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BOOK OF ABSTRACTS

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Ionospheric Radio Occultation Measurements Onboard CHAMP

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The GPS radio occultation measurements of the ionosphere have been performed onboard CHAMP since 11 April 2001. More than 115000 vertical electron density profiles have been derived so far by a model assisted retrieval technique. The talk addresses the capabilities of the ionospheric radio occultation (IRO) technique for routinely monitoring the global ionosphere with the purpose of deriving value added data products and studying ionospheric perturbations. Discussed are the model assisted retrieval technique, operational data processing and results from the validation of vertical electron density profiles. These profiles may not only be used to validate other models, but they also provide a good data basis for developing new models of key ionospheric parameters such as the critical frequency, density peak height, and plasma scale height. Such models would help us to improve retrieval procedures and tomographic reconstruction techniques.

Travelling ionospheric irregularities (TIDs) and other types of ionospheric irregularities may be studied on the basis of CHAMP radio occultation measurements. Shown are the latitudinal distribution and the diurnal and seasonal dynamics of the irregularities. The most prominent feature is the significant enhancement of winter time TID activities over the polar regions. Thanks to the operational data processing capabilities, the data products may also contribute to the space weather monitoring of the ionosphere.

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Abstract

GPS radio occultation measurements of the ionosphere have been performed onboard CHAMP since 11 April 2001 and a large number of vertical electron density profiles have been derived so far by a model assisted retrieval technique. Presented here are model assisted retrieval techniques, operational data processing, and results from the validation of vertical electron density profiles. Discussed also are the capabilities of the ionospheric radio occultation (IRO) technique for routinely monitoring the global ionosphere with the purpose of studying ionospheric perturbations and deriving value added data products.

1. Introduction

The Global Navigation Satellite System (GNSS) ionospheric radio occultation (IRO) technique using Low Earth Orbiting (LEO) satellites is a novel space-based technique which has proved to be a powerful, yet relatively inexpensive tool for deducing the electron density in the entire ionosphere (Jakowski et al., 2002; Heise et al., 2002). No other profiling technique, neither the vertical sounding nor the incoherent scattering, can deliver vertical profiling through the entire ionosphere with global coverage.

This paper presents the IRO technique, details its capability for reconstructing the ionosphere structure, and discuss some of the applications. However, before using it in research, the accuracy and reliability of the retrieval technique must be estimated; so reported first are validation results obtained by using independent data sources. The applications are numerous. For example, several important ionospheric characteristics and phenomena can be further investigated, e.g. the equatorial and winter anomalies, the ion trough, the electron profile expansion due to increase in the solar energy input, etc. Ionospheric irregularities and can also be studied with the help of the radio occultation measurements. One of the prominent features found so far is the significant increase in the intensity of these irregularities over the geomagnetic equator and the polar regions. Finally, addressed are the modelling efforts. On the one hand, the IRO derived electron profiles provide a good data basis for developing new models of key ionospheric parameters (such as the peak density (NmF2), peak density height (hmF2), plasma scale height (Hp), total electron content (TEC), etc.), and can be used to validate other models. On the other hand, models can also help improving the retrieval procedures and tomographic reconstruction techniques.

2. CHAMP IRO retrieval technique

The German CHAMP (CHAllenging Minisatellite Payload) satellite was successfully launched into a near polar orbit, inclination 87° and altitude 450 km, on 15 July 2000. The satellite is equipped with a dual frequency «Black Jack» GPS receiver which enables not only the analysis of the 0.1Hz sampled navigation data (precise time and orbit information) but GPS radio occultation measurements as well. The receiver measures GPS carrier phases in the radio occultation or limb sounding mode starting at CHAMP orbit tangential heights down to the Earth surface with a sampling rate of 1Hz. Furthermore, the 0.1 Hz sampled navigation data may be used for reconstructing the topside ionosphere electron density distribution by data assimilation (Heise et al., 2002). The measured GPS data are automatically checked and pre-processed by a highly flexible operational processing system (Wehrenpfennig et al., 2001). The processing flexibility is achieved thanks to the modular structure of the processing system in which the retrieval modules can be replaced and upgraded in the course of the CHAMP mission.

