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ORIGINAL ARTICLE

Low latitude ionospheric response to March 2015 geomagnetic storm using multi-instrument TEC observations over India

A. Vishnu Vardhan[1] · P. Babu Sree Harsha[1] · D. Venkata Ratnam[1] · A.K. Upadhayaya[2]

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Abstract The regional ionospheric models are successful in capturing the variability of ionosphere with the inclusion of local ground-based GPS observations and location dependent ionospheric dynamics. In this context, there is a need to develop regional ionospheric maps that aids in improving the consistency of global models. In this paper, an attempt is made to understand the potentiality of multi-instrument observations over Indian region. Four different Total Electron Content (TEC) data sources namely from network of GPS receivers, Ionosonde stations, space based COSMIC radio occultation profiles and SWARM mission data is utilized. The multi-source data is chosen for the geomagnetic storm conditions prevailed during March 2015. Data from multiple-sources is observed over the period from 15th March 2015 to 20th March 2015. Validation of ground and space-based TEC data with International GNSS service (IGS) station data is significantly observed.

Keywords GAGAN · VTEC · International GNSS service · Ionosphere · SWARM · Ionosonde

1 Introduction

Geomagnetic storm causes disruption in the Earth's magnetic field by transmission of dissipative solar processes into magnetosphere, ionosphere, and thermosphere system (Paul et al. 2018). The source of geomagnetic storm occurred by coronal mass ejections, co-rotating reciprocating domains, circlet voids, quiet and rapid solar wind torrents (Waheed et al. 2019). During the occurrence of the geomagnetic disturbance immensely reinforced high-latitude energy and propulsion inputs in the upper thermosphere leads to ion drag and active Joule heating that will change the global circulation and neutral temperature (Li et al. 2019). The electron density either increases or decreases during geomagnetic storm periods and the variations termed as "positive" or "negative" ionosphere storm effects (Mansilla 2019). The geomagnetic disturbances result in the deterioration of satellite-based navigation systems signals. The ionospheric irregularities need to be analyzed in-depth with their day-to-day variations to reach a level of forecasting capability over low latitude regions (Ray et al. 2017). The Earth's magnetic flux lines create two-electron density peaks on each of the two sides of the magnetic equator is manifested as the Equatorial Ionization Anomaly (EIA) (Ribeiro et al. 2019).

The total electron content (TEC) determines the total count of electrons present per square meter on the line of sight from the transmitter located on board of the satellite to the receiver present on the ground. The Global Positioning System (GPS) and Ionosonde come under ground-based Instruments whereas Radio Occultation and SWARM comes under space-based instruments to monitor the ionosphere (Bhuyan and Borah 2007). The ionospheric total electron content (TEC) has been broadly reviewed and modeled for the applications like navigation, satellite communication and altimetry. The TEC taken against the ground-based receivers provides better accuracy over the land than ocean. Ionosonde can easily capture point-wise vertical and horizontal changes occurred in the ionosphere (Mungufeni et al. 2019). The ionosphere cause these effects on the re-

✉ D. Venkata Ratnam
dvratnam@kluniversity.in

[1] Koneru Lakshmaiah Education Foundation, Greenfields, Vaddeswaram, Guntur, 522502, India

[2] National Physical Laboratory, K.S. Krishnan Marg, New Delhi, 110012, India

ceived signals, delay due to the existence of free electrons, and refraction, diffraction caused by the irregular distribution of the electron density and the velocity changes in the plasma (De Franceschi et al. 2019).

Many researchers suggest understanding the TEC response with multi-instrument data sources (Pedatella et al. 2009 and Astafyeva et al. 2015). Pedatella et al. (2009) investigated the cause for the long-duration positive storm effects occurred on 2006 using observations from TOPEX, JASON-1 and COSMIC satellites. Matamba et al. (2015) also utilized the observations from Ionosonde and GPS TEC receiver to understand ionospheric climatology over South African region. Şentürk (2020) also investigated global ionosphere response under geomagnetic storm conditions prevailed on June 2015 using global ionospheric maps (GIM's), COSMIC radio occultation profiles and IGS stations, respectively. Apart from global TEC observations, the role of dense regional TEC observations with in specific geographic region during geomagnetic storm conditions is critical. Zhang et al. (2018) utilized observations from crustal movement of observation network over china (CMONOC) to understand TEC variations during geomagnetic storm conditions. Astafyeva et al. (2015) demonstrated the negative and positive storm variations globally for March 2015 St. Patrick's storm with multiple GNSS instruments data. Venkatesh et al. (2017) investigated equatorial ionosphere response for St. Patrick's storm using measurements from ground and space based GNSS observations over the Brazilian sector simultaneously. Joshi et al. (2016) incorporated ionosonde derived vertical drift measurements into Another model of Ionosphere (SAMI2) understood the enhancement and suppression of EIA during the main and recovery phase of storm for 17th 18th March 2015 days, respectively. Patra et al. (2016) also understood multi-instrument ionospheric observations to study the electrodynamics and link of plasma irregularities to St. Patrick's storm over a low-latitude station. Yadav et al. (2016) investigated the TEC variations over the Indian region from 15th to 20th March 2015 days through spatial and temporal maps.

The significance of multiple observations to sense the TEC variations during geomagnetic storm conditions is clearly perceived. To understand the significant geomagnetic storm effects raised on 15th to 20th March 2015 days over Indian region is the point of interest. The similarities in capturing TEC response between ground (from GAGAN network, Ionosonde stations) and space based GNSS observations (from COSMIC RO and SWARM missions) over Indian region is presented.

Table 1 GAGAN Indian Reference Stations (INRES) locations with geographic coordinates

S.No	Location	Latitude (degrees)	Longitude (degrees)
1	Ahmedabad	23.0	72.5
2	Agatti	10.8	72.5
3	Aizwal	23.5	93
4	Bagdogra	27.0	88.5
5	Bangalore	13.0	77.5
6	Bhopal	23.0	77.2
7	Delhi	28.7	77.2
8	Hyderabad	17.5	78.5
9	Jodhpur	26.2	73.0
10	Kolkatta	22.6	88.4
11	Lucknow	26.7	80.8
12	Mumbai	19.0	72.8
13	Port Blair	11.6	92.7
14	Raipur	21.1	81.7
15	Shimla	31.0	77.0
16	Trivandrum	8.4	76.9
17	Visakhapatnam	17.7	83.2
18	Nagpur	21.0	79.0
19	Khajuraho	24.8	79.9
20	Agra	27.1	77.9
21	Aurangabad	19.8	75.3
22	Hubli	15.3	75.0
23	Madurai	9.5	78.0
24	Bhubaneswar	20.2	85.8
25	Gaya	24.6	85.0
26	Guwahati	26.1	91.5

2 Data

2.1 Ground based GNSS observation

2.1.1 GPS Aided GEO Augmented Navigation (GAGAN)

GAGAN is an Indian satellite-based augmentation system (SBAS) consists of twenty-six dual frequency GNSS receivers across Indian region. It is joint project developed by Indian Space Research Organization (ISRO) and Airports Authority of India (AAI) (Sarma et al. 2009). As a part of SBAS system, twenty-six GNSS receivers are placed across Indian region at Indian Reference Stations (INRES). Table 1 gives the list of INRES coordinates are given. These receivers provide total electron content observations for every minute. Now, the raw TEC values are processed to eliminate multipath effects by fixing elevation angle greater than 30°. The receiver and satellite biases are removed for each receiver using Kalman filter based bias elimination procedure

(Shukla et al. 2009). TEC observations after following all the necessary quality checks are considered as reliable and utilized for this study.

