Extreme weather detection using NavIC/GNSS

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Sun: The Source

- The atmosphere of the sun is composed of the photosphere, chromosphere, transition region and the corona.
- The solar activity cycle is about 11 years, where the Sun's north and south poles switch places.
- It takes another 11 years for the Sun’s north and south poles to flip back again.

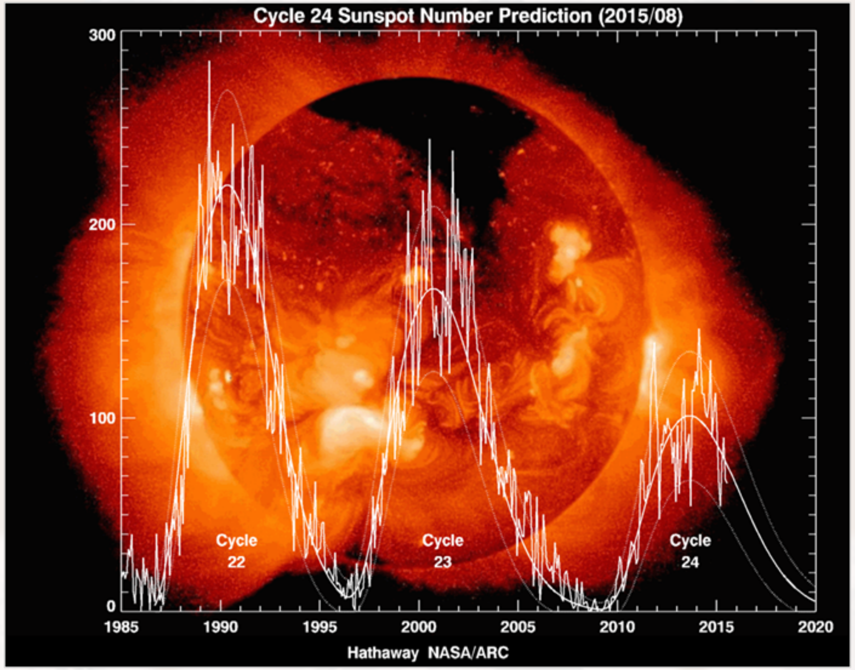


Figure: The solar activity cycle(Courtesy: Hathaway NASA)

Space Weather

Conditions on the sun, in the solar wind, and within Earth's magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems.

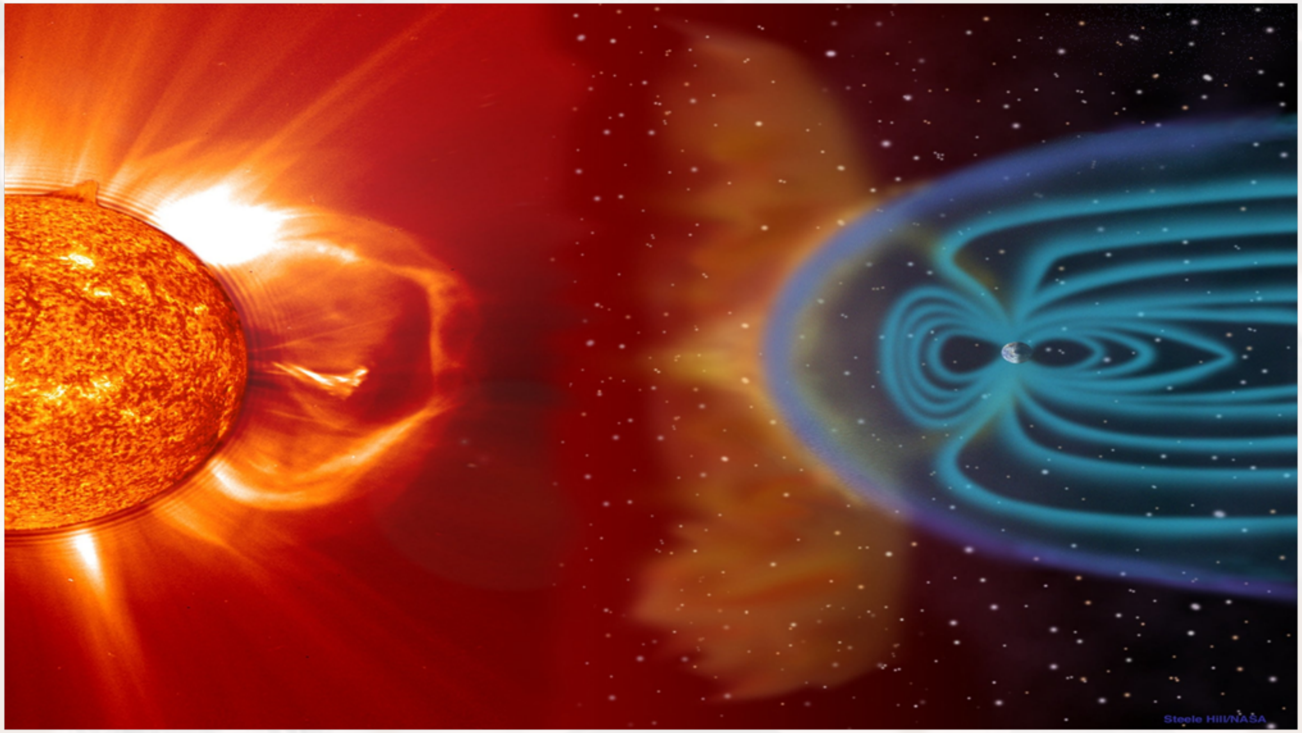


Figure: The Solar-Terrestrial Interaction(Courtesy: https://www.nasa.gov)

The Ionosphere

- The ionosphere is formed by the ionization of three primary atmospheric constituents: N_2, O_2, and O.
- The primary ionization mechanism is photoionization by extreme ultraviolet (EUV) and X-ray radiation.
- Recombination removes free charges and transforms the ions to neutral particles.

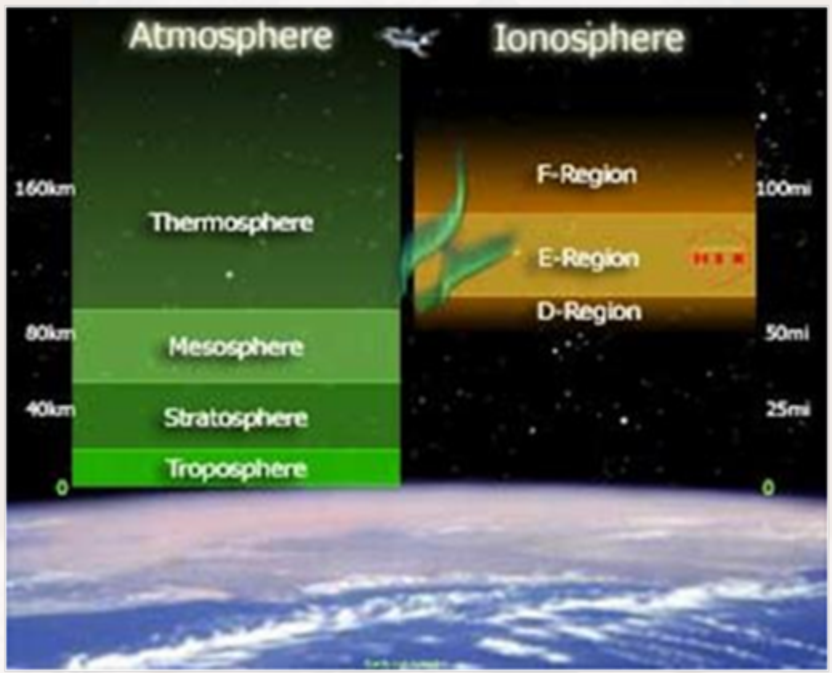


Figure: Temperature and Density profiles of the Ionosphere(Courtesy: stanford.edu)

Total Electron Content: The Probe

- Total number of electrons integrated between two points, along a tube of unit cross-sectional area, often reported in multiples of TEC where 1 TECU = 10^{16} el/m^2.
- It is the key parameter derived from GNSS receivers to represent the status of the ionosphere.
- Strongly affected by solar and geomagnetic activity, plays a major role in characterizing the ionosphere.