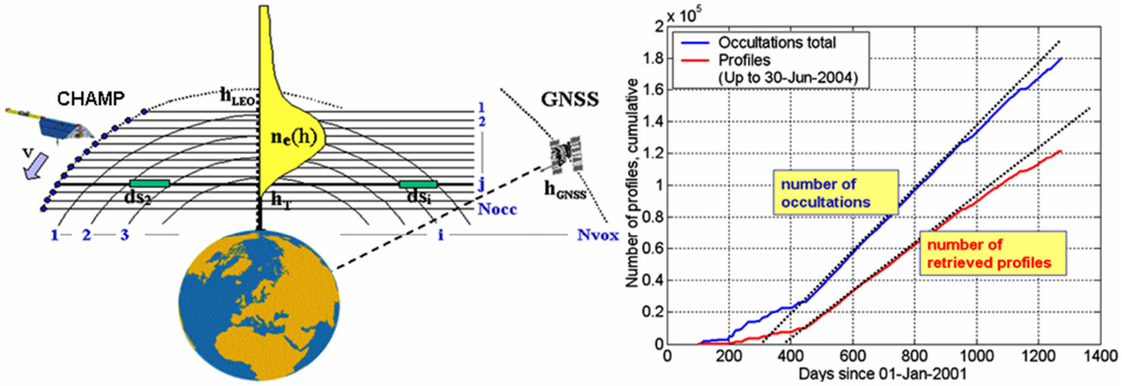

Fig.1. Left: Illustration of the retrieval technique based on CHAMP measurements. Right: GPS-CHAMP radio occultation statistics: total number of occultation events (blue line) and number of successfully retrieved electron density profiles (red line).

Since a large number of ionospheric phenomena are accompanied by (or due to) strong spatial plasma density gradients, and furthermore, because the path through the ionosphere is of length in the order of 1000 – 2000 km, the spherical symmetry assumption of the Abel inversion technique does not, in general, hold. To overcome this methodological restriction, a tomographic solution is required. The tomographic approach (Fig.1, left) developed for the CHAMP data analysis (Jakowski et al., 2002), has the advantage that additional information (e.g. horizontal gradients) from ground based GPS measurements, models and/or other sources can easily be included in the reconstruction of the electron density profile, at least in the post-processing phase. Considering the GPS signal frequencies $L1$ and $L2$, the ionospheric phase delay d_I may be estimated in a first - order approximation by $d_I = \frac{K}{f^2}\int n_e ds$, where K=40.3[m^3s^{-2}], f is the signal frequency, and n_e is the electron density along the ray path s . Due to frequency dispersion, the difference of $L1$ and $L2$ phases may be used to remove all other variable ranging parameters. Thus, the differential GPS phases provide the total electron content along the ray path through a spherically-layered voxel structure. The measured line integral TEC is the sum of the product $n_e \times ds_i$ where n_e is the mean electron density in voxel i and ds_i corresponds to the ray path length in voxel i at measurement j. Simulations have shown that the ray path bending can be ignored in a first-order approximation; hence, the ray path elements can be computed easily according to the satellite geometry defined by the positions of the transmitting GPS satellite and the LEO satellite where the signal is received. The electron density of different shells can successively be derived from a series of 1s sampled measurements j when the tangential point of occultation rays comes closer and closer to the Earth down to the bottom of the ionosphere. If the satellite orbit is well above the $F2$ layer peak, as in the case of the Oerstedt and SAC-C satellites, the comparatively small plasmasphere contribution can be considered to be constant. This simplifying assumption cannot be applied to the CHAMP IRO retrieval algorithms because CHAMP has a rather low orbit height of less than 450 km, which will even further decrease with mission time. To overcome this upper boundary problem, a specific model assisted technique has been developed for the CHAMP data analysis. Practically, the solution starts with the first measurement at the greatest tangential height by using an adaptive model for the topside ionosphere and plasmasphere above the CHAMP orbit height. This adaptive model consists of a Chapman layer whose topside part is extended by a slowly decaying exponential term with a fixed scale height value of 10000 km. Key model parameters such as the plasma scale height at the upper boundary are determined in a few iterations in order to ensure a smooth transition between model values and measurements. It has been found that the crucial element for improving the solution of the upper boundary problem is the topside scale height. To fulfil operational requirements, i.e. to come up with retrieval products within a latency of less than 3 hours, no further data are included in the retrieval procedure and. for reasons of simplicity a spherically layered ionosphere is assumed. The retrieval can be improved if additional information, e.g. on horizontal gradients or local densities, is included in the retrieval procedure.

Horizontal gradients for example, can be deduced from the TEC maps such as those produced from ground based GPS measurements in DLR Institute of Communications and Navigation. On average, from about 200 IRO measurements per day, about 150 electron density profiles (EDPs) are successfully retrieved (Fig.1, right). Because the processing system works automatically, some EDP outliers cannot be avoided; however, the number of such outliers is less than 1%.

3. CHAMP IRO validation

The quality of the CHAMP IRO retrieval technique has been extensively validated using measurements from other techniques – vertical sounding, incoherent scattering, in-situ probing, etc.

