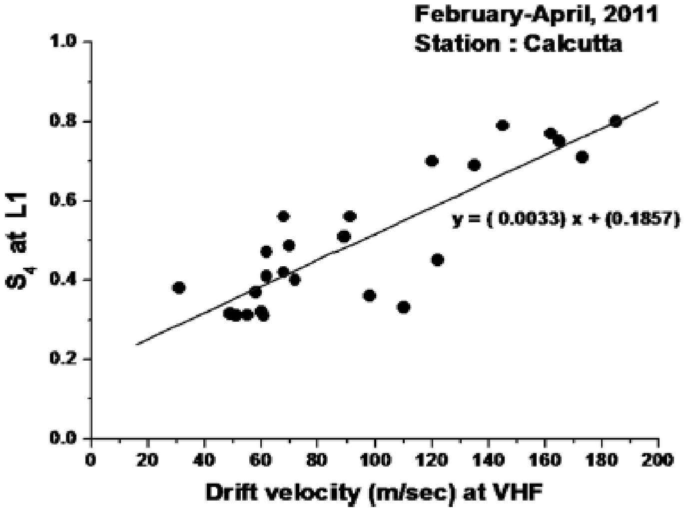


Figure 2. Variation of amplitude scintillation index S_4 at GPS L1 frequency with ionospheric irregularity drift velocity at VHF (250 MHz) measured from Calcutta during February through April 2011.

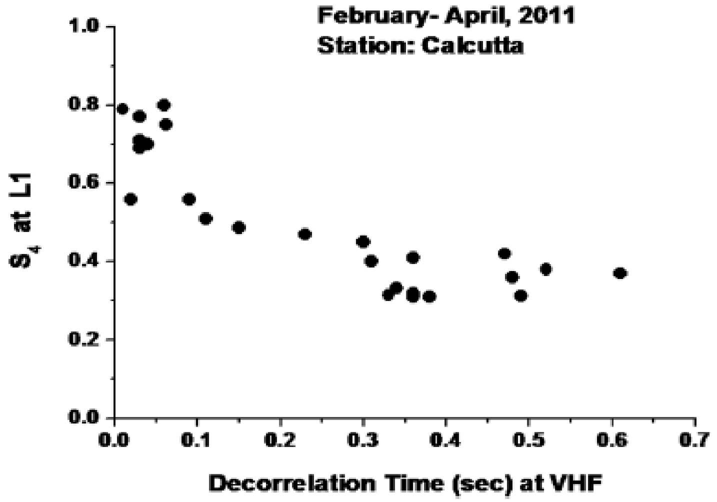
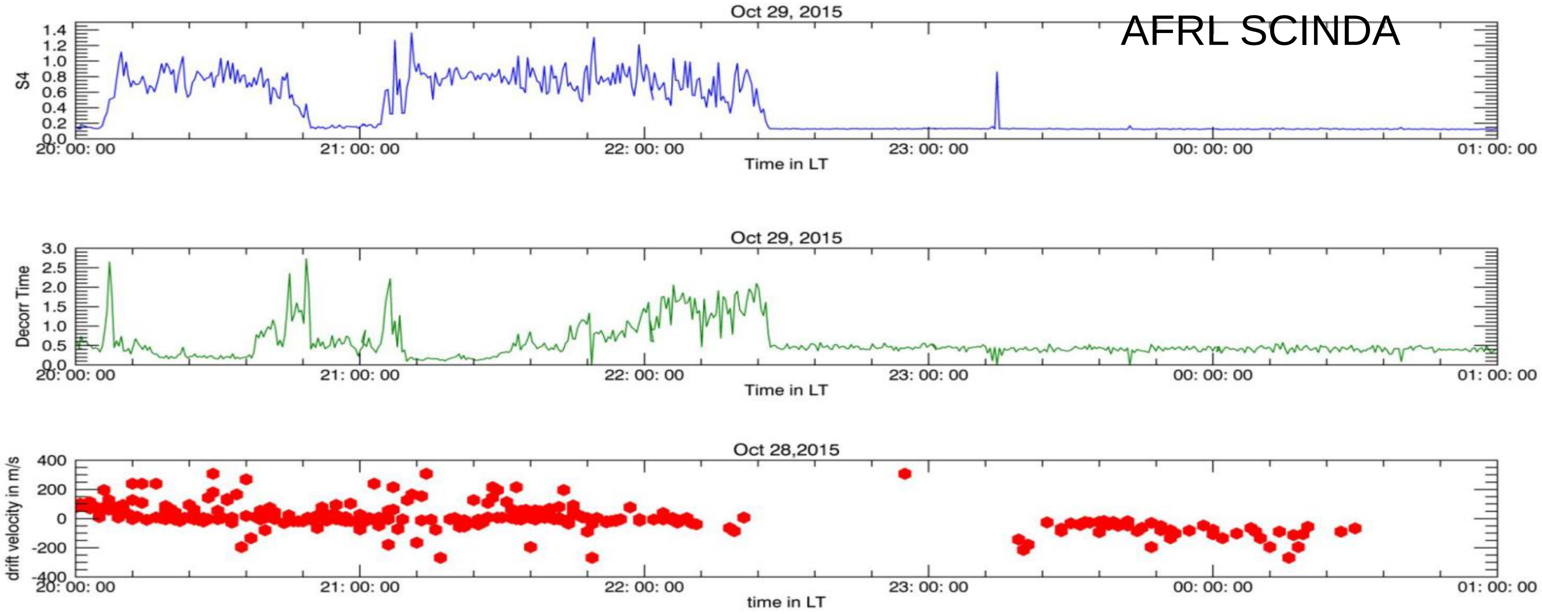


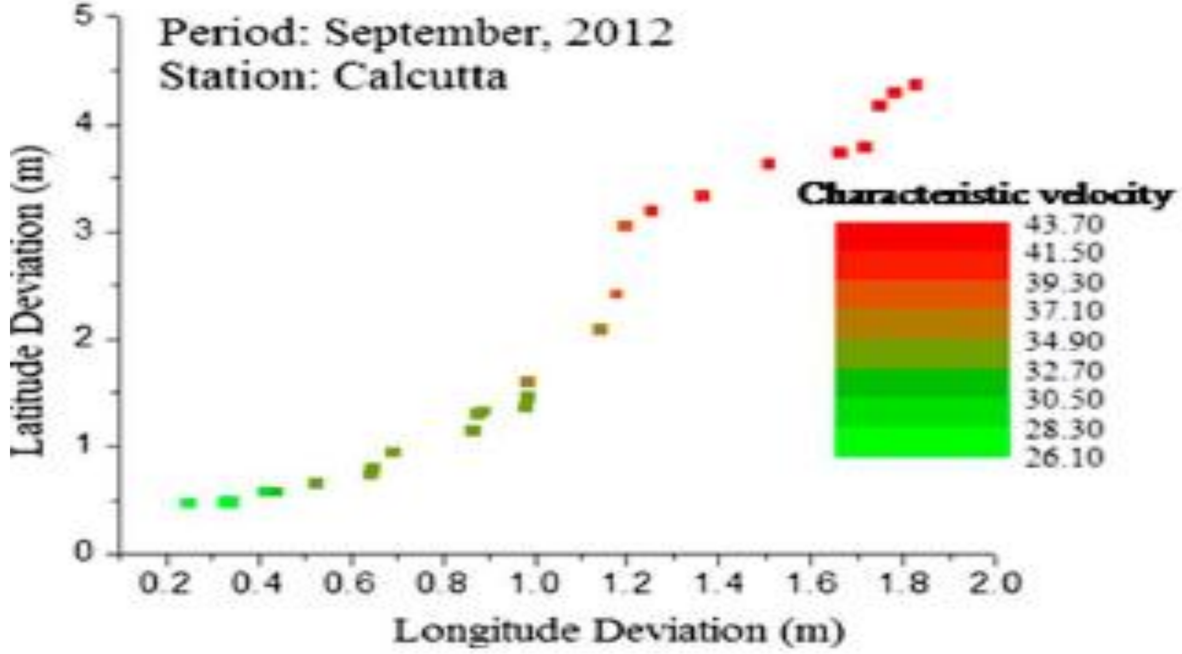
Figure 4. Variation of amplitude scintillation index S_4 at GPS L1 frequency with ionospheric irregularity decorrelation time at VHF (250 MHz) measured from Calcutta during February through April 2011.

