Comparison between observed ionospheric $f_0F_2$ and IRI-2001 predictions over periods of severe geomagnetic activities at Grahamstown, South Africa

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Abstract

The observed ionospheric F2 critical frequency ($f_0F_2$) values over a South Africa mid-latitude station, Grahamstown, (geographic coordinates: 33.3 $\circ$S, 26.5 $\circ$E), were analysed and compared with International Reference Ionosphere (IRI) model, using the CCIR (Comité Consultatif International des Radio communications) and URSI (Union Radio-Scientifique Internationale) coefficients, during four geomagnetically disturbed days in the year 2000. These days are April 5, May 23, August 10 and September 15. The data were analysed for five days around the storm day. Comparisons between the IRI-2001 predicted $f_0F_2$ values, using both CCIR and URSI coefficients and the observed values are shown with their root-mean-square error (RMSE) and the relative deviation module mean (rdmm) for the various storm periods. The CCIR option performed more accurately than the URSI option.

In general, the model generates good results when compared with observed $f_0F_2$ values during geomagnetic storms, although some improvements are still necessary to be implemented in order to obtain better predictions.

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Keywords: Storm; International Reference Ionosphere (IRI); Root-mean-square error (RMSE); Relative deviation module mean (rdmm)

1. Introduction

Ionospheric storms signify a severe form of space weather, which can have large effects on the regular structure of the ionosphere and also have adverse effects on ground and space based communication and navigation systems.

Several researchers (e.g. Rajaram et al., 1971; Batista et al., 1991; Yeh et al., 1992; Walker and Wong, 1993; Sojka et al., 1994; Sobral et al., 2001; Afraimovich et al., 2002; Lastovicka, 2002; Blagoveshchensky et al., 2003) have examined the significant changes in the key ionospheric F-layer parameters, such as the critical frequency of the F2-layer ($f_0F_2$), the virtual height of the F-layer ($h_0F$), the peak height of the F2-layer ($h_{mF2}$), the maximum electron density of the F2-layer ($NmF_2$), and the total electron content (TEC), during geomagnetic storms. Titheridge and Buonsanto (1988) reported that the ionospheric effects of geomagnetic storms are dependent on the time of occurrence and intensity of the storm. These effects are also dependent on the latitude of the station and its location in the summer or in the winter hemisphere (Essex et al., 1981; Schödel et al., 1974). Batista et al. (1991) found large negative phases in $f_0F_2$ at the equatorial station Fortaleza (3$\circ$55'S, 38$\circ$25'W) and at the ionization anomaly crest station Cachoeira Paulista (22.5$\circ$S, 45$\circ$W), in the Brazilian sector, during the great geomagnetic storm of 13–14 March 1989. Sobral et al. (2001) reported that in some cases during the very intense geomagnetic storms of December 1980, April 1981, and September 1982, increases (decreases) in $f_0F_2$ over Cachoeira Paulista, were related to increases (decreases) in the fountain effect, due to storm-induced changes in the ionospheric electric field (Lakshmi et al.,...
Lakshmi et al. (1997) studied a large number of severe storms and observed that, on a large number of occasions, in the post-midnight periods the $foF2$ values collapse to levels significantly lower than their monthly median values during severe storms. The abilities of the International Reference Ionosphere (IRI) to predict ionospheric parameters have been studied extensively (Adewale et al., 2009; Oyeyemi and Adewale, 2009; Xenox, 2002; Adeniyi et al., 2003; Sethi et al., 2004; Batista and Abdu, 2004; Bertoni et al., 2006). The IRI model offers two options for the prediction of $hmF2$ and $foF2$; one uses the CCIR coefficients, which was developed by Comité Consultatif International des Radio communications (CCIR, 1967, 1991); and the other uses the URSI coefficients developed by the Union Radio-Scientifique Internationale (Rush et al., 1983, 1984, 1989; Fox and McNamara, 1988). Validation and modification of the IRI has led to improvements through several versions (Rawer et al., 1978a, 1978b, 1981; Rawer and Minnis, 1984; Bilitza, 1997, 2001; Bilitza and Reinsch, 2008).