IRO retrieved electron density profiles have been compared with vertical sounding measurements from the following digital ionosonde stations: Juliusruh (54.6°N; 13.4°E), Athens (38.0°N; 23.5°E), Rome (41.9°N; 12.5°E), Tortosa (40.8°N; 0.5°E) and Dourbes (50.1°N; 4.6°E). For example, a comparison made with data from the Juliusruh station during the first year of CHAMP IRO measurements yielded quite good results (Fig.2), particularly in the vicinity of the F2 peak density. A follow-on study however, involving all stations and data from the second year of the CHAMP mission, indicates a positive bias of the IRO data in the order of 0.5 MHz and a standard deviation from the mean of about 1 MHz throughout the entire profile.

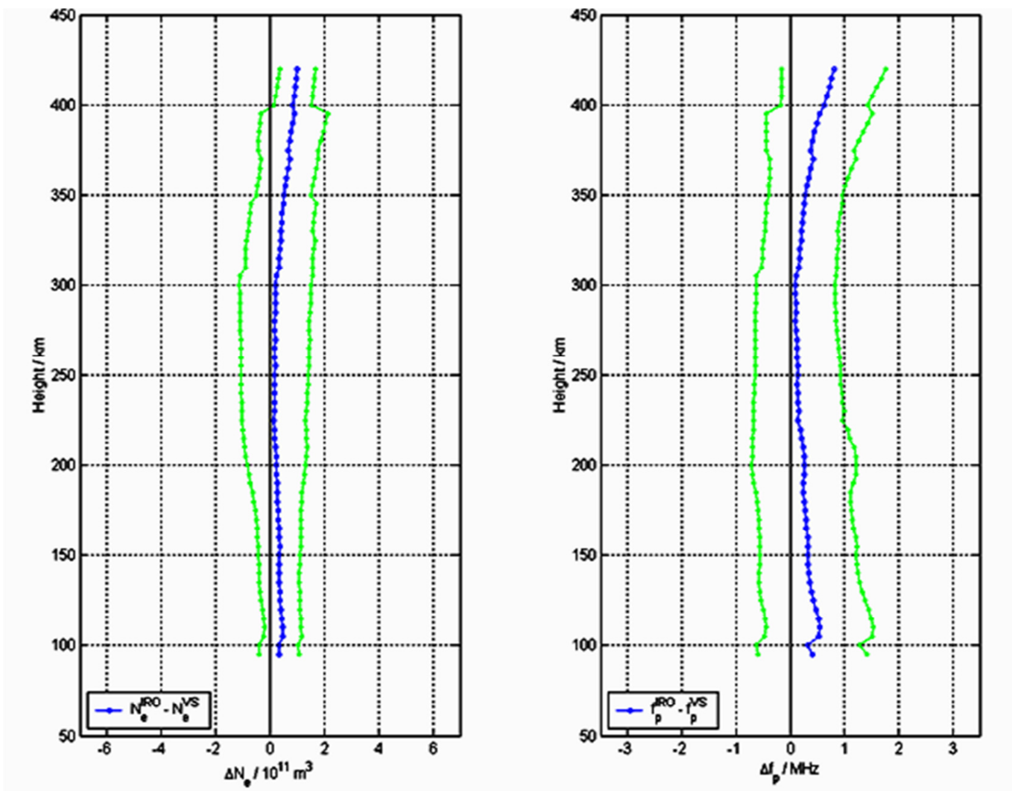

Fig.2. Statistical comparison of electron density profiles retrieved from IRO and VS at Juliusruh (54.6°N, 13.4°E), coincidence radius of 6° and time window of 15 min, 228 profiles retrieved from 29/04/2001 to 30/06/2002. Left panel: electron density, N_e(IRO)- N_e (VS). Right panel: plasma frequency, f_p(IRO)-f_p(VS).

Comparisons were also made between CHAMP IRO and EISCAT (European Incoherent Scatter) vertical electron density profiles (Fig.3). For the retrieved profiles to be considered, observations were required to 'coincide' spatially (cross section diameter of up to 1600 km) and temporally (time window of up to 30 minutes). It was found that the majority of profiles agree well within the error ranges of both methods (Stolle et al., 2004).