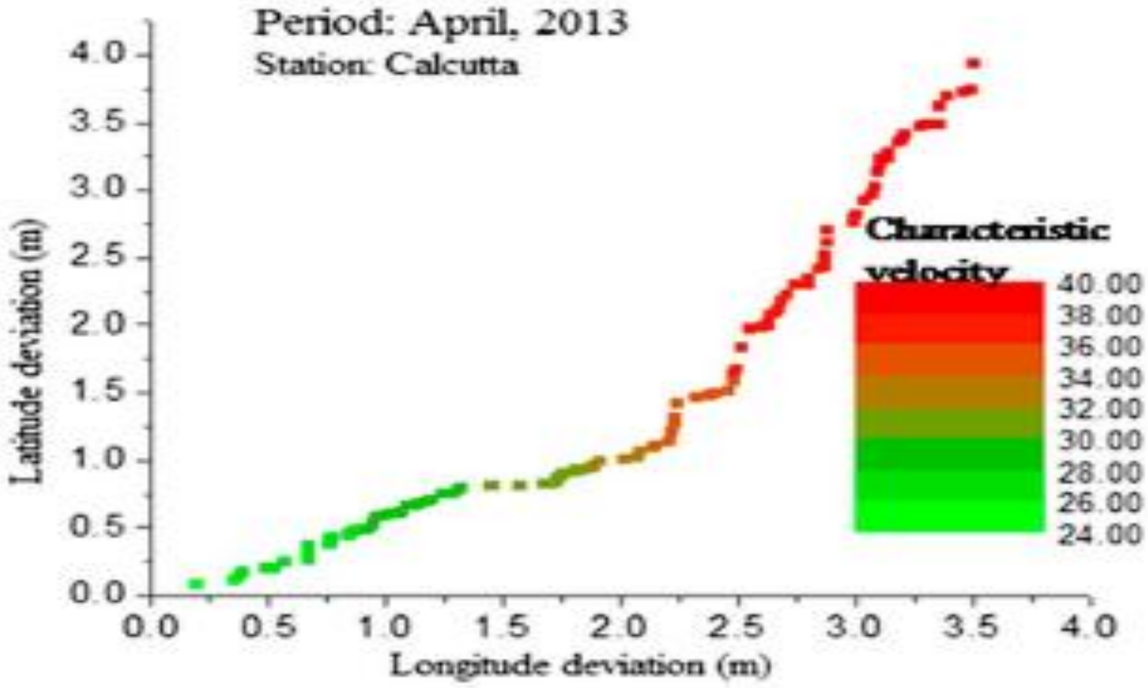


- Irregularity zonal drift velocity at VHF measured using spaced-aerial technique showed correlation with amplitude scintillation index S_4 at L-band – irregularity strength being more during early evening hours, high S_4 values on GPS corresponded to high irregularity drift velocities at VHF
- The irregularity drift velocities gradually decreased at late evening hours with a corresponding reduction in S_4 values
- The schematic on the left shows a snapshot of geostationary VHF amplitude scintillation, corresponding decorrelation times and irregularity drift velocity recorded using the AFRL SCINDA receiver at Haringhata

Das et al., *Radio Sci.*, 49, 851–860, doi:10.1002/2014RS005406, 2014

Correlation of VHF irregularity dynamics with GPS position deviation during periods of scintillation

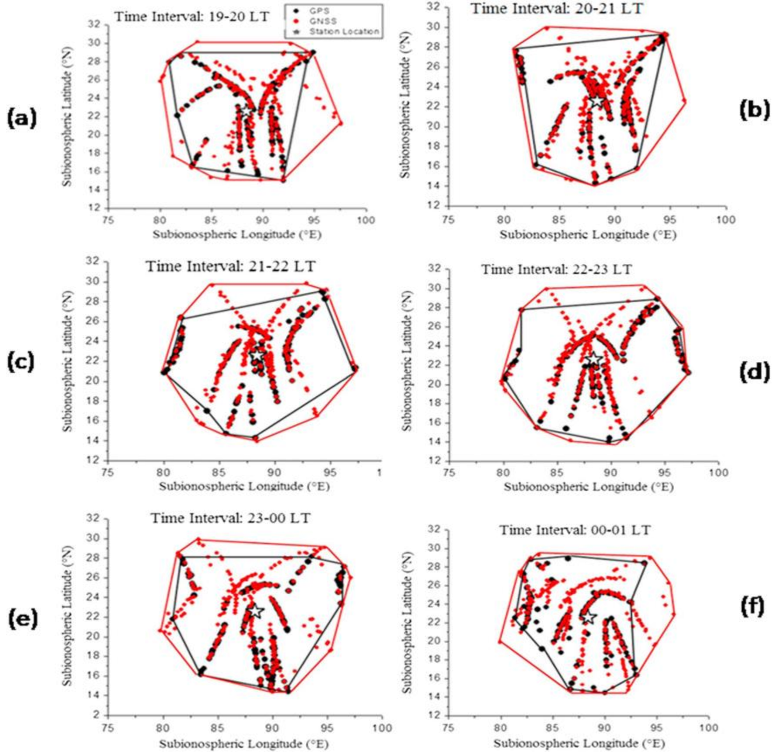




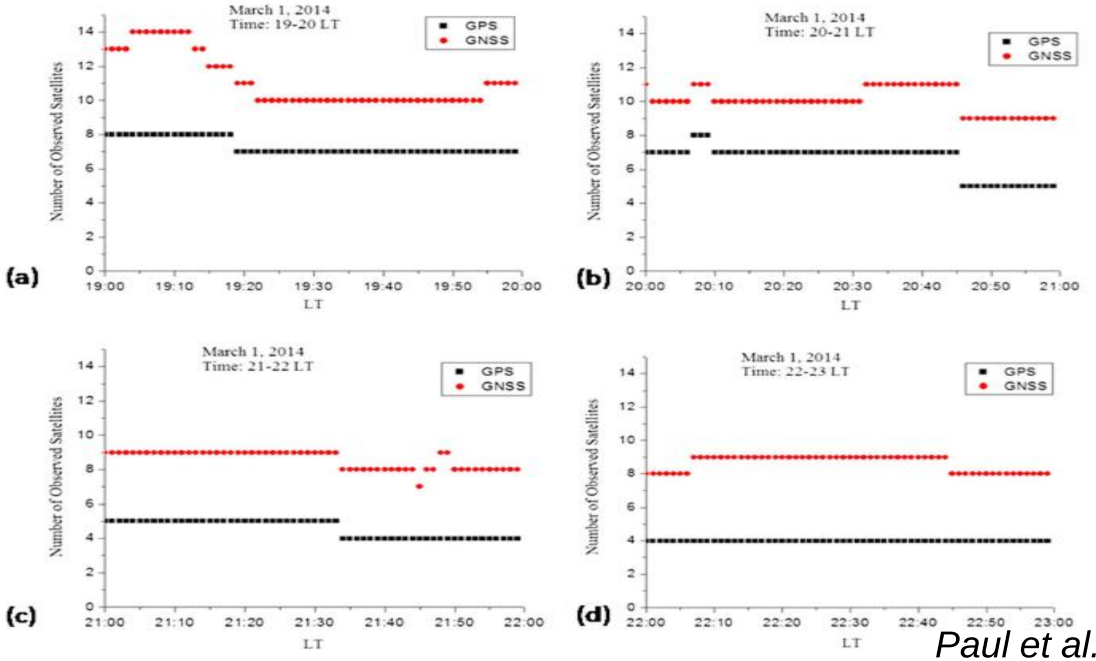
- It has also been noted that when transionospheric GPS links intersect the drifting ionospheric irregularities, position deviations of the receiver occur
- Simultaneous spaced aerial measurements at VHF indicate that the variations of the latitude and longitude of the receiver are non-linear with respect to the irregularity characteristic velocity, the latter being a measure of randomness in the medium of propagation of the signal
- Higher characteristic velocities are found to correspond to larger position deviations of the receiver

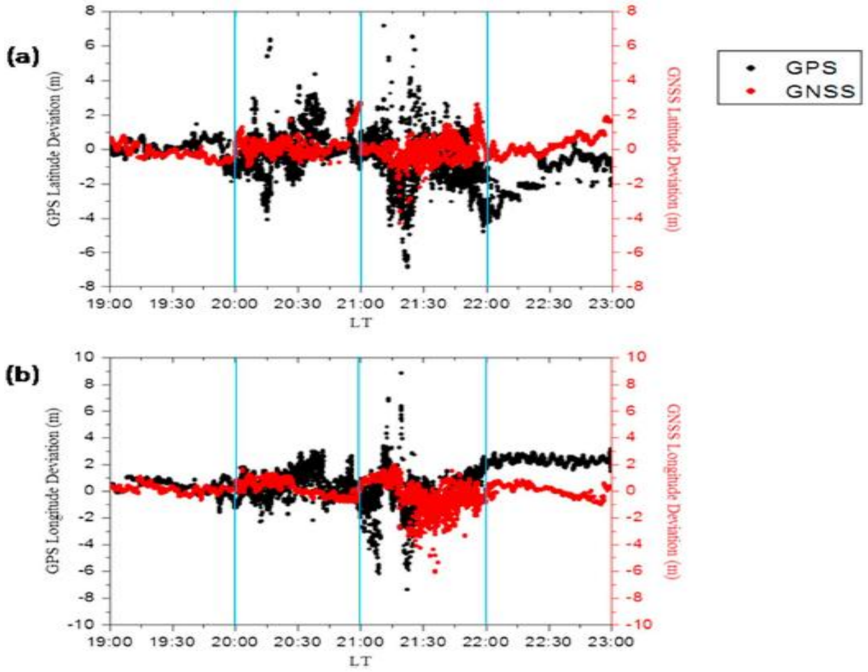
Paul and Paul, *Radio Sci.*, 52, doi:10.1002/2016RS005964, 2017

Application of spatial diversity for deriving GNSS Position information during periods of ionospheric scintillation

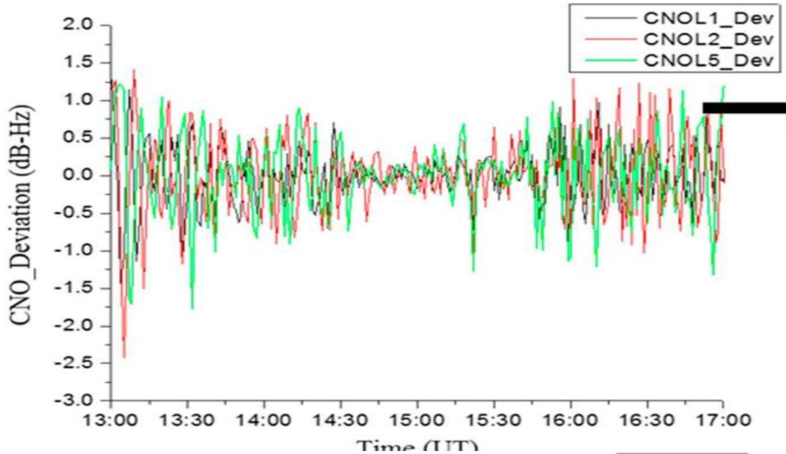


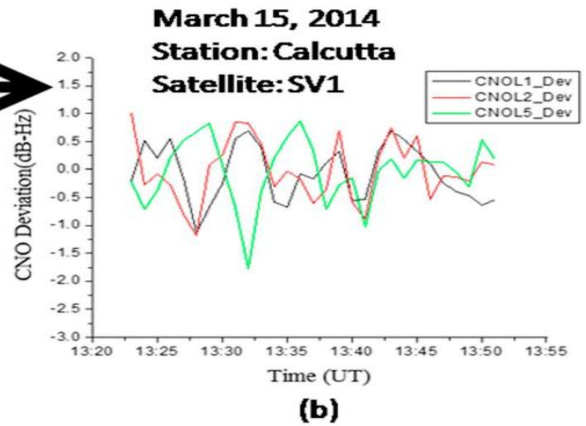
- In the multi-constellation (GPS, GLONASS, Galileo) scenario, larger number of satellite links are available distributed over a larger swath of the observer's sky (~41-67% in latitude, 35-69% in longitude)
- Hence there is an improved receiver-satellite geometry available which is particular useful when number of satellite links reduce when signal fading causes the signal level to fall below the receiver noise floor
- There is corresponding less position degradation of the receiver under multi-constellation environment compared to GPS-only condition

