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Review on Ionospheric response to Total Solar Eclipse

Harkaran Singh

Department of Electronics & Communication Engineering, D.A.V. Institute of Engineering & Technology, Jalandhar, Punjab (India) & Internship Project at Marine & Atmospheric Sciences Department (MASD), Indian Institute Of Remote Sensing (IIRS), ISRO, Dehradun (India)

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ABSTRACT

The ionospheric dynamics is highly influenced by the solar radiation. During a solar eclipse, the moon occults the solar radiation from reaching the ionosphere, which may drastically affect the variability of the ionosphere. The variability of total electron content (TEC) observed by dual frequency Global Positioning System (GPS) receivers has made it possible to study effects of solar eclipse on the ionosphere. Ionospheric behavior during eclipse was analyzed by using TEC data archived at International GPS Satellite (IGS) stations. TEC variations of few consecutive days are used to study instantaneous changes of TEC during the eclipse event. The results generally show TEC decrease. TEC enhancement and depletion were observed during the totality of the eclipse. Some of the total solar eclipse events were taken into account, i.e.;total solar eclipse of November 3 2013 in Africa and 22 July 2009 in different Indian regions; the study found out that the ionospheric TEC was modified by wave-like energy and momentum transport and obscuration of the solar disc due to the total solar eclipse.The variability of ionospheric response to the total solar eclipse has been studied analyzing the GPS data recorded at the four Indian low-latitude stationsVaranasi (100 % obscuration), Kanpur (95 % obscuration), Hyderabad (84 % obscuration) and Bangalore (72 % obscuration). The retrieved ionospheric vertical total electron content (VTEC) shows a significant reduction (reflected by allPRNs (satellites) at all stations) with a maximum of 48 % at Varanasi (PRN 14), which decreases to 30 % at Bangalore (PRN 14). The reduction in VTEC compared to the quiet mean VTEC depends on latitude as well as longitude, which also depends on the location of the satellite with respect to the solar eclipse path. The amount of reduction in VTEC decreases as the present obscuration decreases, which is directly related to the electron production by the photoionization process. The analysis of electron density height profile derived from the COSMIC (Constellation Observing System for Meteorology, Ionosphere & Climate) satellite over the Indian region shows significant reduction from 100 km altitude up to 800 km altitude with a maximum of 48 % at 360 km altitude. The oscillatory nature in total electron content data at all stations is observed with different wave periods which are attributed to gravity wave effects generated in the lower atmosphere during the total solar eclipse.

1. Introduction

The Moon comes between the Earth and the Sun regularly every 223 lunar revolutions, which results in solar eclipse and obscures the solar flux reaching the Earth’s surface. The occultation of the solar disk arises due to the fact that the apparent diameters of the Sun and the Moon as viewed from the surface of the Earth are equal. The partial/total termination of the solar flux affects chemical reactions, production and transport of ionization in the ionosphere (Sharma et al., 2010;Galav et al., 2010; Kumar and Singh, 2012), boundary layerphenomena (Jayakrishnan et al., 2013), ozone production,loss and columnar concentration (Chakrabarty et al., 1997;Kumar and Rengaiyan, 2011) and many other related phenomena including the generation and propagation of gravity waves (Farges et al., 2003). Since an eclipse generally occursat different times of the day in different seasons at different places (varied in latitudes and longitudes) on the globe, it provides unique opportunity to test the proposed hypothesis and to verify the earlier results.

During solar eclipse, the moon passes between the sun and the earth, thereby occulting solar radiation from reaching the earth when the three celestial bodies are aligned in a syzygy. This may drastically affect the dynamics of the ionosphere. Observation of solar eclipse events has been applied in the field of ophthalmology and optometry to study the risk of solar retinopathy. Psychiatrists have investigated the impact of total solar eclipses on the incidences of suicide. In addition, sociologists investigate the impacts of media hypercoverage, greater social cohesion, tourism, and public disruptions related to the eclipse events. Scientists have investigated the response of the earth’s environment to the abrupt and brief disturbance of solar radiation during the eclipse events [1]. These environmental effects cover photochemistry, meteorology, gravity waves, boundary layer physics, and the ionosphere [1–4]. The ionospheric response to solar eclipse events has mainly been investigated using techniques such as rockets, incoherent radar systems, ionosondes, satellite measurements, GPS, and theoretical modeling [5].