2.1.2 VTEC data from Ionosonde instruments

Ionosonde is a ground based passive radar that sweeps frequency from 1 to 20 MHz range. The transmitted signal sweeps frequency and the critical frequency and height at which the signal gets reflected back is recorded. In this study, data from two ionosonde data stations at Hyderabad and Delhi are utilized. The ionosonde instruments are manufactured by Canadian Advanced Digital Ionosonde (CADI) that records time stamp, critical frequency (foF2), critical height (hmF2), vertical total electron content (VTEC) information (Reinisch and Galkin 2011). The VTEC obtained from two stations are utilized for our study.

2.2 Space based GNSS observation

2.2.1 COSMIC RO data

Formosat-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) (F3/C) mission is a US-Taiwan project launched in 2006 (Fong et al. 2008a). Through remote-sensing six F3/C LEO microsatellites record occultation profiles of temperature, refractivity, water vapor and pressure in the neutral atmosphere and electron density and total electron content in the ionosphere (Fong et al. 2008b). COSMIC data is archived by COSMIC Data Analysis and Archive Center. The ionospheric parameters namely electron density is obtained from Level2 interface IonPrf file. COSMIC uses Abel inversion technique for obtaining electron density information. The occulted electron density profiles pass over Indian region are drawn for analysis. COSMIC IonPrf files also provide TEC information as one of the attributes in TEC0 (ionospheric content) and TEC1 (plasmasphere content) terms. The addition of TEC0 and TEC1 is collectively provides reliable TEC observation for an occulted location. Now, the TEC is derived from electron density profiles using Alpha-Chapman function extending the bottom side height to 60 km and top-side height to 1000 km as suggested. Using Simpson's rule TEC value is derived from electron density profile through numerical integration. A comparison on derived TEC and COSMIC TEC is given in this study. The data can be downloaded from https://cdaac-www.cosmic.ucar.edu/cdaac/index.html.

2.2.2 SWARM data

SWARM is European Space Agency (ESA) mission for earth observation. It consists of three satellites named as Alpha (A), Bravo (B) and Charlie (C) at LEO orbit. SWARM satellites A and C are orbited at a height of 460 km and SWARM B satellite is deployed at a height of 510–520 km (Olsen et al. 2013). Two satellites SWARM A and SWARM C travel along same longitudes (approximately 1°–1.5° difference), collects similar TEC information. SWARM B travels at different longitude sector and collects TEC along all latitudes of Indian region. Three satellites absolute STEC data is utilized in this study. The data is obtained from a retrieval interface known as VirES, that is a virtual web based graphical user interface for handling swarm data interactively. The data can be downloaded from https://vires.services/.

3 Results and discussions

Figure 1 gives the scattered VTEC observations obtained from GAGAN network stations for 15th to 20th March 2015, days. For instance, 06:00 UTC, 12:00 UTC, and 18:00 UTC hours given. it is evident that on 15th March 2015, at 06:00 UTC, maximum TEC intensity is spread around 20° N to 25° N latitudes indicating EIA full occupancy (Fig. 1). At 12:00 UTC, decrement in TEC intensity is observed from IPP's indicating leaving trend in EIA. At 18:00 UTC hours, TEC depletions are noticed over the entire Indian region. The solar and geomagnetic indices on 15th March 2015, indicates a quiet day condition. Hence, 15th March 2015, is chosen as reference and TEC variations for other days to understand geomagnetic storm effects observed over the Indian region. On 16th March 2015, at 06:00 UTC, TEC intensity was high at 20° N to 25° N latitude as the previous day. At noon UTC, there is a decrease in TEC intensity, but slightly larger VTEC values noticed in comparison with 15th March 2015. At 12:00 UTC, there is a complete reduction in VTEC value over the entire Indian region. The day of 17th March 2015 is considered as storm day (initial phase of the storm). TEC intensity spread across 15° N to 25° N latitudes, and lesser VTEC values are noticed from IPP's compared with 15th and 16th March 2015 days respectively. At 12:00 UTC, VTEC intensity is even decreased, and maximum VTEC is around 50 TECU, respectively. At 18:00 UTC, VTEC intensity is below 20 TECU over the entire Indian region. Unlike previous considered days, on the post-storm day (18th March 2015) at 06:00 UTC TEC spread is between 10° N to 20° N. With the latitudinal comparison of the TEC spread during quiet time, ionospheric conditions on 18th March 2015, the TEC intensity is reduced, and shift of maximum TEC (EIA) is towards lower latitudes. These two conditions explain the occurrence of adverse storm effects over the Indian region on 18th March 2015.

Even at 12:00 UTC drastic decrease in TEC values is noticed over latitudes higher than (20° N), that is not persisted on storm and pre-storm days, respectively. At 18:00 UTC, a

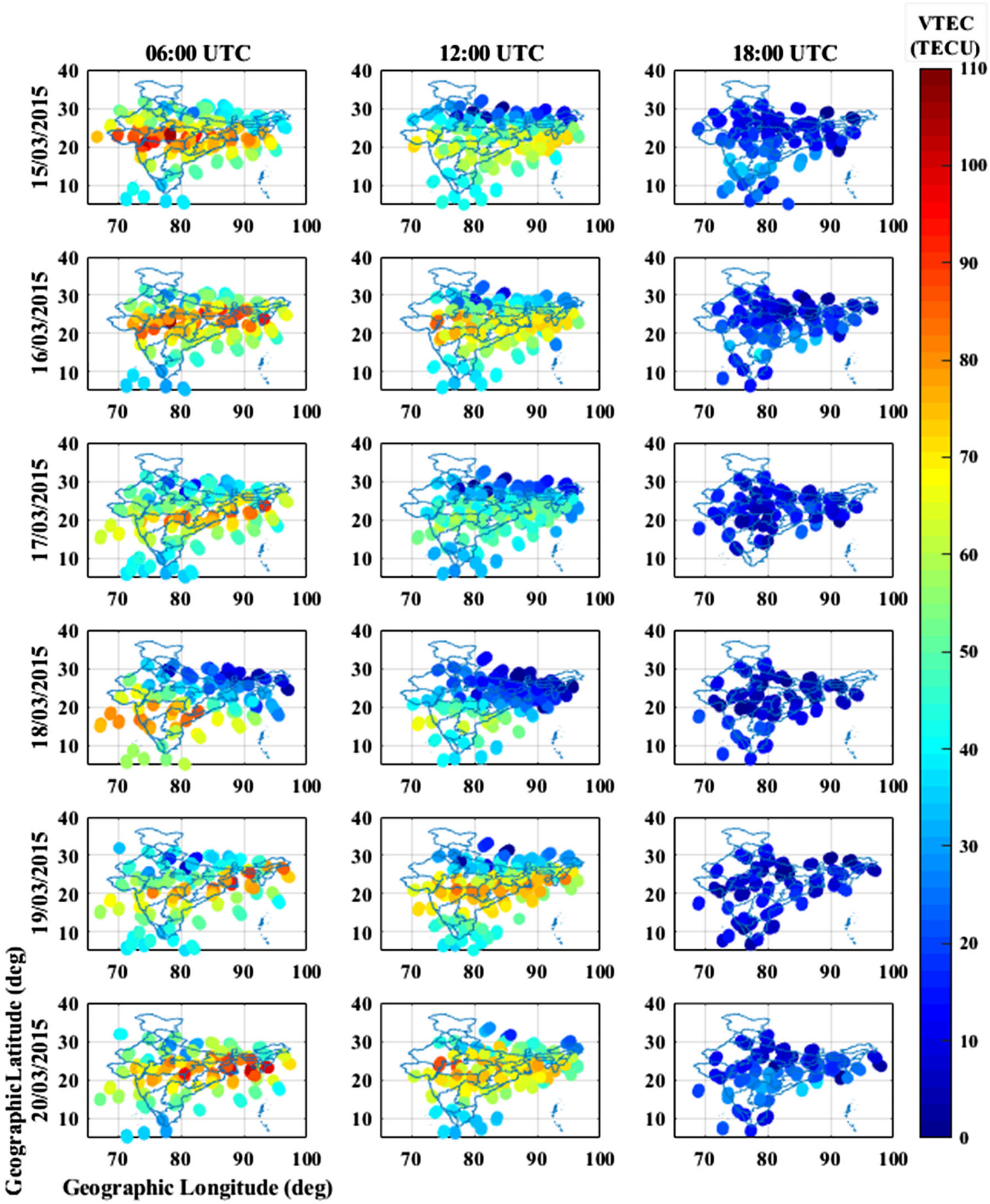

Fig. 1 IPP VTEC observations obtained from GAGAN network for 15th to 20th March 2015 days