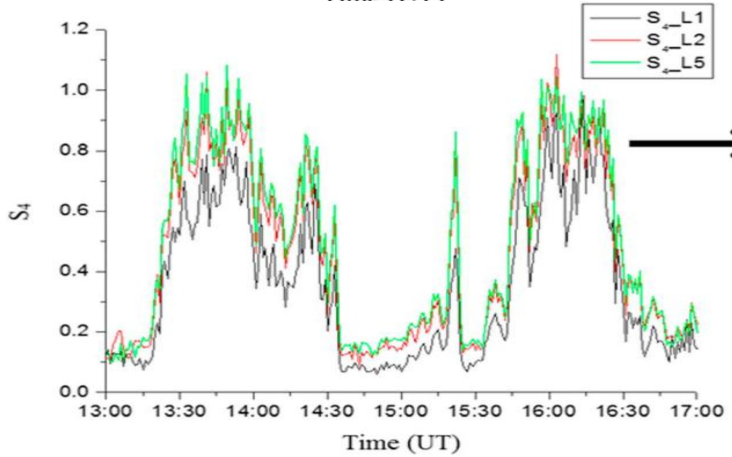


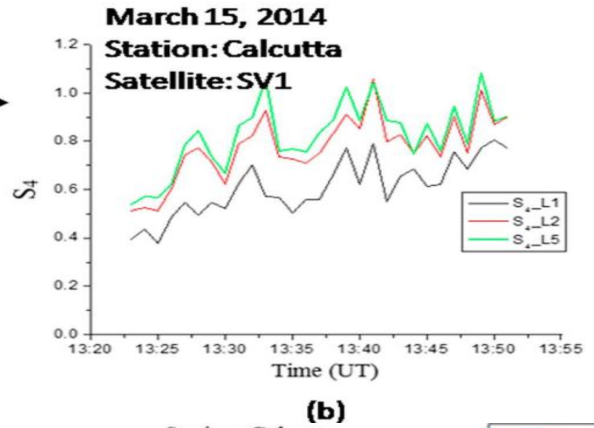


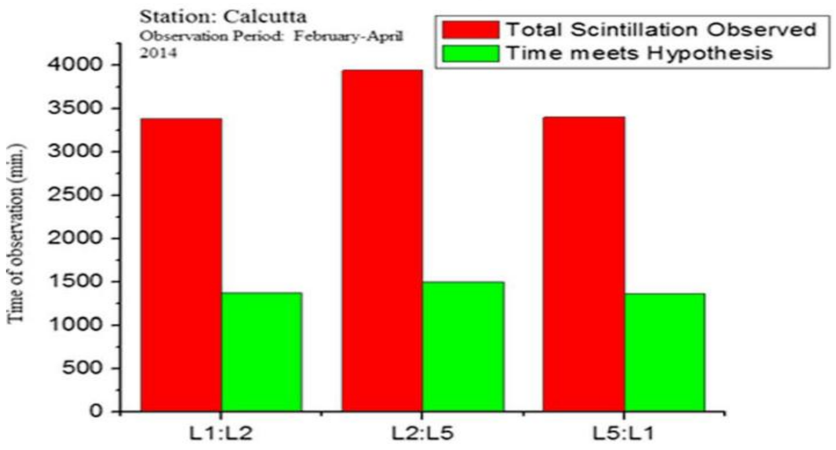
Paul et al., *Radio Sci.*, *52*, doi:10.1002/2016RS006076, 2017

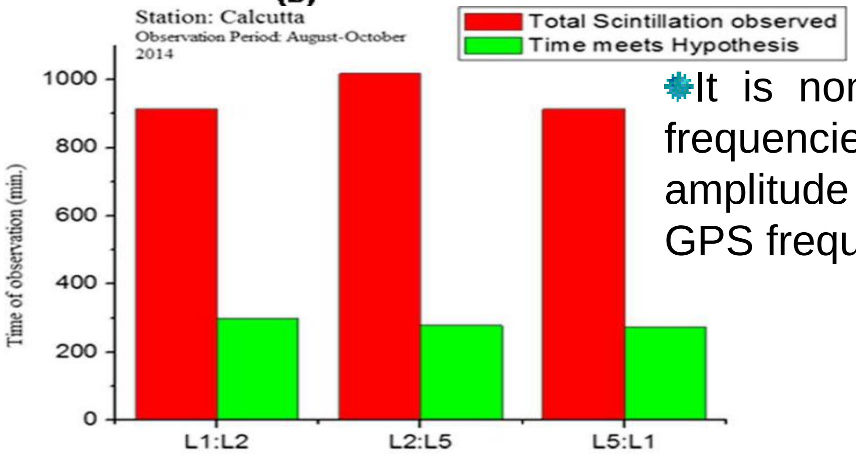










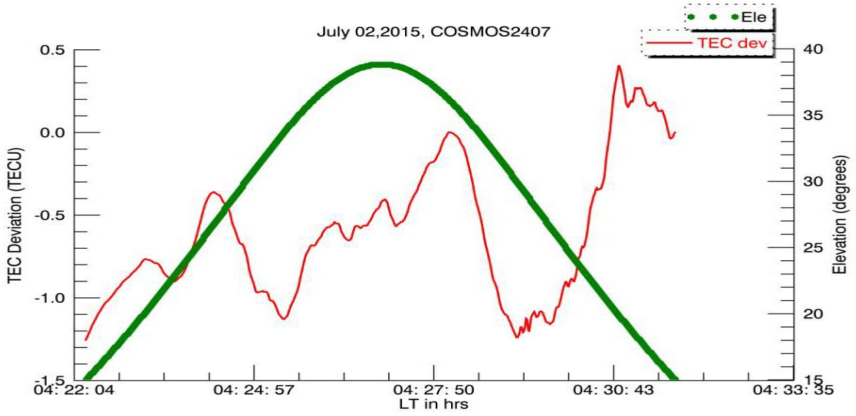


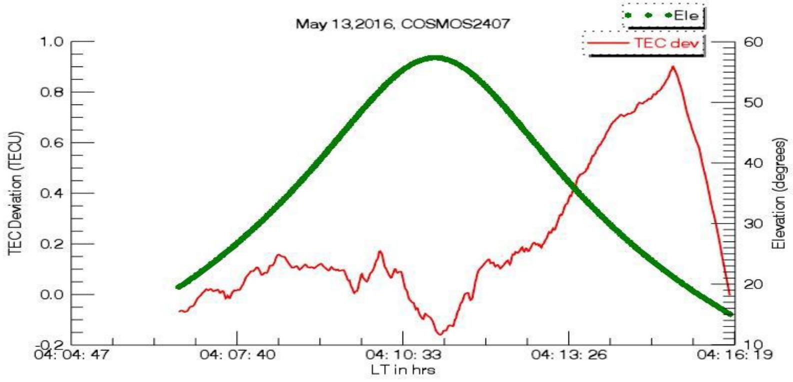
Application of frequency diversity for deriving GNSS Position information during periods of ionospheric scintillation

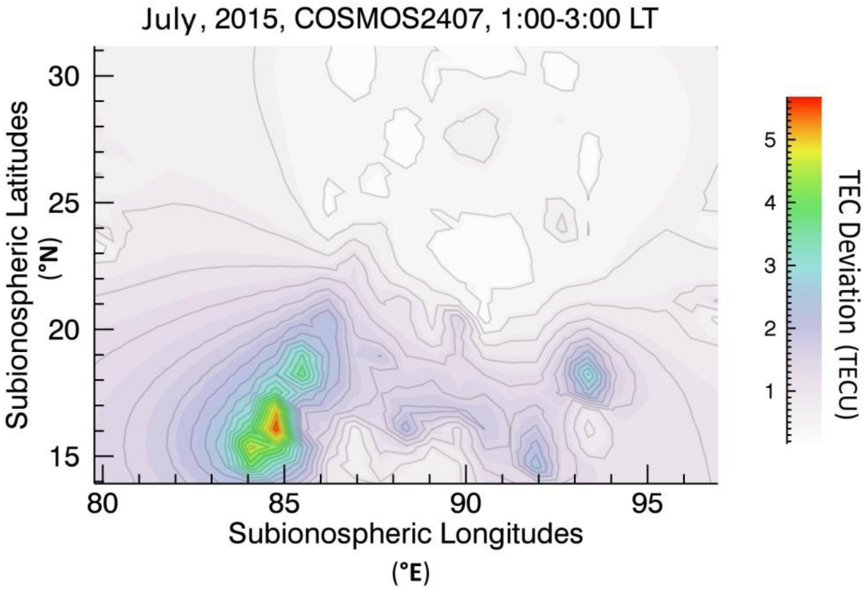
- Differences are noted in terms of fluctuations in carrier-to-noise ratios (C/N_o) of multi-frequency GPS signals at L1, L2 and L5 while being scattered by ionospheric irregularities
- It is hypothesized that periods of decorrelation between a pair of GPS signal frequencies may be utilized for deriving receiver position information – if all the different GPS signals were correlated, then during periods of signal fading caused by ionospheric irregularities, no position information could be derived
- It is nominally found that a pair of GPS frequencies are decorrelated 30-40% of amplitude scintillation time on that pair of GPS frequencies

