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The subauroral electron density trough: Comparison between satellite observations and IRI-2007 model estimates

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Abstract.

We compare electron density predictions of the International Reference Ionosphere (IRI-2007) model with in-situ measurements of the satellites CHAMP and GRACE for the years from 2005 to 2010 over the subauroral regions. The electron density between 58° and 68° Mlat are considered. The trough region N_e peaks during local summers and attain the valley during local winter. Around -100°E and 60°E, two larger electron density sectors features can be seen in both two hemisphere during all three seasons, which attributed to the electron extending from middle latitude to trough region. From 2005 to the beginning of 2010, the model overestimates the trough region N_e by 20% on average and the decrease of N_e in this region can also be seen during the last solar minimum. In the southern hemisphere, the model prediction shows quite well consistence with the observation during all three seasons while the huge difference between observations and model estimation imply that the IRI-2007 model needs significant improvement to predict better the trough region in northern hemisphere.

1. Introduction.

Latitudinally narrow and longitudinally extended depressions in the electron density have been identified as a major morphological feature of the ionosphere at middle and high latitudes from both satellite and ground observations [e.g. Muldrew, 1965; Sharp, 1960; Grebowsky et al., 1983; Whalen, 1987]. These depressions have become known as the mid-latitude or the main ionospheric trough if they are located on the equatorward side of the auroral oval and high-latitude trough if found poleward of the auroral boundary [Werner and Prölss, 1997]. An electron temperature enhancement in the main trough was first observed by Norton and Findlay [1969] using data from the Alouette 2 satellite. They observed the subauroral red arc as the airglow of atomic oxygen at 630 nm wavelength accompanied by reduced electron density in the region of the arc. Double peaks of electron temperature enhancement were obtained by Horwitz et al. [1986] and Brace et al. [1988]. Watanabe et al. [1989] used electron temperature probe data on board the Ohzora satellite to verify the existence of the double peak signature of the temperature, the anisotropy of the temperature, and the non-Maxwellian distribution of the electron energy. They suggested that the electrons in the ionospheric trough region are heated by the heat flux from the magnetosphere. Sojka et al. [1985] used the high latitude ionospheric model and found that the ionospheric trough in the southern hemisphere is much deeper than that in the northern hemisphere. Afonin et al. [1993], using ion density winter measurements on the Kosmos-900 satellite from 1977 to 1979, found the longitudinal variations of the trough position to be different in the different hemispheres. In the northern hemisphere the trough has the shape of a double wave (wavelength 180° of

longitude) with an amplitude of 4-6° in latitude, both on day and night side, whereas in the southern hemisphere, there is just a single wave (wavelength 360° in longitude) with an amplitude of about 6° in latitude on the night side and 12° in latitude on the day side. Werner and Prölss [1997], using Dynamics Explorer 2 (DE-2) satellite data, found the position of the ionospheric trough minimum highly dependent on magnetic activity and magnetic local time. After that Prölss [2006], using DE-2 satellite data, found that for geomagnetically quiet conditions ($D_{ST} \approx 0$), the electron temperature peak is located slightly poleward of 60° magnetic latitude (Mlat). For each decrease of the Dst index by 10 nT it moves equatorward by about 1° in latitude. To a lesser degree the latitude of the heating effect also depends on magnetic local time (MLT), exhibiting a significant asymmetry about the midnight sector [Prölss, 2006].

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). IRI describes monthly averages of the electron density, electron temperature, ion composition (O^+ , H^+ , N^+ , O_2^+ , NO^+ , Cluster+), ion temperature and ion drift in the ionospheric altitude range of 50-1500km. [e.g., Bilitza, 1992, 2003; Bilitza and Reinisch, 2007]. The IRI model is an empirical model based on a large collection of satellite and ground-based observations, and it is expected to give a reasonably accurate description of the ionosphere under quiet geomagnetic conditions.

