TEC derived from incoherent scatter measurements during solar maximum and their comparison with IRI-2001 model

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The diurnal and seasonal variations of the total electron content (TEC), derived from high resolution electron density profiles measured with the Arecibo (18.4°N, 66.7°W, dip 50°N) incoherent scatter radar, are examined during high sunspot activity period (1989-90). Median values of TEC are then obtained at each hour during different seasons and compared with those obtained from the latest available International Reference Ionosphere (IRI-2001) model. The diurnal variations of TEC show more or less similar trend during all the seasons (i.e. maximum around daytime and minimum around midnight) with the largest values of TEC during equinox. The variability of TEC is larger at night than by day during all the seasons. Comparison of the diurnal variation of the observed median values of TEC with those predicted by the IRI model reveals, in general, similar trend during all the seasons and at all local times except during winter, when the IRI exhibits diurnal peak of TEC at around 0900 hrs LT, and the observed median peak occurs at around 1400 hrs LT. Discrepancies between the IRI and the median values exceed 40% during nighttime for winter and equinox. However, during daytime, they are less than 20% for all the seasons, except winter morning hours. The TEC peak content increases by a factor of around 4 from solar minimum (1975-76) to solar maximum (1989-90).

Keywords: TEC, IRI Model, Incoherent scatter, Sunspot activity, Electron density
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1 Introduction
The effects of ionosphere on a very high frequency radio waves have been studied for many years using radio signals from the artificial earth satellites and these studies are very useful for the evaluation of communication and navigation systems. Most of these effects are directly proportional to the number of free electrons encountered by the wave on its passage through the ionosphere. In order to determine the satellite position, the ionospheric corrections are to be applied, which are proportional to the total electron content (TEC) along the path from satellite to the tracking station. The TEC is thus very important parameter to monitor the behaviour of the ionosphere and also it improves the accuracy of the ionospheric correction that is needed for satellite orbit determination. Since TEC measurements are not always available, the ionospheric models are used to calculate TEC. At present, one of the widely used empirical model of monthly mean ionosphere is the International Reference Ionosphere (IRI), which is the outcome of joint working group of the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR). The IRI provides the monthly median values of electron density, electron temperature and ion composition as a function of height for a given location, time and sunspot number. The IRI model is being refined and updated following the annual IRI workshops and it has led to improvements through several versions. Recently, the most updated version of this model namely, IRI-2001 is available on internet.

Studies of the diurnal and seasonal variations of the TEC using geostationary satellite at low latitudes have been done by many workers. However, only a few papers have been published that deal with the comparison of TEC with the IRI model. These workers have used old versions of the IRI model, i.e. IRI-79 (Ref.12) and IRI-90 (Ref.13) to obtain TEC and reported that IRI gives a good description of mid-latitude ionosphere, but fails to reproduce TEC at low latitudes. Since, the major contribution to TEC comes from around F2-region of the ionosphere and in view of the discrepancies cited above, the efforts were made by the IRI Task Force in 1995 to establish profile shape parameters $B_0$, $B_1$ that determine the bottomside thickness and shape of the F2-region, respectively. The new $B_0$, $B_1$ values were thus generated using data from several ionosondes including low and mid-latitude stations through the efforts of International Center of Theoretical Physics (ICTP) in order to give the better representation of
electron density distribution, particularly, at low latitudes. This has led to a revised model of the IRI, i.e. IRI-2001 available on internet with additional features like F1-layer occurrence statistics, more realistic description of low latitude bottomside thickness and inclusion of model for storm-time conditions.

In the present paper, the performance of IRI-2001 has been evaluated as a predictor of TEC against measurements at a low latitude station, Arecibo (18.4°N, 66.7°W, dip 50°N) during high solar activity period (1989-1990). The IRI-2001 offers two options for obtaining electron density distribution below the F2-peak, i.e. (i) the Gulyaeva's (1987) model based on half density height (the height where the density below the F2-peak falls off to half the peak value ) and (ii) a new table of values of \( B_0 \) and \( B_1 \). In this study, the TEC predicted values have been generated using both the options of the IRI-2001 and compared them with the observations. Also, in order to examine the solar activity control on TEC, the TEC values derived in the present work for solar maximum (1989-1990) period have been compared with those obtained earlier during solar minimum (1975-1976) by Sethi et al.

2 Data base

The data base employed in the present study are the high resolution electron density (\( N_e \)) profiles measured with incoherent scatter (IS) radar at a low latitude station, Arecibo. The IS power profile was measured from 100 to 555 km with a single 4 μs pulse length, providing an effective height resolution of 0.6 km. The time resolution is about 1 min. The power profile was converted into \( N_e \) profile by using simultaneously measured electron to ion temperature ratio profile. The profile was finally calibrated by reading \( N_eF_2 \) from an on-site ionosonde. In the present work, the data for a period of solar maximum from March 1989 to January 1990 containing around 17465 \( N_e \) profiles have been employed. During this period, the solar activity as represented by R12 (12 month running average sunspot number) varies between 150 and 158.