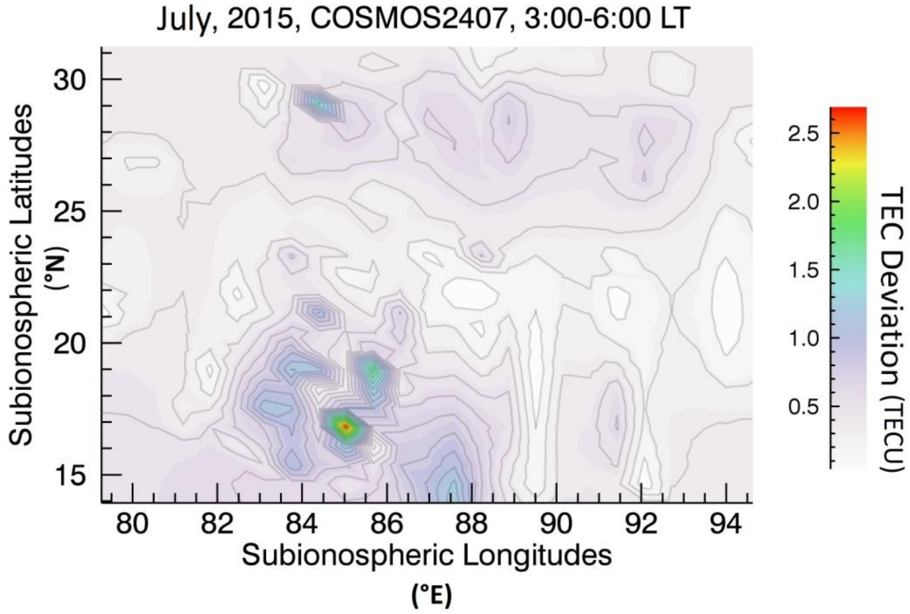
Goswami et al., Radio Science, 52. / https://doi.org/10.10022017RS006295, 2017

Observations of ionospheric irregularities during post-midnight hours using 150,400 MHz coherent radio beacon (CRABEX)



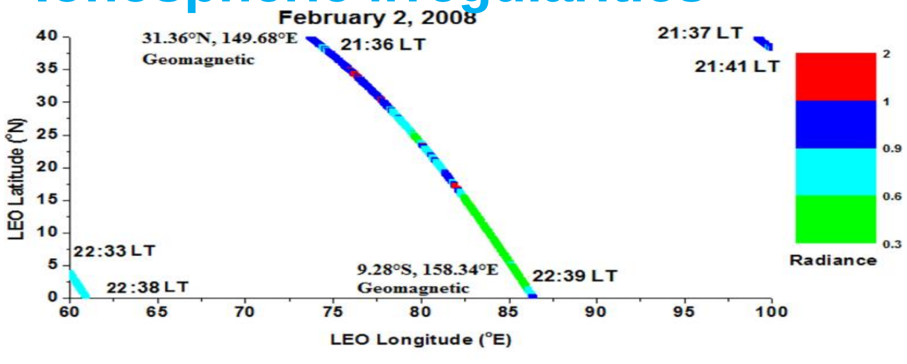




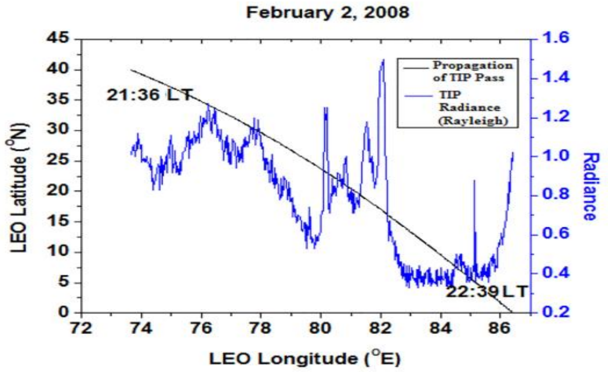


- Observations of depletions in TEC have been observed from Haringhata when receiving signals from LEO satellites transmitting satellite beacon at 150, 400MHz
- Interestingly, some of these cases have been reported during post-midnight and early evening hours of local summer months
- These irregularities are not likely to be freshly generated, rather they may be ‘fossil bubbles’ or drifting from the transitional mid-latitudes
- Similar cases have been reported from Calcutta in *Das et al.* [*J. Atmos. Sol. Terr. Phys.*, *121*, 188–195, 2014]

Optical observations (TIP, 135.6nm) of Ionospheric irregularities



(a)

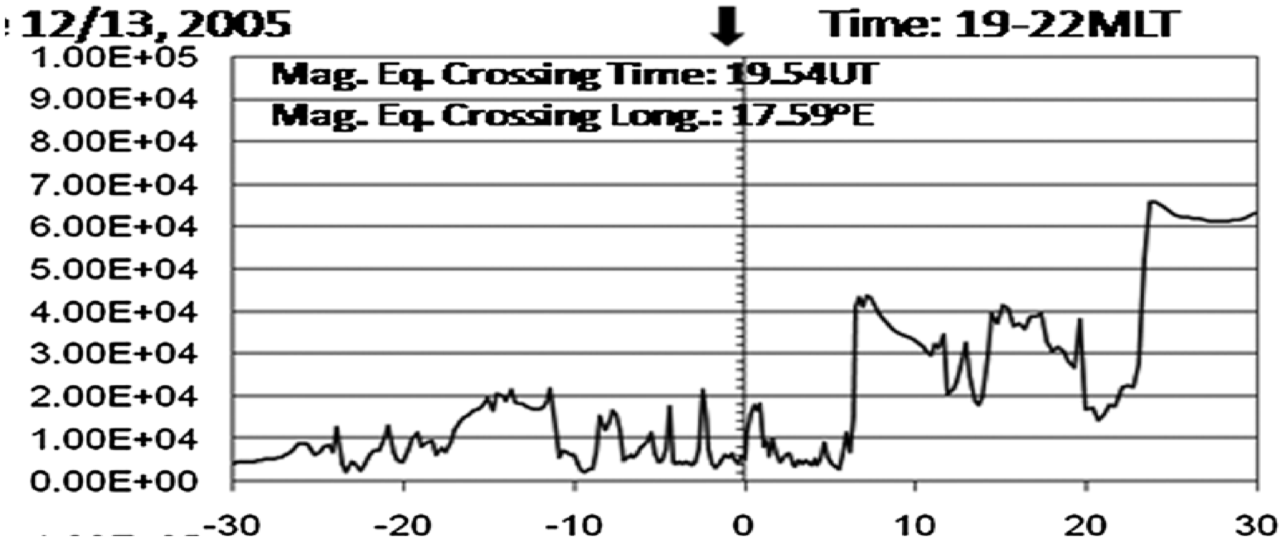


(b)

- Fluctuations in radiance have been noted measured by the Tiny Ionospheric Photometer (TIP) onboard COSMIC satellite at 135.6nm
- Such fluctuations act as a metric for indicating presence of ionospheric irregularities

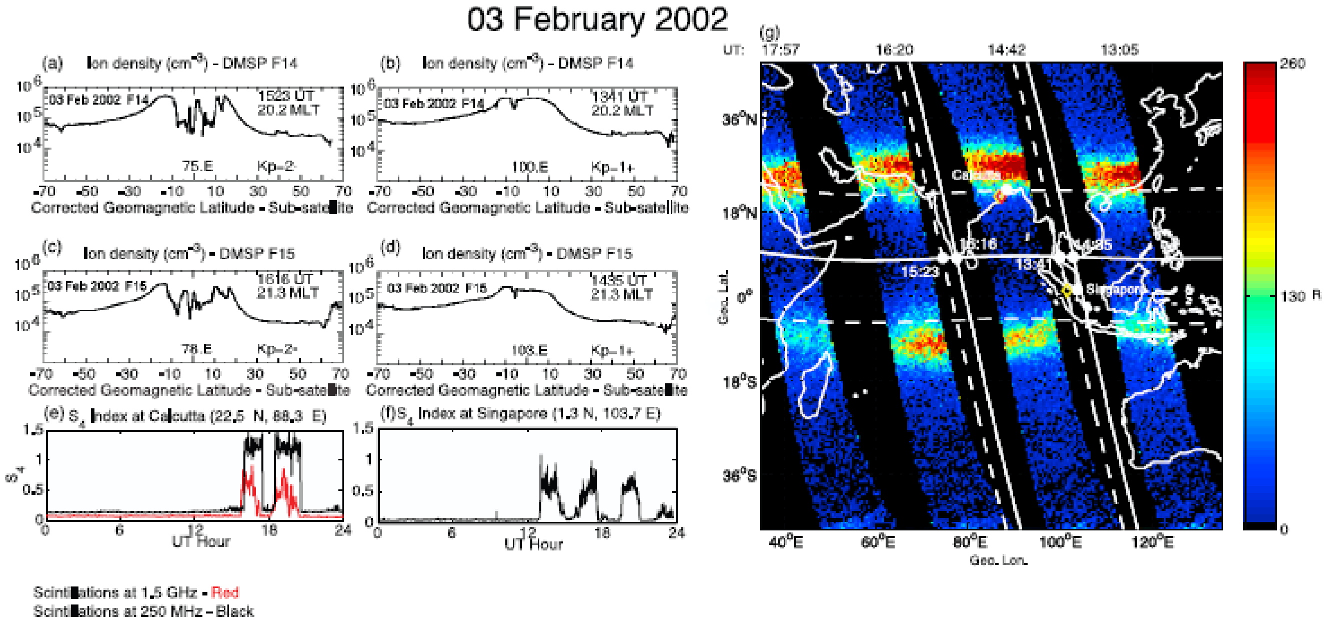
Paul et al., Adv. Space Res., *65*, 1402–1413, 2020