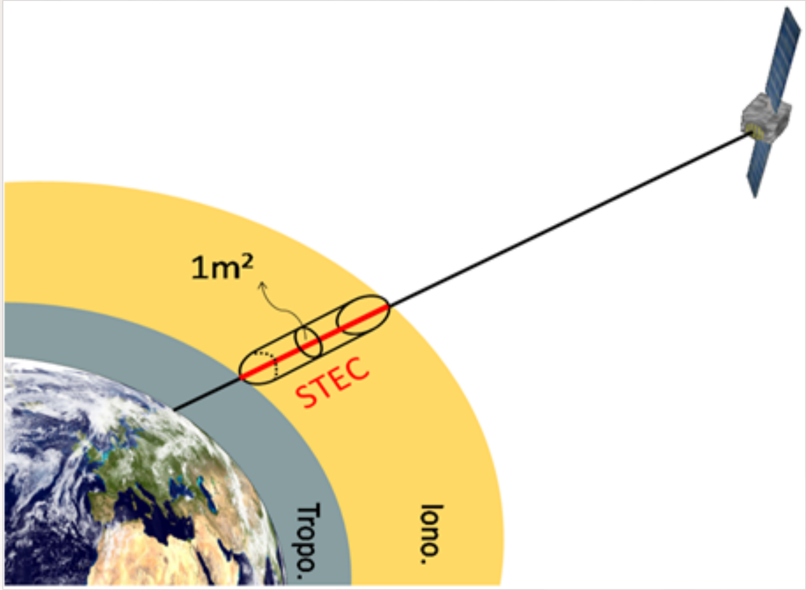


Figure: Ionospheric TEC(courtesy: gnss.be)

Receiver facilities at IIT Indore

- Facilities: Two GNSS, Two ACCORD and Two DATA PATTERNS receivers.
- These multi-constellation, multi frequency receivers are capable of receiving signals of frequencies L1(1575.42 MHz), L2(1227.60 MHz) and L5(1176.45 MHz) for GPS and L5, S1(2492.02 MHz) for NavIC are operational at IIT Indore.
- Studies: Space Weather, Differential NavIC and Differential GNSS.

GPS Receiver

GPS Antenna

NavIC Receiver

NavIC Antenna

Figure: NavIC/GNSS antennas and receivers at IIT Indore

Effects of CME and CIR induced geomagnetic storms over India sector

- A magnetic filament in the Sun's northern hemisphere erupted on October 8, 2016 around 16:00 UT hurling a CME into space.
- The CME arrived at L1 point on October 12, 2016 around 21:30 UT.
- The Dst was minimum on October 13 at 18:00 UT with a value of -104 nT indicating an intense storm further supported by IMF, Bz staying below -10 nT > 3h.
- A CIR was observed on October 14, 2016 that caused HSSW streams which caused IMF, Bz to fluctuate rapidly.

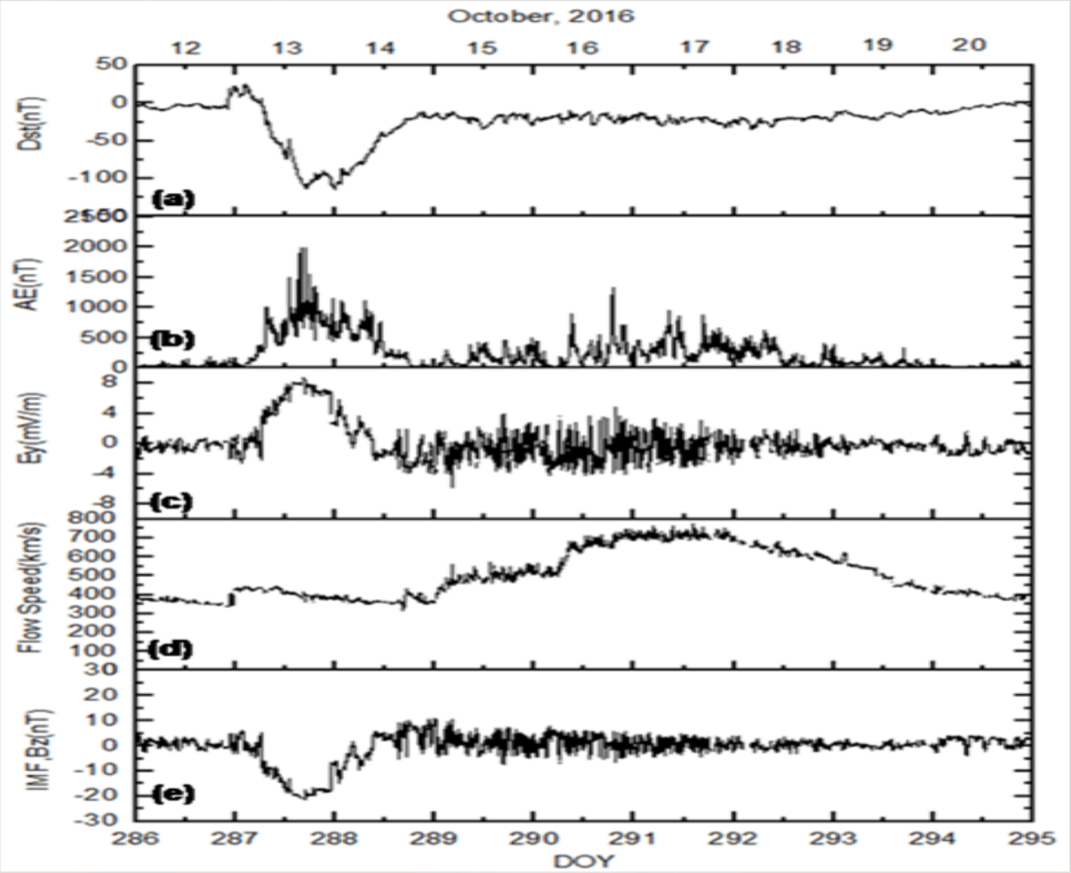


Figure: Interplanetary and Dst parameters during the storm of 12-20, October 2016 (Chakraborty, S., et.al, 2019, Advances in Space Research)

Effects of CME and CIR induced geomagnetic storms over India sector

- Enhancements in diurnal maximum observed from all the stations.
- Storm induced enhancements of about 20-45 TECU over quiet time values(in red) observed.
- The HSSW streams had been one of the cause for the enhancements observed.

