Topside plasma scale height modelling based on CHAMP measurements: first results

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Summary. Presented are first results in retrieving, analysing, and modelling the topside plasma scale height with the help of CHAMP ionospheric radio occultation observations. The value of the scale height, at and immediately above the ionospheric F2-layer density peak altitude, is of crucial importance for the GPS TEC calculation and plasma density reconstruction procedures. Based on the accumulated year-long time series data, obtained were diurnal, seasonal, and latitudinal variations of the topside plasma scale height. Considering the growing CHAMP measurement data base, it will be possible to develop a new empirical model to be used for improving the process of electron density profile retrieval by delivering an improved initial guess.

Key words: Scale Height, Occultation Method, Empirical Modelling

1 Introduction

One of the most important characteristics of the ionosphere-plasmasphere system is the plasma scale height, defined as $H_P=kT_P/m_ig$, where $T_P=0.5(T_i+T_e)$ is the plasma temperature, T_i and T_e –ion and electron temperatures, k – Boltzmann's constant. Considering its dependence on the plasma temperature and composition, obviously H_P varies with altitude. The value of the scale height in the topside ionosphere region -- the region situated immediately above the height (h_mF_2) of the ionospheric F2 peak electron density -- is of particular 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 350 km, provides excellent opportunities for observation of the topside ionosphere on a global scale, including the plasma scale height.

The purpose of this paper is to present first results in retrieving, analysing, and simulating the topside plasma scale height with the help of CHAMP occultation measurements. A scale height value is deduced directly from a vertical electron density profile reconstructed via ionospheric radio occultation (IRO) measurements (Jakowski et al., 2002). Latitudinal and seasonal variations of the plasma scale height have been obtained for both day-time and night-time conditions. Considering the steady growing CHAMP measurement data base, it will be possible to develop a new empirical model of the plasma scale height to be used in several applications - improving the retrieval of IRO-based electron density profiles by delivering an improved initial guess, further developing novel reconstruction techniques, investigating the ionosphere-plasmasphere composition and dynamics.

2 GPS Radio Occultation Measurements of the Ionosphere

The ionospheric radio occultation (IRO) measurements, carried out onboard CHAMP, started on 11 April 2001. Because the horizontal gradients can be quite large, 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. 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.

An occultation event is defined by a series of TEC measurements along ray paths traversing the ionosphere with tangential heights of these ray paths decreasing to the bottom of the ionosphere. Constructed is a system of linear equations 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.

3 Scale Height Retrieval

The plasma scale height is deduced directly from the electron profiles reconstructed from the IRO measurements. 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):

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

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 10000km) 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.

4 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. Three seasons are considered - winter, equinox, and summer, defined as 91 day periods centred on the 356, 81 and 264, 173 day of year, with respect to the opposite seasons in both hemispheres. Day-time and night-time conditions are investigated using 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. 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, 3 main geomagnetic latitude regions are defined – low (0-30°N), middle (30-60°N), and high (60-90°N). In this study we have used only high-quality values (checked for consistency). To give an idea of what the scale height measurements are in terms of quantity as well as temporal and spatial distribution, presented in Fig.1 are the scale height's latitudinal (day-time only) and diurnal (all seasons together) observations with their corresponding median values.

The latitudinal behaviour is relatively well manifested during the equinoxes. Medians increase in pole-ward directions from a minimum of 62 km up to a maximum of 70 km. Detected is also larger data scattering at higher latitudes.

Due to the vigorous selection process and the relatively short time series of observations, the data are scarce in some local time intervals which impedes the analysis of the diurnal variations. However, as seen from Fig.1(right) significant variations are expected with pronounced peaks formed in the morning, noon and evening hours.

A more detailed analysis of the latitudinal, diurnal, and seasonal variations is presented next. To facilitate the analysis, plotted are the median values (solid circles) together with the number of observations on which the corresponding median is based (bars).