DMSP F15 June 12/13, 2005



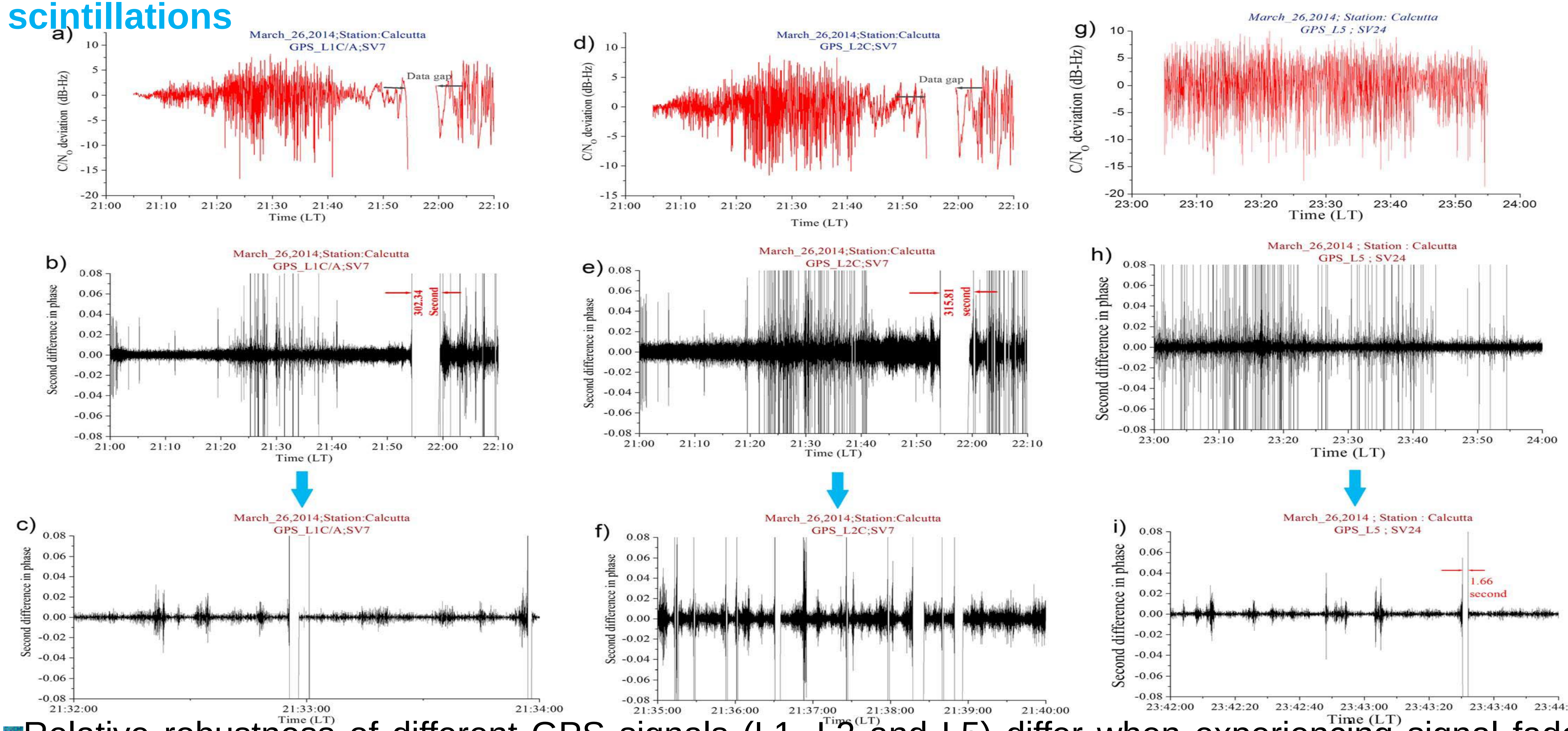
- Depletions in ionization density measured by DMSP and radiance by GUVI have also been noted over the Indian longitude sector during local dusk sector

Ray et al., *Radio Sci.*, 50, doi:10.1002/2014RS005422, 2015



Su Basu et al., *J. Geophys. Res.*, 114, A04302, doi:10.1029/2008JA013899, 2009

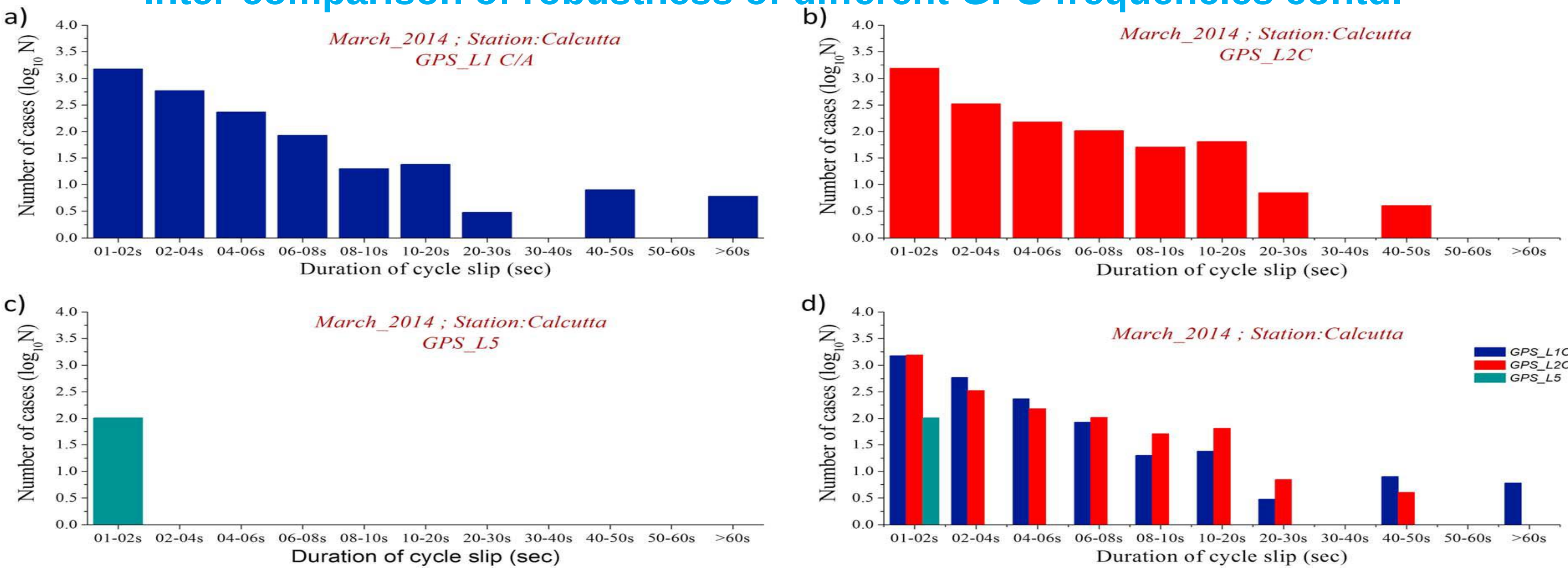
Inter-comparison of robustness of different GPS frequencies during periods of ionospheric scintillations



- Relative robustness of different GPS signals (L1, L2 and L5) differ when experiencing signal fades arising out of intersection with ionospheric irregularities
- Duration of signal loss-of-lock is found to be different even though the satellite links share a common ionospheric volume

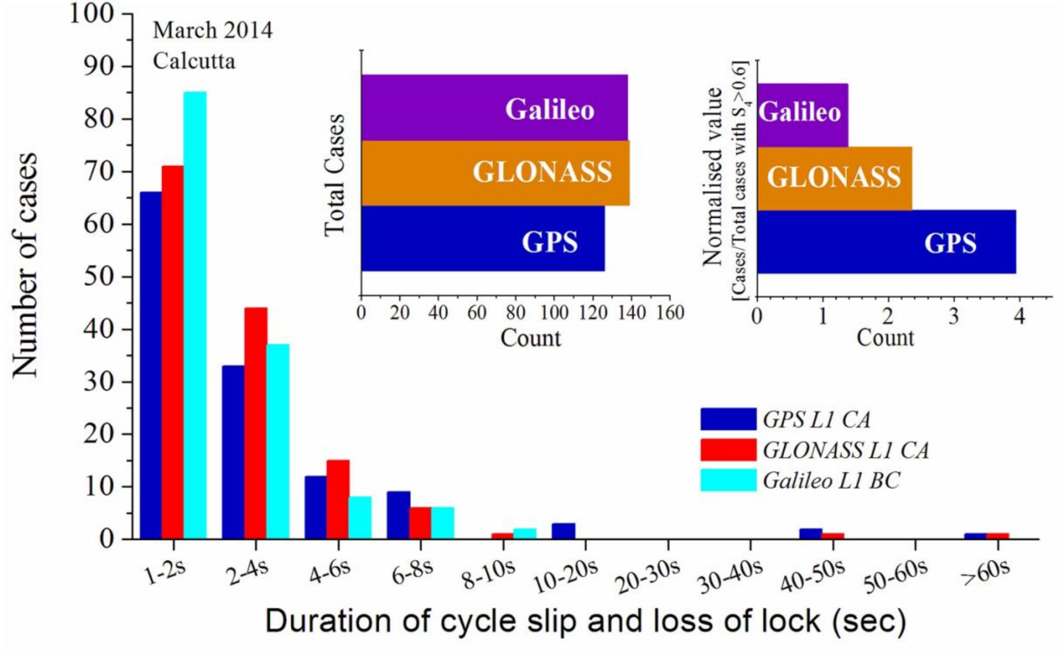
Biswas et al., *Space Weather, 17.* https://doi.org/10.1029/2018SW002105, 2019