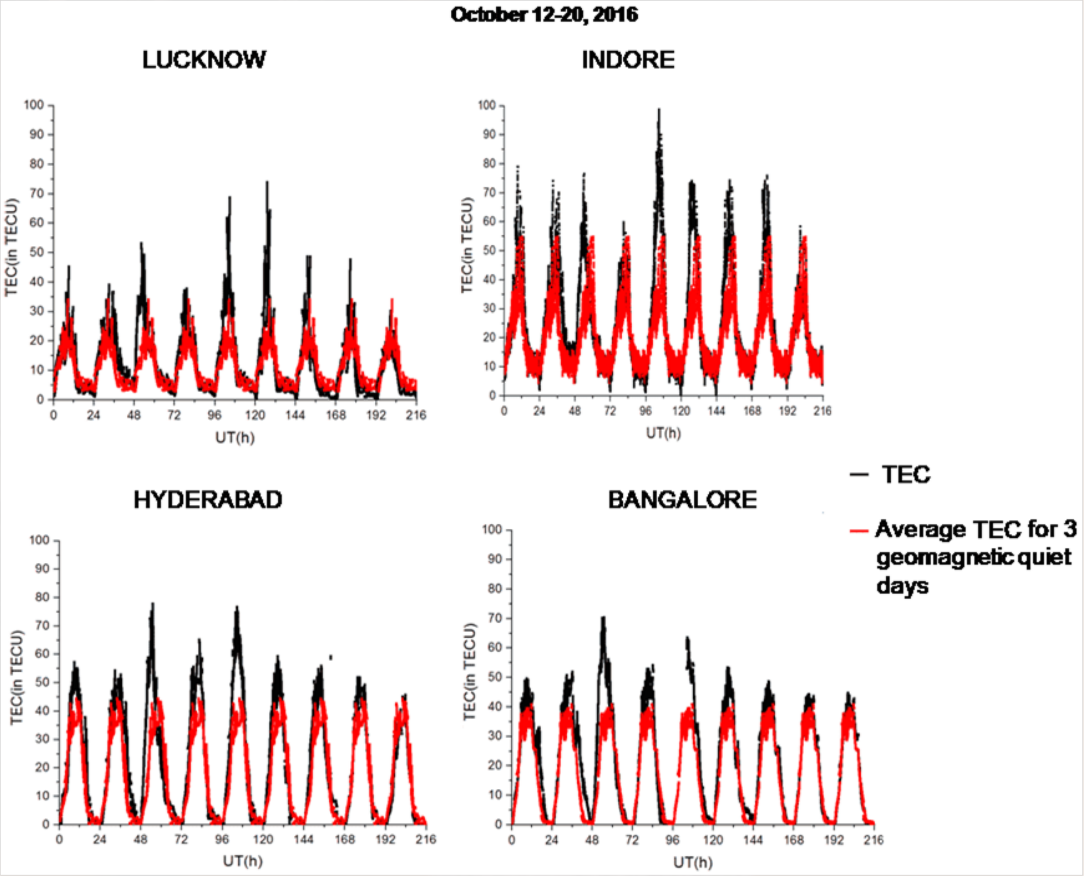


Figure: Diurnal TEC variations over different stations selected to ensure spatial distribution (Chakraborty, S., et.al, 2019, Advances in Space Research)

Effects of CME and CIR induced geomagnetic storms over India sector

- GUVI on-board the TIMED spacecraft provides the thermospheric column number density ratio of O and N_2 at N_2 column number density level of $10^{17}cm^2$.
- Describes the effect of thermospheric neutral composition change on the ionosphere considerably varying during magnetic storms.
- Mainly over all the stations on October 16, 2016 thus validating TEC enhancement observed on this day.

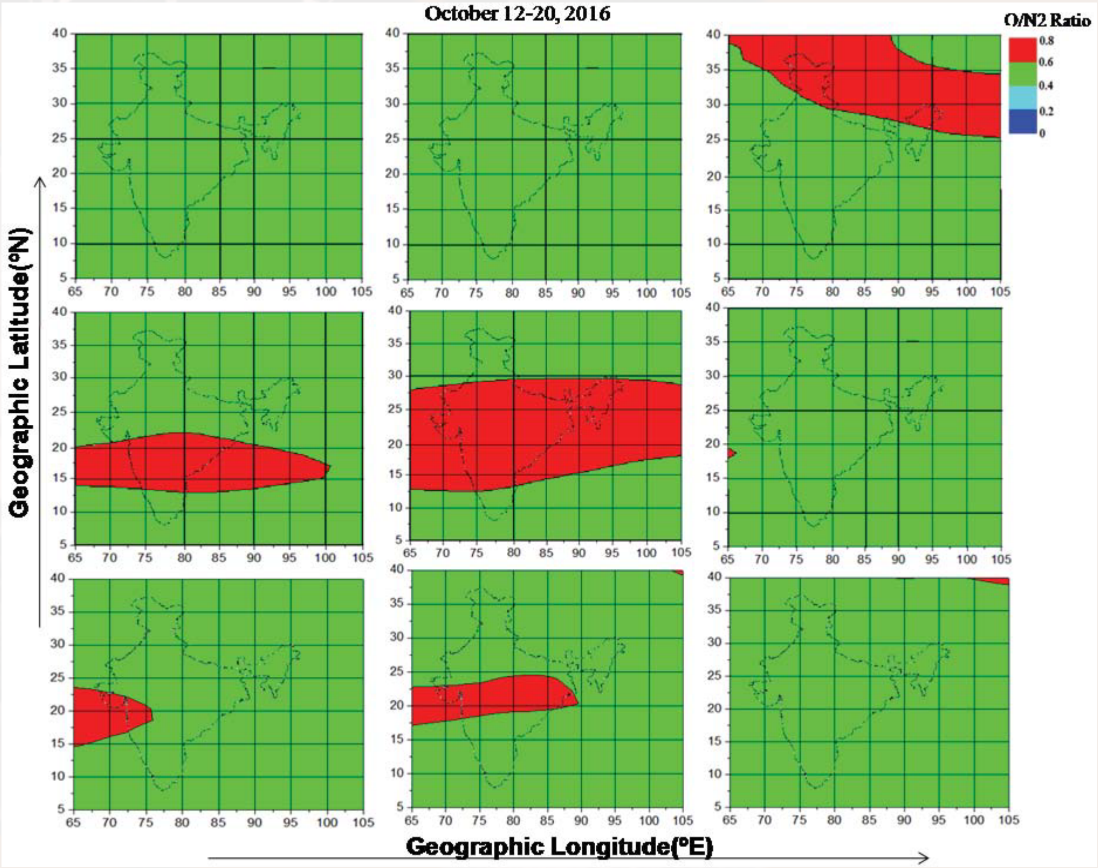


Figure: Thermospheric O/N_2 ratio over the Indian sector during October 12-20, 2016 (Chakraborty, S., et.al, 2019, Advances in Space Research)

Calculation of IPP and TEC

At any point, azimuth(A_z) and elevation(E) of the line-of-sight vector from user to satellite along with user's latitude-longitude(ϕu, λu) is necessary to calculate the IPP(ϕpp, λpp) locations(Rama Rao et., 2006) and is given as:

$$\Psi_{pp} = \frac{\pi}{2} - E - \sin^{-1}\frac{R_e.\cos(E)}{R_e + h}$$

$$\phi_{pp} = \sin^{-1}[\sin\phi_u * \cos\Psi_{pp} + \cos\phi_u * \sin\psi_{pp} * \cos A_z]$$

$$\lambda_{pp} = \lambda_u + \sin^{-1}\frac{\sin\psi_{pp} * \sin A_z}{\cos\phi_{pp}}$$

The frequency dependence of the ionospheric TEC(Roth and Lanyi, 1988) is:

$$\rho_{iono} = 40.3 * \frac{STEC}{f^2}$$

where ionodelay is in m, f is the frequency in Hz. To calculate VTEC from STEC, the mapping function(Jakowski et al., 2011) is:

$$M_F = \left[1 - \left(\frac{R.\cos E}{R + h}\right)^2\right]$$

where R is the Earth's radius, E the elevation angle and h the ionosphere's altitude(350 km).