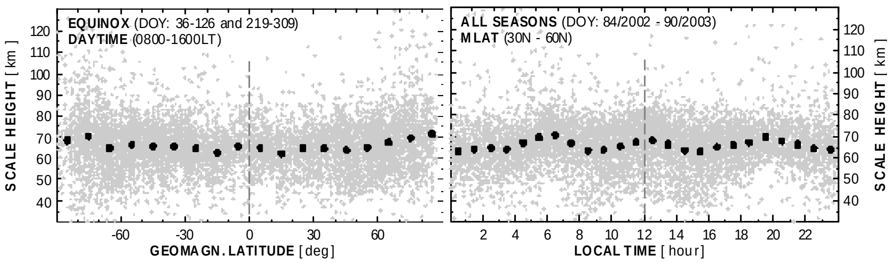

Fig. 1. Topside plasma scale height deduced from IRO measurements – individual measurements (dots) and median values (solid circles). Fig.1(left): latitudinal variations at day-time equinox conditions. Fig.1(right): diurnal variations at middle latitudes and all seasons.

4.1 Latitudinal variations

To better understand the latitudinal behaviour of the plasma scale height, both night-time and day-time measurements have been sorted according to season (Fig.2). During night-time, the plasma scale height tends to increase at higher latitudes. The increase is most obvious in summer, when the median values range between 60 and 74 km. During day-time, the latitudinal increase is generally preserved, but with a few exceptions. At equinox, the values increases from 63 to 70 km. At summer, the scale height is higher – it averages 65 km over the equator and increases up to the record 74 km over the poles. An interesting case is the winter-time distribution – the median values in the equatorial region are around 68 km and are of the same magnitude as the median values over the poles. At the same time, a pronounced decrease is observed in the 45°-55° latitude band where the scale heights drop even below the 50 km mark. This phenomenon is probably due to the ion trough and/or serious violation of the diffusive equilibrium conditions, e.g. when strong vertical plasma fluxes occur (Jakowski et al., 1981).

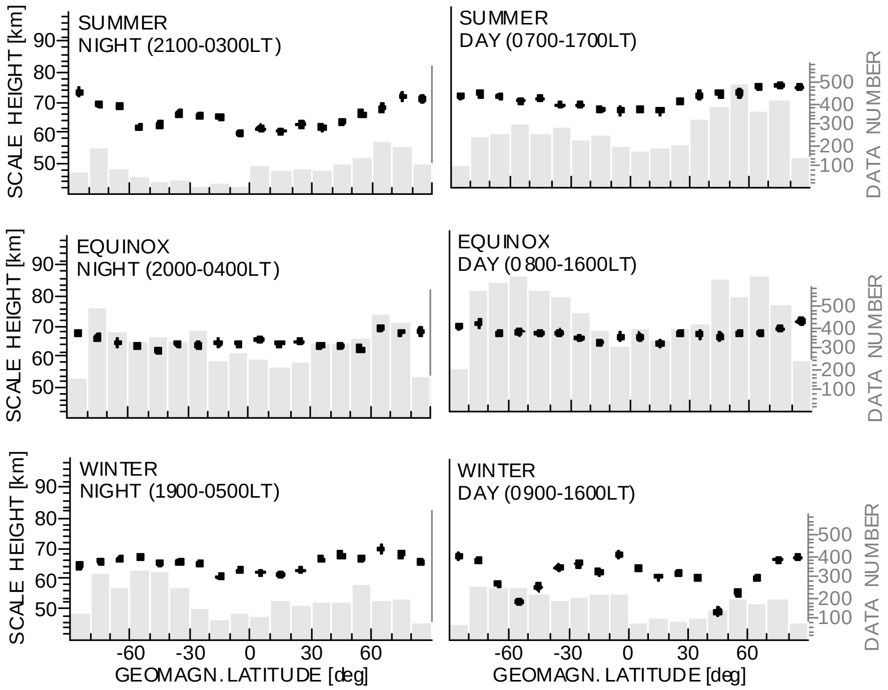

Fig. 2. Topside plasma scale height deduced from IRO measurements – observed latitudinal variations during winter (bottom panels), equinox (middle panels), and summer (top panels) conditions.

4.2 Diurnal variations

Due to the 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 much more complex, as it was already suggested by Fig.1(right) where data from all seasons and middle latitudes were assembled. 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.3, top panels).

As mentioned before, the data base is limited in some time intervals, so definitive conclusions is too early to make. However, an interesting correlation is detected between the plasma scale height and equivalent slab thickness (TEC/N_mF_2) measurements. For comparison (Fig.3), 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. As seen in the figure, the correlation is very strong, particularly in winter, 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.

