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Topside plasma scale height retrieved from radio occultation measurements

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Abstract

The plasma scale height is one of the important ionospheric characteristics due to its intrinsic connection to the ionospheric plasma temperature and composition, and thus to the shape of the electron density profile. Therefore, the knowledge of the plasma scale height values and variation is of crucial importance when addressing several open scientific and technological questions such as the upper ionosphere temperature balance, ion composition, storm dynamics, etc. While the plasma scale height value in the bottomside ionosphere can be deduced directly and reliably enough by vertical incidence sounding, the plasma scale height in the topside ionosphere is difficult to obtain. The ionospheric radio occultation (IRO) technique, based on low-earth-orbiting (LEO) satellites, is capable of delivering valuable information on the topside plasma scale height behaviour and of providing a rich database for consequent development of new empirical models of the plasma scale height and density. The purpose of this paper is to present a new procedure for retrieval of the topside plasma scale height value from IRO measurements by the LEO satellite CHAMP. First results from the analysis of the topside plasma scale height's temporal and spatial variations are also provided.

Keywords: Plasma scale height; Ionospheric radio occultation; Reconstruction techniques

1. Introduction

One of the most important characteristics of the ionosphere–plasmasphere system is the plasma scale height, defined as $H_P = kT_P/m_i g$, where T_P is the plasma temperature, T_i and T_e are the ion and electron temperatures, k is the Boltzmann's constant, m_i is the ion mass, g is the acceleration due to gravity. Practically, H_P is the vertical distance in which the plasma concentration changes by a factor of an exponent (e 2.718281828). Given its dependence on the plasma temperature and composition, both varying with altitude (Figs. 1 panel A and panel B), the plasma scale height value will obviously also vary with altitude (Fig. 1 panel C). The initial assessment of the topside ionosphere scale height and its intrinsic connection with the topside electron density profile (EDP) is of crucial importance for the reliability of various GPS TEC calculation and plasma density reconstruction techniques (Heise et al., 2002; Stankov et al., 2003). The CHAMP satellite (Reigber et al., 2003), orbiting the Earth in the altitude region from 450 down to about 300 km, provides excellent opportunities for observation of the topside ionosphere on a global scale, including the plasma scale height.

First results from the retrieval and analysis of the topside plasma scale height behaviour, based on CHAMP ionospheric radio occultation (IRO) measurements (Jakowski et al., 2002), are presented here. Latitudinal, seasonal, and diurnal variations have been already obtained. Considering the increasing number of low-earth-orbiting (LEO) satellites and the growing IRO measurement data base, it will be possible to develop a new empirical model of the topside plasma scale height to be used in several applications, such as improving the IRO-based EDP retrieval or various ionosphere–plasmasphere composition and dynamics.

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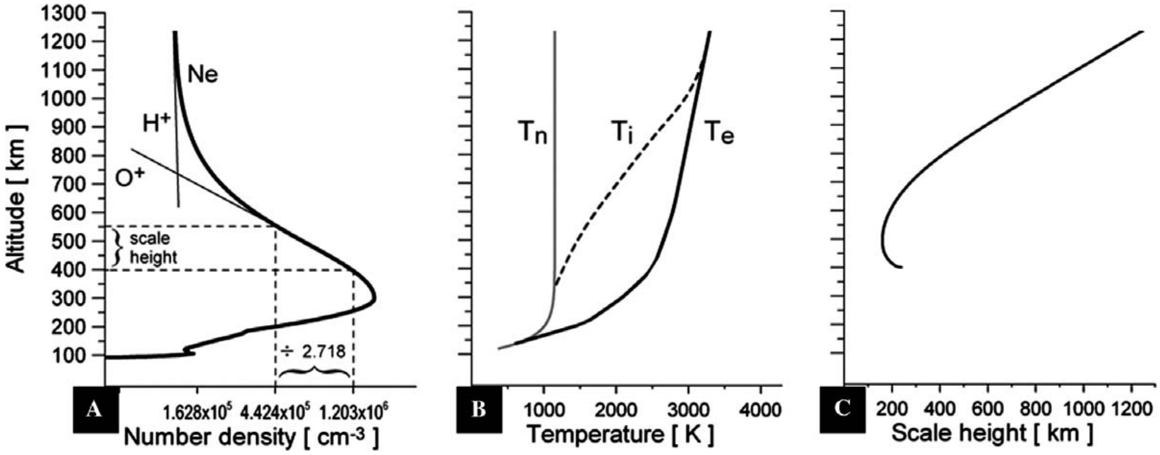

Fig. 1. Schematic view of the O^+, H^+, and Ne vertical density profiles (panel A), vertical profiles of the neutral (Tn), ion (Ti), and electron (Te) temperatures (panel B), and the topside plasma scale height deduced from the electron profile (panel C).

