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Remote sensing of the ionosphere by space-based GNSS observations

N. Jakowski [a], S. Heise [b], S.M. Stankov [a,*], K. Tsybulya [a]

[a] German Aerospace Centre (DLR), Institute of Communications and Navigation (IKN), Kalkhorstweg 53, D-17235 Neustrelitz, Germany
[b] GeoForschungsZentrum (GFZ), Department of Geodesy and Remote Sensing, D-14473 Potsdam, Germany

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Abstract

The GNSS-based radio occultation measurements establish the foundation of a novel remote sensing technique capable of reliably deducing the electron density distribution in the entire ionosphere from the GNSS satellite heights down to the bottom ionospheric heights. The ionospheric radio occultation measurements have been carried out onboard the German low orbiter CHAMP since 11 April 2001. Presented and discussed here are some important results obtained during this highly successful mission.

Keywords: GNSS; Remote sensing; Ionospheric radio occultation

1. Introduction

The Global Positioning System (GPS) ionospheric radio occultation (IRO) technique onboard Low Earth Orbiting (LEO) satellites is a space-based technique which has proved to be a powerful, yet relatively inexpensive tool for profiling the electron density in the ionosphere from top to bottom. Information on the reconstructed electron density distribution might be used not only to validate already existing models but also to create a good data basis for developing new models of other key ionospheric parameters such as the critical frequency (foF2), the F2-layer peak height (hmF2) and the plasma scale height.

The accuracy and reliability of the IRO retrievals have already been estimated. All this has been done by comparisons with measurements obtained by quite different techniques such as vertical sounding, incoherent scatter radar probing or in situ measurements (Jakowski et al., 2004; and references therein). Although the good agreement between IRO measurement data and many other types of independent measurements has proved the high quality of the IRO retrieval technique, the validation process should continue.

This paper presents the IRO technique capabilities for developing plasma density reconstruction methods and data assimilation procedures, and also for monitoring the ionosphere on a global scale. Several investigations have been carried out and some of them are presented here. Future tasks aim at operational monitoring which can be used to study ionospheric composition, dynamics, disturbances, and to deduce valuable data products.

2. 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 0.1 Hz sampled navigation data received at the upward looking antenna (precise time and orbit

* Corresponding author. Tel.: +49 3981 480 113; fax: +49 3981 480 123.
E-mail address: Stanimir.Stankov@dlr.de (S.M. Stankov).

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information) but of GPS measurements as well. 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 receiver measures GPS carrier phases in the radio occultation or limb sounding mode starting at CHAMP orbit tangent point (this point on the ray path which is closest to the Earth's centre) down to the Earth surface (Fig. 1). The CHAMP observations are first received at the DLR Remote Sensing Data Centre in Neustrelitz and are then forwarded to the principal owner, the GeoForschungsZentrum (GFZ) in Potsdam. 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 system in which the retrieval modules can be replaced and upgraded in the course of the CHAMP mission.

Since a large number of ionospheric phenomena is accompanied by (or is due to) strong spatial plasma density gradients, and furthermore, because the ray 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 developed for the CHAMP data analysis (Jakowski et al., 2002), has the advantage that additional information from ground based GPS measurements (e.g., horizontal gradients), 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 the following: $d_{\mathrm{I}} = \frac{K}{f^2}\int n_{\mathrm{e}}\,\mathrm{d}s$, where $K = 40.3\ \mathrm{m}^3\,\mathrm{s}^{-2}$, 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 (TEC) along the ray path through a spherically layered voxel structure (Jakowski et al., 2004; and references therein). The measured line integral TEC is the sum of the products $n_{\mathrm{e}} \times \mathrm{d}s_i$ where n_{e} is the mean electron density in voxel i and $\mathrm{d}s_i$ corresponds to the ray path length in voxel i. Simulations have shown (Jakowski, 1996) 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 is successively derived from a series of 1 s sampled measurements 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 (http://web.dmi.dk/fsweb/projects/oersted/) and SAC-C (http://orbis.conae.gov.ar/sac-c/) satellites, the comparatively small plasmaspheric contribution can be considered constant in space. This simplifying assumption cannot be applied to the CHAMP IRO retrieval algorithms because CHAMP has a rather low orbit height of initially 450 km, which is even further decreased 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 10,000 km. Key model parameters such as the plasma scale height at the upper boundary are determined in a few iterations (currently 6) 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 (Jakowski et al., 2002; Stankov and Jakowski, 2005). To fulfil operational requirements, i.e., to come up with retrieval products within a latency of less than 3 h, 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/IKN (Jakowski, 1996). On average, from about 200 IRO measurements per day, about 150 electron density profiles (EDP) are successfully retrieved.