Liu et al. [2007] have used CHAMP electron density data at 400 km altitude over the period Aug. 2000 to Aug. 2006 for validating parts of the IRI-2001 model [Bilitza, 2003]. Particular emphasis was put on the equatorial ionization anomaly (EIA) during daytime and post-sunset hours. They conclude that IRI reproduces the EIA around noon rather well for all levels of solar flux. Conversely, the ion fountain effect around 20:00 LT is too weak in the model, in particular for moderate to strong solar activity. As can be seen in Figure 6 of Liu et al. [2007], the observed Ne profiles across the EIA exhibit higher crest values, which appear at larger distances to the dip-equator, and Ne is more depleted above the equator. All this indicates that IRI-2001 underestimates the effect of the vertical plasma drift during post-sunset hours.

Lühr and Xiong [2010] compare electron density predictions of the IRI-2007 model with in-situ measurements of the satellites CHAMP and GRACE during the years 2000 to 2010. Global-averages of the electron density are considered. During the first half of the period (2000-2004) measurements and collocated model predictions track each other reasonably well at both sampling heights. From 2005 onward the overestimation of the electron density by the model is progressively increasing. Annual averages show that IRI-2007 values are too high by 50% for 2008 and by more than 60% during 2009. An inspection of the latitudinal and local time distribution reveals that the too high predictions primarily occur at low latitudes during daytime hours. From comparison with observations it becomes obvious that IRI-2007 is strongly overestimating the equatorial ion fountain effect during the last deep solar minimum.

The purpose of this study is to investigate the reliability of the IRI model for reproducing the electron density trough in the subauroral region. Since the trough represents one of the ionospheric regions with lowest electron content (in particular during dark hours), it is of interest for calibrating total electron content (TEC) measurements derived from GPS signals. Here the antenna bias of

satellite-borne GPS receivers can be determined most reliably. For example, Heise et al. [2002] used a model-based approach for estimating the differential code bias of the CHAMP GPS receiver. Regions of low electron content are most suitable for determining the additive code bias. Reliable predictions of the trough region are thus rather relevant for satellite TEC measurements.

We first present a characterization of the trough regions in the two hemispheres based on 5 years of CHAMP and GRACE data. Then we make use of measurements from these satellites for a direct comparison with the IRI-2007 model. Differences are considered independently for the hemispheres and for each season. In the discussion section we compare our results with previous publications.

2. Data

The CHAMP satellite was launched on 15 July 2000 into a circular, near-polar orbit (inclination: 87.3°) with an initial altitude of 456 km. By the end of 2009 the orbit has decayed to 310 km. The local time of the orbital plane changes by 1 hour in 11 day, requiring about 130 days for covering all local times [Reigber et al., 2002]. The Planar Langmuir Probe (PLP) on board the satellite was taking measurements of the electron density every 15 s. CHAMP PLP readings have been validated by comparison against digisonde measurements at Jicamarca [McNamara et al., 2007]. Their study revealed a good agreement between PLP and digisonde recordings. The mean difference amounted to only 4% with a standard deviation of 8.8%.

GRACE, comprising two spacecraft GRACE-A and GRACE-B, was launched on 17 March 2002 into a near-circular, polar orbit (inclination: 89°) with an initial altitude of about 490 km. The altitude of these satellites is quite stable over the years. During the years of interest (2005-2009) it stays around 480 km. The local time of the orbital plane processes by 4.5 minutes every day taking the mission 160.5 days to sample all local times [Tapley et al., 2004]. The two satellites follow each other at a distance of about 220 km. The total electron content (TEC) between the spacecraft can be deduced from the K-Band Ranging (KBR) data. When dividing the horizontal TEC by the distance between the spacecraft we get the average electron density. A more detailed description of the electron density retrieval is given in section 3 of Xiong et al. [2010]. *Ne* estimates based on radio wave measurements, in principle, do not require calibration. However, there may be an arbitrary bias value. By considering long and continuous data series we have well constrained the additive value, see also Lühr and Xiong. [2010].