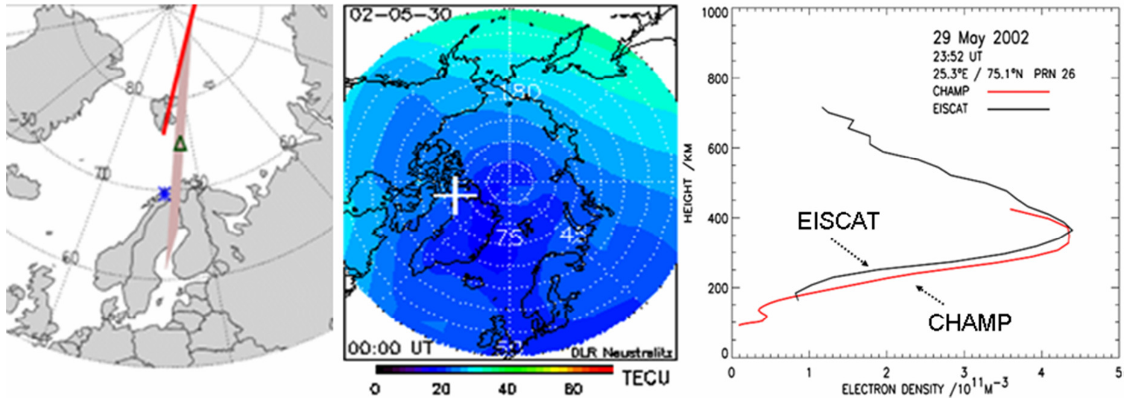

Fig.3. Comparison between CHAMP IRO and EISCAT measurements, 29 May 2002, 23:52UT. Left panel: the scheme of measurements. Middle panel: the polar TEC map at the time of measurements. Right panel: the retrieved vertical electron density profiles.

Another opportunity to evaluate the accuracy of the IRO technique was the comparison with direct electron densities measured by the planar Langmuir probe onboard CHAMP. The comparison of the in-situ densities with the upper start values of the electron profiles showed a quite consistent correlation (Jakowski et al., 2002).

Beside the above-mentioned studies, comparison with reconstruction results from the Multi-Instrument Data Analysis System (MIDAS) algorithm was also performed. The algorithm is designed to assimilate data from a number of different measurement techniques, thus allowing the spatial and temporal factors to be accounted for during the inversion process. For the purpose, various types of ionospheric data have been collected: International GPS Service (IGS) network data, true height profiles from vertical ionograms, Navy Ionospheric Monitoring System (NIMS) observations from Italy, etc. The experimental results proved an excellent agreement between the specification of ionospheric electron concentration using MIDAS and CHAMP IRO measurements (Spalla et al., 2003).

4. CHAMP IRO applications

4.1 Topside plasma density reconstruction

New techniques for retrieving the topside electron density distribution from space-based observations of the total electron content have been developed and used for studying various ionospheric phenomena. For example, one of the reconstruction techniques is based on GPS data pre-processing, calibration of link-related TEC, and assimilation of calibrated TEC into a suitable ionospheric model. During the pre-processing stage, detected outliers are being removed and cycle slips corrected. The ionospheric combination of GPS pseudo ranges and carrier phases is used to derive the TEC value; the latter being consistently calibrated for receiver and satellite differential group delay biases. The calibration of numerous link-related TEC values for instrumental biases is performed with the help of parameterized ionospheric models. After calibrating the differential phases, the absolute TEC data are assimilated into a parameterized ionospheric model by a method which ultimately delivers a 3D reconstruction of the electron density for each CHAMP revolution (Heise et al., 2002). Another example is the reconstruction method combining various types of measurements – space-based IRO data, ground-based vertical sounding, and empirical values of the upper ion transition height. By assuming adequate topside density distribution, the profile reconstruction technique derives the unknown topside ion scale heights and the corresponding ion and electron density profiles (Stankov et al., 2003). Some of the important applications of the above-mentioned methods include the development and evaluation of empirical and theoretical ionosphere-plasmasphere models.

The knowledge of the plasma scale height behaviour can substantially help the GNSS-based TEC calculation, plasma density reconstruction procedures, and modelling efforts. IRO can actually deliver values of the topside plasma scale height (Fig.4, right top panel); each value is retrieved from an EDP at the upper boundary region of the measurements. The experience proves that the topside scale height depends strongly on the ionosphere-plasmasphere temperature (notice the increased values in the summer hemisphere), composition and dynamics. Considering the growing CHAMP measurement data base, it will be possible to develop a new empirical model to be used for accelerating/improving the process of electron profile retrieval by delivering an improved initial guess (currently fixed at 80 km) on the scale height value. Another important ionosphere characteristic, the equivalent slab thickness, $\tau = TEC / N_m F_2$, can also be deduced from IRO profiles (right bottom panel).