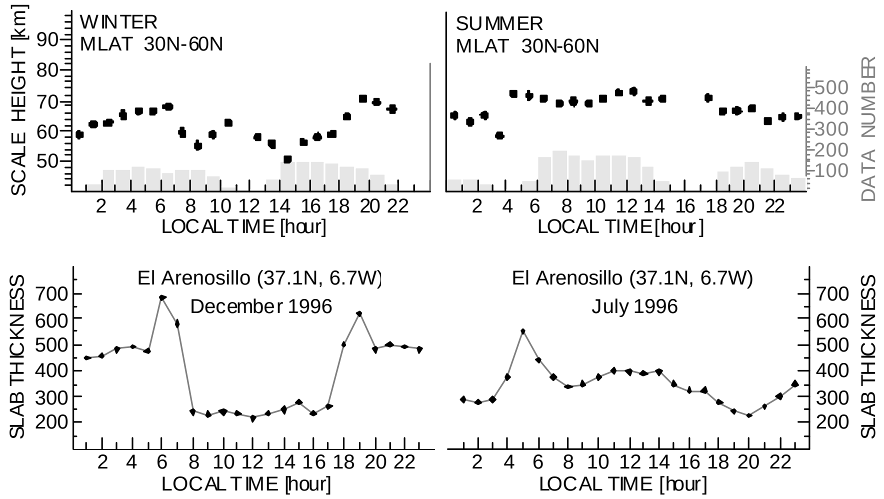

Fig. 3. Topside plasma scale height deduced from IRO measurements – observed diurnal variations at middle latitudes during winter (top left-hand panel) and summer (top right-hand panel) conditions. Comparison is made with slab thickness (TEC/N_mF_2) calculations at the El Arenosillo (37.1N,6.7W) ionosonde station (bottom panels). Notice the relatively good correlation between scale height and slab thickness values, particularly at the winter-time morning and evening hours.

4.3 Seasonal (annual) variations

Having IRO observations from a full year, preliminary estimations of the seasonal differences in the scale height behaviour are possible to obtain. Here, presented are results (Fig.4) from the Northern hemisphere only.

Night-time, the seasonal differences in the median values are relatively small. However, the latitudinal increase is obvious – the median value (calculated over the whole year) increases from about 64 km at low latitudes up to about 71 km at the highest latitudes.

Day-time, the seasonal differences are larger and hence, are far more evident. The latitudinal increase is again preserved. Strongest seasonal differences are observed at middle latitudes where the winter-time minimum is at 51 km and the summer-time maximum is at 74 km, a quite impressive increase of about 45%. And if the differences in the median values are so large, one should certainly expect even larger differences in the individual scale height values.

