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Based on kriging, ionospheric maps for India's TEC, ROTI, and amplitude scintillation index (S)

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ABSTRACT

The receivers are part of the GPS-aided geo-stationary earth orbit augmented navigation program over the Indian region. The study covers a wide area, spanning from 65°E to 100°E in geographic longitude and from 5°N to 40°N in geographic latitude, with a 2° × 2° grid separation. To generate the one-minute spatial TEC maps, the researchers use the Kriging method. Additionally, the study generates ROTI and S4 maps at 5-minute intervals. The researchers evaluate the performance of the regional TEC maps during a severe geomagnetic storm condition. During the St. Patrick's storm from 15 to 20 March 2015, the researchers analyze the patterns of equatorial ionization anomaly (EIA) TEC structures using the generated TEC maps. The proposed TEC maps show the northern crest of EIA features with their latitudinal extent and TEC strength.The Kriging method used in this study identifies suppressed and downshifted EIA features on 18 March 2015. Furthermore, the researchers analyze the movement of plasma bubbles over Indian latitudes during the transition period of a geomagnetic storm on 17 March 2015.In summary, this study focuses on creating regional maps of ionospheric parameters over the Indian region using GPS data and the Kriging method. The researchers investigate ionospheric structures and their behavior during severe geomagnetic storm conditions.

Introduction

The relationship between TEC and the ionospheric delay between the GNSS L1 and L2 signals is direct [1-2]. The TEC map is a useful instrument for observing the ionosphere. Grid-based ionospheric TEC maps would be beneficial for satellite-based augmented systems (SBAS), such as the wide area augmentation system (WAAS) for the United

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States of America, the GPS-aided geostationary earth orbit (GEO) augmented navigation (GAGAN) for India, the MTSAT (multi-functional transport satellite) satellite-based Augmentation System for Japan, and the European Geostationary Navigation Overlay Service (EGNOS) for Europe [3]. Investigations into ionospheric gradients caused by geomagnetic storm impacts, the Equatorial Ionisation Anomaly (EIA), plasma bubbles, travelling ionospheric disturbances, atmospheric gravity waves from the lower atmosphere, etc. can be helped by TEC maps [4-5], among other things [6].To study the ionospheric irregularities after sunset, the researchers generate rate of TEC index (ROTI) maps using datasets from the International GNSS Service (IGS) for the period between 15 and 20 of the study. They utilize the Global Ionospheric Maps (GIMs) from the Centre for Orbit Determination in Europe, which employ a higher-order spherical harmonic function model to create a global ionospheric TEC map. The resolution of the TEC map is $2.5° \times 5°$ grid, providing a detailed representation of the ionospheric Total Electron Content (TEC) distribution on a global scale. Data sets to track regional ionospheric phenomena across the Indian region are available from Indian SBAS, GAGAN's 26 dual frequency GPS TEC stations [7]. India is under the low latitude zone geographically, hence a suitable geostatistical interpolation method is required to estimate the TEC values of the ionospheric grid. In order to study the dynamic behaviour of ionospheric space weather outcomes, [8] created TEC maps utilising GAGAN data by binning all of the ionospheric pierce sites for 5 min of time. The evolution (from sunrise to post noon) and degeneration (from post noon to mid-night) of the EIA during the stormy conditions on St. Patrick's Day in 2015 were clearly explained [9]. [10] employed the kriging method to generate Total Electron Content (TEC) maps with a 10-minute time rate. In a separate study focusing on the Southern European region, ionospheric TEC maps were also created using the kriging technique with higher temporal resolution (1-minute) and finer spatial resolution ($0.5° \times 0.5°$) [11]. Most interpolation algorithms, including kriging, utilize a linear unbiased predictor to map data points. The success of the kriging method lies in minimizing error variances under the assumption of multivariate normality within the estimated region. Both Ordinary Kriging (OK) and Universal Kriging (UK) are minimum error variance estimators but differ in their approach to the priori trend model. The OK method uses constant trend values, while the UK method selects a polynomial trend from different

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data points in the two-dimensional space. Chinese, Japanese, and Turkish regions are strongly represented on regional TEC maps [12].For GPS and SBAS applications over the Indian subcontinent, several researchers have developed ionospheric TEC grid estimate using a variety of approaches, including kriging, planar-fit, inverse distance weighted, and lowest mean square error [13]. IPP altitude of 350 km is valid with higher elevation angle (>40°) across the Indian subcontinent. Kriging is a reliable method for modelling ionospheric time delays among all of these models. In their study, [14] successfully implemented the Ordinary Kriging (OK) method to enhance the accuracy and smoothing of Global Ionospheric Maps (GIM) Total Electron Content (TEC) maps by approximately 2.5%. They validated their results by comparing them with data from International GNSS Service (IGS) stations and spatial maps of ROTI and S4. In Section 4 of their research, the authors draw conclusions, emphasizing the benefits and advantages of the generated Regional Ionospheric Maps (RIMs).