3 Analysis and results

To examine the seasonal variations, the data have been grouped into summer (May, June and August of 1989), winter (February and November of 1989, January of 1990) and equinox (March, April and October of 1989) containing 6286, 4114 and 7065 \( N_e \) profiles, respectively. The TEC is derived by performing numerical integration over a height range 100-555 km for each \( N_e \) profile individually.

Figure 1 [(a)-(c)] show the diurnal variations of mass plot of TEC (1 TEC unit = \( 10^{16} \text{el. m}^{-2} \)) for summer, winter and equinox. It can be noted from the Fig.1[(a)-(c)], that the variability of TEC, in general, is larger during night than by day during all the seasons. For the same local time and in the same season and for about same solar conditions, the TEC varies by as much as a factor of two during night
time. Since the day-to-day variability of any parameter is best described by the ratio of the standard deviation to the monthly mean, Fig. 2 shows the diurnal variations of such ratios expressed in percentage for the three seasons. In can be observed from Fig. 2 that the variability in terms of percent standard deviation ranges from 10 to 15 during daytime for all the seasons, indicating that TEC variability does not show any significant seasonal dependence during daytime. However, during nighttime and morning hours, the variability, in general, varies from 20 to 40% for all the seasons except during equinox for the pre-midnight hours, where the variability is within 15%. Similar day-to-day variability at a low latitudes is reported earlier\textsuperscript{17-19}. The diurnal variations of median TEC shown in Fig. 3[(a)-(c)] during different seasons reveal that during all the seasons, the value of TEC starts decreasing from its nighttime value of about 30 units at around 0000 hrs LT to minimum value of about 10±5 TEC units between 0400 and 0500 hrs LT and thereafter TEC increases gradually and the diurnal peak is found to be centered between 1200 and 1400 hrs LT. The diurnal maximum is almost flat during winter, but relatively sharp during summer and equinox.

The IRI predicted values of TEC are obtained up to 555 km for a given local time and month relating to the three seasons as mentioned above and \( R12 \) corresponding to a given month using both the options of the IRI model, i.e. IRI (Bo Tab)\textsuperscript{15} and IRI (Gulyaeva)\textsuperscript{16}. The TEC values thus obtained are averaged over respective months to represent the seasonal predicted value. It is pointed out here that TEC predicted values using both the options as shown in Fig. 3[(a)-(c)] exhibit identical diurnal trends at all local times during all the seasons, except during summer and equinox around noontime. During this time period, the IRI (Gulyaeva)\textsuperscript{16} option produces somewhat higher values of TEC than those obtained by IRI (Bo Tab)\textsuperscript{15} option.

Comparative studies between median values of TEC and the IRI predicted values reveal that both the

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**Fig. 2** — Variability of observed TEC (expressed as a ratio of standard to the monthly mean) against local time for summer, winter and equinox

**Fig. 3** — Plot showing diurnal variations of observed median values of TEC along with the IRI predicted values using both the options namely Gulyaeva (1987) and Bo Tab for (a) summer, (b) winter and (c) equinox
predicted and median values during summer [Fig. 3(a)] show good agreement during 0000 and 1000 hrs LT. However, around post-noon hours till about 2000 hrs LT, the IRI model somewhat underestimates the TEC values. Around noontime, the IRI predicted values of TEC using IRI ($B_0$ Tab)$^{15}$ option is in better agreement with the observed TEC than those predicted by IRI (Gulyaeva)$^{16}$ option. Discrepancies between the observations and the IRI predictions can be noted during winter as shown in Fig. 3(b). The IRI exhibits diurnal peak of TEC around 0900 hrs LT, while the observations show a peak at around 1400 hrs LT. Also, the diurnal maximum of the observed TEC shows a flat trend from 1000 to 1400 hrs LT, while the IRI fails to reproduce the observed data in this time period and show a gradual fall. The IRI model overestimates the observed values from 0600 to 1200 hrs LT and underestimates outside this time period. During equinox, as illustrated in Fig. 3(c), the IRI predicted values are somewhat closer to observations from 0600 to 0900 hrs LT, while outside this time period, the IRI in general, underestimates the TEC. Around noontime, again the IRI ($B_0$ Tab) option provides a better agreement with the observations than those obtained using IRI (Gulyaeva) option. The deviation between the IRI and the median values, in general, remains less than 20% during summer (at all local times) and equinox (daytime). However, during nighttime, the deviation varies from 20 to 50% in equinox. During winter, the percentage difference between the two, varies from 20 to 30% between 0600 and 1200 hrs LT and between 30 and 50% during post-sunset hours. The difference between the two, outside this time period, remains less than 20%.