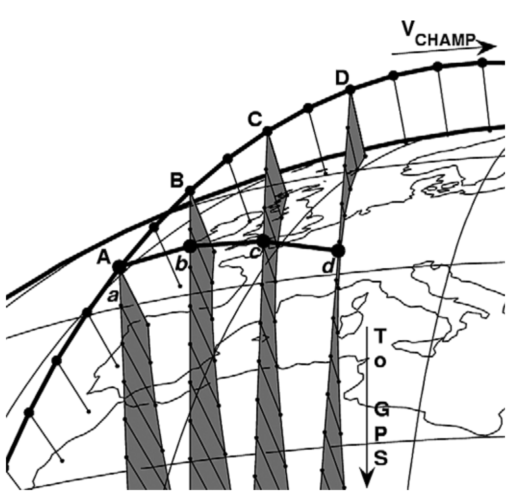

Fig. 1. GPS radio occultation geometry and tangent point trajectory for a typical occultation event.

Because the processing system works automatically, some EDP outliers (due to data errors) cannot be avoided; however, the number of such outliers is less than 1%.

3. Global monitoring of basic ionospheric characteristics

Key ionospheric parameters are the peak electron density NmF2 and the corresponding height hmF2. The peak density NmF2 is related to the ionosonde-measured critical frequency foF2 by the relation $\mathrm{NmF2} = 0.0124 \times (\mathrm{foF2})^2$ in SI units. The CHAMP/IRO experiment provides global information on NmF2; the lack of global coverage is one of the major deficiencies of the ground-based observations. As an example of the IRO capabilities, presented here are results of the foF2 and hmF2 monitoring (Fig. 2) based on measurements from April to August 2002. Latitudinal, longitudinal, and seasonal differences are clearly observed.

4. Regular access to topside ionospheric and plasmaspheric characteristics

The plasma scale height value in the region immediately above the ionospheric F2-layer density peak is very important for the TEC calculation and plasma density reconstruction procedures utilizing GPS radio occultation measurements. It has been shown that the topside plasma scale height depends strongly on the ionosphere–plasmasphere temperature, composition and dynamics and that it is possible to utilize the IRO observations for acquiring a valuable knowledge of the scale height behaviour (Stankov and Jakowski, 2005). Based on the time series data accumulated so far, obtained were latitudinal, diurnal, and seasonal variations of the topside plasma scale height (Fig. 3). It is clear that the scale height generally increases in poleward directions, particularly during equinox and summer. Strong seasonal differences are also observed at middle latitudes where day-time median values in summer are about 45% higher than in winter. Diurnal variations appear to exist but are very complex and additional data is needed. However, no significant hemispheric differences are detected. Considering the analysis of the scale height behaviour and 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 of the topside electron density profile. In this model, the plasma scale height is approximated by a multivariable 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. As already mentioned, model results can be directly implemented into the density profile retrieval procedure by delivering an improved initial guess.

5. Electron density reconstruction

Several new methods for retrieving the topside electron density distribution from space-based observations of the total electron content have been developed.

For example, in addition to the IRO measurements, 10 s sampled navigation data measured with the zenith viewing antenna can effectively be used for probing the ionosphere. The reconstruction technique consists of the following main parts – 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