IPP Ray paths of NavIC and GPS from the receiver location

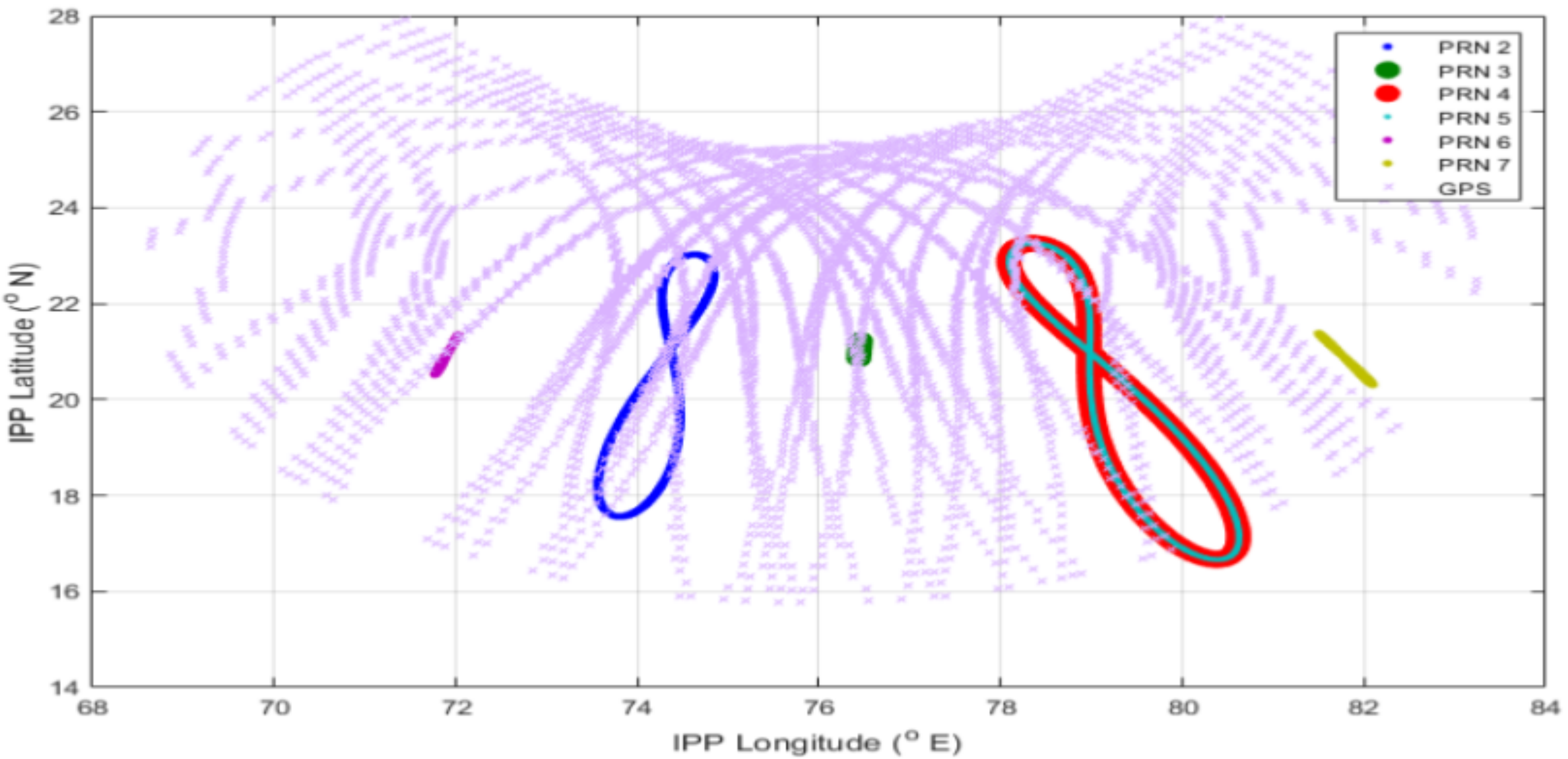


Figure: IPP as observed from receiver location (Ayyagari, D., et.al, 2019, under review in Advances in Space Research)

Ray paths for NavIC and GPS in IPP grid

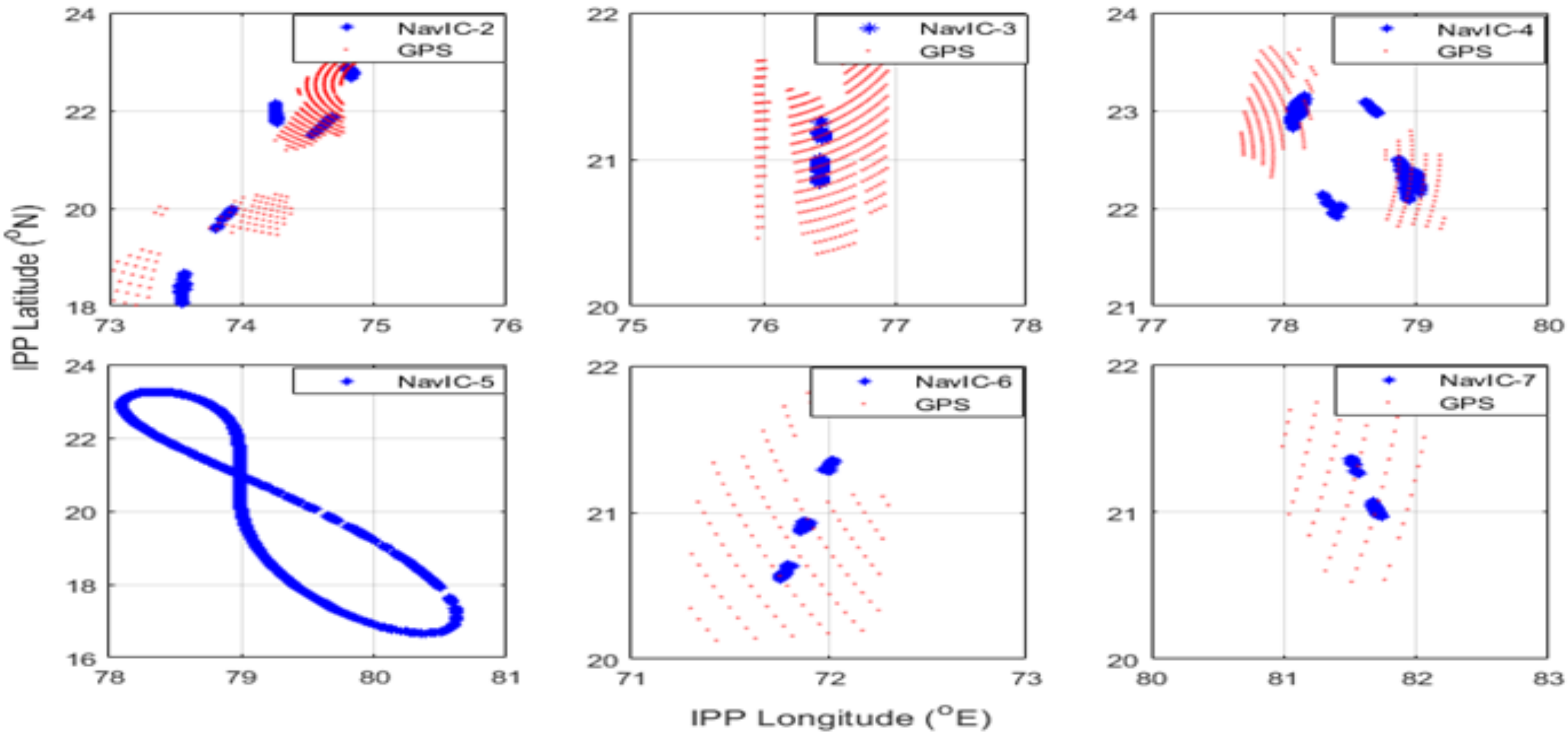


Figure: IPP 1^o X 1^o grid (Ayyagari, D., et.al, 2019, under review in Advances in Space Research)