Methodology

The Indian Space Research Organization (ISRO) and the Airports Authority of India collaborated on the GAGAN project to develop the Indian Satellite-Based Augmentation System (SBAS). The primary objective of this project was to enhance civil aviation applications. GAGAN utilizes 26 GPS dual-frequency receivers, specifically the Novatel GSV 4004 receivers, to offer improved accuracy, integrity, and availability of GPS signals over the Indian region. These receivers record various parameters such as GPS week, GPS time, PRN number (Pseudorandom Noise code), elevation angle, azimuth angle, slant Total Electron Content (TEC), and S4 measurements (which quantifies the amplitude scintillation of GPS signals).

S_4 data analysis:

GPS signals are subjected to abrupt, rapid fluctuations due to ionospheric scintillations. The scale of amplitude scintillation (weak (0.2 S4 0.4), moderate, and strong) can be determined by the amplitude scintillation index (S4) calculated from signal intensity.Strong (S4 > 0.6), (0.4 S4 0.6) activity. Other examples of estimating S4 index from received signal strength can be found [25].Various methods can be used to calculate optimal weight estimates (Wi) while satisfying the requirement defined in

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equation (9). The value of N, representing the number of spatial locations, can be selected based on the desired spatial resolution. For each of the N spatial locations, the kriging method is employed to estimate the Total Electron Content (TEC) value. This estimation involves using different weight factors determined by the semivariogram function, which is computed based on all the available Ionospheric Pierce Points (IPPs) for that specific hour. The semivariogram function proves useful in capturing the spatial correlations observed in the data for the chosen location.A similar process is followed for the generation of Rate of TEC Index (ROTI) and amplitude scintillation index (S4) maps with a temporal resolution of 5 minutes, ensuring appropriate spatial coverage is maintained for these maps as well.

Results and discussions:

To study the response of the kriging TEC method during the geomagnetic storm on St. Patrick's day in March 2015, the researchers considered a total of six days of GPS TEC data over the Indian region, covering the period from 15 to 20 March 2015. The data was collected from the GPS TEC network reference stations, indicated by red triangles Using this collected data, ionospheric TEC, Rate of TEC Index (ROTI), and amplitude scintillation index (S4) maps were generated for the entire Indian region. The latitudinal range of these maps extends from 5°N to 40°N, while the longitudinal range spans from 65°E to 100°E, with a grid separation of 2° × 2°.To ensure a detailed representation, the researchers chose a temporal resolution of 1 minute for TEC maps and 5 minutes for ROTI and S4 maps. This allowed them to capture variations in ionospheric conditions with higher temporal precision.On 17 March 2015, there was a significant geomagnetic storm with various interesting observations:At 05:00 UTC, the Interplanetary Magnetic Field (IMF) Bz component pointed north, reaching 20.1 nT.One hour later, at 06:00 UTC, the IMF Bz component changed direction and pointed south with a magnitude of -5.9 nT. Simultaneously, a solar wind (SW) plasma with a speed of 500 km/s was observed (Fig. 2).The Kp index, which measures global geomagnetic activity, reached a value of 5.7.The Dst index, which indicates the strength of the geomagnetic storm, exhibited a positive peak with 56 nT at 05:00 UTC.The daily averaged F10.7, a measure of solar radio flux, was recorded as 113.2 solar flux units (sfu).The sudden storm commencement (SSC) occurred around 05:00 UTC, marking the initial phase of the

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storm.At 08:00 UTC, the IMF Bz turned further south, reaching -16.3 nT.At 11:00 UTC, the plasma was moving with a speed of 568 km/s, and the Kp index reached its maximum value of 7.7.The Dst index showed a more negative value of -63 nT, indicating the main phase of the geomagnetic storm conditions.The IMF Bz remained south for the rest of the day, from noon until midnight on 17 March 2015.These observations collectively indicate the occurrence and intensity of the geomagnetic storm on that particular day.