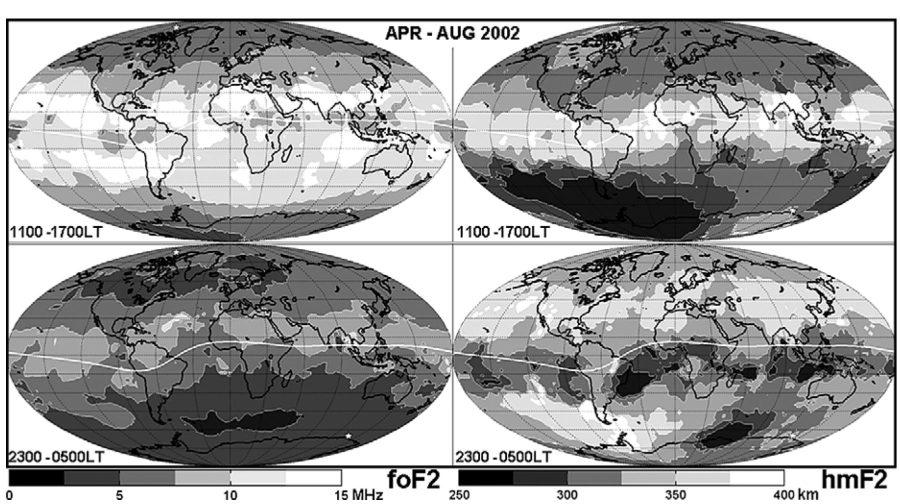

Fig. 2. Global monitoring of the foF2 and hmF2 characteristics using the CHAMP/IRO measurements (April–August 2002).

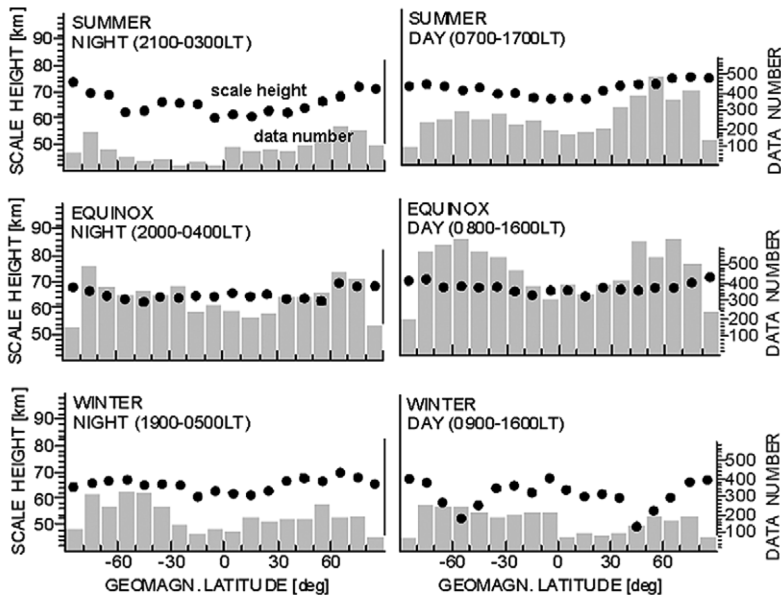

Fig. 3. Latitudinal, seasonal, and day/night variations of the topside plasma scale height obtained from IRO measurements.

phases is used to derive the TEC value; the latter being consistently calibrated for receiver and satellite differential group delay biases. The calibration of the numerous link-related TEC values for instrumental biases is performed with the help of a parameterized ionospheric model (Daniell et al., 1995). Considering that the GPS differential code biases are relatively well estimated by the GPS processing centres, the calibration procedure is rather focused on the estimation of the CHAMP receiver bias. Our results show that the latter is quite stable – RMS does not exceed 1.0 TECU (1 TECU $= 10^{16}\,\mathrm{m}^{-2}$). After calibration, the absolute TEC data are assimilated into the parameterized ionospheric model by a method which can ultimately deliver 3D reconstructions of the electron density (Heise et al., 2002).

Another example is the reconstruction method combining various types of measurements – space-based IRO data, ground-based vertical sounding measurements, and in situ observations of the upper ion transition height (modelled). By assuming adequate topside density distribution (Exponential, Epstein, or Chapman layers), 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 methods include the development and evaluation of both, the background models and other empirical and theoretical ionosphere–plasmasphere models.

6. Global monitoring of ionospheric irregularities

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

- Occultation TEC time-dependency TEC(t) is converted to space-dependency TEC(s), where s is the distance passed by the tangential point from the occultation starting moment. In more detail: for each moment of the occultation, first, the GPS and CHAMP coordinates are taken, than the exact space position of the GPS-to-CHAMP line is calculated, and, finally, the coordinates of the tangent point are found. Equipped with the above information, we can convert the TEC time-dependency TEC(t) to a space-dependency TEC(s), where s is the distance passed by the tangent point from the occultation start (points a, b, c, d in Fig. 1). For every occultation s changes from 0 to the so called "smear length" (D-length) of trace of the occultation point (i.e., the distance a–d in Fig. 1).
- TEC(s) is approximated by a set of polynomials $P(s)$. Typically, it is a nine-point cubic approximation.
- Polynomials are subtracted from TEC(s) to filter the "natural" change of TEC during the occultation (due to varying density of large-scale ionospheric layers) but leave in place the small scale irregularities.
- The difference $\mathrm{TEC}_{\mathrm{pol}}(s) = \mathrm{TEC}(s) - P(s)$ is differentiated to get the TEC gradient ($\mathrm{TEC}'(s)$). Actually, $\mathrm{TEC}'(s)$ shows how intensive the variations of TEC are due to short-scale irregularities.
- The root mean square (RMS) of the gradient is calculated as $G_{\mathrm{RMS}} = \sqrt{\frac{1}{D}\int_0^D (\mathrm{TEC}'(s))^2\,\mathrm{d}s}$. If a simple average was calculated instead, positive and negative values of the TEC gradient along the path of the occultation would compensate each