Validation of NavIC derived VTEC

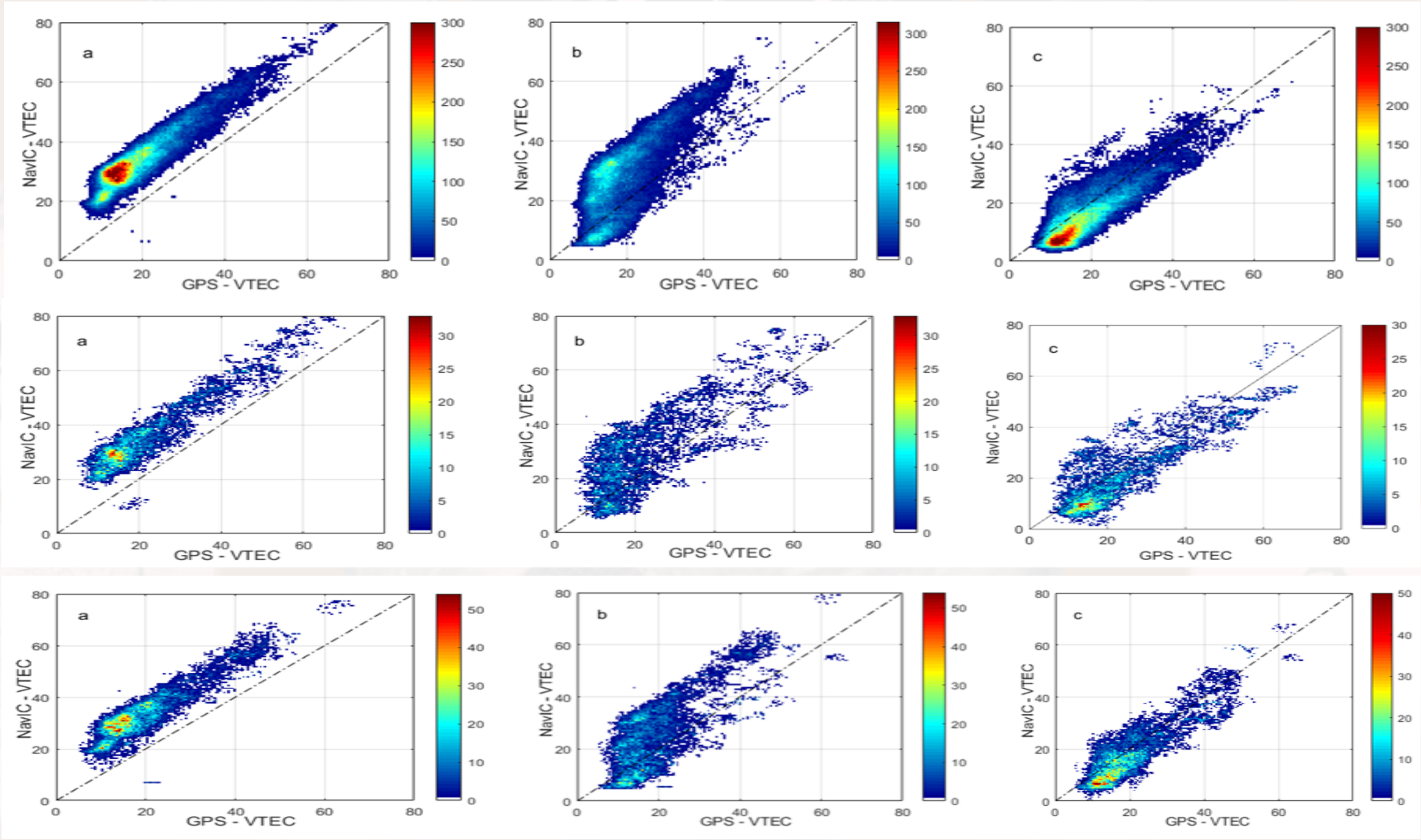


Figure: The VTEC measured from IPP 1^o X 1^o grid of NavIC plotted against GPS for all 365(viz.disturbed+quiet) days(top panel), quiet days(Kp<4, middle panel) and disturbed days(Kp>5, bottom panel) during the span of September 2017-2018 (Ayyagari, D., et.al, 2019, under review in Advances in Space Research)

Difference in TEC estimates of NavIC to GPS(ΔTEC_{NG})