2. Observations and literature review

- The ionization of gas molecules and/or atoms in the ionosphere by the ultraviolet radiation and X-rays from the sun depends on solar intensity, solar cycle, and seasons [6]. These external factors affect ionization in the ionosphere simultaneously with the internal processes such as chemical reactions amongst the gas molecules and atoms, electrodynamic drifts, and neutral wind effects among others [6]. Since solar eclipse progressively reduces the solar spectral flux, the layers of the ionosphere are equally disturbed. Furthermore, at the lower edges of the ionosphere, recombination coefficient is higher than the recombination rate at higher altitudes. This leads to the lowering of ionization at the lower edges of the ionosphere. Again, the loss rate of ionization at different layers of the ionosphere depends on the chemical composition of each layer [6].

- Reference [7] showed that, during an eclipse event, the electron density profile experiences a trough in the eclipse zone. The trough is generated by an increase in the charge order processes, the two charge processes in which ions are driven through neutral atmosphere produce. Thus, the above processes are known to cause a faster recovery of foF1 (critical frequency of F1 layer) and delayed recovery of foF2 (critical frequency of F2 layer) after the end of the eclipse. Furthermore, during an eclipse event, the stratification of the F layer into F1 and F2 sub layers becomes distinct. According to [8], this is due to a large upward drift of the F layer to higher altitudes during the solar eclipse. This drift may also slow down the diffusion and hence reduce the ionization of the F2 region and increase the accumulation of ionization in the F1 region, making the stratification more prominent. Besides, the factor is given by where is the linear loss coefficient, is the recombination coefficient, and is the rate of production of ions and electrons. The factor quantifies the stratification of the F1 and F2 regions [9]. During solar eclipse, decreases as the solar disc is obscured and also decreases as the temperature decreases due to the eclipse shadow region. Hence, the value of becomes larger around the solar eclipse time, which is attributed to increased stratification of the F layer [10].

- For example, [11] used GPS receivers located at Wuchang and Guangzhou in China to determine the effect of October 24, 1995, solar eclipse on the ionospheric TEC. The study observed a negative deviation in TEC during the eclipse, which is proportional to the degree of obscuration by the lunar disc. Furthermore, the observed maximum negative deviation from the reference levels recorded during the pre- and posteclipse days ranged from 20% to 50%. The absolute maximum negative deviation was found to be $1*10^{17}$electrons per square metre at Wuchang, while it was twice at Guangzhou. The maximum deviation was more at Guangzhou due to the fact that it was closer to the center of totality than Wuchang. Therefore, a total eclipse negatively affects the TEC in the ionosphere. In another study, [12] studied the ionospheric response to the total solar eclipse of July 22, 2009, by analyzing the data from four low-latitude GPS stations in India. The ionospheric vertical TEC (VTEC) showed a significant reduction at all the four stations. The authors further showed that the amount of reduction in VTEC decreased as the obscuration decreased. This is a clear manifestation of the direct dependence of electron production on photoionization process. The solar eclipse of July 22, 2009, was again studied by [13]. The authors investigated the behaviour of the ionosphere by measuring the variation in TEC for three (pre-, post-, and eclipse) consecutive days. This eclipse event was complicated by the simultaneous occurrence of a geomagnetic storm which lasted for 10 hours. The results of the GPS data collected from Chongqing and Wuhan and IGS stations at Wuhan and Shao indicated that the instantaneous TEC values declined by about 1–4 TECU at the measurement points depending on the location and time during which the measurement was taken.

- Furthermore, [5] studied the effect of the solar eclipse of January 15, 2010, and observed that the decrease in the electron density during the eclipse event occurred throughout the E and F1 layers simultaneously. In the F2 layer, the decrease in electron density began at the lower end and extended progressively towards the peak of the F2 region. The experimental measurements and theoretical simulation of results indicate that the eclipse events have more pronounced effects during the midday than in the morning and afternoon hours [5]. They attributed these effects to the fact that a decrease in solar radiation due to the eclipse event resulted in a decrease in the electron production rate and, consequently, the electron concentration. However, the change in the electron concentration in the F2 layer was affected by photochemical processes as well as electrodynamical and neutral forcing processes.