2. Scale height retrieval

The GPS ionospheric radio occultation (IRO) measurements, carried out onboard CHAMP, started on 11 April 2001. The dual frequency carrier phases of the GPS signals are used to compute the total electron content (TEC) along the 1 Hz sampled occultation ray paths. To enable consideration of the horizontal gradients, particularly during ionospheric storms and/or near the crest region, a tomographic approach (Jakowski et al., 2002) is utilised for retrieving the vertical refractive index profile instead of the widely used Abel inversion technique. An occultation event is defined by a series of TEC measurements along ray paths traversing the ionosphere with tangential heights that are decreasing to the bottom of the ionosphere. A system of linear equations is constructed for the electron density in the different shells. If the electron density distribution above the top shell (traversed by the first ray of the occultation event) is available a priori (first guess), e.g., from a model, then the electron density in this top shell can be deduced. Hence, starting from the top shell, the electron density in each shell below can be successively determined. Finally, the solution of the above-mentioned system provides the IRO-based vertical electron density profile.

Considering the CHAMP decaying orbit from 454 km at the beginning of the mission down to about 300 km at the end of the projected 5 year lifetime, special care is required when determining the upper boundary (at the CHAMP altitude) condition. This is due to the fact that the above-lying ionosphere and plasmasphere can contribute up to estimated 50% of the total signal. To overcome this problem, the inversion is assisted by an adaptive electron density model of the topside ionosphere and plasmasphere (TIP):

$$N_e(h) = N_mF_2 \exp(0.5(1 - z - \exp(-z))) + N_{P0} \exp(-h/H_{PP}), \qquad (1)$$

where $N_e(h)$ is the electron density, $z = (h - h_mF_2)/H_{PI}$, N_mF_2 and h_mF_2 are the peak electron density and height, H_{PI} is the plasma scale height in the topside ionosphere, H_{PP} is the plasma scale height (fixed at a constant value of 10,000 km) in the plasmasphere, and N_{P0} is the electron density at the plasmasphere basis. In the occultation retrieval, the free parameters N_mF_2, h_mF_2 and H_{PI} are adjusted iteratively, starting from some plausible values. The iteration process deliver a ‘smooth’ transition from TIP electron densities to the values computed from IRO data. This procedure yields directly the plasma scale height at the upper boundary of the retrieved electron density profile. A comparison between measurements of N_mF_2 and h_mF_2 deduced from IRO-based profiles and from ground ionosondes shows standard deviations of 18% and 13%, respectively (Jakowski et al., 2004). It should be stressed that in the original retrieval procedure (Stankov and Jakowski, 2005) the scale height value was obtained directly from the TIP formula (1), at 425 km altitude. In this way, considering the fact that we are using the Chapman ionospheric model to assist the reconstruction of the topside ionospheric electron density profile, H_{PI} is actually closer to the neutral gas (atmospheric) scale height in the topside ionosphere rather than the ‘real’ plasma scale height as deduced from the electron density profile. While the scale height value obtained directly from the TIP formula is very convenient for modelling/validation purposes, it will be better (in view of future comparison with other types of observations) to present here the ‘real’ plasma scale height value as deduced from the electron profile (Fig. 1 panel A). This ‘real’ value, at its minimum in the topside ionosphere (Fig. 1 panel C), is about two times larger than the value obtained from the formula.