We define: $\Delta TEC_{NG} = \frac{TEC_{NavIC} - TECGP_S}{TEC_{GPS}}$

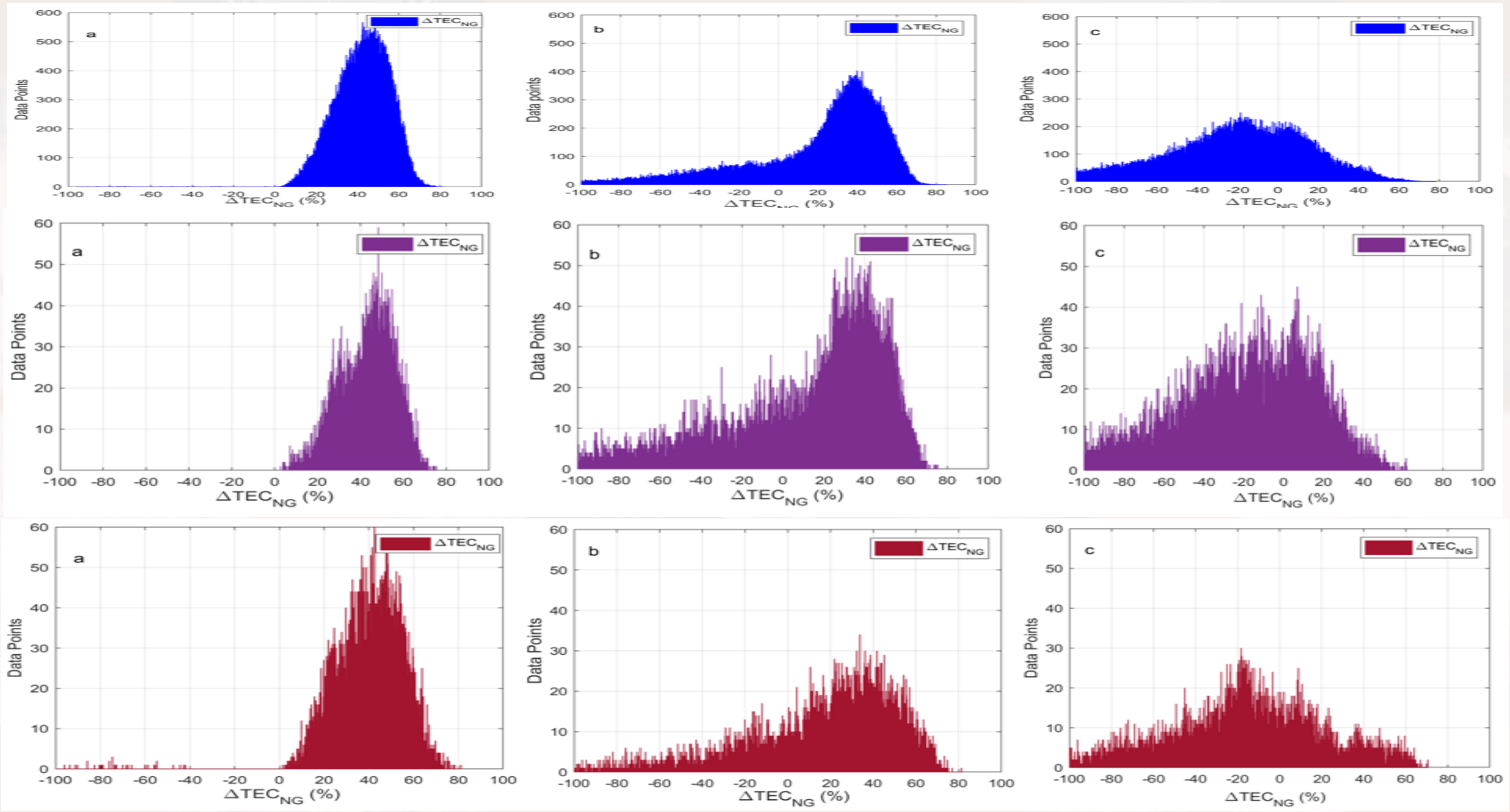


Figure: Distribution of ΔTEC_{NG} during one year observations using NavIC & GPS for all 365 days(top panel), quiet days(middle panel) and the disturbed days(bottom panel) (Ayyagari, D., et.al, 2019, under review in Advances in Space Research)

Response to Geomagnetic storms using NavIC and GPS

- The flare of Class X was observed on September 6 from the AR 2673 at 09:10 UT that sparked a G3 (strong) level geomagnetic storm observed on September 8, 2017.
- Another G3 level geomagnetic storm was observed at 05:59 UT on September 28, 2017.

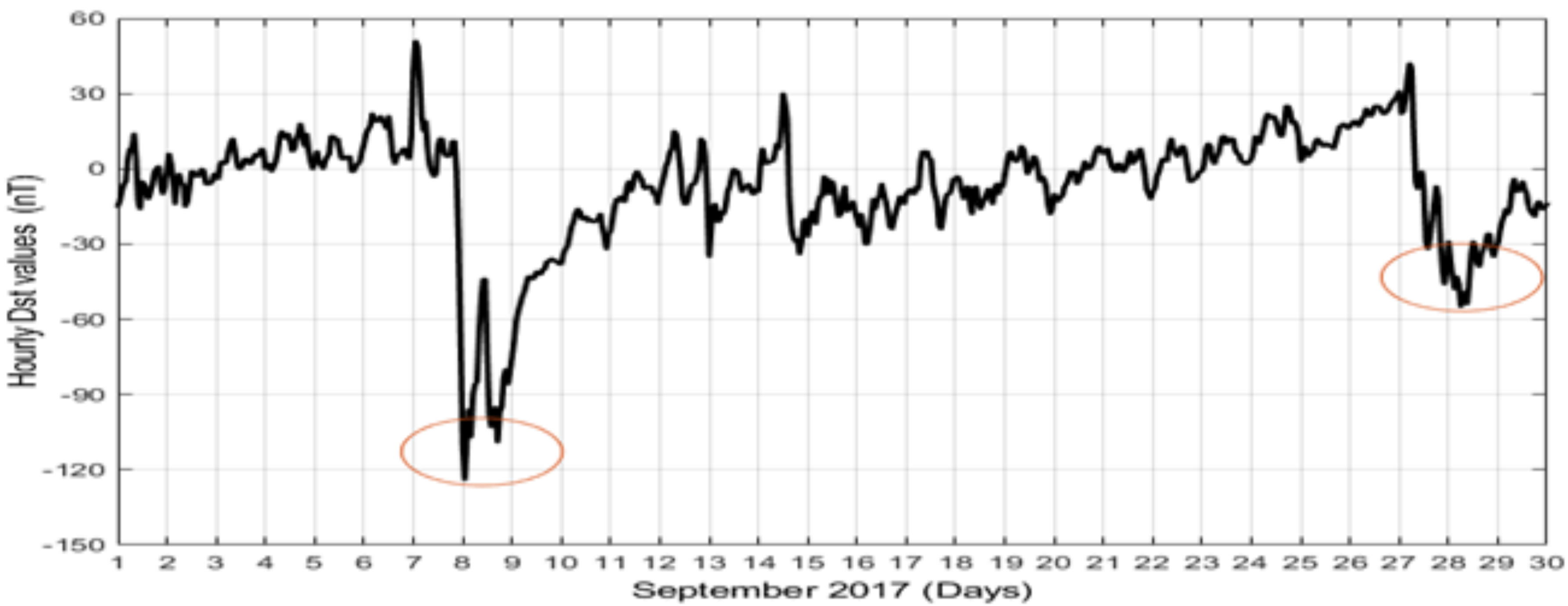


Figure: Variation of the Dst index for September 2017, Storm days are indicated.

Response to the intense storm of September 8, 2017

The pre-storm day(September 7), diurnal maximum values observed were about 75 TECU whereas the monthly mean at that instant was about 40 TECU. Thus an enhancement of 35 TECU over quiet time values were observed from NavIC & GPS.