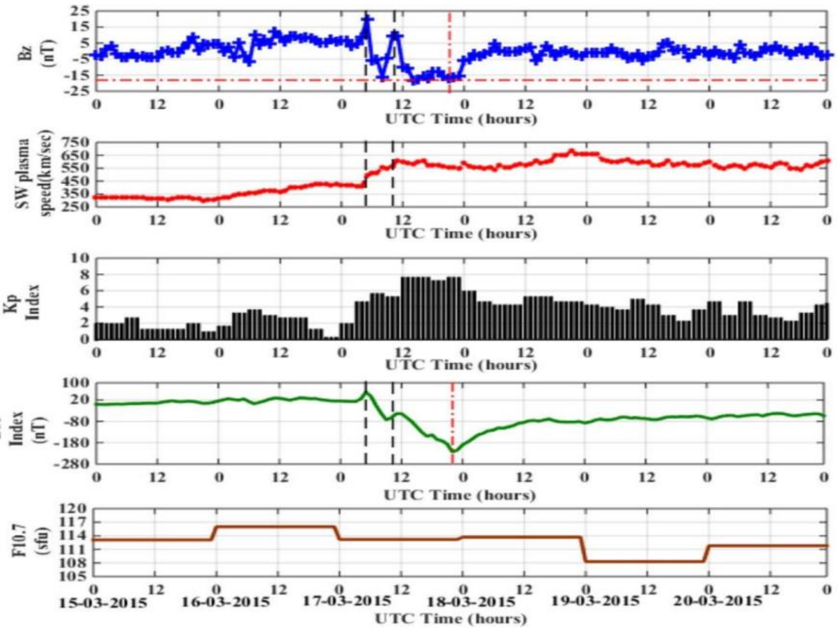

Fig. 1 Hourly geomagnetic and solar indices for the period of March 15 to 20

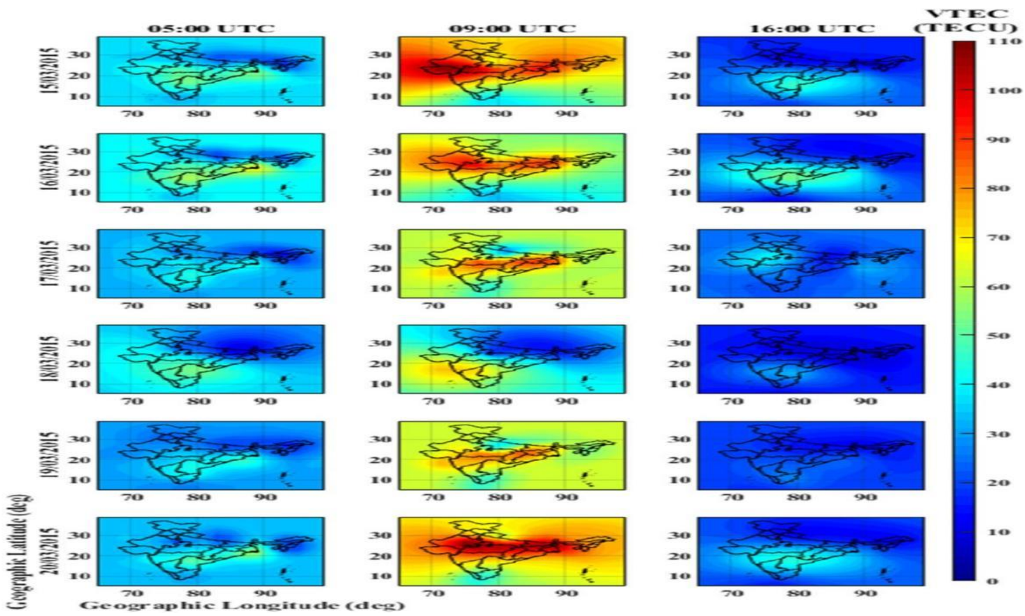

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Fig. 2 Spatial TEC maps produced for days 15-20 of March 2015 at 05:00 UTC, 09:00 UTC, and 16:00 UTC using the proposed kriging method.