decrease in VTEC values noticed on 18th March 2015. On 19th March 2015, maximum TEC spread is noticed around 20° N to 25° N latitudes. The TEC depletions are observed on 16th March 2015. At 12:00 UTC TEC spread is even visible for 15° N to 25° N, and intensity is more than the previous day. At 18:00 UTC, complete decrement in VTEC over the entire Indian region is noticed. This explains the rejuvenation of the ionosphere from the disturbed condition. On 20th March 2015, the maximum TEC spread was occupied around 15° N to 25° N latitudes for 06:0 and 12:00 UTC hours. At 18:00 UTC, there is a TEC reduction over the entire Indian region.

To understand the spatial TEC structure for the 15th to 20th March 2015, days the IPP's are linearly interpolated to the geographic location (latitude: 5° N to 40° N) and (longitude: 65° E to 100° E). Triangulation based linear inter-

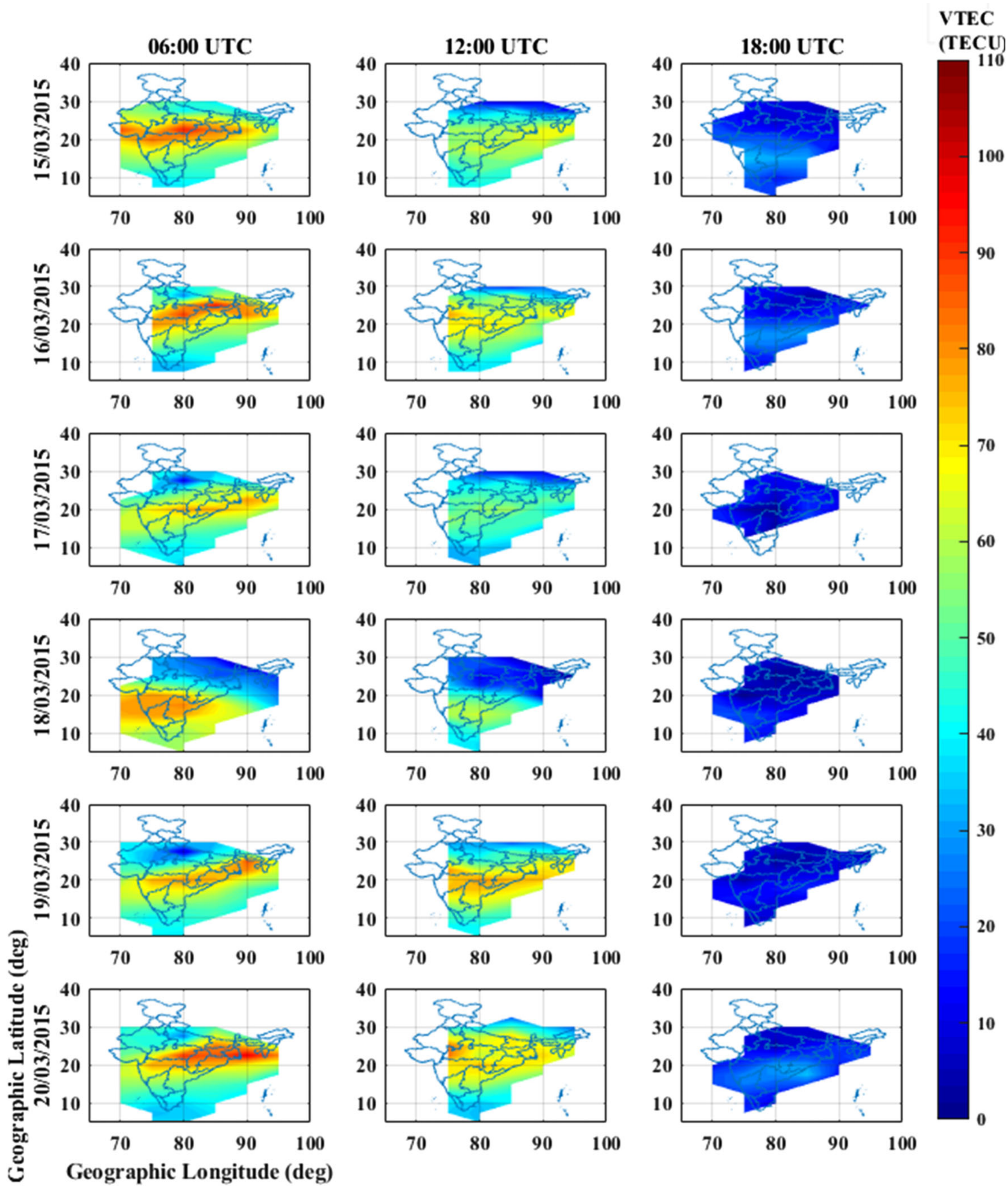

Fig. 2 Linear interpolated VTEC data obtained from GAGAN network for 15th to 20th March 2015 days

polation provides weights at the observation locations only if there are at least two VTEC observations from neighbouring grid points. Figure 2. gives such linear interpolated VTEC spatial maps at 06:00, 12:00 and 18:00 UTC hours, respectively. From 15th to 20th March 2015, at 06:00 UTC, the maximum VTEC is observed as 79, 84, 77, 74, 81, and 83 TECU, respectively. On 17th March 2015 (storm day), decrement in TEC is noticed, and on post-storm, day (18th March 2015) shift in TEC intensity towards low latitudes is also observed from linear interpolated TEC maps. On the 19th and 20th March 2015 days, the VTEC structure is same as observed on 15th March 2015. Similarly, at 12:00 UTC hour the negative storm effect is captured clearly from VTEC observations. On 20th March 2015, enhanced VTEC structures rise could be attributed to an increase in plasma recombination after disturbed storm conditions.