other. Squaring makes the values positive at all points. The result is obtained in TECU/km and may serve as a generic measure of the ionospheric irregularity in the region of occultation. Typically, its values are much higher at day time, and much lower at night time, because enhanced electron concentration N_e brings with itself enhanced N_e variation.
- To detect gravity waves and other phenomena linked to the neutral atmosphere it is necessary to filter out the variations due to electron density changes. So the RMS gradient G_{RMS} can be normalized – divided by maximal TEC value measured during the occultation. In this case the unit of the variation measure is km^{-1} (or the percentage of TEC change per kilometre of smear length).

The results of the above-described algorithm show a global distribution of wavelike structures. Considering the observations during northern summer of May–July 2002 (Fig. 4, left), we found a strong enhancement at southern high latitudes, i.e., during winter. In addition, enhanced Travelling Ionospheric Disturbance (TID) activity near the equator is also observed. The pronounced TID activity in winter at high latitudes indicates possible tracing of Atmospheric Gravity Waves (AGW) coming from lower atmospheric layers. The lower temperatures in winter may modify the atmospheric filter function in such a way that AGWs may penetrate more favourably than under summer conditions. In general, the opposite behaviour is observed during the winter of November 2002–January 2003 (Fig. 4, right).

7. High precision monitoring of major ionospheric phenomena

There are two prominent features of the ionosphere which can easily be detected and monitored via the occultation measurements – the equatorial crest and the mid-latitude trough.

The equatorial crest (Fig. 5) is characterized by anomalous increase in electron density on both sides of the geomagnetic equator and manifests large variability including north-south and winter-summer asymmetries, rapid diurnal and seasonal changes, so-

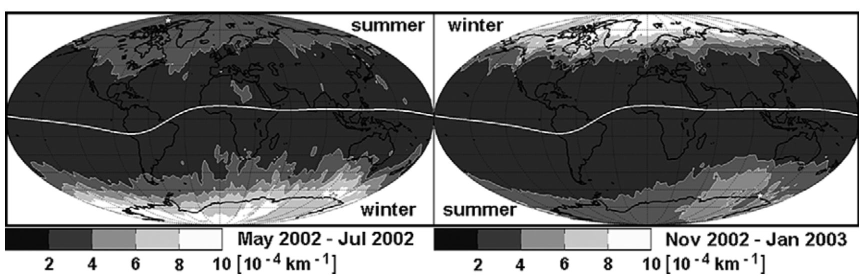

Fig. 4. Fluctuations, visible in CHAMP IRO measurements under summer/winter conditions, indicate enhanced variability in polar areas (winter) and near the geomagnetic equator.

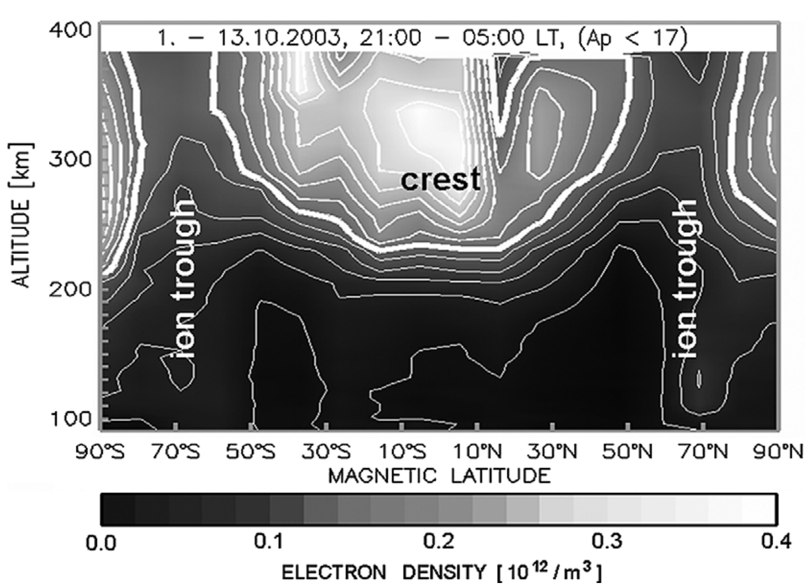

Fig. 5. The equatorial crest and the ion trough observed via the IRO measurements during 1–13 October 2003, 21:00-05:00LT.