3. Scale height behaviour

Using observations from one full year (April 2002–March 2003), an important insight into the plasma scale height behaviour has been acquired for various local time, season, and latitudinal conditions. During this period, the solar activity is on descent – the F10.7 monthly average falling from about 200 down to 120. Day-time and night-time conditions are presented. To minimise the dawn/dusk effects we have used data from variable local time ranges (windows) depending on season: larger windows are used for extracting summer day-time values and larger windows are applied on the winter night-time data. It should be noted however that in general, the day/night definition is not well suited for the polar regions and thus, the results from both polar regions should be interpreted with caution as data can be mixed (day-time with night-time observations). Diurnal variations are obtained using one hour periods but results are not yet reliable due to scarcity of data in some periods. To investigate the latitudinal variations, three main geomagnetic latitude regions are defined – low (0–30°N), middle (30–60°N), and high (60–90°N). The CHAMP IRO data has been checked for quality of retrieval (including data consistency check) and thus, the CHAMP data quality classification have been developed. The data quality ranges from 0 (highest quality) to 9 (lowest quality). In this study we have used only high (level 0) and good (level 1) quality values. Analysis of the latitudinal, seasonal, and diurnal variations is presented next. For the purpose, we have plotted the median values (solid circles) together with the number of observations on which the corresponding median is based (vertical bars).

3.1. Latitudinal variations

To better understand the latitudinal behaviour of the topside plasma scale height, the observations have been sorted into 10°-wide bins with respect also to the above defined night-time/day-time conditions and the three seasons (Fig. 2). During night-time, the plasma scale height tends to increase at higher latitudes. The increase is most obvious in the summer, when the median values range between 120 km over the equator and record 150 km over the poles. During the day, the latitudinal increase is generally preserved but with some exceptions, most notably during winter. At equinox, the day-time values increase from 125 to 130 km up to 140 km. In the summer, the scale height is on average higher – from 130 km over the equator to almost reaching 150 km in the polar regions. The winter-time distribution presents the most intriguing case when the median values in the equatorial region are around 135 km and are of similar magnitude as those from the polar regions. At the same time, a pronounced decrease is observed in the middle latitude band where the scale height drops below the 100 km mark. This phenomenon is probably due to the ion trough and/or serious violation

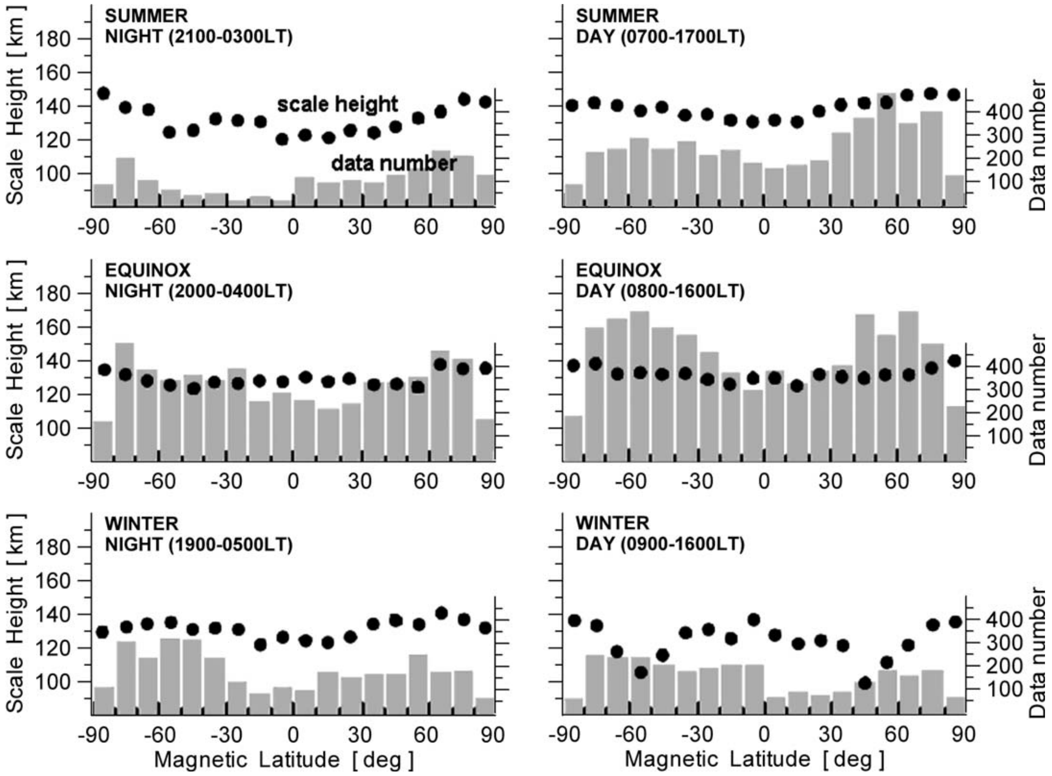

Fig. 2. Topside plasma scale height deduced from CHAMP IRO measurements. Observed latitudinal variations in winter (bottom panels), equinox (middle panels), and summer (top panels), during night-time (left panels) and day-time (right panels) conditions. For the high/polar latitude regions (70°, 90°), the 'summer night' and 'winter day' plots may contain data from both day- and night-time conditions.

of the diffusive equilibrium conditions, e.g., when strong vertical plasma fluxes occur.