A meridional cross-section at 80° E chosen to understand temporal EIA structure variations over latitudes (5° N

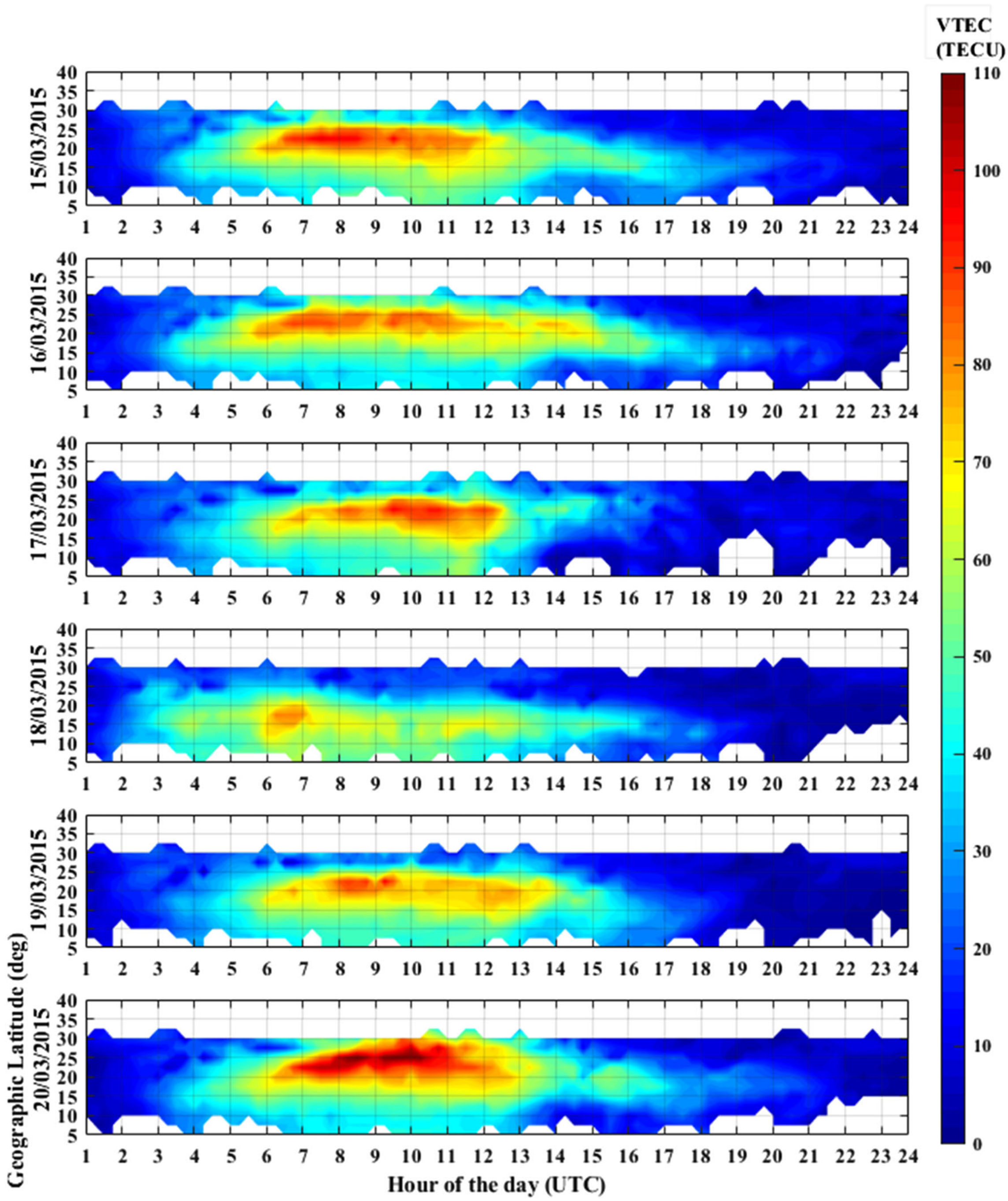

Fig. 3 Meridional cross-section representing EIA at 80° E longitude for 15th to 20th March 2015 days

to 40° N) for 15th to 20th March 2015 days (Fig. 3). Here, EIA entry, occupancy and exit times are needed to understand delay or advance in the EIA occurred due to geomagnetic conditions. As the time at the EIA VTEC value greater than 30 TECU and having an entry wedge shape is chosen as EIA entry time. The maximum VTEC and occupancy to all-time with latitudes is treated as EIA occupancy time. The leaving EIA TEC tails observed with VTEC higher than 30 TECU is considered as EIA exit time. On 15th and 16th March 2015 days, EIA entry, occupancy, and exit hours are noticed as 03:00 UTC, 08:00 UTC, and 16:00 UTC hours, respectively. On 17th March 2015 (storm day), EIA entry is observed at 03:00 UTC. EIA occupancy is noticed around 10:00 UTC and EIA exit are noticed at 14:00 UTC. On storm day, a shorter EIA period is noticed. The shorter time length of EIA could be due to incurred changes in the initial and main phase of the storm. It is observed around 12:00 UTC TEC enhancement is observed on 17th

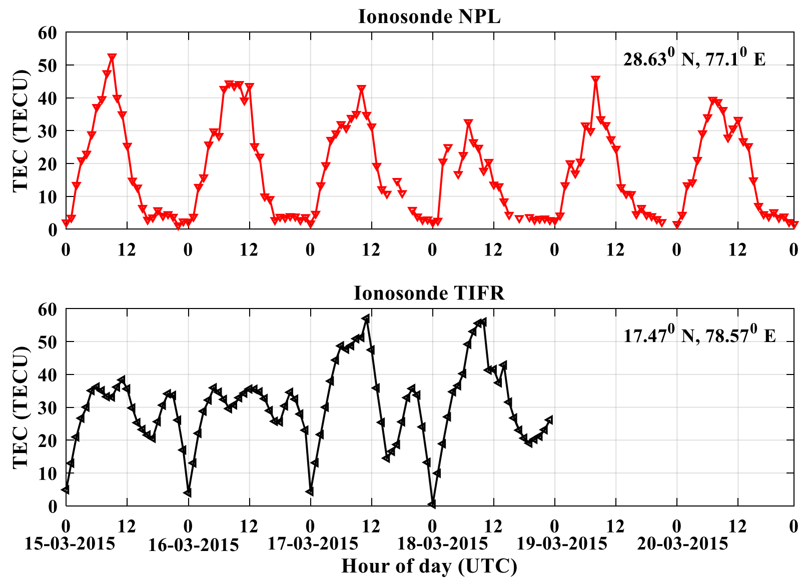

Fig. 4 Estimated VTEC from ionosonde instruments (NPL and TIFR) for 15th to 20th March 2015 days

March 2015, could be a sign of PPEF, and later sudden decrease of TEC at evening hours showcase the role of DDEF. On 18th March 2015 (post-storm day), complete inhibition of EIA is noticed for the entire day. TEC intensity/plasma is drastically reduced with maximum TEC of about 60 to 70 TECU. Unlike storm day, EIA entry time is noticed at 03:00 UTC and tails of EIA are seen at 15:00 UTC. It is demonstrating the negative storm ionospheric behaviour over the Indian region. On 19th March 2015, plasma transport from low latitudes is started to drift upwards due to a reduction in negative storm effect Even then, EIA tails are observed at 15:00 UTC. There is enormous plasma transport back to higher latitudes because of the reduction in adverse storm effects. It is created a significant accumulation of electron density that increased in TEC intensity more significantly than 100 TECU (Fig. 3). The TEC values are higher than in previous days and are clearly noticed.

Two independent Ionosonde point-based measurements are given for further investigation. Two ionosondes, namely Ionosonde NPL (28.63° N, 77.1° E) and Ionosonde TIFR (17.47° N, 78.57° E) TEC diurnal variations are presented (Fig. 4). From 15th to 20th March 2015 days, there is a gradual decrement of TEC from 15th to 18th March 2015, and slight increment of TEC is noticed for 19th and 20th March 2015 days, respectively Ionosonde NPL (Fig. 4). On comparison with 15th March 2015, there is about 20 TECU of maximum TEC variation on 18th March 2015. From Ionosonde NPL, it can be claimed the occurrence of adverse storm condition over the Indian region. There is only four days of data available from Ionosonde TIFR (15th to 18th March 2015). Unlike, Ionosonde NPL there is about 20 TECU of TEC enhancement noticed between 15th and 18th March 2015. This is certain that Ionosonde NPL is at high latitude (28° N) where electron density inhibited on 18th March 2015, that reached towards low latitude and equator. Ionosonde TIFR is a low latitude station that has an accumulation of electron density during 18th March 2015 (Fig. 4). This clearly explains the dynamic behaviour of the ionosphere due to geomagnetic storm conditions.