- The solar eclipse of November 3, 2013, was widely referred to as a hybrid solar eclipse due to the occurrence of both annular and total solar eclipse phenomena. The path of lunar umbral shadow moved from the northern Atlantic Ocean through Gabon, Republic of Congo, Democratic Republic of Congo, Uganda, north western Kenya, and Ethiopia and ended in Somalia.
- The totality of this eclipse lasted for a maximum period of about 1 minute and 39 seconds. In Uganda, the lunar disc was observed to touch the solar disc at around 13:06 UT (16:06 LT), culminating into a total eclipse at 14:22 UT (17:22 LT). The total eclipse had a magnitude of 1.03. The duration of the total solar eclipse at Owiny (2.56°N, 31.42°E) was 22.3 seconds.

3. Data Sources and Processing

The GPS_TEC algorithm developed by [15] was used to derive TEC values at the equatorial stations with an elevation mask of 20°. The GPS_TEC algorithm uses the phase and code values associated with the L1 and L2 GPS frequencies to remove the tropospheric water vapour and clock error effects to calculate relative slant TEC. Absolute TEC values are obtained by taking into account the differential satellite biases and the receiver biases [16]. The equivalent VTEC at altitude of 350 km was calculated by using the thin shell model and averaging the TEC for individual visible satellites. The VTEC derived from the STEC was used to derive the disturbance (VTEC perturbation) in the ionospheric electron density. The data for each GPS station for 2-3 days before and after the eclipse was used as background (quiet day) data to calculate the background mean VTEC () of the data points for every 30 seconds. The mean VTEC was then subtracted from the disturbed day VTEC to obtain the perturbation (VTEC), similar to [12]: Wavelet analysis was done using the TEC perturbation. Wavelet analysis provides information on the temporal characteristics of the signal. Spectral analysis performed in this study implemented wavelet transform presented in [17]. The Morlet wavelet was chosen as the mother wavelet because it consists of a plane wave modulated by a Gaussian.

4. Results and Conclusions

- This section presents results based on TEC measurements from four equatorial GPS stations. The results entail variability of VTEC, VTEC perturbation (TEC), and TEC along signal path (STEC). The results also include wavelet analysis for determining the presence of wave-like structures and traveling ionospheric disturbances (TIDs). The reduction in VTEC depends on latitude as well as longitude, which also depends on the location of the satellite with respect to the solar eclipse path [12]. The amount of reduction in VTEC is proportional to the obscuration of the lunar disc, which is directly related to the electron production by the photoionization process [12].
- Several studies of TEC variability [18, 19] have shown higher daytime TEC values during the equinoctial months, moderate values during the summer, and the least values in the winter months. The particular eclipse of November 03, 2013, lies within winter season. During sunrise, the magnetic flux tubes get filled up because of their small volume resulting in sudden increase in ionization due to increasing thermospheric temperatures [18, 19]. The gradual increase in TEC to a maximum value at peak hours of the day at these equatorial latitude stations could be attributed to the solar extreme ultraviolet (EUV) ionization coupled with upward vertical E× B drift. The observed nighttime TEC enhancements may be attributed to tidal winds which blow the ionization across geomagnetic fields. Meanwhile, the nighttime decrease could be due to the small size of the magnetic flux tubes that makes the electron content in these tubes collapse rapidly after sunset in response to the low temperatures in the thermosphere at night, leading to low TEC values [18, 19].
- The study observed a negative deviation in TEC (≥20 TECU) during the eclipse proportional to the degree of obscuration by the lunar disc. Furthermore, the observed maximum negative deviation recorded during the pre- and posteclipse days ranges from 5 to 15 TECU. Measurements from the four stations showed reduction in the amount of incoming solar radiation after the eclipse onset. The size of the reduction is closely related to the eclipse magnitude. Changes induced in the spectral solar irradiance during the eclipse resulted in decreased photoionization activity in the ionosphere. The ionospheric response to solar eclipse varies with latitude variations. The different behavior may be due to the fact that electron density is more controlled by the transport process than by the production rate [12]. However, TEC decrease during solar eclipse is dependent on latitude and local time. The latitudinal variation may arise due to the latitudinal variation of magnetic inclination angle, which influences plasma diffusion. The dependence on local time is attributed to the rate of electron loss, which is related to the local-time dependent background density [12]. However, processes such as equatorial electrojet (EEJ) and the equatorial ionospheric anomaly (EIA) may complicate detection of the impact of solar eclipse in the equatorial region. The oscillatory nature of VTEC perturbation at all stations may be attributed to gravity wave effects generated in the lower atmosphere during the total solar eclipse [12].
- 2 Total electron content (TEC) measurements: The ionospheric variability can be studied using the temporal evolution of total electron content, which is derived from either carrier phase measurements or pseudo-range measurements. The GPS receiver Trimble 5700 and Zephyr Geodetic antenna (Rover configuration) are used for the data collection. The system can simultaneously record dual frequency signals from 12 satellites. Using the software, the data recorded in RINEX (Receiver Independent Exchange) format are converted into the slant total electron content (STEC) along the path of the signal propagation from the satellite to the receiver, which is converted again into the vertical total electron content (VTEC) using the simple procedure discussed elsewhere (Mannucci et al., 1993; Langleyet al., 2002; Ramarao et al., 2006; Kumar and Singh, 2011).Path of the maximum obscuration and the path of the satellite designated by PRN 14 and 31, are shown in Fig. 1. PRN 14 and 31 specify the chosen GPS satellites for which data are available at all four stations. The Varanasi station lies inside the total obscurity zone, whereas Kanpur lies near but outside the total obscurity zone. The Bangalore station is at the largest distance from the obscurity zone but lies closer to the Equator. Both Bangalore and Hyderabad are inside the equatorial anomaly region, whereas Varanasi lies at the edge of EIA zone. The eclipse time and percent obscuration at different stations are given in Table 1.The eclipse occurred during the local morning hours and continued for about 2 h. On the