The inputs for the IRI-2001 and IRI-2007 models are (1) sunspot number, *R*, (2) global ionospheric index, *IG*, and (3) the 3-hourly magnetic, *a_p* index. *IG* is an ionospheric effective solar index that is based on foF2 measurements from selected ionosondes and a correlation with the Consultative Committee of International Radio Communications (CCIR) maps [Liu et al., 1983]. For the calculations presented here we have used the IRI-2007 version updated on 28 May 2010. Selected options are:

foF2: URSI

Ni: DS-95 & TTS-03

Ion drift: not computed

Te: Te topside (Intercosmos)

ESF: not computed
Topside model: NeQuick

3. Trough observations from satellites

The ionospheric trough region is located on average slightly poleward of 60° magnetic latitude during geomagnetically quiet times. Since it varies a few degrees in latitude dependent on geomagnetic activity and MLT [e.g., Prölss, 2006], we have considered averages over the latitude range of 58° - 68° Mlat (irrespective to the actual trough position) from both hemispheres for further analysis. The data selected for this study are from quiet times ($K_p \leq 3.5$) and from the 5 years, 2005 to the beginning of 2010. This period coincides with the deep minimum at the end of solar cycle 23. Fig.1 shows the electron density distribution over the polar regions of both hemispheres, as sampled by CHAMP and GRACE during the 5 years. Here the data have been smooth by a filter over 31 days. This filter length is chosen since IRI predictions represent monthly averages. From this figure we can clearly see that around $\pm 60^\circ$ Mlat, both at CHAMP and GRACE altitudes; N_e attains a minimum and is smaller than at other latitudes except near the South Pole. It is interesting to mention that the value of N_e is smallest during 2008 and 2009, the epoch of the recent solar minimum. Lowest electron densities are not always recorded on the date of local winter solstice. This is because the orbital local time also influences the day when we sample the dark ionosphere. The local times of the CHAMP and GRACE orbits vary independently from each other.

Fig.2 shows the temporal variations of the electron density averaged over the trough region (58°-68° Mlat) separately for the two hemispheres. Both at CHAMP (450 -> 300 km) and GRACE (~480 km) heights we find large intra-annual variations of N_e (for more details on the altitude evolutions see Xiong et al., 2010). The curves reflect primarily the seasonal variation of the electron density in the ionospheric trough region. Rather prominent are the minima around local winters. Peak densities are obtained during local summers. This is different from equatorial regions, where N_e shows maxima in equinoxes and a minimum during June solstice [e.g. Rishbeth and Müller-Wodarg, 2006]. As a consequence of the global June solstice minimum the electron density peak values are smaller in the northern than in the southern hemisphere. During this low solar activity phase the N_e observations in the trough region track each other qualitatively quite well at the two altitudes. Interestingly, the electron density observed by CHAMP is significantly higher than that at GRACE during local summer, but during the dark seasons the N_e values at both altitudes attain on some days similar values. This means, the relative variation of N_e between the seasons is at CHAMP about two times larger than at GRACE.

In order to deduce the dependence of trough region electron density on solar activity, we have divide the data separately for the two hemisphere into the three Lloyd seasons, Equinox (Mar., Apr., Sep., and Oct.), June Solstice (May, June, July, and Aug.) and December Solstice (Nov., Dec., Jan., and Feb.). For this analysis all the data during quiet times ($K_p \leq 3.5$), from the start of the missions until end of 2009, are used. This provides readings over a much larger range of solar flux than shown in Figure 2. From Figs. 3 and 4, presenting CHAMP and GRACE data, respectively, we can see that the daily averaged trough N_e values show a good linear relationship with the solar flux index P10.7 during all seasons, The used solar flux index is defined as

$P10.7_t = (F10.7_t + F10.7A)/2$, where $F10.7A$ is the average solar flux index over 81 days

centered on the current day. As expected, during all the seasons, the slopes of the regression lines are bigger at CHAMP altitude than that at GRACE altitude. At both altitudes the slopes vary from season to season. They are bigger during Equinoxes and December solstice than around June solstice. In particular in Fig. 3 there are many readings from days with largely enhanced Ne values. These ‘out-layers’ can be related to days of magnetic storms.