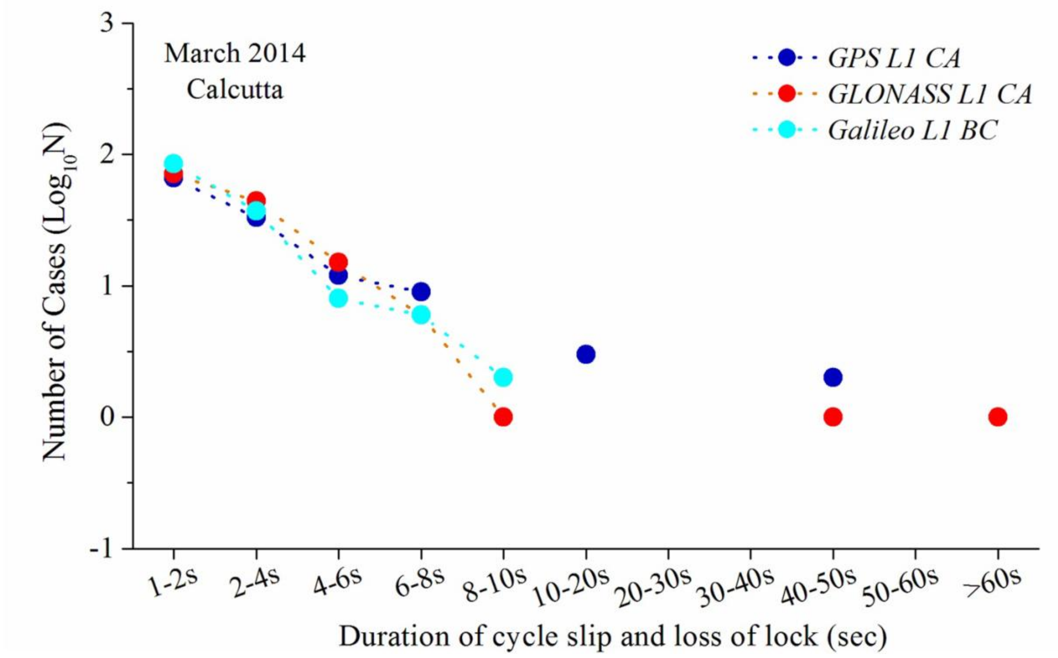
Inter-comparison of robustness of different GPS frequencies contd.



- Cases of cycle slip in excess of 10s are not found in GPS L5 signal although L1 and L2C signals exhibit such cycle slips at the same time
- GPS l5 signals is found to be more robust compared to L1 and L2C
- This may be attributed to the characteristics of the PRN code superposed on the L5 signal

Biswas et al., *Space Weather, 17.* https://doi.org/10.1029/2018SW002105, 2019





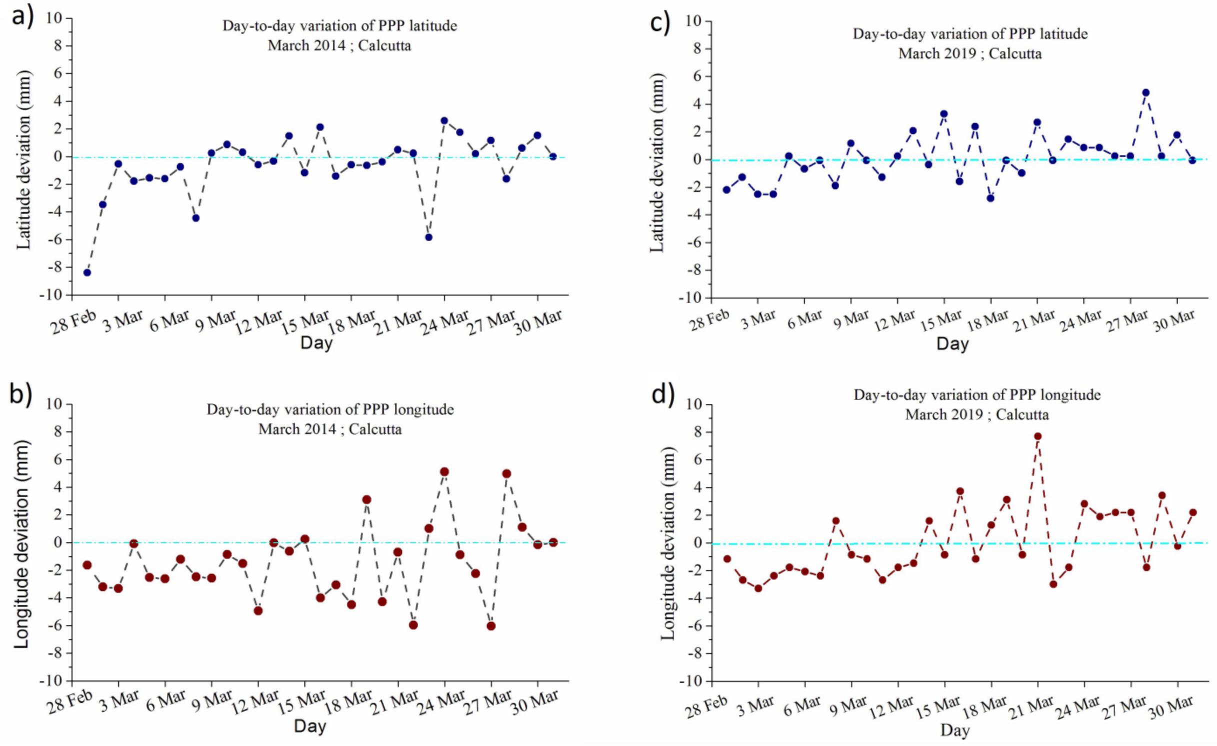
Relative robustness of GNSS Constellations during periods of ionospheric scintillations

- Comparison of relative robustness of the 3 GNSS constellations, namely, GPS, GLONASS and Galileo have been performed for March 2014 from Calcutta

- Duration of cycle slips and loss of lock have been found to be relatively less at GLONASS L1 C/A compared to GPS and Galileo

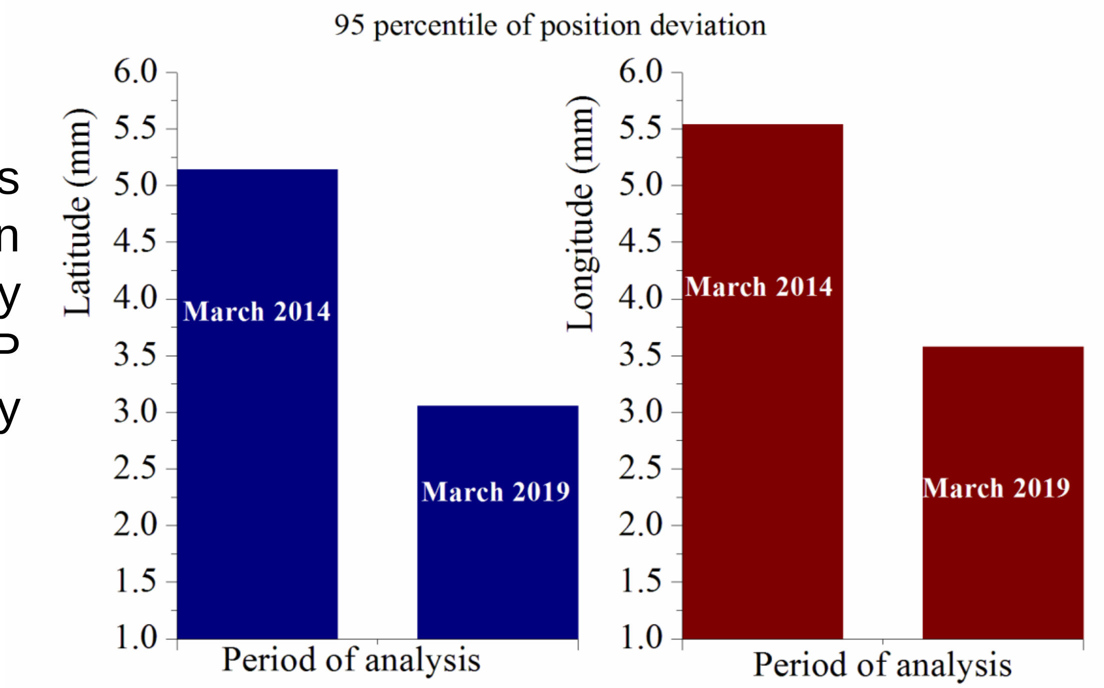
*Biswas and Paul, Radio Sci.,56, e2020RS007119., https://doi.*org/10.1029/2020RS007119, 2021