The IRI-2001 (Bilitza, 2001) model contains a reliance on geomagnetic activity based on an empirical storm-time ionospheric correction model (STORM) (Araujo-Pradere, 2002). This storm correction in IRI is driven by the previous time history (33 h) of ap and is intended to scale the normal quiet-time $foF2$ value to account for storm-time changes in the ionosphere. Few researchers have actually considered the prediction abilities of the IRI model during geomagnetic storms (Araujo-Pradere, 2002; Mansilla et al., 2004).

During geomagnetic storms all ionospheric characteristics are affected. It is important, therefore, that the IRI-2001 model be tested against available observations. This paper presents the comparison of $foF2$ values predicted by IRI-2001 model with observed values over a mid-latitude Southern Hemisphere station during geomagnetic storms.

2. Data and method of analysis

Data recorded by a digital ionosonde located at a mid-latitude South Africa station, Grahamstown (geographic coordinates: 33.3°S, 26.5°E), during four storms in 2000 (April 5, May 23, August 10 and September 15) were analysed and compared with IRI-2001 predictions. The ionospheric data is obtained through the database of the Space Physics Interactive Data Resource, SPIDR (http://spidr.ngdc.noaa.gov/). The storms were selected under a single criterion: $Dst < -100$ nT for at least four consecutive hours. The hourly values of a continuous 5-day period of $foF2$ values (120 values) were used, in order to see the full picture of the disturbed period.

Apart from using the method of pure visualization of different curves plotted, we also employed the use of a criterion called “relative deviation module mean” (rdmm), used by Bertoni et al. (2006), in order to quantify the agreement/disagreement between the observed and modelled curves, which is calculated according to the following expression:

$$\text{rdmm}, <\Delta> = \frac{1}{N} \sum_{i=1}^{N} \frac{|x^o_i - x^m_i|}{x^o_i}$$ (1)

where $x^o_i$ and $x^m_i$ represent observed and modelled values, respectively, and $N$ is the number of data points. According to Bertoni et al. (2006), modelling generally exhibits a reasonable to good agreement when, besides visually, the rdmm reaches values equal to or less than 0.06, and a reasonable to poor agreement for higher values.

Also, the root-mean-square error (RMSE) has been used here to evaluate the performance of the IRI-2001;

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (foF2^o_i - foF2^m_i)^2}$$ (2)

where $N$ is the number of data points and $foF2^o_i$ and $foF2^m_i$ are the observed and predicted $foF2$ values, respectively.

The percentage deviation between the IRI-2001 (CCIR and URSI) model results and the observed values of $foF2$ was also analysed, according to the following equation:

$$\% \text{ Deviation} = \frac{x^o_i - x^m_i}{x^m_i} \times 100$$ (3)

where $x^o_i$ and $x^m_i$ represent the observed and modelled values, respectively.

3. Results

Figs. 1–4 show from the top, the Dst-index, $foF2$ and percentage deviation for all the four storm periods considered in this work. The x axis corresponds to the time, from 00:00 UT on the first day to 23:00 UT on the fifth day of each period analysed. Table 1 shows the numerical values of rdmm for each of the five days of the storm periods. Table 2 shows the numerical values of RMSE for each of the five days of the storm period.

Figs. 1(a)–(c) show the variations of Dst-index, $foF2$ values and percentage deviation for the 5–9 April, 2000 storm period. A severe magnetic storm commenced at 16:00 UT (LT = UT + 2 h) on April 6, 2000 with a maximum negative excursion in Dst = −288 nT at 01:00 UT on April 7 prior to a long recovery phase. During the period when the storm was most severe the value of $foF2$ decreased with the main phase of the storm. The predicted values (CCIR and URSI) also show a reduction in $foF2$, although not to the extent of the observed. Table 1 shows the rdmm values. The rdmm has values greater than 0.06 for both CCIR and URSI predictions, indicating a reasonable to poor agreement. The rdmm and RMSE have the highest values on 7 April, 2000. The percentage deviation reached the maximum value of 55% around the main phase of the storm.