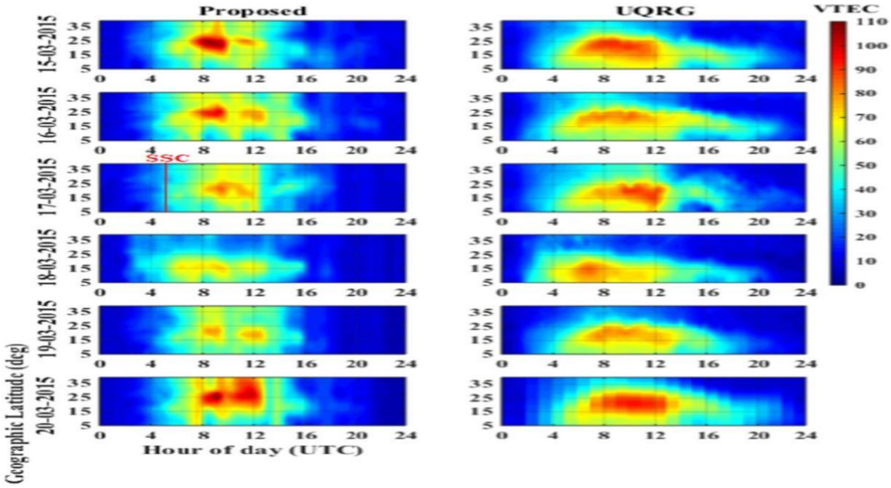

Fig. 3 Temporal EIA structures for days 15-20 of March 2015 provided by proposed kriging method and UQRG TEC maps at 75°E longitude

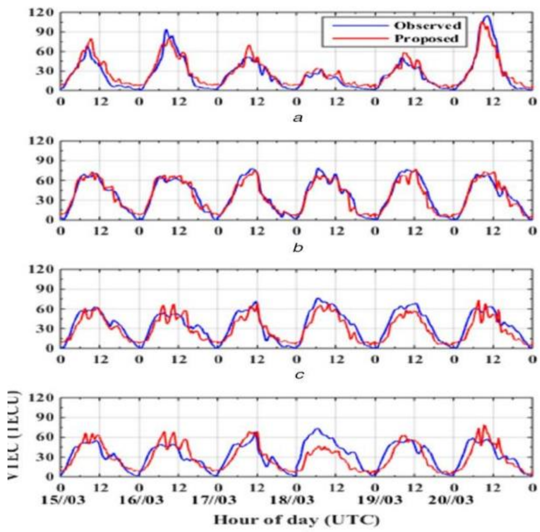

Figure 6: Four IGS stations (LCK4, HYDE, IISC, and PBRI) were used to validate the proposed kriging method TEC for the days of March 15 to 20 in 2015.

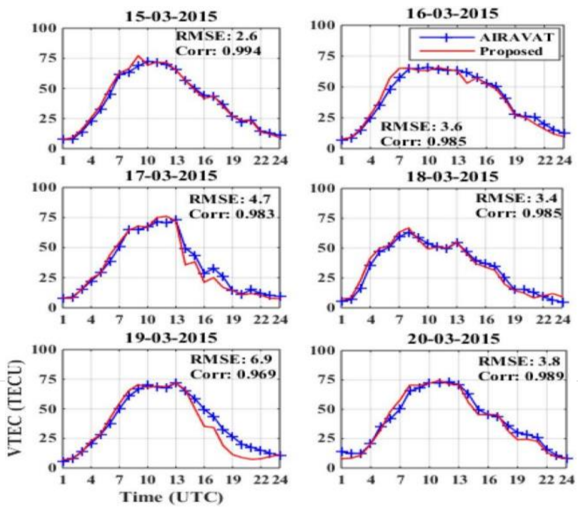

Fig. 7. Validation of suggested kriging TEC with AIRAVAT TEC for days 15-20 of arch 2015 at 17.5°N latitude and 80°E longitude