Effects of equatorial ionosphere on PPP



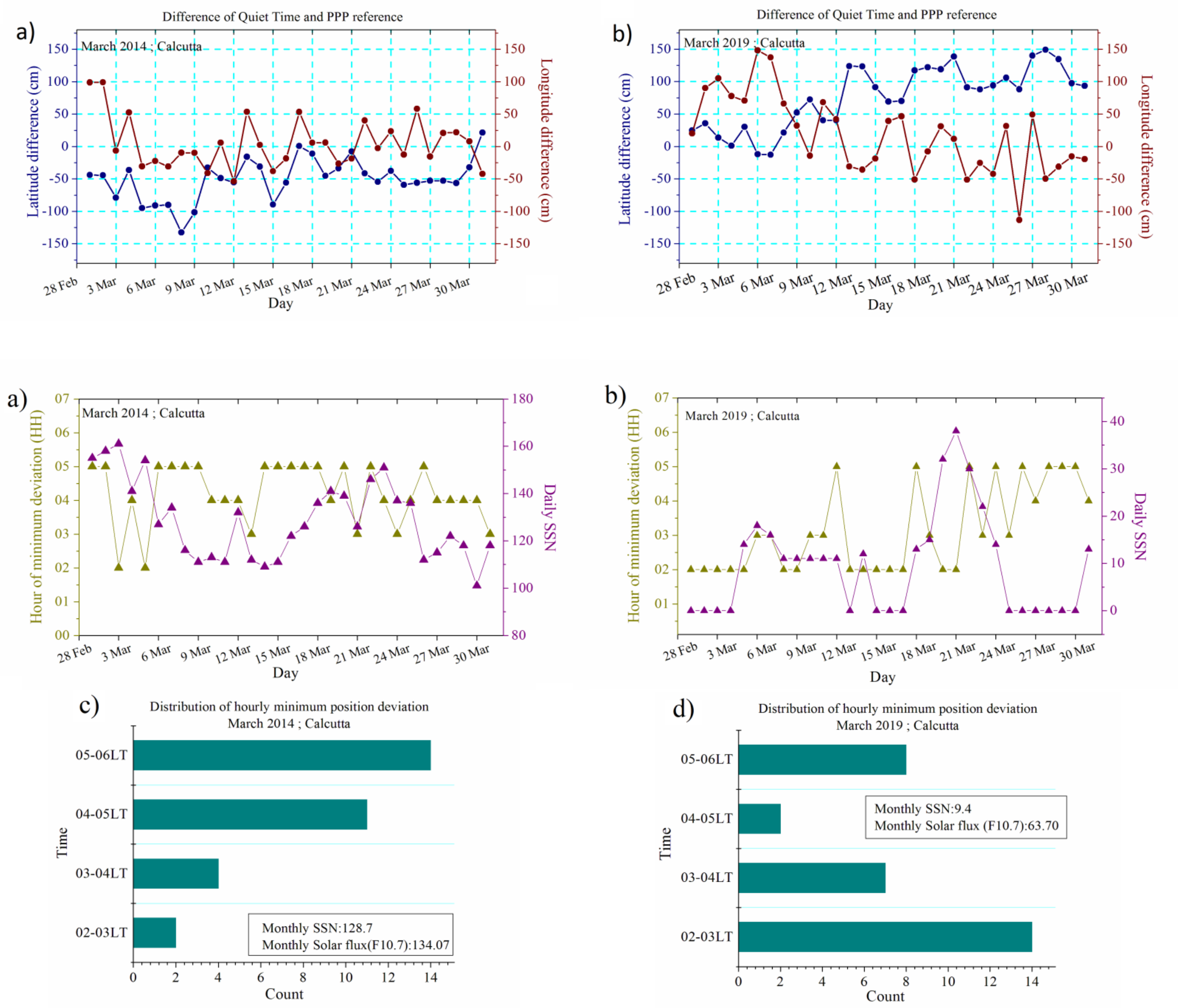
■Day-to-day variation of position of the receiver, has been derived using PPP, over 31 days of March 2014, a high solar activity period and March 2019, a low solar activity period.

■The precise position of the station lies well within 10mm of accuracy during both a high and low solar activity period, justifying the expected cm level accuracy of a PPP technique.



■However, minute observation of the PPP solution indicates effect of solar activity persists, although in mm order. Deviation in PPP solution is found to be higher during a high solar activity period, compared to a low solar activity one, indicating PPP solutions to be evidently affected by the solar activity conditions.

Biswas et al., *Radio Sci.*, 2021 (under revision)

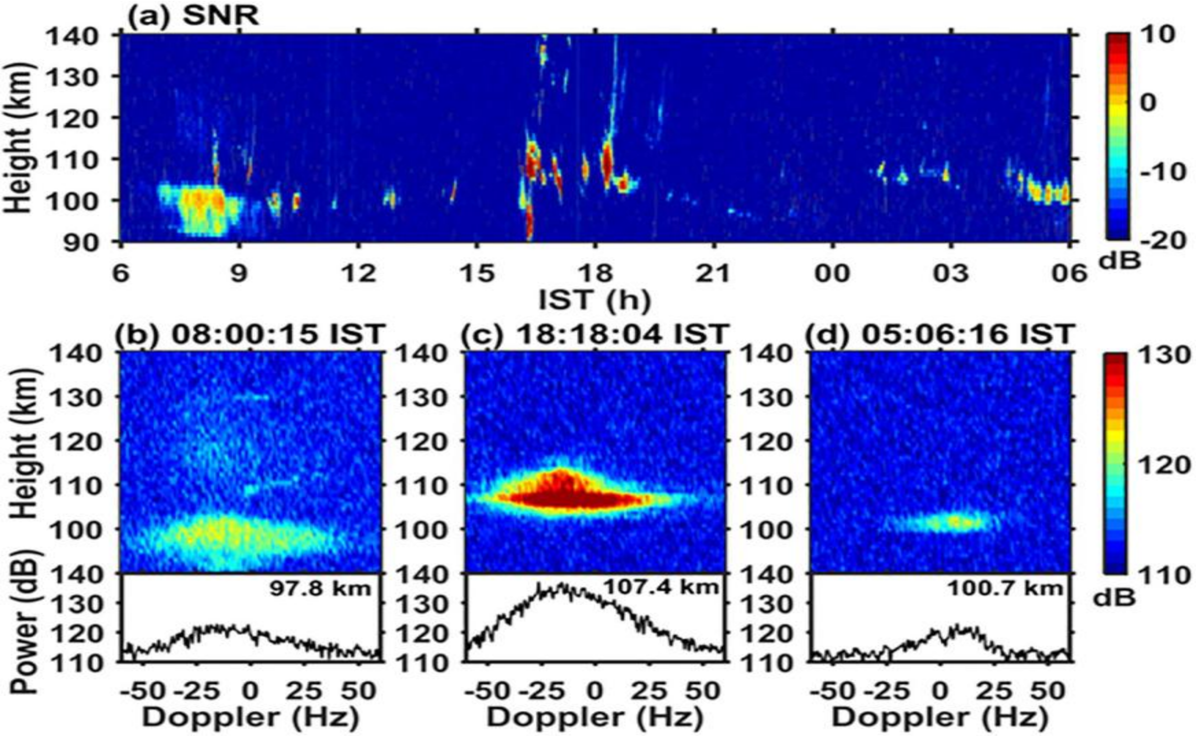


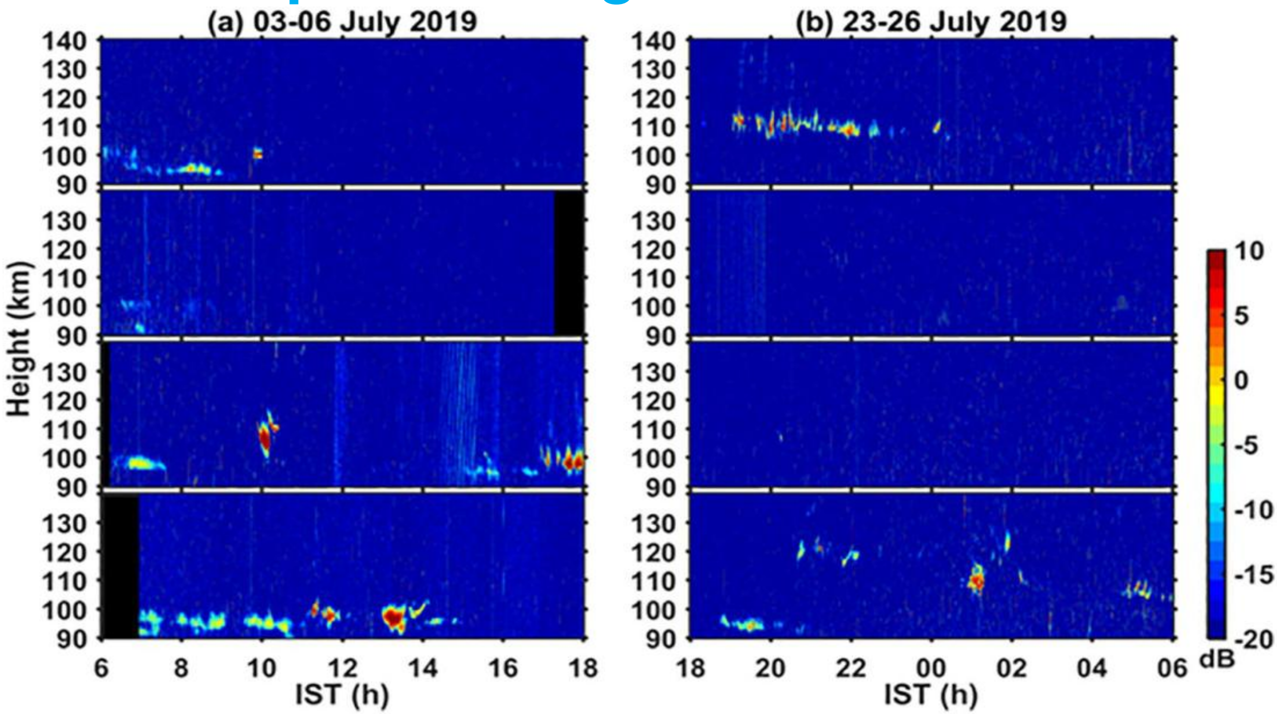
Effects of equatorial ionosphere on PPP contd.