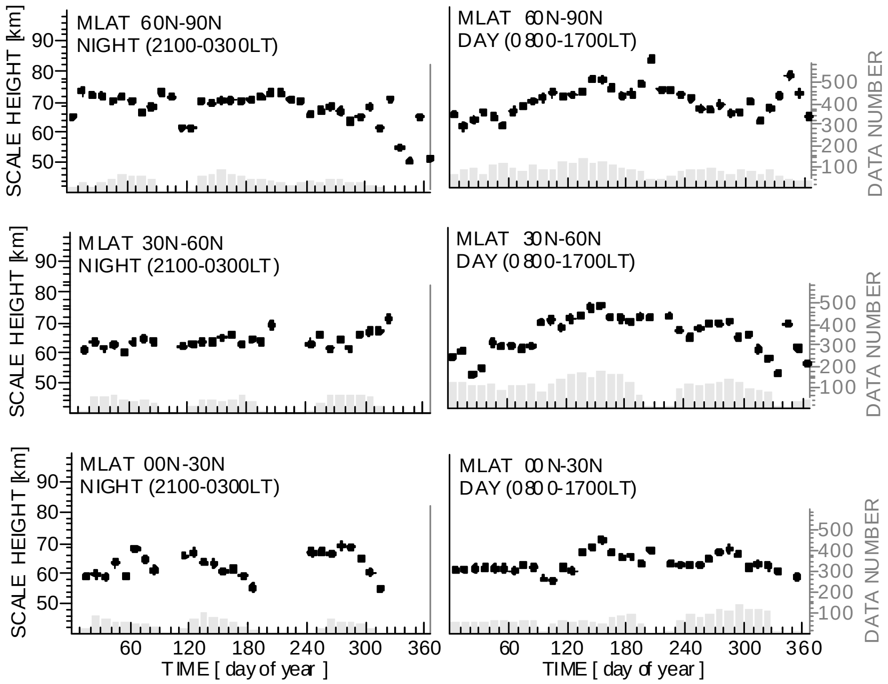

Fig. 4. Topside plasma scale height deduced from IRO measurements – observed annual variations in winter (bottom panels), equinox (mid panels), and summer (top panels) during night-time (left-hand panels) and day-time (right-hand panels) conditions.

5 Empirical modelling of the plasma scale height

Considering the analysis of the plasma scale height variations, it becomes quite obvious that an empirical model would be very helpful for many purposes.

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:

$$P(C,N;X) = \sum_{I} C(I).G(I,X) = \sum_{i_1=1}^{n_1}\sum_{i_2=1}^{n_2}\sum_{i_3=1}^{n_3} C(i_1,i_2,i_3).g_1(i_1,x_1).g_2(i_2,x_2)g_3(i_3,x_3)$$

where

$C(I) = C(i_1,i_2,i_3)$ - coefficients

$G(I,X) = g_1(i_1,x_1)\,g_2(i_2,x_2)\,g_3(i_3,x_3)$ - generalised basis function

$N = (n_1,n_2,n_3)$ - number of basis functions

$I = (i_1,i_2,.i_3)\ ,\quad i_m = 1,2,\ \dots\ ,\ n_m\ ;\quad m = 1,2,3$ - indices

$X = \prod_{m=1}^{3}[x_L^{(m)}, x_R^{(m)}]\ ,\quad x \in X \subset \Re^3$ - variables

and the set (g_1, g_2, g_3) is a system of linearly independent functions on the domain of the $m^{\text{-th}}$ parameter x_m , e.g. algebraic basis (1, x, x^2, ...). The method of least-squares fit is applied for determining the coefficients.

Based on the year-long measurements and the analysis presented in the previous parts, a preliminary version of the described model has been already prepared and some exemplary model calculations are given in Fig.5. The model is regularly being upgraded in step with the growing IRO measurement database. When possible, longitude and solar activity dependence will be also included.

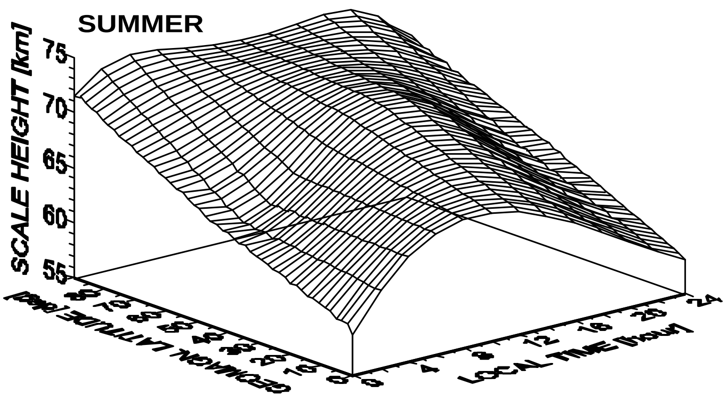

Fig. 5. Exemplary model calculations of the plasma scale height for summer conditions: latitudinal vs. diurnal variations.

6 Conclusions

Presented were first results from retrieving, analysing, and modelling the topside plasma scale height using IRO measurements onboard CHAMP. Several conclusions can be made at this stage of the investigations.

First and foremost, it has been proved 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 daytime median values in summer are about 45% higher than in winter.

Fourth, diurnal variations appear to be very complex and additional data is needed.

Fifth, no significant hemispheric differences are detected.

A new empirical model is being developed, which will be capable of delivering the scale height with respect to latitude, local time, and season. Model results can be directly implemented into the density profile retrieval procedure by delivering an improved initial guess.

Finally, it has been shown that it is possible to utilize the IRO observations onboard CHAMP for acquiring a valuable knowledge of the plasma scale height behaviour, which in turn can be successfully applied in the development and improvement of electron density reconstruction techniques, development and validation of both empirical and theoretical models, and ionosphere composition studies.

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