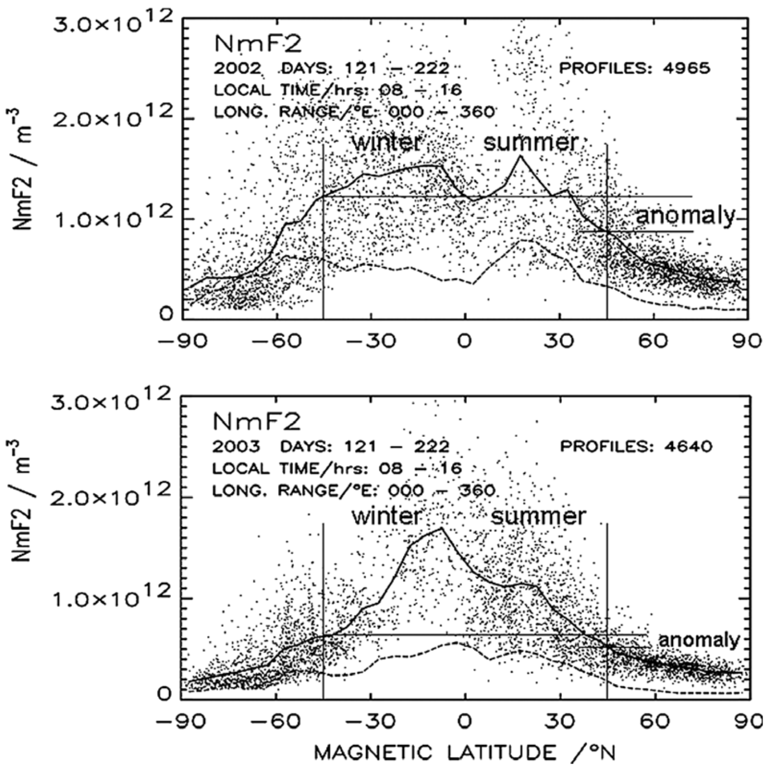

Fig. 6. The winter anomaly deduced from day-time IRO measurements during the summer months of May, June, and July of year 2002 (top panel) and year 2003 (bottom panel). The solid line represents the averaged NmF2 and the dashed line represents the standard deviation. The anomaly is obviously increasing in line with solar activity.

lar activity dependence, etc. Due to data averaging, the equatorial anomaly is not very clear in Fig. 5; however, in Fig. 6 it is clearly seen together with another interesting phenomenon – the winter anomaly (i.e., the higher NmF2 values during winter). Considering the higher solar activity in 2002, the winter anomaly is obviously better pronounced at higher solar activity.

The ion trough is characterized with abrupt gradients in electron densities within relatively short horizontal distance (Fig. 5). Its extent and depth vary strongly in latitude, longitude, local time, season, solar activity and geomagnetic activity. The influence of both, the crest and the trough, on the propagation conditions is well known. Capturing their characteristics and variability is a challenging task but IRO measurements proved to be quite efficient in this direction.

8. Summary and outlook

Presented was a review of the capabilities of the space based GNSS measurements. The large data base of IRO-derived electron density profiles, established since the start of the CHAMP IRO measurements, is a valuable source for the international scientific community. IRO data establish a new type of global data sets of vertical electron density profiles characterized by a significant horizontal averaging, thus, IRO is well suited for modelling purposes. Also, the presented studies allow useful validations of existing ionospheric models. Nevertheless, a high resolution reconstruction of the ionospheric electron density distribution requires the combination of ground and space-based GNSS sounding measurements (Stankov et al., 2003; Stolle et al., 2003). The focus of the future work will be to demonstrate and use the capabilities of the complex reconstruction methods in a more systematic way, which includes accuracy, reliability, resolution, availability, and suitability for operational applications.

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