- The difference between Ionospheric Quiet Time reference and PPP solution for 31 days of March 2014. The difference is observed to be within 132 cm in latitude and within 100 cm in longitude.
- Similar analysis for 31 days of March 2019 shows the difference to be within 150 cm in both latitude and longitude. These values are substantial keeping in mind the position accuracy outliers specified to be within 50 cm (Witte & Wilson, 2005; Matosevic et al., 2006)
- The ionospheric quiet time (03-05 LT) of the day, expected to reflect the minimum effect due to ionospheric activity, is observed to change and shift towards 04-06 LT for a high solar activity period and towards 02-04 LT for a low solar activity one.
- Diurnal minimum value of receiver position deviation mainly occurred during 04-06 LT in March 2014 (nearly 81% of the cases) and 02-04 LT for March 2019 (about 68% of the cases).

Biswas et al., *Radio Sci.*, 2021 (under revision)

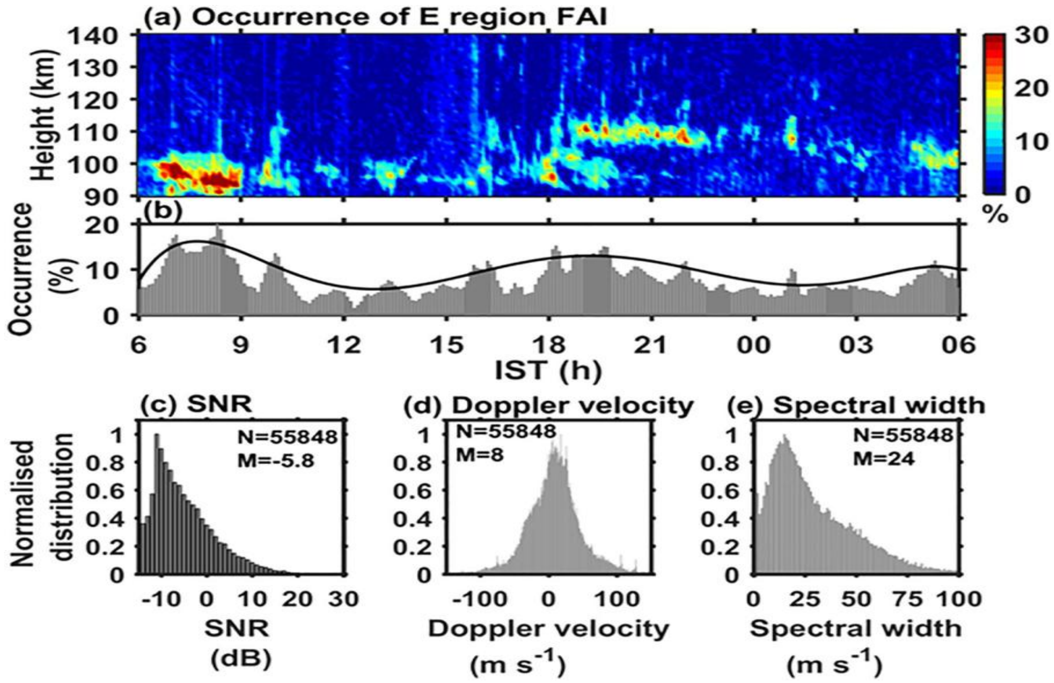
VHF Radar observations of ionospheric irregularities





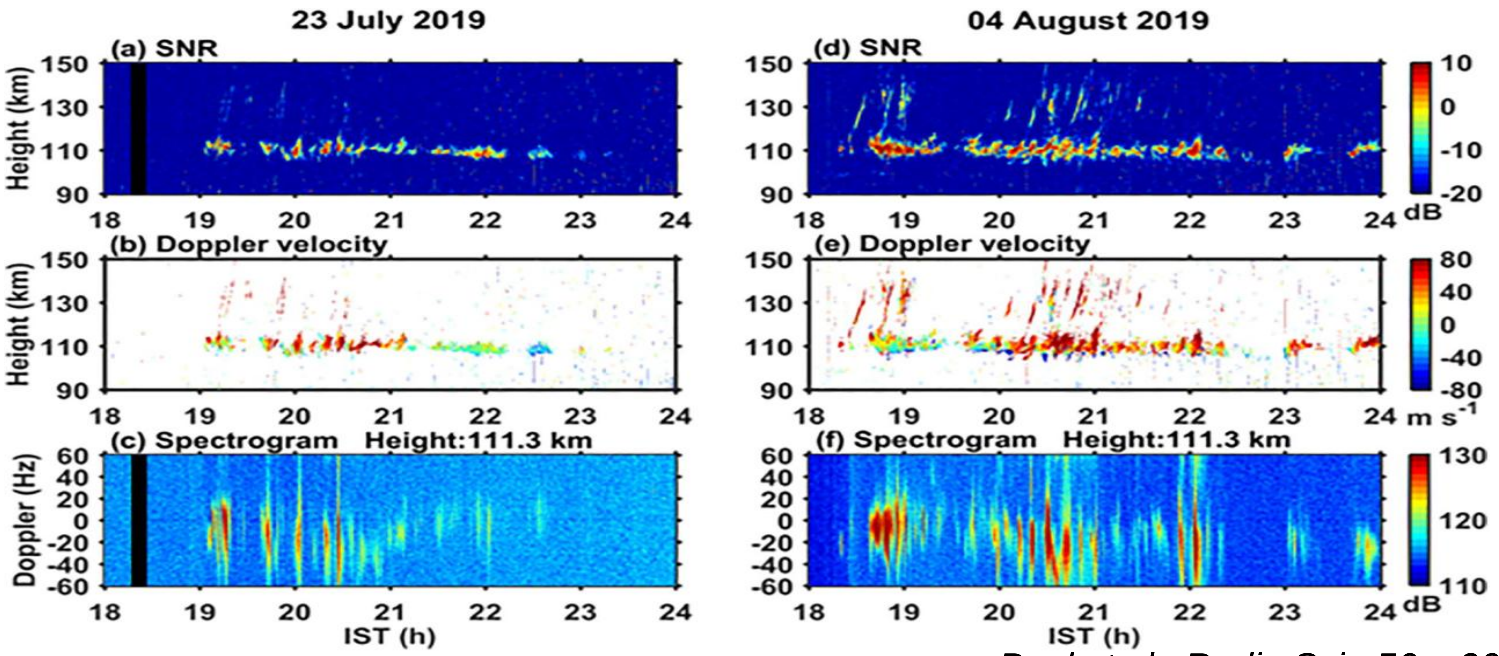
- A fully active phased-array radar is operational at Haringhata at 53MHz, this being the only such radar at this frequency in the entire South-East Asian longitude sector
- Campaign mode observations of E-region Field Aligned Irregularities (FAIs) have been conducted during July-August 2019
- Diurnal cycle of operation reveals backscattered signals from ionospheric irregularities at heights of 100-120km, mainly confined to time intervals of 06-09 IST, 15-18 IST and 05-06 IST [IST = UT + 05:30]
- It may be recalled that Haringhata is located at a magnetic dip of 36.2°N and hence the Doppler spectra are quite similar to those of off-equatorial low latitudes and mid-latitudes
- Large day-today variabilities have been noted during radar operations for daytime (July 3-6, 2019) and night-time (July 23-26, 2019)

Paul et al., *Radio Sci.*, *56, e2021RS007289. https://doi.*org/10.1029/2021RS007289, 2021



- Some features observed on the E-region FAI signatures are their descending pattern and patchiness in the echoing morphology.

- Based on these, it may be concluded that the *E region FAI echoes over Haringhata can be characterized by type-2* echoes with occurrence morphology dominated by patchiness and descending pattern.



- In addition, one can notice quasi-periodic (QP) echoes occurring on July 23. These echoes are embedded in a slowly descending echoing layer.

Paul et al., Radio Sci., 56, e2021RS007289. https://doi.org/10.1029/2021RS007289, 2021

Summary and Conclusions

1. Ionospheric irregularities impact transionospheric satellite signals at different frequencies in the equatorial and low latitudes
2. The effect of these irregularities are found as fluctuations in received amplitude and phase of satellite beacon and GPS/GNSS signals, depletions in ionization density and TEC, fluctuations in measured radiance at optical wavelengths and backscattered echoes in radar
3. VHF amplitude scintillations were mostly intense, often saturated and the corresponding zonal drift velocities decreased from about 150m/s in the early evening hours to around 50m/s at midnight
4. GPS receivers show degradation in position information during periods of ionospheric scintillations, the amplitude scintillation index showing correlation with VHF irregularity drift velocities and decorrelation times
5. Multi-constellation satellite signals show improvement in performance even during periods of scintillations due to increased coverage of the sky and hence, relatively less satellite outages compared to only GPS
6. Multi-frequency operations of GNSS receivers indicate possibility of using signal decorrelation time for deriving position information
7. TEC depletions measured using LEO satellite signals indicate presence of 'fossil bubbles' or drifting irregularities during post-midnight to early morning hours
8. Indication of relative robustness of satellite navigation constellation and operating frequency have been found
9. Ionospheric effects on PPP are noted with definite solar activity dependence
10. E region FAI echoes were mostly confined to altitudes of 90–120 km with daytime FAI being confined to 100 km. Echo SNR were between −15 and 20 dB, which implies echoes were 35 dB higher than the background noise
11. Doppler spectra are type-2 in nature with mean Doppler velocity in the range of −100 to 120 m s−1 and spectral width limited to 100 m s−1. While the occurrence of the FAI echoes displayed large day-to-day variations, the echoes tend to occur more during the morning (06–09 IST) and evening (18–21 IST) with relative less occurrence during the noon and midnight
12. The morphology of the FAI echoes show descending pattern, patchiness and quasi periodic (QP) behavior

Thank You

Stay safe and stay well