Similarly, to understand the geomagnetic storm effect over Indian region from space based GNSS observations occultation VTEC points obtained from COSMIC satellite mission are drawn for 15th and 20th March 2015 days. Figure 5 gives occultation VTEC point. There are about eight VTEC occultation points on 15th March 2015 (Table 2). The maximum TEC is 57 TECU at 08:28 UTC at 26° N and 69° E geographic coordinates occulted by RO satellite with GPS PRN 19 satellite. The derived TEC from the COSMIC profile gave 53.8 TECU. On 16th March 2015, there are six occultation profiles passed over the Indian region. The maximum VTEC from the occultation point is observed to be 56 TECU at 21° N and 92° E coordinate. The proposed TEC is about 46 TECU. On storm day, 18th March 2015, seven occultation profiles are noticed. The maximum TEC from occultation points is 48 TECU and 49 TECU from COSMIC and derived COSMIC RO profiles at 6° N and 91° E coordinate around 09:50 UTC obtained from PRN 28 satellite (Table 2). It is observed that occultation TEC is high value towards the equator, suggesting negative storm behaviour. Only four occultation profiles were observed on 19th March 2015. Among the recorded occultation profiles, maximum TEC is about 43 and 48 TECU from COSMIC and derived COSMIC RO profiles situated at 10° N and 83° E coordinate around 15:23 UTC. For the next day, March 20 2015 there are six occultation profiles recorded with maximum TEC of 54 and 38 TECU from COSMIC and derived COSMIC RO values at 14° N and 84° E geographic coordinate around 13:12 UTC occulted from GPS PRN 28 satellite (Table 2).

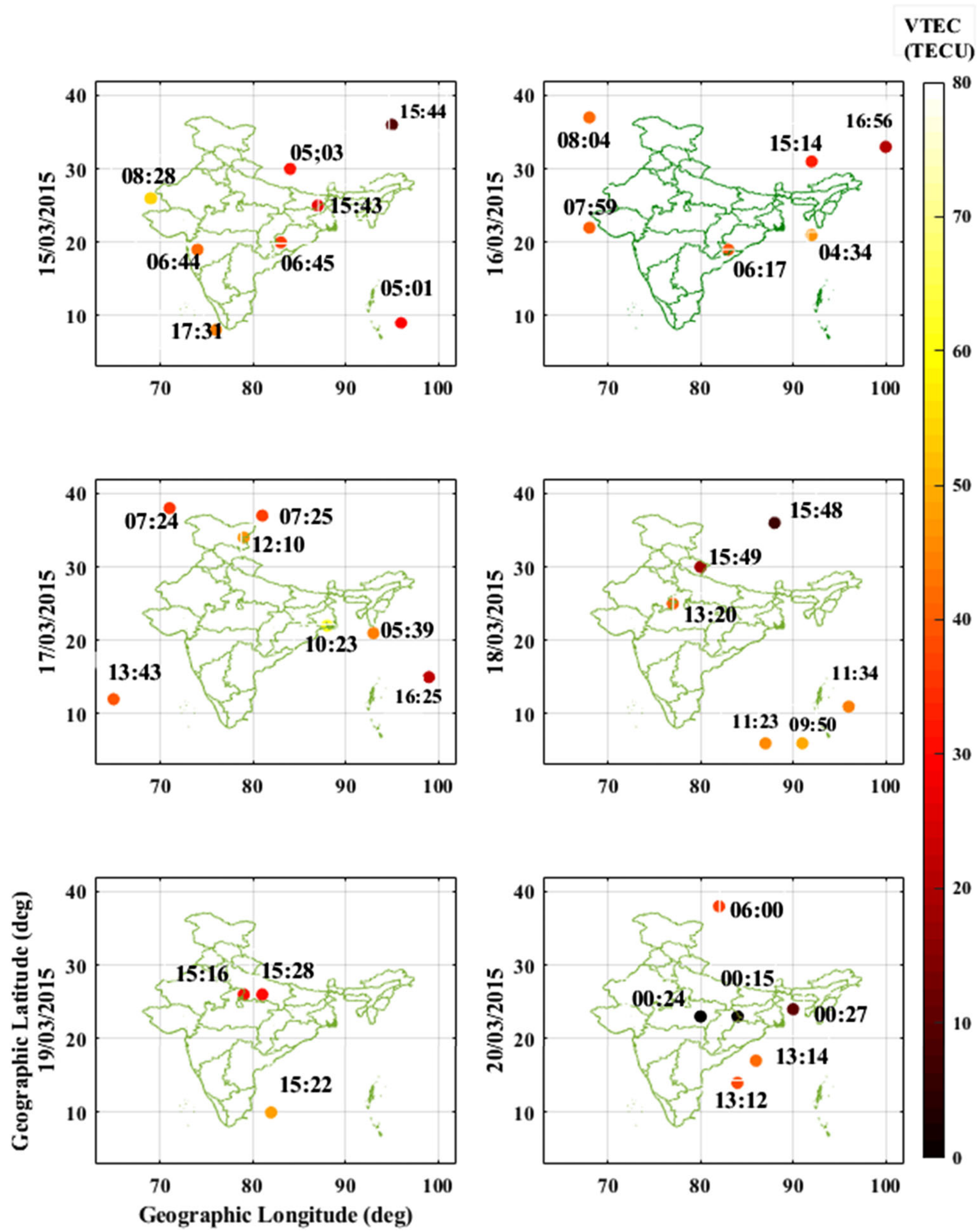

Fig. 5 Radio occultation VTEC points over Indian region for 15th to 20th March 2015 days (Time instants given in inside figure)

SWARM longitudinal VTEC profiles are also observed for 15th to 20th March 2015 days. It is evident from time instants that SWARM profiles are obtained before 05:00 UTC and after 13:00 UTC hours (Fig. 6). Table 3 gives the SWARM satellites (Alpha (A), Beta (B) and Charlie (C)) track pass time information for 15th to 20th March 2015 days over Indian region. On 15th March 2015, from obtained SWARM VTEC tracks maximum is recorded as 40 TECU at 13:00 UTC from Alpha (A) and Charlie (C) satellites (Table 3). On 16th March 2015, seven SWARM tracks were recorded over the Indian region with a maximum of 40 TECU around 14:00 UTC (Fig. 6). Only four SWARM tracks are recorded on 17th March 2015 with maximum TEC of 30 TECU around 14:00 UTC from Alpha (A) and Charlie (C) satellites (Table 3). A total of seven SWARM satellite tracks are observed on 19th March 2015. At 12:00 UTC, maximum TEC of 35 TECU is noticed. With five SWARM tracks recorded on 20th March 2015 maximum of 40 TECU is noticed around 13:00 UTC respectively (Fig. 6).