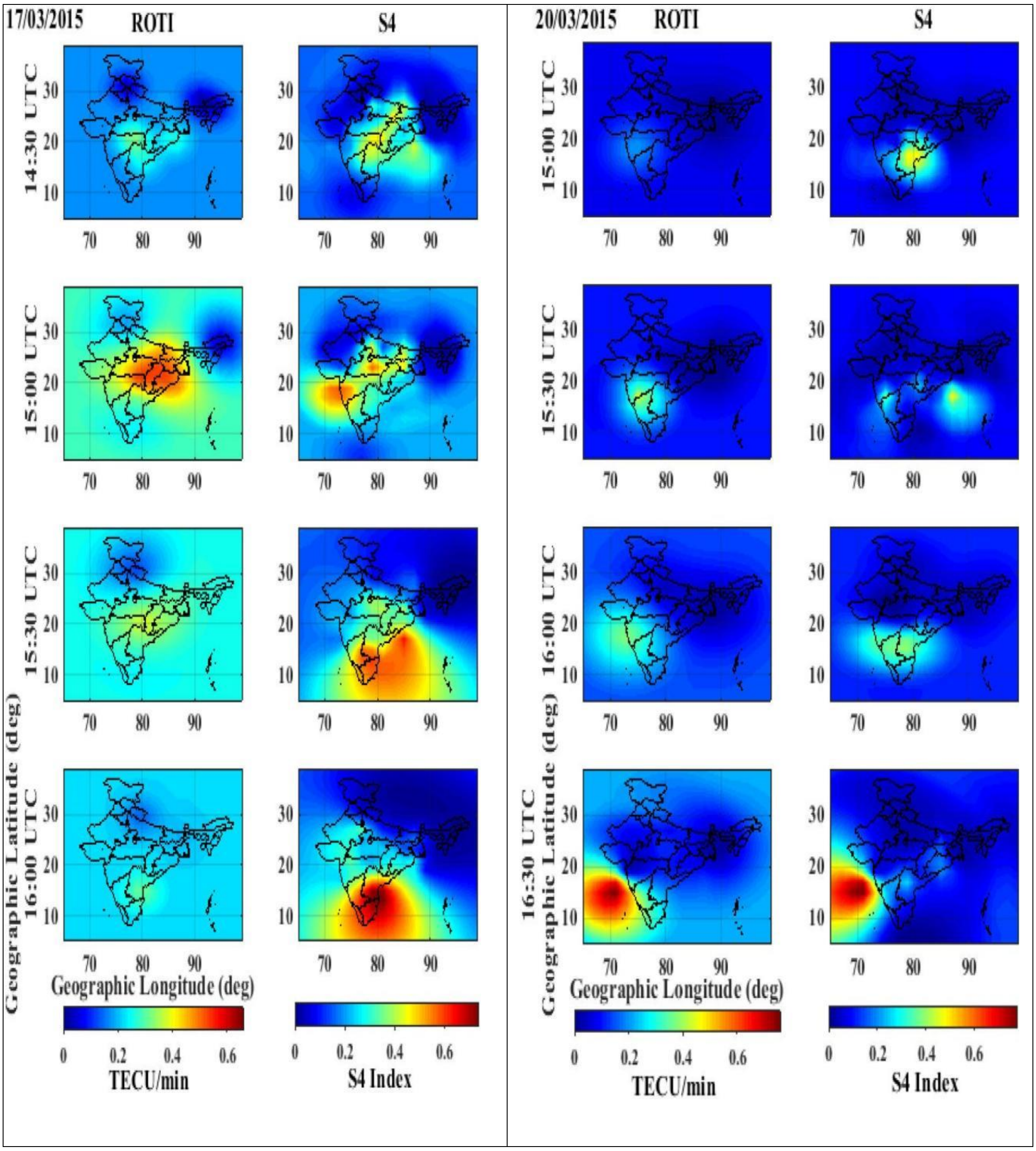

Fig. 9 Geographical ROTI and S4 maps for 14:30–16:00 UTC on March 17, 2015

Fig. 10 Spatial ROTI and S4 maps for 15:00–16:00 UTC on March 20, 2015.

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Conclusions

The following is a summary of the work's main results.

(i) The kriging method successfully represents both spatial and temporal Equatorial Ionization Anomaly (EIA) Total Electron Content (TEC) structures for the days 15–20 March 2015. The TEC enhancement observed around 10:00 UTC on 17 March 2015 can be attributed to post-pre-noon Equatorial Plasma Enhancement (PPEF).

(ii) The kriging method estimates a latitudinal shift of about 6° towards the geomagnetic equator in the EIA crest on 18 March 2015 compared to 17 March 2015.

(iii) The discussed geomagnetic storm exhibits a long-duration recovery phase that continues for the days 19 and 20 March 2015. The kriging method captures TEC enhancements on 20 March 2015.

(iv) Validation of the kriging method using data from International GNSS Service (IGS) stations demonstrates the significance and accuracy of the proposed TEC maps. Additionally, the kriging method TEC is validated with AIRAVAT TEC to further assess the model's accuracy.

(v) The generated Rate of TEC Index (ROTI) and amplitude scintillation index (S4) maps visualize the occurrence of plasma bubbles on 17 and 20 March 2015 during post-sunset hours over the Indian region.

(vi) On 17 March 2015, the ROTI and S4 maps generated using the kriging method show an increase in the latitudinal extension of plasma bubbles above 10° of the geomagnetic equator over the Indian region.

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