day of eclipse, sky was cloud-free and clear with no rainfall. However, a geomagnetic storm is reported on 22 July 2009. The magnetometer data from Indian stations reveal the storm-related changes in the ground magnetic field after 04:00 UT (09:30 LT). As the solar eclipse occurred before the magnetic storm, we safely assume that the results presented in this paper are unaffected by the magnetic storm before 09:30 LT, whereas after the 09:30 LT data may be affected by the magnetic storm. The data from Kanpur are obtained under the exchange program, whereas the data for Hyderabad and Bangalore stations in compact RINEX FORMAT are downloaded from the International GNSS Service (IGS) website. We have also studied the percentage changes in VTEC (% DVTEC), which is obtained using the relation

$$\mathrm{DVTEC}=((\text{Eclipse day VTEC}-\text{Background VTEC})/\text{Background VTEC})\times 100$$

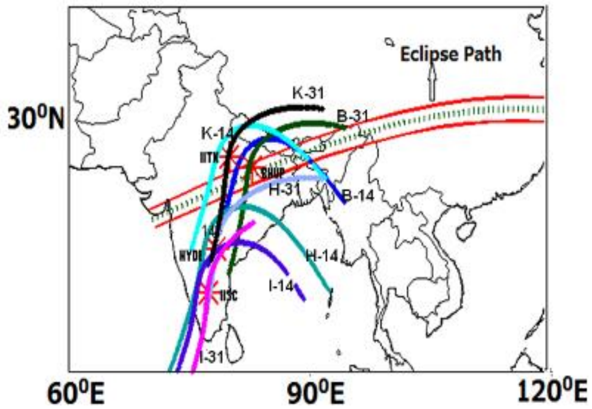


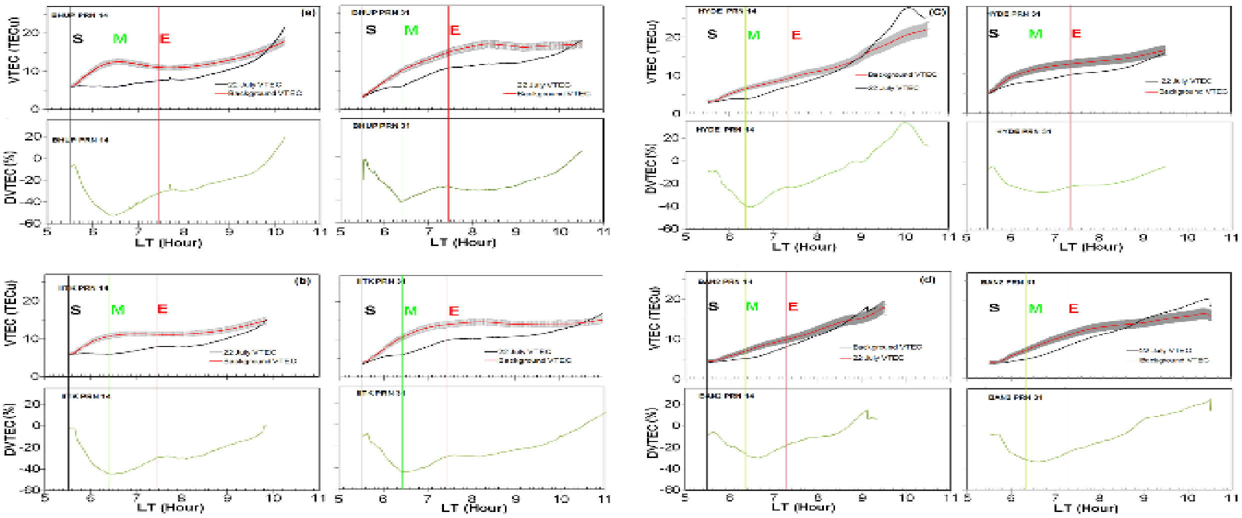
Fig. 1.Map showing the path of maximum obscuration for totalsolar eclipse of 22 July 2009, location of the stations in the Indian region, paths of the satellites designated by PRN 14 and 31. “K” stands for Kanpur,“B” for Varanasi, “H” for Hyderabad and “I” forIISc Bangalore.