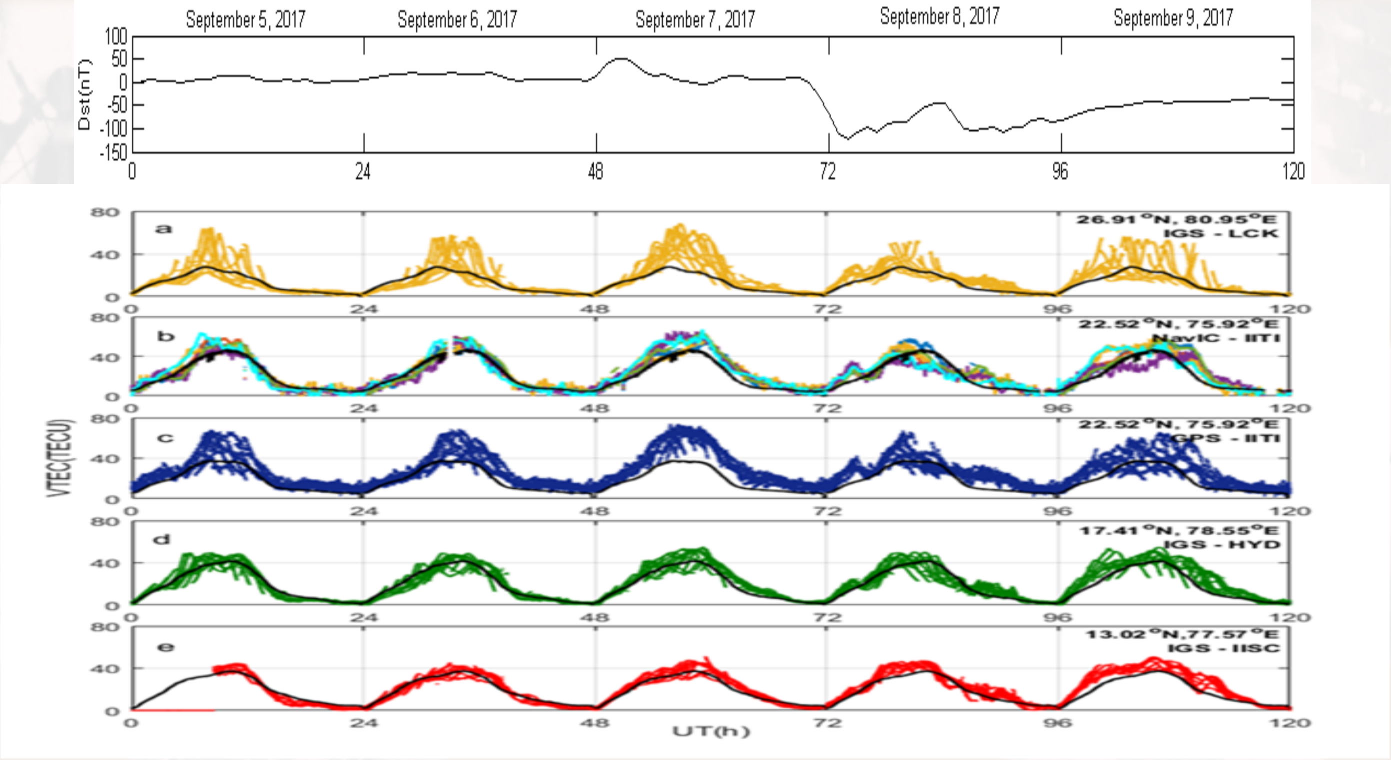


Figure: VTEC variation during September 5-9, 2017 over stations: (a) Lucknow, (b-c) Indore, (d) Hyderabad and (e) Bengaluru. Monthly mean TEC values are shown in black. (Ayyagari, D., et.al, 2019, under review in Advances in Space Research).

Response to the moderate storm of September 28, 2017

The storm day and after (September 28, 29 and 30), diurnal maximum values observed were close to 80 TECU whereas the monthly mean at that instant was around 40 TECU. Thus an enhancement of 40 TECU over quiet time values were observed.

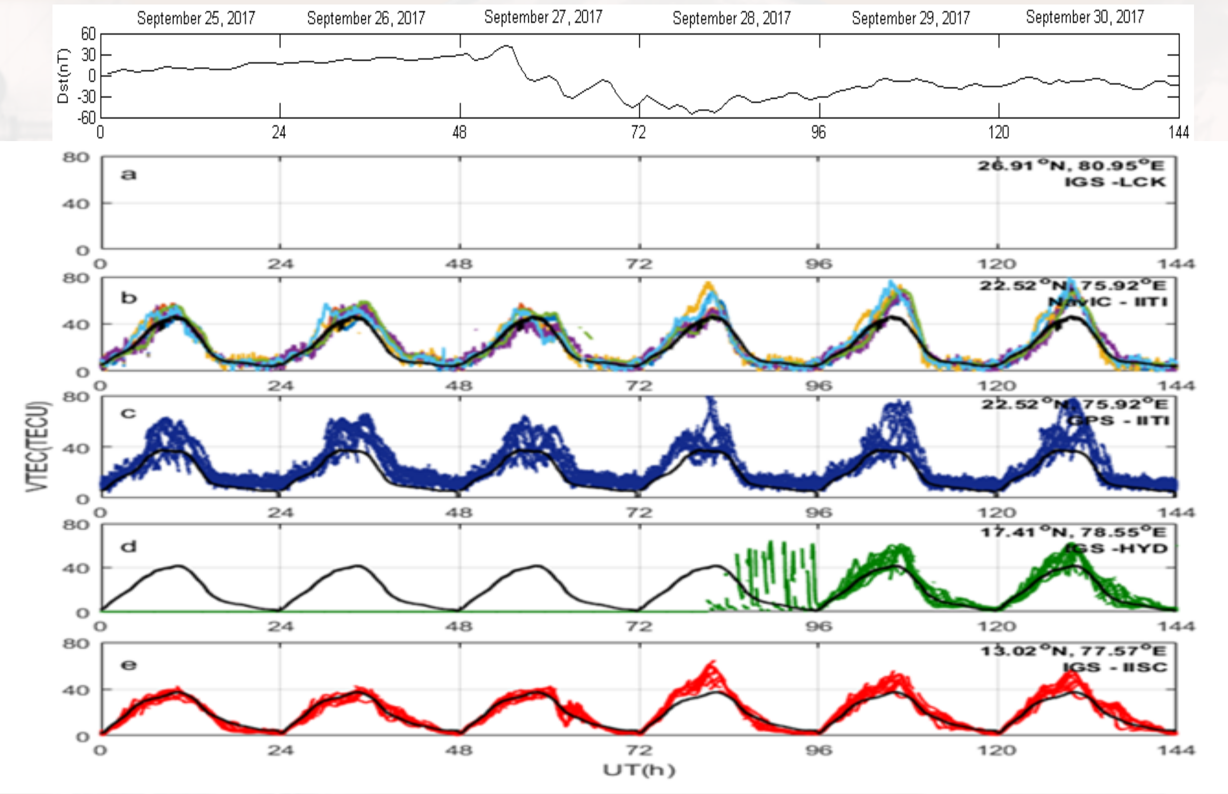


Figure: VTEC variation during September 25-30, 2017 (Ayyagari, D., et.al, 2019, under review in Advances in Space Research)

Ionospheric Scintillation observed using NavIC w.r.t GPS

Ionospheric scintillation is a phenomenon which is best described as a rapid or sudden change in phase and amplitude of a satellite signal when it passes through ionosphere.