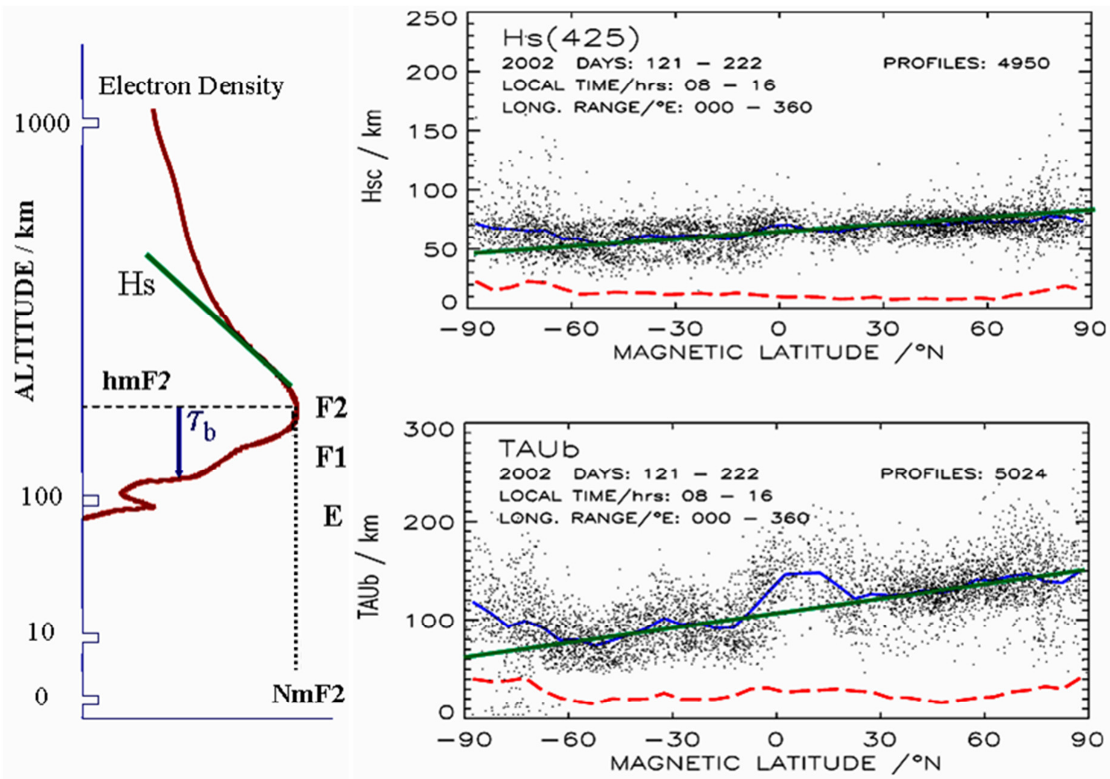

Fig.4. Left: Schematic view on the electron density profile and its main characteristics. Right: Latitudinal distribution of the topside scale height at 425 km (top panel) and the equivalent slab thickness (bottom panel); assembled from all local time and longitude sections, and days 121-222 of year 2002. Dashes represent the standard deviations.

4.2 Investigation of major ionospheric phenomena

The CHAMP IRO experiment provides actual information on the global state of the ionosphere; the lack of global coverage is one of the major deficiencies of the ground-based observations. Also, IRO measurements are easier to compare with other satellite-based observations. There are two prominent features of the ionosphere which can easily be detected and monitored via the occultation measurements - the mid-latitude ion trough and the equatorial crest. The ion trough is characterized with abrupt gradients in the electron density within relatively short horizontal distances; both its extent and depth vary strongly in latitude, longitude, local time, season, solar activity and geomagnetic activity. The equatorial crest is characterized with increased electron density on both sides of the geomagnetic equator and also manifests large variability including winter-summer and north-south asymmetries, rapid diurnal and seasonal changes, solar activity dependence, etc.

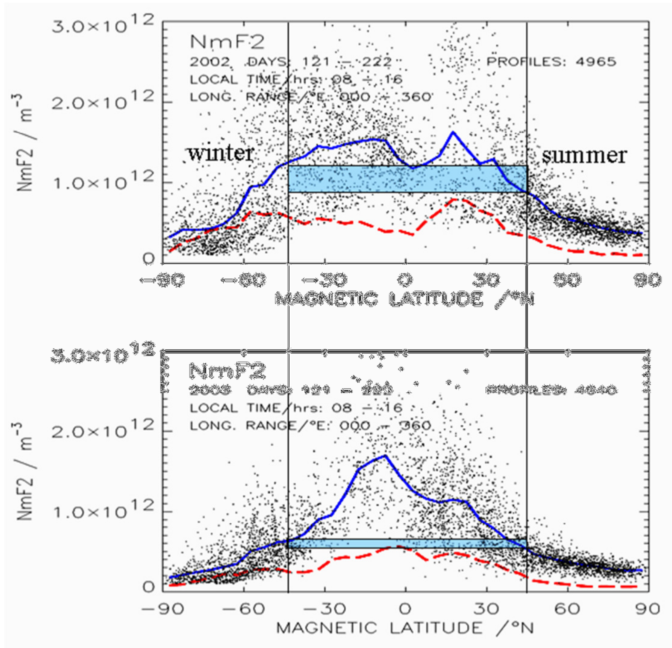

Fig.5. The winter anomaly deduced from day-time IRO measurements for days 121-222 of year 2002 (top panel) and year 2003 (bottom panel). The estimated standard deviations denoted with dashes. Notice the solar activity dependence.