TEC values provided by the multiple ground and space based GNSS observations discussed earlier are compared with IGS stations' GPS VTEC data (Fig. 7). Six IGS stations that are near to the Indian region, namely LHAZ, LCK4, HYDE, IISC, SGOC and PBRI stations are selected. The diurnal VTEC profiles given by IGS stations are correlated with GAGAN VTEC data, VTEC occultation points obtained from COSMIC RO, SWARM VTEC points, and Ionosonde measurements. Figure 7 gives a multi-instrument

Table 2 Occultation VTEC points obtained from COSMIC RO mission along with GPS satellite number over Indian region for 15th to 20th March 2015 days. The proposed TEC is estimated from analytical fitting and given TEC is obtained through Abel inversion technique

Day	Satellite number	Time	Latitude, longitude	Derived COSMIC TEC	COSMIC TEC
15-03-2015	16	05:01:06	9,96	29.6	51
	19	05:03:53	30,84	31.4	41
	19	06:44:45	19,74	41.5	54
	27	06:45:32	20,83	37.1	51
	19	08:28:06	26,69	53.8	57
	24	15:44:00	36,95	9.3	13
	15	15:43:41	25,87	27.1	24
	12	17:31:47	8,76	44.6	39
16-03-2015	27	04:34:26	21,92	46.20	56
	27	06:17:08	19,83	38.7	51
	19	07:59:03	22,68	40.8	48
	04	08:04:11	37,68	41.5	41
	15	15:14:50	31,92	32.8	25
	32	16:56:59	33,100	20.3	18
17-03-2015	12	05:39:43	21,93	44.6	46
	25	07:24:19	38,71	35.8	35
	29	07:25:37	37,81	37.3	33
	9	16:25:16	15,99	21.4	28
	28	10:23:03	22,88	62	70
	17	12:10:04	34,79	47.4	44
	23	13:43:13	12,65	38.7	36
18-03-2015	7	15:48:53	36,88	7.05	7
	20	15:49:12	30,80	18.73	20
	28	09:50:44	6,91	49.1	48
	16	11:23:20	6,87	45.0	46
	32	11:34:43	11,96	44.8	39
	23	13:20:27	25,77	40.7	37
19-03-2015	04	15:16:35	26,79	38.5	29
	09	15:22:38	10,82	48.6	43
	10	15:28:08	26,81	30.9	27
	20	15:28:12	26,79	30	27
20-03-2015	12	06:00:12	38,82	36.2	34
	25	00:15:37	23,84	2.88	3
	16	00:24:41	23,80	3.33	5
	27	00:27:10	24,90	11.05	8
	20	13:12:36	14,84	38.1	54
	10	13:14:00	17,86	42.44	53

view of VTEC profiles during geomagnetic storm days. The blue line indicated VTEC patterns from IGS data. The VTEC obtained from GAGAN data is given in red line. To symbolize SWARM VTEC data black asterisk is used. COSMIC and derived COSMIC VTEC points are given as cyan and magenta asterisk points (Fig. 7). The LHAZ and LCK4 are stations located at greater than 25° N latitude. The VTEC data from GAGAN and IGS stations shown the negative

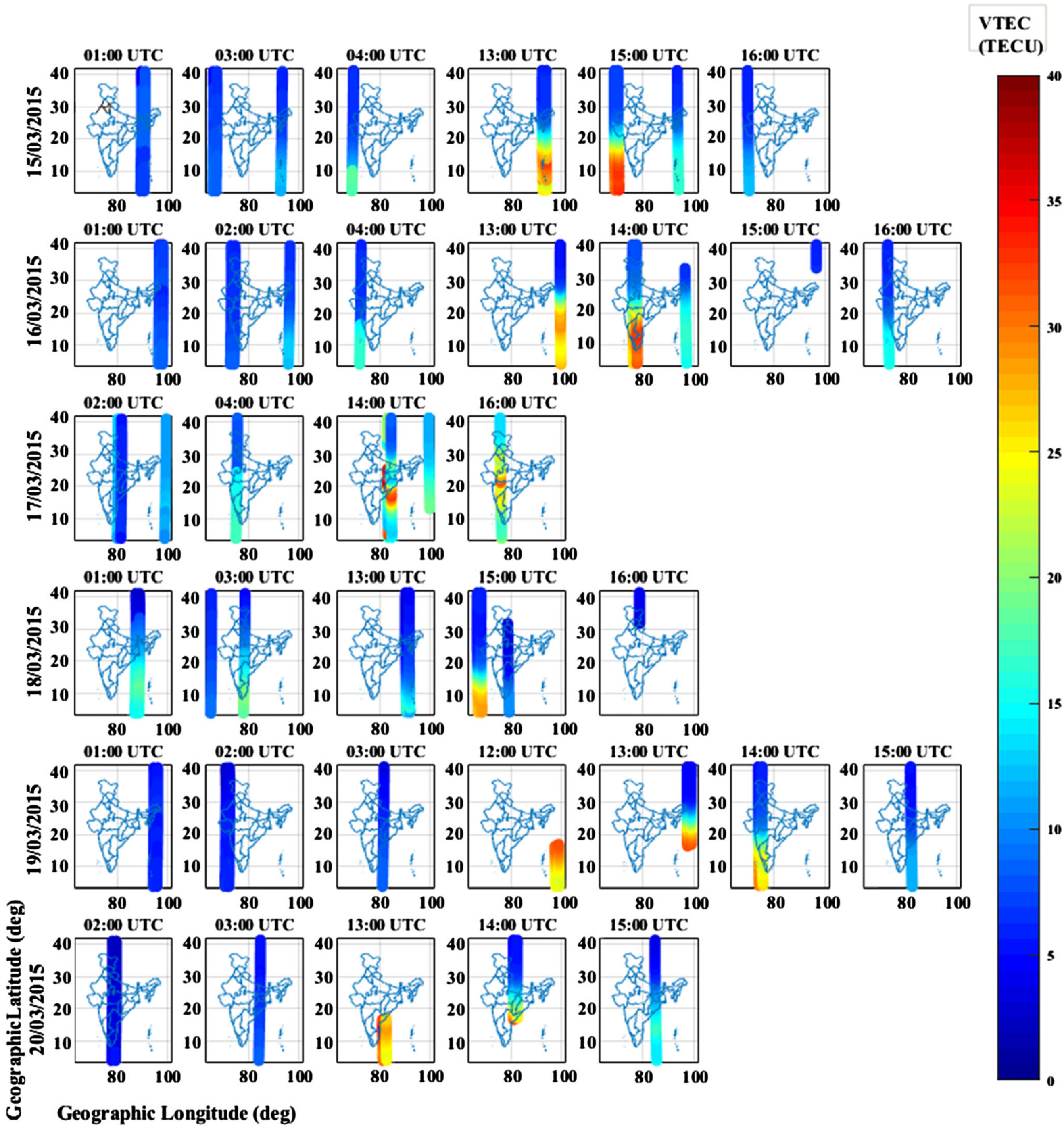

Fig. 6 VTEC time instant profiles plots obtained from SWARM satellites for 15th to 20th March 2015 days

ionospheric behaviour. On 18th March 2015, huge VTEC decrement is noticed from LHAZ, LCK4 stations.

The IGS stations HYDE and IISC are between 10° N and 20° N latitudes. On 17th March 2015, there is slight VTEC increment for HYDE and IISC stations. Even on post-storm day (18th March 2015), slight VTEC enhancements are noticed from IGS and GAGAN data over these two stations. The Ionosonde TIFR also confirms the VTEC enhancements for 17th and 18th March 2015 days. This could be due to transport of electron density from high latitudes towards equator on 17th and 18th March 2015 days due to geomagnetic storm conditions. The stations SGOC and PBRI are below 12° N latitudes also experienced increment in VTEC on post-storm day (18th March 2015). GAGAN VTEC data is not available at PBRI station. The days 19th and 20th

Table 3 Time instant traces and satellite number recorded from SWARM mission data

Day	15/03/2015	16/03/2015	17/03/2015	18/03/2015	19/03/2015	20/03/2015
Time Instants	01(A, C)	01(A, C)	02(A, B, C)	01(A, C)	01(A, C)	02(A, C)
	03(A, B, C)	02(A, B, C)	04(B)	03(B, C)	02(A, C)	03(B)
	04(B)	04(B)	14(A, B, C)	13(A, C)	03(B)	13(A, C)
	13(A, C)	13(A)	16(B)	15(A, B, C)	12(A, C)	14(A, C)
	15(A, B, C)	14(A, B, C)		16(B)	13(A, C)	15(B)
	16(B)	15(B)			14(A, C)	
		15(B)			15(B)	

March 2015 also considered as post-storm days. The stations LHAZ and LCK4 has huge increment in TEC on 20th March 2015. There is large amount of plasma electron density transport on 20th March 2015 day is evident from these two stations. The maximum VTEC of about 110 TECU is observed from LCK4 and 80 TECU is observed from LHAZ station.