Fig. 5 shows the electron density distribution of the subauroral trough as measured by CHAMP during the 5 years 2005-2010. Readings are presented in solar zenith angle versus longitude frames separately for the two hemispheres and the three seasons. As expected, Ne values become generally very small for solar zenith angles larger than 100° . Somewhat elevated electron densities are recorded during the local summer seasons. In the northern hemisphere Ne levels are well organized by the solar elevation angle with little dependence on longitude. Different from that, the longitude sectors around $100^\circ W$ and $60^\circ E$ in the southern hemisphere show quite interesting features. During all three seasons Ne is larger in $60^\circ E$ longitude sectors than in other sectors. Around December solstice the electron density high, extending from $140^\circ W$ to $20^\circ W$ longitude, can be associated with the Weddell Sea Anomaly. This southern summer feature is well known and has been described by several authors [e.g. Dudeney and Piggott, 1978; Horvath and Essex, 2003; Chen et al., 2011]. Our results confirmed that at both CHAMP and GRACE altitudes, the Weddell Sea Anomaly is prominent during December solstice. In case of the enhanced Ne around $60^\circ E$ an inspection revealed that in this sector a ton of higher electron density is extending from mid latitudes near the South Atlantic Anomaly south-eastward into the trough region. The GRACE satellites, flying more than 100 km higher, recorded much the same Ne distribution in the subauroral trough as CHAMP, but at reduced values (cf. Fig. 2). For that reason GRACE results are not shown here.

4. IRI signatures of the trough regions

One aim of this study is to test, how well the IRI model predicts the sub auroral trough region. For that purpose Ne values are calculated from IRI-2007 along the orbits of CHAMP and GRACE within the latitude ranges of the trough ($\pm 58^\circ - \pm 68^\circ Mlat$). The distribution of Ne obtained from IRI for the CHAMP case is plotted in a solar zenith angle versus longitude frame. From Fig. 6, we can see that the Ne distribution in the southern hemisphere is almost the same as in Fig. 5; however, the Ne values overall are slightly larger. We recognize around December solstice the Weddell Sea Anomaly at longitudes around $100^\circ W$, and during all seasons the electron density is enhanced around $80^\circ E$ longitude.

In the northern hemisphere the story is surprisingly different. Large electron densities are predicted for winter season at solar zenith angles up to 150° . Conversely, lowest Ne values are predicted around June solstice even at solar zenith angles of 60° . Furthermore, the Ne anomalies around $100^\circ W$ and $80^\circ E$ longitudes in the southern hemisphere appear also in the northern at similar longitudes. This result from IRI is in sharp contrast to the observations of CHAMP in the northern hemisphere. For completeness we have also calculated electron density from IRI along the GRACE orbit (not shown). The result is again very similar to that shown in Fig. 6.

In order to analyze the differences between IRI-derived electron densities, CHAMP and GRACE measurements more quantitatively we perform correlations between the data sets. Fig. 7 presents

the results from CHAMP altitude. In the southern hemisphere (bottom row) the correlation between model and measurement is rather good with correlation coefficients around 0.9. Only around December solstice, when the significant anomalies are present, the scatter is somewhat enhanced. It is quite obvious, however, that IRI values are systematically too larger. The average bias we have determined by taking the median value of all the differences between IRI and CHAMP *Ne* data. The bias amounts to about $50 \times 10^3 \text{ cm}^{-3}$, except for June Solstice there the bias is a little lower, about $30 \times 10^3 \text{ cm}^{-3}$. As expected, the correlation between model and measurement is poor for the northern hemisphere (Fig. 7, top row). While some relationship may be suggested for the equinox seasons, the correlation breaks down for June and December solstices. The results obtained for CHAMP altitudes are nicely confirmed by the corresponding GRACE data. The correlation analysis for the southern hemisphere, shown in the bottom row of Fig. 8, provides the same good coefficients as in the case of CHAMP. At GRACE altitude the bias of IRI *Ne* values is about $10 \times 10^3 \text{ cm}^{-3}$. For the trough in the northern hemisphere the GRACE measurements also confirm the poor performance of IRI. All these results indicate that the IRI-2007 model overestimates the trough electron density in the southern hemisphere and has a problem in the northern hemisphere.