An interesting phenomenon is the winter anomaly, i.e. the higher peak density values during winter. The anomaly can be easily detected and investigated via IRO measurements (Fig.5). Another phenomenon related to the equatorial crest is the observed latitudinal shift (Fig.6). The fact is probably due to the enhanced level of night-time ionisation in the summer hemisphere; such enhanced ionisation agrees very well with the increased scale height in the summer hemisphere (Fig.4).

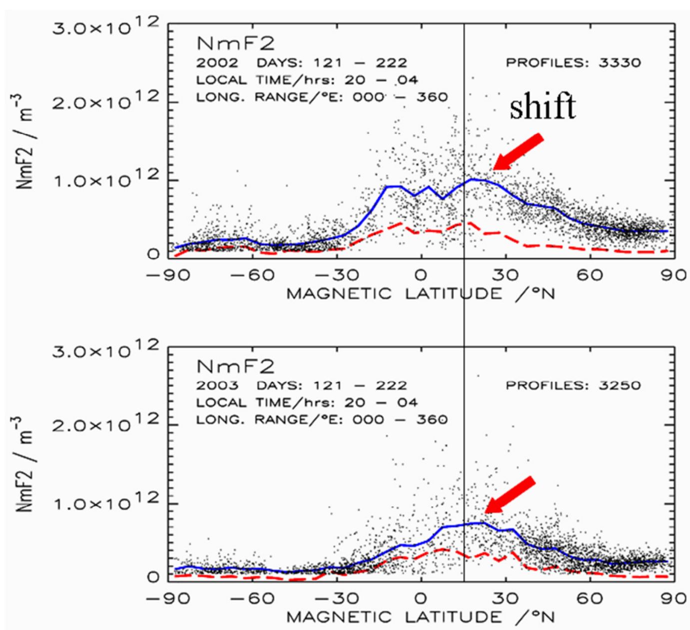

Fig.6. The averaged peak density (solid line) deduced from day-time IRO measurements for days 121-222 of year 2002 (top panel) and year 2003 (bottom panel). The estimated standard deviations denoted with dashes. Notice the latitudinal shift toward North.

Well known is the influence of both the ion trough and the equatorial crest on the propagation conditions. Therefore, catching the extent, magnitude and variability of the crest/trough is a challenging task; IRO measurements proved to be quite efficient in this direction (Fig.7).