Since, the TEC are expected to show the solar activity variations, the median values of these parameters have, therefore, been compared in Fig. 4[(a)-(c)] for solar maximum (1989-1990) with those obtained earlier$^7$ for solar minimum (1975-1976). It can be noted from Fig. 4[(a)-(c)], that the peak electron content increases by a factor of around 4 during all the seasons, from low to high solar activity. Figure 5[(a)-(c)] shows diurnal variation of predicted values of TEC for high (1989-1990) and low (1975-1976) solar activity periods using IRI ($B_0$ Tab) option of the IRI model. For low solar activity (LSA), the predicted diurnal variations of TEC are obtained for day 15 of May, June, July and August representing summer; January, February, November and December representing winter, and March, April, September and October representing equinox of 1975 and 1976. The TEC values thus obtained are averaged over respective months to represent the seasonal predicted values. The R12 during 1975-1976 varies from 12 to 22 units. It is noted from Fig. 5[(a)-(c)] that the IRI predictions show more or less similar increase in TEC from low to high solar activity as shown in Fig. 4[(a)-(c)].
4 Discussion

The comparisons of TEC obtained from Faraday rotation technique, with earlier versions of IRI model had been made by several workers at low latitude stations\textsuperscript{2,3,6,20}. Using TEC measurements from Faraday rotation at Sydney (31°S), McNamara and Wilkinson\textsuperscript{2} reported that discrepancies between the IRI and the observations exceeded by 30%. The predicted TEC values during high solar activity were always too high in winter with errors as large as 50%. McNamara and Wilkinson\textsuperscript{2} compared the IRI-79 (Ref.\textsuperscript{12}) model with TEC observations and reported that IRI model produced a better representation of mid-latitude ionosphere and failed to reproduce observed values of TEC at low latitudes. They reported that IRI-79 severely underestimated the TEC and the daytime difference could reach 50%. They had attributed these discrepancies to the shape of $N_e$-$h$ profiles.

Comparisons of the observed TEC at a low latitude station, Havana (23.1°N, 277.5°E) were made with those obtained from the IRI-90 model\textsuperscript{13} by Ezquer et al.\textsuperscript{6}. They reported that during equinox, when the highest TEC occurred, the IRI-90 underestimated TEC by about 25%. They also suggested that $N_e$-$h$ profile was broader than that given by IRI profile.

Iyer et al.\textsuperscript{20} had validated the IRI-90 model with TEC data from two equatorial anomaly crest stations and showed that the IRI-90 model underestimates TEC during afternoon hours (except in summer) during high solar activity.

Recently, using measurements of Faraday rotation of VHF beacon transmission from signals, Souza et al.\textsuperscript{21} have developed local empirical model for TEC for the Brazilian low latitude and compared with those calculated by the IRI-95 model. They have found agreement between the two during afternoon hours near solar maximum with the underestimated values of TEC predicted by IRI model except at autumn.

Comparisons of TEC with the earlier versions\textsuperscript{12,13} of the IRI model, i.e. IRI-79 and IRI-90 (as reported by a few workers above) have shown the daytime discrepancies exceeding 30%, while the IRI-2001 model, in general, provides a better agreement with observations having discrepancies much less than 20% except for winter morning hours. This is because, the electron density distribution in the IRI-2001 model below the F2-peak depends mainly on $B_0$, $B_1$ parameters, which have been modified using data from several ionosondes including low and mid-latitude stations. The Gulyaeva’s option\textsuperscript{16}, in the IRI-2001 as well in IRI-90 although recommended choice for low latitudes, yet it does not adequately represent bottomside profile shapes. Using digital ionosonde observations at a low latitude station, New Delhi (28.6°N, 77.2°E), Sethi et al.\textsuperscript{22} have compared bottomside $N_e$-$h$ profiles with those obtained from the IRI-2000 model\textsuperscript{1} using both the Gulyaeva’s and $B_0$ Tab options. They have reported that during all the seasons, $B_0$ Tab option as compared to Gulyaeva’s
option, reveals a better agreement with the observations.

From post-noon hours till around midnight, the IRI-2001 model underestimates TEC for winter and equinox, as previous workers too have shown the similar results. The discrepancies during this time period varies from 30% to 50% and this underestimation may be due to inadequate profile shapes in the topside.

5 Conclusions

The purpose of this paper is to assess the prediction of TEC using latest available International Reference Ionosphere (IRI-2001) model against measurements at a low latitude station, Arecibo, during high solar activity. The present study shows that IRI model produces reasonably good agreement on TEC, particularly, between 0600 and 1200 hrs LT during summer and equinox with the least discrepancies during summer. The major discrepancies occur in this time period during winter, where the IRI model overestimates the observed TEC and exhibits diurnal peak at around 0900 hrs LT as against observations which show diurnal peak at around 1300 hrs LT. Around noontime during summer and equinox, the TEC values predicted by IRI-2001 using $B_0$ Tab option, are generally in a better agreement with the observed values than those obtained using Gulyaeva option in the IRI model. During post-noon hours, the IRI model, in general, underestimates TEC during all the seasons. During nighttime, the IRI model gives better prediction for summer and winter months, while during equinox the IRI model underestimates, TEC. Since at low latitudes the electron density distribution is affected by $E\times B$ drifts and neutral winds, which are highly local time and season dependant, these effects are not well taken in the IRI model. Also, it is suggested to carry out comparative study of topside profiles with the IRI model in order to improve its predictability, particularly for low latitudes.

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