Similarly, observations from space-based missions like COSMIC also correlated with VTEC values given by GAGAN and IGS stations data on 16th March 2015 (cyan and magenta asterisks) (Fig. 7). For SGOC station, COSMIC RO VTEC is correlated with GAGAN and IGS data for 16th and 19th March 2015 days, respectively with TEC values of about 30 TECU and 50 TECU at 13:00 UTC. For LCK4 station, on 15th March 2015, the COSMIC RO VTEC points observed around 12:00 UTC `are in matching with GAGAN and IGS data with about 30 TECU, respectively. The SWARM VTEC data points also captured negative storm effect prevailed on 18th March 2015 observed over LHAZ and LCK4 stations respectively at 13:00 UTC (black asterisk). For HYDE station, SWARM VTEC data points recorded around 01:00 UTC is correlated with IGS and GAGAN VTEC data on 16th March 2015. On 18th March 2015, around 13:00 UTC, SWARM data gave 28 TECU is much close to GAGAN and IGS station at HYDE station. For IISC station, SWARM data shown TEC deviation on 15th, 19th, and 20th March 2015 around 12:00 UTC (black asterisk) (Fig. 7). Rather, SWARM gave similar VTEC values as GAGAN and IGS data around 01:00 UTC for 18th and 19th March 2015 days, respectively. The SWARM VTEC data points noticed over SGOC station at 01:00 UTC is in correlation with GAGAN and IGS data, whereas deviation is observed at 12:00 UTC hours. Similarly, at PBRI station, the SWARM VTEC data points values recorded at 01:00 UTC of 18th and 19th March 2015 days are closer with IGS data. For 12:00 UTC of 16th March 2015, SWARM VTEC data has greater deviation with IGS data (Fig. 7). SWARM satellites measures TEC data up to 520 kilometres. Thus, upper part of ionosphere is not included. This could be a possible reason for the TEC deviation between COSMIC RO and SWARM with GAGAN TEC data. These deviations are high during daytime and less for dawn and dusk hours respectively (Fig. 7). The COSMIC and SWARM observations are sparse. They are observed a few over Indian region. To understand the level of differences, mean TEC deviation is estimated between GAGAN and IGS stations (Table 4).

4 Conclusions

Some of the key points drawn from ground and space based GNSS observations are given below.

- Both IGS, GAGAN VTEC data followed almost similarly for 15th to 20th March 2015 days.
- COSMIC RO profiles information also greatly understood the negative storm ionospheric conditions.
- SWARM data also captured decrement in VTEC values at LCK4 station in correlation with IGS, GAGAN VTEC data.
- Ionosonde NPL also successfully explained the VTEC variations due to geomagnetic storm conditions.
- Ionosonde TIFR is in correlation with GAGAN, IGS and COSMIC RO data points during storm (17th March 2015) and post-storm (18th March 2015) days.
- SWARM has good correlation with IGS, GAGAN data during 01:00 UTC. Still, SWARM shown deviations in TEC values during 12:00 UTC hours with IGS and GAGAN data at SGOC and PBRI station.

The multi-instrument data impact in understanding geomagnetic storm conditions based on TEC data is presented. The analysis is useful for understanding regional low-latitude ionospheric morphology during disturbed conditions. These abundant VTEC observations from ground based and space based GNSS observations are highly recommended to understand the regional ionospheric behaviour. These multiple data sources could act like reliable observations those can drive the regional and global ionospheric models. In future, these multiple data sources will be driven into the global ionospheric model through the process of data assimilation.

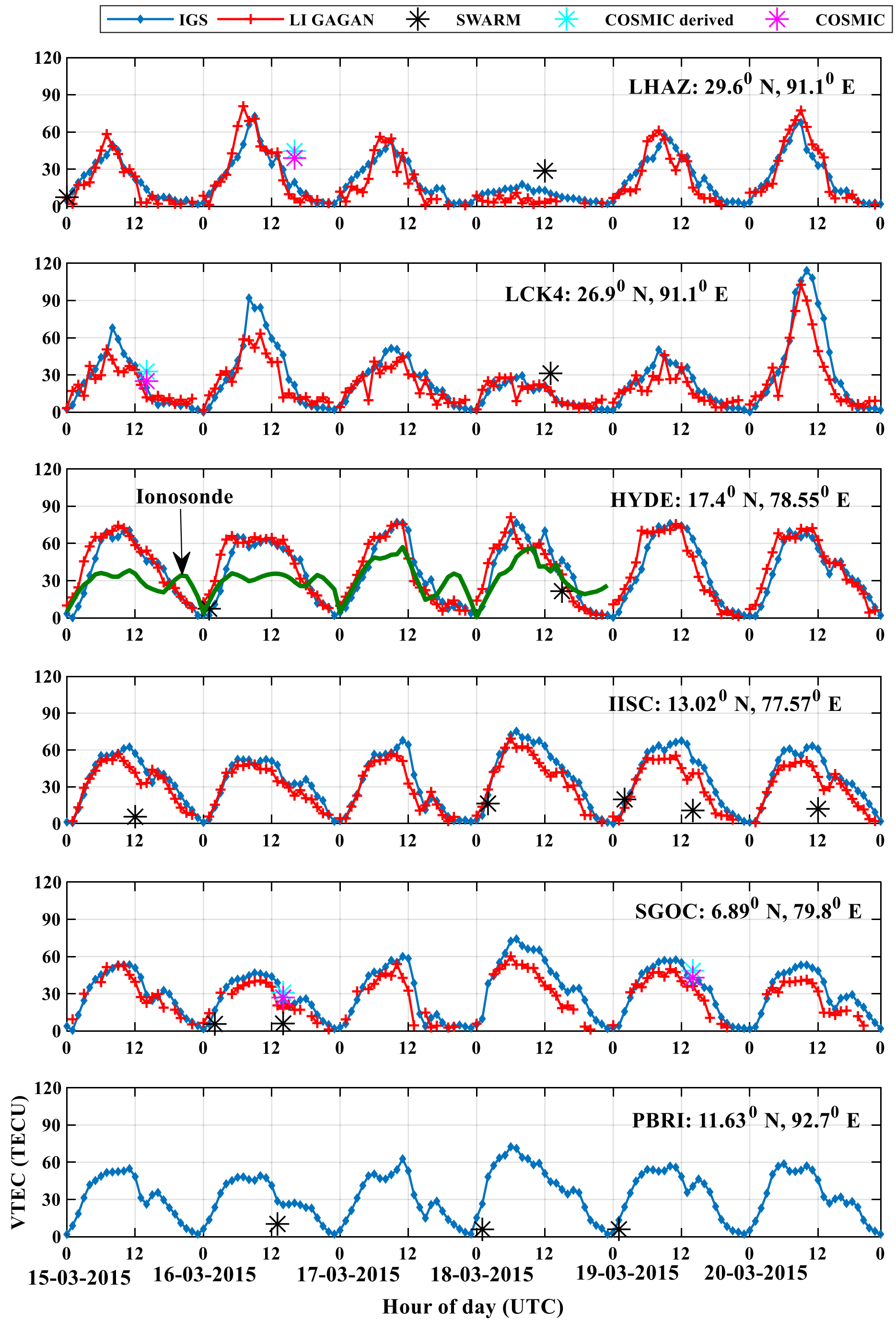

Fig. 7 Comparing multi-instrument VTEC data obtained from GAGAN, COSMIC RO, SWARM and Ionosonde instruments with truth data (IGS data) for 15th to 20th March 2015 days