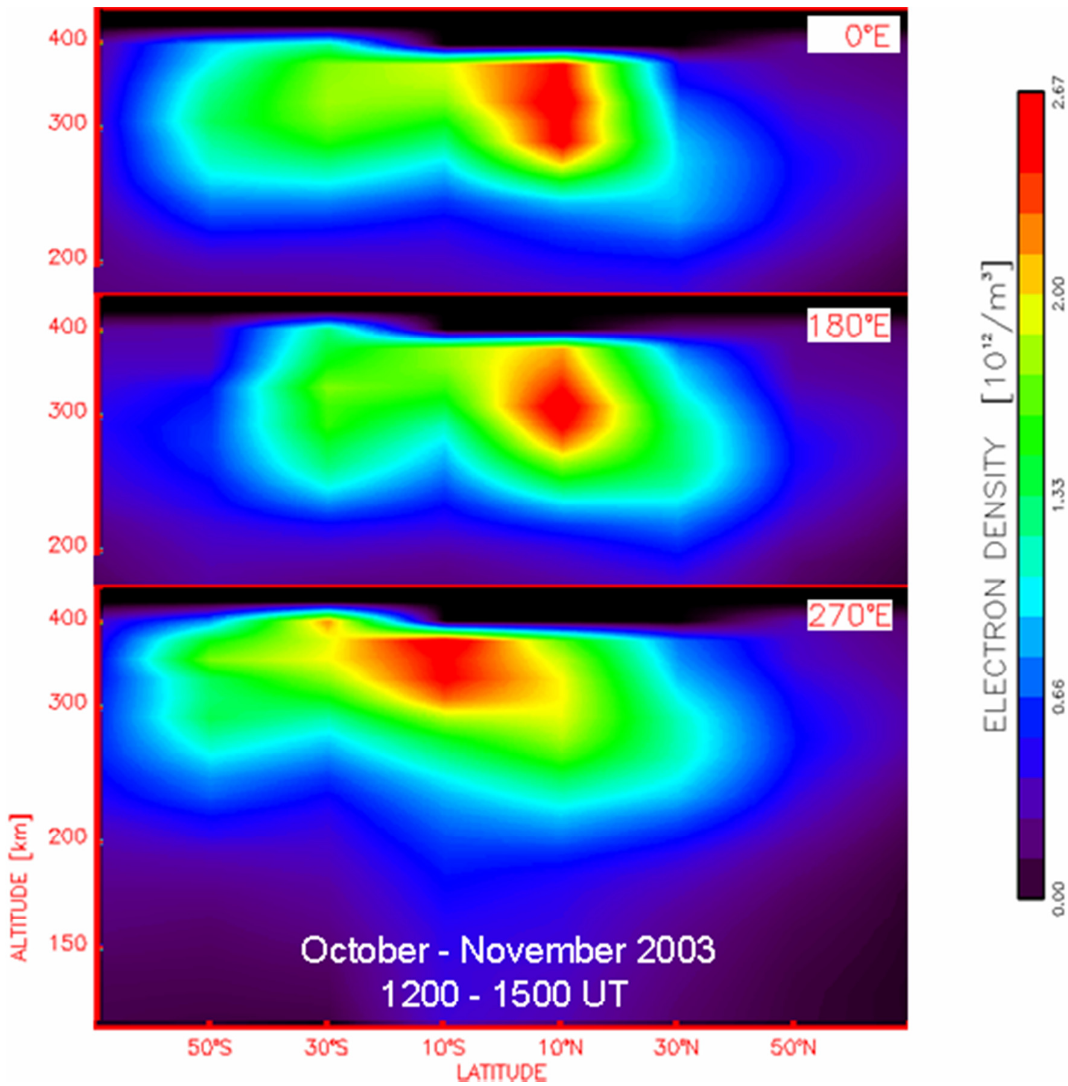

Fig.7. The equatorial crest observed via the IRO measurements during October and November 2003, 21:00-05:00LT, in different longitude sections – 0ºE (top), 180ºE (middle), and 270ºE (bottom).

4.3 Global monitoring of basic ionospheric characteristics

Key ionospheric parameters are the peak electron density NmF2 and the corresponding height hmF2. The peak density is correlated with the critical frequency foF2 by the relation $NmF2 = 0.0124\times(foF2)^2$ in SI units. All these parameters are available from ground-based ionosonde observations. However, the lack of global coverage is one of the major deficiencies of the ground-based observations; the CHAMP IRO experiment provides actual information on the global state of the ionosphere. Also, IRO measurements are much easier to compare with other types of satellite-based observations. As an example of the IRO capabilities, presented here are results of the foF2 and hmF2 monitoring (Fig.8) based on measurements from April-August 2002. Latitudinal, longitudinal, and seasonal differences are clearly observed.

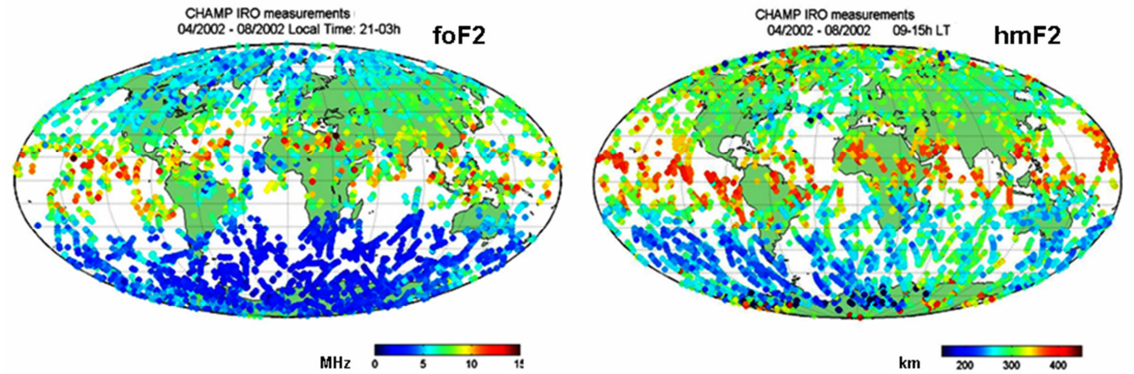

Fig.8. Global monitoring of foF2 (left) and hmF2 (right) using CHAMP IRO measurements, 04/-08/2002.