5. Discussion

Based on 5 years data of CHAMP and GRACE observations, we have investigated the subauroral electron density trough in both hemispheres at two altitudes. At both altitudes an *Ne* minimum lower than at other latitudes is founded around 60° Mlat during dark periods. Compared to equatorial regions, where *Ne* shows maxima in equinoxes and a minimum during June solstice, the trough region *Ne* peaks during local summers and attains the valley during local winter. The interesting thing is that the peak value of *Ne* during local summer is almost two times larger at CHAMP altitude than at GRACE altitude while during local winter *Ne* at both altitudes attains on some days similar values at both heights although GRACE flies about 100km higher than CHAMP. This is caused by a beating of seasonal and local time effects, which is different for the two spacecraft. Moreover, the *Ne* peak values in the trough region show a clear decrease from 2005 to 2009 and reach a minimum between 2008 and 2009 (cf. Fig. 2). This minimum coinciding with low solar activity is also confirmed by low-latitude *Ne* observations [Lühr and Xiong, 2010], thermosphere density observations [Emmert et al., 2010] and GPS TEC observations [Liu et al., 2011].

According to observations by Lühr and Xiong [2010], the IRI-2007 model overestimates the equatorial region *Ne* by 50% in 2008 and 60% in 2009 both at CHAMP and GRACE altitudes. They suggest that this is mainly because the model strongly overestimates the equatorial ion fountain effect at daytime during the last extended solar minimum. In this study we also found that the IRI-2007 model overestimates the *Ne* value in the trough region by about 20% on average from 2005 to 2009 at CHAMP and GRACE altitudes. Without considering the bias the model predicts quite well all seasons in the southern hemisphere. The predicted *Ne* values become generally small, as expected, for solar zenith angles larger than 100° when the ionosphere is in shadow. IRI reflects quite well the larger values in the longitude sectors around 100° W (Weddell Sea Anomaly) near December solstice. Also the higher electron densities around 80° E of longitude are present during all seasons, which are qualitatively consistent with CHAMP and GRACE observations.

To our surprise, the IRI-2007 model predictions for the northern hemisphere are quite poor. The expected dependence on solar zenith angle during solstices is not reflected. Large Ne values show up in winter and very small during summer season. This is the reason for the complete break-down of the correlation with observations as shown in Figures 7 and 8. During equinoxes Ne predictions show much too large values around $100W^{\circ}$ at solar zenith angles above 130° , which does not make sense and is not consistent to our observations. The huge difference between observations and model estimation imply that the IRI-2007 model needs significant improvement to predict better the trough region in the northern hemisphere.

One purpose of this study was to find out the suitability of IRI predictions of the electron density in the trough region for calibrating TEC measurements derived from satellite GPS receivers. This task can be performed by IRI-2007 sufficiently well in the southern hemisphere, when considering the determined bias. The northern hemisphere trough predictions, however, are not suitable for this purpose with the present version of IRI.

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Figure 1. The north (top) and south (bottom) hemisphere electron density distribution of CHAMP (left) and GRACE (right) over Mlat from 2005 to 2010. For each panel dayside and night side is separated.

Figure 2. Electron density observed by CHAMP and GRACE in the trough regions of the two hemispheres. Readings within the region are averaged over 31 days.

Figure 3. Linear relation between electron density in the trough region and solar flux index, P10.7, at CHAMP altitude.

Figure 4. The same as Fig. 3, but for GRACE data.

Figure 5. The solar zenith angle/ longitude distribution of subauroral electron density at CHAMP altitude in southern (left) and northern (right) hemisphere, during Equinoxes (top), June solstice (middle) and December solstice (bottom).

Figure 6. The same as Fig. 5, but use the N_e derived from IRI-2007 model at CHAMP altitude.

Figure 7. Linear relationship between observed and modeled Ne values in the trough regions at CHAMP altitude.

Figure 8. The same as Fig. 7, but for GRACE altitude.