3.2. Seasonal (annual) variations

Preliminary estimations of the seasonal scale height behaviour have been obtained for the Northern hemisphere (Fig. 3). Night-time, the data are relatively scarce and highly dispersed, particularly in the winter. Nevertheless, the results show small season-to-season differences but the average increase from lower to higher latitudes is obvious. Day-time, the seasonal differences are larger and far more evident. The largest summer/winter ratio is observed at middle latitudes; there, the winter-time minimum is approximately 100 km and the summer-time maximum is near 150 km, an impressive increase of about 50%. Again, the average scale height increases toward higher latitudes.

3.3. Diurnal variations

Due to correlation with the plasma temperature, the plasma scale height is expected to be higher during the day and lower during the night. Although this is what is generally observed, the diurnal behaviour is actually quite complex. The figure shows significant increases of about 12% in the morning, noon, and evening values. A closer look into the data reveals that the high values at noon come from summer-time observations, while the morning and evening rises come mostly from winter-time observations (Fig. 4, top panels). As mentioned before, the data base is limited in some time intervals, so it is too early to draw definitive conclusions. However, an interesting correlation is detected between the plasma scale height and equivalent slab thickness (TEC/N_mF_2) measurements. For comparison, median values of the winter-time and night-time scale height are plotted together with corresponding slab thickness estimations over an ionosonde station in the same latitude band (Fig. 4, bottom panels). The correlation is obvious in the winter morning and evening hours, despite the fact that the scale height observations are made during high solar activity and the ionosonde observations are gathered during a period of low solar activity. There are also substantial differences between the diurnal behaviour of the scale height at different latitudes but additional data are required for a proper analysis of these deviations.

3.4. A note on the longitudinal variations

It is well known that the ionospheric *F* region experiences noticeable differences along geographic/geomagnetic longitude due to the characteristics of the geomagnetic field. In addition, diurnal, latitudinal, and longitudinal variations of both the plasma density and composition, in combination with the zonal and/or meridional neutral winds, can cause pronounced differences of the electron temperature between different longitude zones, between different seasons and hemispheres. It should be then natural to expect longitudinal differences in the shape of the electron profiles and from there to expect changes in the scale height, too. Our results however show no indication