Figs. 2(a)–(c) show the variations of Dst-index, $foF2$ values and percentage deviation for the 23–27 May, 2000
storm period. Sudden commencement (SC) occurred at 17:02 UT on May 23, with a maximum negative excursion in Dst = \(-147\) nT at 08:00 UT on May 24 followed by an irregular recovery phase. The best agreement occurred for CCIR predictions on 23 and 26 May, where the rdmm value equals 0.06. During the main phase of the storm, there were no significant changes in the value of \(f_0F_2\) for both the observed and predicted. The URSI coefficient greatly underestimated the observed \(f_0F_2\) when compared with the CCIR coefficient. The percentage deviation for the CCIR coefficient exceeded 60%.

Figs. 3(a)–(c) show from the top, the Dst-index, \(f_0F_2\) and percentage deviation for the storm of 10–14 August 2000. SC at 05:01 UT on 10 August and the minimum of Dst (-106 nT) occurred at 06:00 UT on 11 August, when the magnetic field started to recover. The Dst-index indicates a second storm with the value reaching a minimum of \(-235\) nT at 09:00 UT on 12 August followed by a recovery phase. During the main phase of the storm, there were no significant changes in the value of \(f_0F_2\) for both the observed and predicted values, although the rdmm values (\(<D_{\text{CCIR}}>=0.21\) and \(<D_{\text{URSI}}>=0.22\)) of the day with maximum negative excursion in Dst value gave the highest values. The percentage deviation for CCIR predictions reached a maximum value of 71% at 19:00 on 14 August.

Figs. 4(a)–(c) show the Dst-index, \(f_0F_2\) and percentage deviation for the storm of 15–19 September 2000. SC at 14:44 UT on September 18, with a maximum negative excursion in Dst = \(-201\) nT followed by a recovery phase which lasted until about 09:00 UT the next day. During the main phase of the storm there was a slight decrease
in $f_{o}F_{2}$ for both the observed and predicted values. The percent deviation never exceeded 60%.

4. Discussion

It has been reported in several papers that the most prominent feature observed during an ionospheric storm is the decrease in $f_{o}F_{2}$ and the total electron content (TEC) (Lakshmi et al., 1991, 1997; Batista et al., 1991). The reports indicate that the precipitation flux and the related convection electric field in the polar thermosphere can produce strong heating which can alter the global thermospheric wind system and the neutral composition. The change in neutral composition is responsible for the dramatic reduction in electron density (Prolss and von Zahn, 1974; Chandra and Spencer, 1976; Forbes, 1989). Figs. 1(b) and 4(b) show reasonable prediction of the dramatic reduction in $f_{o}F_{2}$ values during the April storm but Fig. 2(b) and 3(b) did not show reduction in observed and predicted $f_{o}F_{2}$ values during the storm period.

The plots obtained from the observed and predicted data were analysed in two ways: visually and quantitatively. The quantitative method involves the use of the rdmm value (Bertoni et al., 2006) and the RMSE analysis. The IRI-2001 model, using CCIR and URSI coefficients, presented a reasonable to poor simulation of the ionospheric $f_{o}F_{2}$ parameter during geomagnetic storms, considering both the visual and quantitative analysis. The visual analysis revealed that both the CCIR and URSI coefficients underestimate and overestimate the observed values at different hours. The rdmm exhibited values higher than 0.06 reaffirming the reasonable to poor agreement in $f_{o}F_{2}$ for both the observed and predicted values. The percent deviation never exceeded 60%.

Fig. 3. Behaviour of (a) Dst-index, (b) $f_{o}F_{2}$ values and (c) percent deviation for the storm period August 10–14, 2000.

Fig. 4. Behaviour of (a) Dst-index, (b) $f_{o}F_{2}$ values and (c) percent deviation for the storm period September 15–19, 2000.
between the model and the observed values. Table 1 shows rdmm values of the order of 0.06–0.28 and 0.09–0.31 MHz for CCIR and URSI, respectively. The RMSE values are relatively higher on the days with maximum negative excursion in Dst value when compared to other days. Table 2 shows RMSE values of the order of 0.45–2.12 and 0.73–2.16 MHz for CCIR and URSI, respectively.