- The background VTEC for the reference is obtained by averaging the VTEC values of 17, 18, 19, 20, 27, 28, and 31 July. These days are considered based on the consideration of a few days before and after the eclipse during the quiet period. From 22 July to 26 July, there was a magnetic storm. In order to substantiate and confirm the TEC data from GPS measurements, the electron density profile measured from COSMIC mission during the eclipse period and the average electron density profile obtained from the available data before and after the eclipse day are analyzed. The COSMIC mission data are stored at the University Corporation for Atmospheric Research in Boulder, USA and data downloaded from online sources.

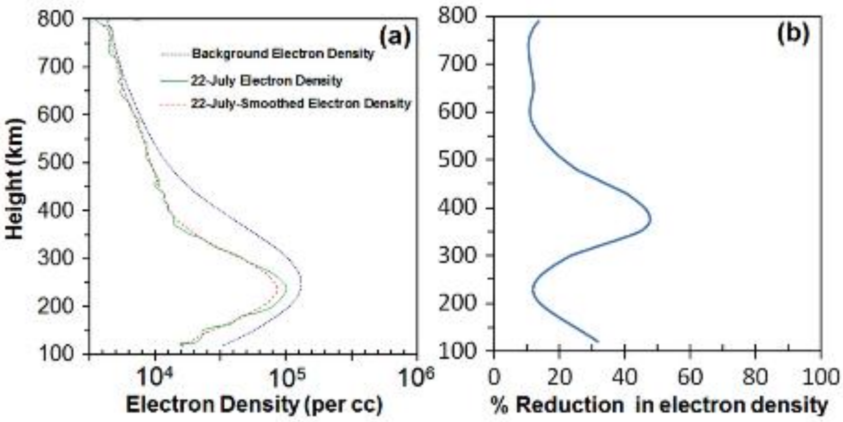
- Fig.2.Variation of VTEC compared to quiet mean VTEC and percentage change in VTEC compared to quiet mean VTEC (DVTEC) estimated from PRNs 14 and 31 data during total solar eclipse period at(a)Varanasi,(b)Kanpur (IITK),(c)Hyderabad (HYDE) and (d)Bangalore(IISC)

Table 1. Local circumstances for total solar eclipse on 22 July 2009 at all four locations.