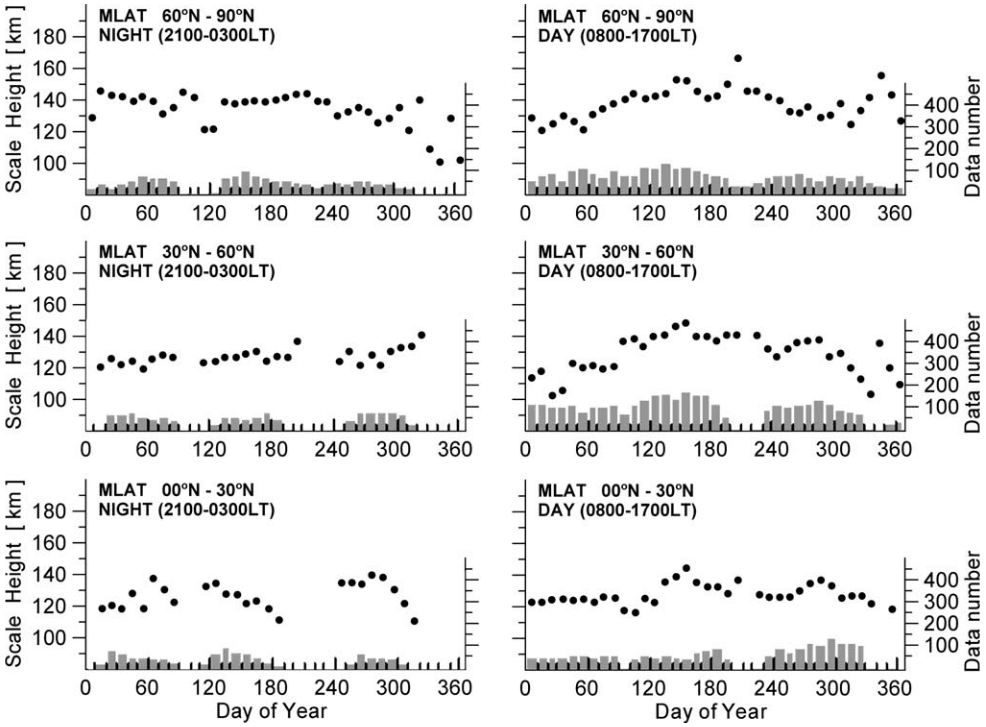

Fig. 3. Topside plasma scale height deduced from IRO measurements – observed annual variations in winter (bottom panels), equinox (mid panels), and summer (top panels) during night-time (left-hand panels) and day-time (right-hand panels) conditions.

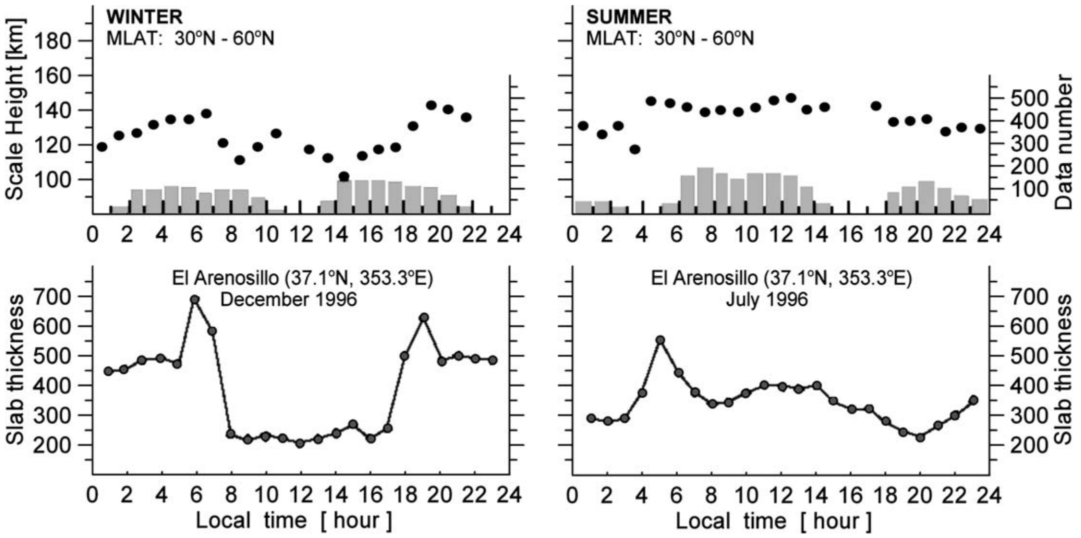

Fig. 4. Topside plasma scale height deduced from IRO measurements – observed diurnal variations at middle latitudes during winter (top left-hand panel) and summer (top right-hand panel) conditions. Comparison is made with slab thickness (TEC/N_mF_2) calculations at the El Arenosillo (37.1N,6.7W) ionosonde station (bottom panels). Notice the relatively good correlation between scale height and slab thickness values, particularly at the winter-time morning and evening hours.

of major geomagnetic longitude differences, probably due to insufficient measurements yet. We have therefore ignored the eventual existence of longitudinal variations when analysing the other types of variations.

4. Summary and conclusions

We presented first results from the retrieval and alalysis of the topside plasma scale height using IRO measurements onboard CHAMP. It has been shown that it is possible to utilise these observations for acquiring a valuable knowledge of the plasma scale height behaviour. First and foremost, it has been proven that the topside plasma scale height depends strongly on the ionosphere–plasmasphere temperature, composition and dynamics. Second, it is clear that the scale height generally increases in poleward directions, particularly during equinox and summer. Third, strong seasonal differences are observed at middle latitudes where day-time median values in summer are about 50% higher than in winter. Fourth, diurnal variations appear to be very complex and additional data are needed. Fifth, no significant hemispheric differences are detected. Finally, after considering the analysis of the scale height variations, a new empirical model is currently being developed. In this model, the plasma scale height is approximated by a multi-variable polynomial delivering the scale height values with respect to geomagnetic latitude, local time, and season. The method of least-squares fit is applied for determining the coefficients. Model results can be directly implemented into the density profile retrieval procedure by delivering an improved initial guess.

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