5. Conclusions

The IRI-2001 predictions have been compared with observed foF2 for 5 days around the magnetic storm-time periods (120 hourly values), in order to observe the complete morphology of the disturbed period. The ability of the IRI-2001 model to predict the storm-time foF2 value has been determined by comparing the prediction with the observed ionospheric response for a mid-latitude station during the four storms recorded in year 2000. It is found that the IRI-2001 model captures the trend of the changes in foF2 at the station considered during magnetic storm events, that is, it predicts the decrease in foF2 values. The assessment of the prediction has been quantified by evaluating both the RMSE and rdmm from the IRI-2001, using both CCIR and URSI coefficients.

The agreement between observed and model predicted values of foF2 for the storm periods seems to be quite encouraging. Discrepancies are higher during the storm days. The percentage deviation of the observed values with respect to IRI-2001 remains within 80% during all the storm periods. Generally, IRI-2001 (using both CCIR and URSI coefficients) model predicts foF2 values close to the observed ones with the CCIR-IRI model performing better than the URSI-IRI model.

However, the results of this study highlight the need for further validation studies using more stations and also different geomagnetic storm periods in order to have a better picture of the effectiveness of the IRI model at predicting ionospheric parameters at different latitudes and also during different seasons.

Ataq et al. (2009) reported that the observed foF2 are in better agreement with the predicted results of the IRI-2007 model than the values of the previous version of the IRI model. This can be expected since Bilitza and Reinisch (2008) describe the various improvements, which are added to the latest version of the IRI-2007 model.

Acknowledgements

We are grateful to all developers of IRI (Bilitza, 2004) for making this model available. We are also grateful for the free access to Space Physics Interactive Data Resource, SPIDR database.

References


Table 1

Values of rdmm for all days of the storm periods.

<table>
<thead>
<tr>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/4/2000</td>
<td>0.09</td>
<td>0.17</td>
<td>23/5/2000</td>
<td>0.06</td>
<td>0.10</td>
<td>10/8/2000</td>
<td>0.14</td>
<td>0.12</td>
<td>15/9/2000</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>6/4/2000</td>
<td>0.11</td>
<td>0.16</td>
<td>24/5/2000</td>
<td>0.12</td>
<td>0.12</td>
<td>11/8/2000</td>
<td>0.15</td>
<td>0.12</td>
<td>16/9/2000</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>7/4/2000</td>
<td>0.28</td>
<td>0.31</td>
<td>25/5/2000</td>
<td>0.08</td>
<td>0.13</td>
<td>12/8/2000</td>
<td>0.21</td>
<td>0.22</td>
<td>17/9/2000</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>8/4/2000</td>
<td>0.09</td>
<td>0.18</td>
<td>26/5/2000</td>
<td>0.06</td>
<td>0.10</td>
<td>13/8/2000</td>
<td>0.13</td>
<td>0.14</td>
<td>18/9/2000</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>9/4/2000</td>
<td>0.07</td>
<td>0.16</td>
<td>27/5/2000</td>
<td>0.09</td>
<td>0.10</td>
<td>14/8/2000</td>
<td>0.17</td>
<td>0.09</td>
<td>19/9/2000</td>
<td>0.18</td>
<td>0.17</td>
</tr>
</tbody>
</table>

The rdmm values for the day with maximum negative excursion in Dst value are bold.

Table 2

Values of RMSE for all days of the storm periods.

<table>
<thead>
<tr>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
<th>DATE</th>
<th>CCIR</th>
<th>URSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/4/2000</td>
<td>1.041</td>
<td>1.677</td>
<td>23/5/2000</td>
<td>0.612</td>
<td>0.725</td>
<td>10/8/2000</td>
<td>0.919</td>
<td>0.758</td>
<td>15/9/2000</td>
<td>0.956</td>
<td>1.766</td>
</tr>
</tbody>
</table>

The RMSE values for the day with maximum negative excursion in Dst value are bold.