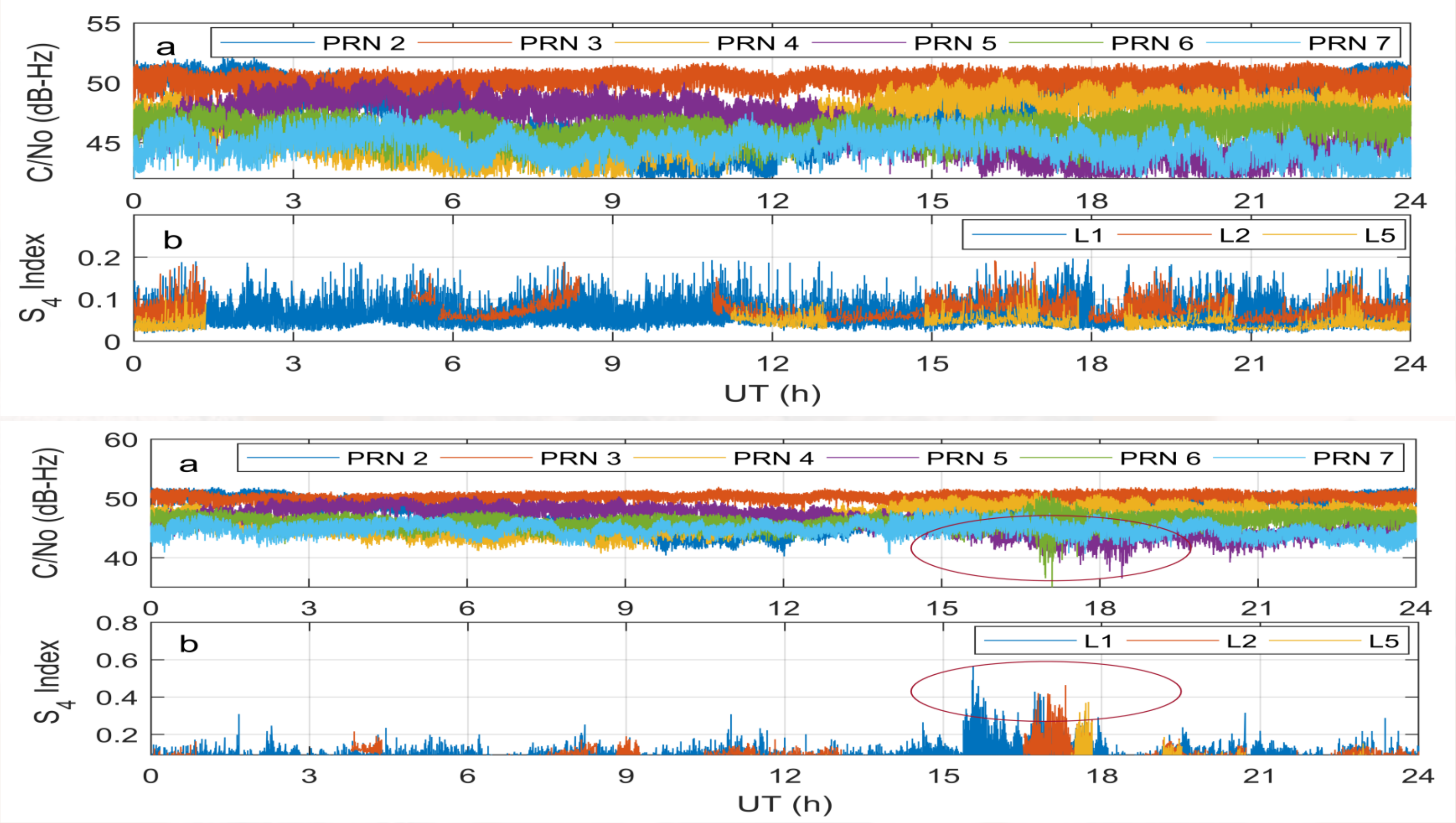
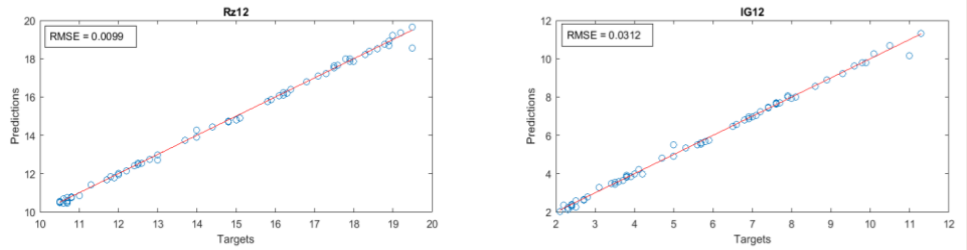


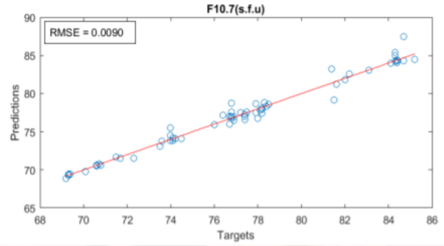
Figure: C/No of NavIC with S_4 index as observed from GPS from the same location for a quiet day(top panel) and September 8, 2017(bottom panel).

ANN based modelling of the Ionosphere: initial results

- The well accepted International Reference Ionosphere (Rawer and Bilitza, 1989) model has been used to create data set for training and testing where Training:Testing = 3:1.
- A feed-forward network with 25n, single hidden layer have been used wherein the hourly TEC values consist of the input layer while the 13-month running mean of ssn(Rz12), the ionospheric index and F10.7 radio flux are the targets.
- Activation function: $\tanh x = \frac{1-e^{-2x}}{1+e^{2x}}$.
- The error function at the end of one feed forward process:

$$RMSE = \frac{Predictions \ - Targets}{Targets} * 100$$





Parameters	RMSE
Rz12	0.0099
IG12	0.0312
F10.7	0.0090

Figure: Prediction against Targets of the Network (Chakraborty, S., et.al, 2020, in prep.)

Conclusion

Serial No.	Extreme Weather Events	GNSS/NavIC observations
1	Intense Storms of October 2016 and May 2017	Drastic enhancement of about 20-45 TECU, over quiet time values, were observed in the GNSS TEC due to the dynamic nature of the storms of October 2016 and 10-20 TECU enhancement for the May 2017 storm.
2	Intense Storm of September 8, 2017	TEC enhancement was observed on the pre-storm day (September 7, 2017) by both NavIC and GNSS. The enhancement of 35 TECU was recorded as the diurnal maximum went up to 75 TECU.
3	Moderate Storm of September 28, 2017	TEC enhancement was observed on three days including the storm day (September 28-30, 2017) by both NavIC and GNSS. The enhancement of 40 TECU was recorded as the diurnal maximum went up to 80 TECU, even though the storm intensity had been less in comparison to the September 8, 2017 storm
4	Amplitude Scintillation during intense storm of September 8, 2017	Distinct Random Fluctuations in both the receivers' S_4 index were observed on the storm day . So changes were captured when observation was done for a quiet day of the month.

References

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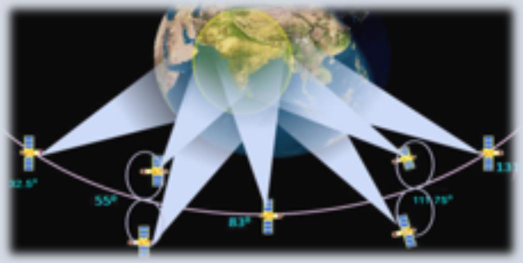
Executive Summary

- **<u>Research Article Published</u>**:
- Chakraborty, S., Ray, S., Sur, D., Datta, A., Paul, A., "Effects of CME and CIR induced geomagnetic storms on low-latitude ionization over Indian longitudes in terms of neutral dynamics", Advances in Space Research (2019), https://doi.org/10.1016/j.asr.2019.09.047.
- **<u>Publications under review</u>**:
- "Performance of NavIC for studying the ionosphere at an EIA region in India" in Advances in Space Research, Elsevier.
- **<u>Publications in preparation:</u>**
- "ML approach in predicting solar and geophysical indices".
- "Ionospheric Scintillation study to detect Equatorial Plasma Bubbles over the Indian longitude sector".

- **<u>Conference and other publications</u>**:
- S.Chakraborty and A.Datta , "Study of the Ionospheric Total Electron Content over central India using Artificial Neural Network", 2019 URSI Asia-Pacific Radio Science Conference(AP-RASC)(doi: 10.23919/URSIAP-RASC.2019.8738226).
- D.Ayyagari, S. Chakraborty and A. Datta, "Ionospheric observations over central part of India using comparative study of NavIC and GNSS", 2019 URSI Asia-Pacific Radio Science Conference(AP-RASC)(doi:10.23919/URSIAP-RASC.2019.8738226).
- Talk by Mr. Sumanjit Chakraborty titled "Analysis of the ionospheric TEC over central India during low solar activity using ANN" at EXPUNIV 2018 at SNBNCBS, Kolkata.
- Talk by Ms.Deepthi Ayyagari titled "Ionospheric observations over central part of India using comparative study of NavIC and GNSS" at the 3\nth{7} Annual meeting of ASI held at Christ University, Bengaluru.



Thank You