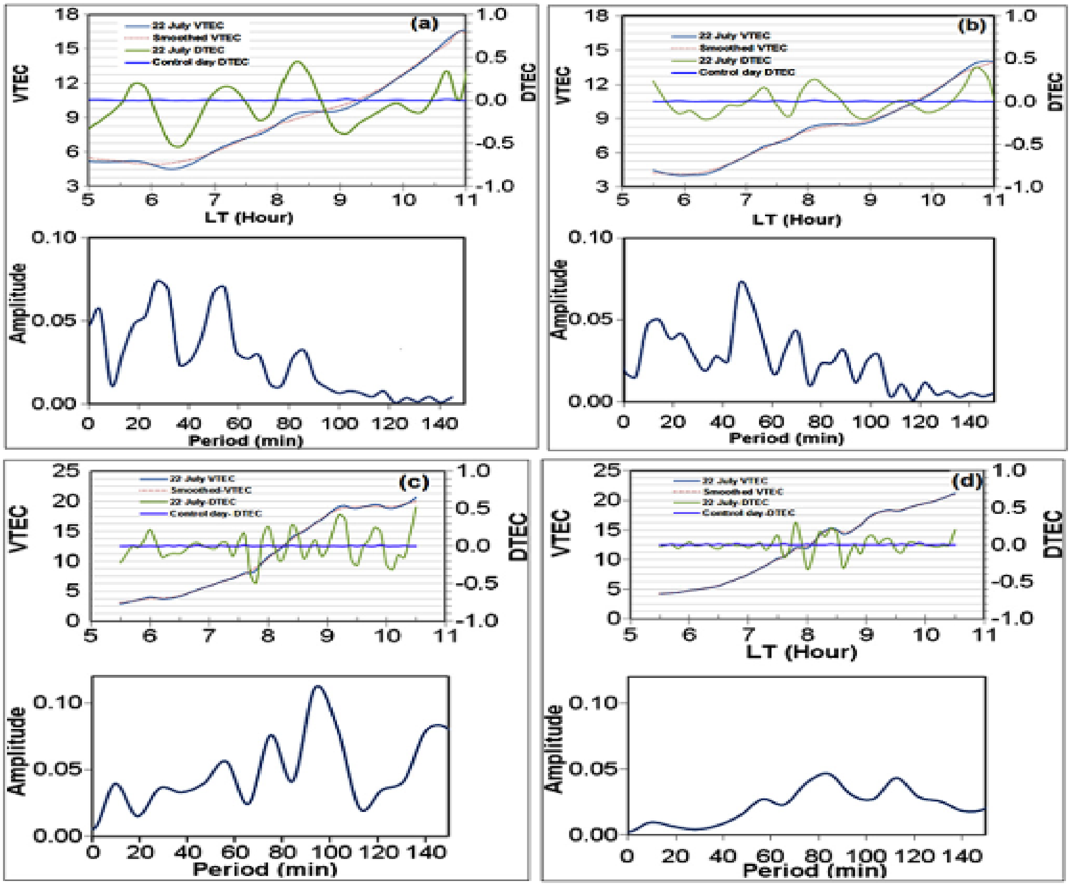
Station	Geog. latitude	Geog. longitude	Start of partial eclipse	Maximum eclipse	End of minimum eclipse	Maximum obscuration rate (%)
Varanasi	25°16′ N	82°59′ E	00:00 UT	00:55 UT	01:57 UT	100
Kanpur	26°18′ N	80°12′ E	00:01 UT	00:55 UT	01:56 UT	95
Hyderabad	17°20′ N	78°30′ E	23:58 UT on 21 July	00:52 UT	01:50 UT	84
Bangalore	12°58′ N	77°33′ E	23:59 UT	00:51 UT	01:47 UT	72



- Fig.3.(a)Variation of electron density profiles obtained from the FORMOSAT-3/COSMIC GPS-RO satellites over Indian zone for the eclipse day (22 July 2009) and the mean during quiet day. The smoothed electron density profile on the eclipse day (running mean) is also shown and (b)the percentage change in electron density compared to smoothed electron density profile of quiet mean value over the Indian region



- Fig. 4.Variation of VTEC, smoothed TEC (best polynomial fit to VTEC curve) and DTEC curve obtained by subtracting best polynomial fit to the original VTEC. Bottom panel shows the Fourier analysis of DTEC. (a)Varanasi, (b)Kanpur, (c)Hyderabad and (d)Bangalore.



5. Summary

The diurnal variation of VTEC during the total solar shows significant reduction during the eclipse period and beyond. The maximum reduction occurs a few minutes (2–15 min) after the maximum obscuration time, which may be due to the involved timescale in photoionization and transport phenomena. The maximum reduction (PRN 14) is observed at Varanasi, which lies inside the total obscuration. The amount of reduction decreases as the percent obscuration decreases. However, for PRN 31, the maximum reduction is observed at Kanpur, which lies at the outer edge of the total obscuration. This result may be due to the satellite path relative to the solar eclipse obscuration. The recovery of VTEC to a normal value occurs first at those stations, which lie in the partial obscuration region with a smaller percent of obscuration as compared to full obscuration. The vertical electron density profile shows significant reduction in electron density from 100 to 800 km altitude with a maximum of 48 % decrease at 360 km altitude. The significant decrease at higher altitude causes longer recovery time to the normal value after the end of eclipse, because transport processes are slow compared to photoionization. The Fourier analysis of VTEC shows the presence of wavy structures having periods between 40 and 120 min, which are attributed to the eclipse-induced cooling of the stratosphere/mesosphere.

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