Table 4 Mean TEC deviations between GAGAN TEC and IGS stations (LHAZ, LCK4, HYDE, IISC, SGOC) for 15th to 20th March 2015 days

Station ID	Geographic latitude (deg)	Geographic longitude (deg)	Mean TEC deviation (TECU)					
			Day of month					
			15-03-2015	16-03-2015	17-03-2015	18-03-2015	19-03-2015	20-03-2015
LHAZ	29.6° N	91.1° E	1.86	1.5	3.9	5.08	2.9	1.3
LCK4	26.9° N	91.1° E	2.6	5.54	4.1	1.1	3.75	7.3
HYDE	17.4° N	78.55° E	5.1	4.8	0.5	1.05	0.49	3.2
IISC	13.02° N	77.57° E	5.3	4.1	3.6	6.5	8.3	8.5
SGOC	6.89° N	79.8° E	2.6	4.1	4.3	10	4.4	7.2

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References

Astafyeva, E., Zakharenkova, I., Förster, M.: Ionospheric response to the 2015 St. Patrick's Day storm: a global multi-instrumental overview. J. Geophys. Res. Space Phys. **120**(10), 9023–9037 (2015)

Bhuyan, P.K., Borah, R.R.: TEC derived from GPS network in India and comparison with the IRI. Adv. Space Res. **39**(5), 830–840 (2007)

De Franceschi, G., Spogli, L., Alfonsi, L., Romano, V., Cesaroni, C., Hunstad, I.: The ionospheric irregularities climatology over Svalbard from solar cycle 23. Sci. Rep. **9**(1), 1–14 (2019)

Fong, C.J., Shiau, W.T., Lin, C.T., Kuo, T.C., Chu, C.H., Yang, S.K., Chi, S.: Constellation deployment for the FORMOSAT-3/COSMIC mission. IEEE Trans. Geosci. Remote Sens. **46**(11), 3367–3379 (2008a)

Fong, C.J., Yang, S.K., Chu, C.H., Huang, C.Y., Yeh, J.J., Lin, C.T., Kuo, Y.H.: FORMOSAT-3/COSMIC constellation spacecraft system performance: after one year in orbit. IEEE Trans. Geosci. Remote Sens. **46**(11), 3380–3394 (2008b)

Joshi, L.M., Sripathi, S., Singh, R.: Simulation of low-latitude ionospheric response to 2015 St. Patrick's Day super geomagnetic storm using ionosonde-derived PRE vertical drifts over Indian region. J. Geophys. Res. Space Phys. **121**(3), 2489–2502 (2016)

Li, J., Wang, W., Lu, J., Yue, J., Burns, A.G., Yuan, T., Dong, W.: A modeling study of the responses of mesosphere and lower thermosphere winds to geomagnetic storms at middle latitudes. J. Geophys. Res. Space Phys. **124**(5), 3666–3680 (2019)

Mansilla, G.A.: Ionospheric disturbances at low and mid-low latitudes of the South American sector during the March 2015 great storm. Adv. Space Res. **63**(11), 3545–3557 (2019)

Matamba, T.M., Habarulema, J.B., McKinnell, L.A.: Statistical analysis of the ionospheric response during geomagnetic storm conditions over South Africa using ionosonde and GPS data. Space Weather **13**(9), 536–547 (2015)

Mungufeni, P., Migoya-Orué, Y., Habarulema, J.B., Radicella, S.M.: Estimation of equivalent ground-based total electron content using CHAMP-based GPS observations. Adv. Space Res. **64**(1), 199–210 (2019)

Olsen, N., Friis-Christensen, E., Floberghagen, R., Alken, P., Beggan, C.D., Chulliat, A., van den IJssel, J.: The Swarm satellite constellation application and research facility (SCARF) and Swarm data products. Earth Planets Space **65**(11), 1 (2013)

Patra, A.K., Chaitanya, P.P., Dashora, N., Sivakandan, M., Taori, A.: Highly localized unique electrodynamics and plasma irregularities linked with the 17 March 2015 severe magnetic storm observed using multitechnique common-volume observations from Gadanki, India. J. Geophys. Res. Space Phys. **121**(11), 11–518 (2016)

Paul, B., De, B.K., Guha, A.: Latitudinal variation of F-region ionospheric response during three strongest geomagnetic storms of 2015. Acta Geod. Geophys. **53**(4), 579–606 (2018)

Pedatella, N.M., Lei, J., Larson, K.M., Forbes, J.M.: Observations of the ionospheric response to the 15 December 2006 geomagnetic storm: Long-duration positive storm effect. J. Geophys. Res., Space Phys. **114**(A12) (2009). https://doi.org/10.1029/2009JA014568

Ray, S., Roy, B., Paul, K.S., Goswami, S., Oikonomou, C., Haralambous, H., Chandel, B., Paul, A.: Study of the effect of 17–18 March 2015 geomagnetic storm on the Indian longitudes using GPS and C/NOFS. J. Geophys. Res. Space Phys. **122**(2), 2551–2563 (2017)

Reinisch, B.W., Galkin, I.A.: Global ionospheric radio observatory (GIRO). Earth Planets Space **63**(4), 377–381 (2011)

Ribeiro, B.A.G., Fagundes, P.R., Venkatesh, K., Tardelli, A., Pillat, V.G., Seemala, G.K.: Equatorial and low-latitude positive ionospheric phases due to moderate geomagnetic storm during high solar activity in January 2013. Adv. Space Res. **64**(4), 995–1010 (2019)

Sarma, A.D., Ratnam, D.V., Reddy, D.K.: Modelling of low-latitude ionosphere using modified planar fit method for GAGAN. IET Radar Sonar Navig. **3**(6), 609–619 (2009)

Şentürk, E.: Investigation of global ionospheric response of the severe geomagnetic storm on June 22–23, 2015 by GNSS-based TEC observations. Astrophys. Space Sci. **365**(7), 1–15 (2020)

Shukla, A.K., Das, S., Nagori, N., Sivaraman, M.R., Bandyopadhyay, K.: Two-shell ionospheric model for Indian region: a novel approach. IEEE Trans. Geosci. Remote Sens. **47**(8), 2407–2412 (2009)

Venkatesh, K., Tulasi Ram, S., Fagundes, P.R., Seemala, G.K., Batista, I.S.: Electrodynamic disturbances in the Brazilian equatorial and low-latitude ionosphere on St. Patrick's Day storm of 17 March 2015. J. Geophys. Res. Space Phys. **122**(4), 4553–4570 (2017)

Waheed, M.A., Khan, P.A., Gwal, A.K.: Distribution of intense, moderate and weak geomagnetic storms over the solar cycle. Indian J. Phys. **93**(9), 1103–1112 (2019)

Yadav, S., Sunda, S., Sridharan, R.: The impact of the 17 March 2015 St. Patrick's Day storm on the evolutionary pattern of equatorial ionization anomaly over the Indian longitudes using high-resolution spatiotemporal TEC maps: new insights. Space Weather **14**(10), 786–801 (2016)

Zhang, W., Zhao, X., Jin, S., Li, J.: Ionospheric disturbances following the March 2015 geomagnetic storm from GPS observations in China. Geod. Geodyn. **9**(4), 288–295 (2018)