4.4 Global monitoring of ionospheric irregularities

Another important application of the IRO measurements is the monitoring of the ionospheric irregularities. In order to estimate the level of these irregularities with the help of radio occultation data, the following algorithm has been developed:

- The TEC occultation time dependency, *TEC(t)* , is converted to the space dependency, *TEC(s)*, where *s* is distance passed by the tangential point from the start of the occultation event. For each occultation, *s* changes from 0 to the so called "smear length" *D* - the length of the occultation point's trace.
- The space dependency *TEC(s)* is approximated by a set of polynomials *Pol(s).* Typically, nine-point cubic approximation is used.
- The polynomials *Pol(s)* are subtracted from the *TEC(s)* dependency to filter the "natural" change of TEC during occultation, i.e. the change caused by the varying density of large-scale ionospheric layers. The small scale irregularities however, are 'left' in the measurements.
- The result, $TEC_{pol}(s) = TEC(s) - Pol(s)$, is then differentiated to get the corresponding TEC gradient. The derivative $TEC'(s)$ shows how intensive are the variations of TEC due to short-scale irregularities.
- Calculated is the RMS of the gradient, G_{RMS} (in units of $TECU/km$), which may serve as a generic measure of the ionospheric irregularity in the region of the occultation. Typically its values are higher at day time and lower at night time.
- To filter out gravity waves and other phenomena linked to neutral atmosphere it is necessary to filter out the variations due to electron density changes. Therefore, the RMS gradient G_{RMS} can be normalized, so it is divided by the TEC maximal value measured during the occultation. In this case, the measurement unit of the variation is km^{-1} (or the percentage of the TEC change per kilometre of smear length).

The above-described algorithm was applied to CHAMP IRO measurements and the results show the global distribution of ionospheric irregularities. After considering the observations during the northern summer of 2002 (Fig.9, left), we found a strong enhancement at southern high latitudes i.e. during winter. Such pronounced winter-time activity at higher latitudes possibly indicates the tracing of atmospheric gravity waves (AGW) coming from lower atmosphere layers; the lower temperatures in winter may modify the atmospheric filter function in such a way that AGWs may penetrate more favourably in winter than in summer. In general, the opposite behaviour is observed during the northern winter of November 2002–January 2003 (Fig.9, right).

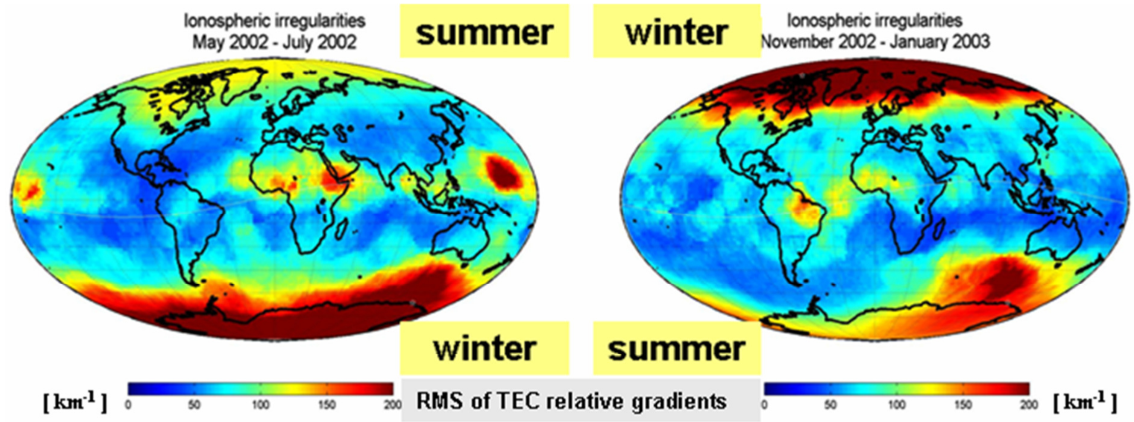

Fig.9. Intensity of ionospheric irregularities detected via CHAMP IRO measurements from May 2002 to July 2002 (left) and from November 2002 to January 2003 (right). Clearly visible is the increased intensity of the irregularities over the geomagnetic equator and the polar areas, particularly during winter.

5. Summary and outlook

Presented here was a brief review of the DLR experience with the CHAMP IRO occultation measurements. This innovative GNSS technique opens a new dimension for regularly monitoring the ionosphere-plasmasphere system on a global base.

The accuracy and reliability of the retrievals have been estimated extensively during the years. Although the demonstrated good agreement between IRO measurement data and many other types of independent measurements has proved the quality of the IRO retrieval technique, the validation process should continue. The results obtained so far suggest that the IRO retrieved electron density profiles and deduced parameters provide a consistent description of the general ionospheric behaviour. This indicates also that IRO data should have a great potential for studying a number of ionospheric phenomena, for developing/evaluating ionospheric models, for reconstructing the 3D electron density distribution of the ionosphere by data assimilation or tomographic techniques, etc.

The focus of the future work will be to further develop and utilise the IRO capabilities for operational applications.

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