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Ionospheric space weather effects monitored by simultaneous ground and space based GNSS signals

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Abstract

Ionospheric space weather effects can degrade the performance of global navigation satellite systems (GNSS), i.e. their accuracy, reliability and availability. However, well established ground based and innovative space based GNSS measurements offer the unique chance for a permanent monitoring of the electron density structure of the global ionosphere–plasmasphere system. In this paper we review various types of perturbations in the ionospheric plasma density and distribution. In order to analyze these space weather effects we use 30 s sampled measurements provided by the global GPS ground tracking network of the IGS. Furthermore, to get a more comprehensive view on the perturbations analyzed also are simultaneously obtained GPS measurements onboard the LEO satellite CHAMP (challenging minisatellite payload). Whereas the ground based measurements show strong horizontal redistribution of plasma during ionospheric storms, the space-borne measurements indicate a severe vertical redistribution of the ionospheric plasma during the selected events. The role of the various dynamical forces such as meridional winds and electric fields is also discussed.

Keywords: Ionosphere; Radiowave propagation; Radio occultation; Navigation systems; Space weather

1. Introduction

It is a well-known fact that the ionospheric plasma can significantly influence the propagation of radio waves. Numerous studies have been made on this subject on a broad international level and are going on to measure space weather induced effects, to understand and to mitigate this impact on technical systems and to forecast its behaviour. Ionospheric disturbances can cause range errors, rapid phase and amplitude fluctuations (radio scintillations) of satellite signals leading to degradation of the system performance, its accuracy and reliability. However, well established ground-based and innovative space-based GNSS measurements offer the unique chance for a permanent monitoring of the electron density structure of the global ionosphere–plasmasphere system. The understanding of the structure and dynamics of this complex system is a key to successfully overcome problems associated with its perturbations.

The aim of this paper is to demonstrate that different GNSS techniques may provide quite different views on the ionospheric behavior and structure. Although different techniques yield different parameters it is expected that they provide a consistent description of the physical processes controlling the plasma behavior.

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This study attempts to find out whether this expectation is justified in particular under severe perturbed space weather conditions.

Whereas ground based measurements of the total electron content (TEC) of the ionosphere have already a long tradition (Davies, 1980), innovative space GNSS techniques have been developed in recent years which are not yet well established for a routine sounding of the ionosphere (Hajj and Romans, 1998; Jakowski et al., 2002b). GNSS receivers installed on low-earth-orbiting (LEO) satellites for navigation purposes provide a unique opportunity for obtaining valuable information on the ionosphere and plasmasphere. In this study we use GPS data from the German geo-research LEO satellite CHAMP (Challenging Minisatellite Payload) that was launched on 15 July 2000 into a circular and near polar orbit with an inclination of 87° and an initial altitude of 454 km (Reigber et al., 2000). As pointed out in the following section, both the 1 Hz sampled ionospheric radio occultation (IRO) measurements as well as the 0.1 Hz sampled navigation data were used to retrieve the vertical electron density distribution of the ionosphere which completes the horizontal TEC information derivable from ground based GNSS measurements.

2. Ground-based GNSS measurement technique

Since 1995 DLR operates a system for regularly processing ground based GPS data and producing maps of the ionospheric TEC over the European region using mainly measurements of the ground station network of the International GPS Service IGS (http://www.kn.nz.dlr.de/daily/tec-eu/). These GPS data allow the determination of slant TEC values along numerous satellite-receiver links over the European area with 30 s time resolution. The instrumental biases are separated from the observations by assuming a second-order polynomial approximation for TEC variations over the observing GPS ground station. Both the TEC and the instrumental satellite-receiver biases are estimated simultaneously by a Kalman filter run over 24 h. The calibrated slant TEC data are then mapped to the vertical by applying a mapping function which is based on a single layer approximation at $h_{sp} = 400$ km. In a final step the observed TEC data are combined with a regional TEC model, Neustrelitz TEC Model (NTCM), in a way that the map provides measured values near measuring points and model values at regions without measurements. The advantage of such assimilation technique is that even in the case of a low number of measurements it delivers reasonable ionospheric corrections which can be provided to users to help them enhance accuracy and integrity of positioning (Jakowski, 1996).

The current TEC database developed at DLR comprises complete data set from the previous 10 years. This large database—containing data from all solar conditions—is an optimal background for the validation of all types of ionospheric correction especially at highly disturbed ionospheric conditions where other measurement techniques are limited (e.g. ground ionosondes).

Enhanced space weather impact is expected at the high-latitude ionosphere because of their strong electrodynamic coupling with the magnetosphere and the solar wind. High latitude plasma convection, electric field, and precipitation of energetic particles are the most powerful driving forces for highly dynamic and complex processes causing large variability of the plasma density. In particular, enhancements of the solar wind energy generate large perturbations in the high-latitude ionosphere and thermosphere that commonly propagate towards lower latitudes. So, the high latitudes are a kind of a ‘‘space weather kitchen’’ for numerous perturbation phenomena observed in mid-latitudes. The monitoring of the total ionization of this region may improve our understanding of complex coupling processes between the solar wind, magnetosphere, ionosphere and thermosphere. In order to monitor the Northern high latitude ionosphere, we apply the same procedure as used for monitoring the European ionosphere (e.g. Jakowski et al., 2002c).

The measured and calibrated slant TEC data are converted to vertical TEC maps over the entire Northern polar cap at latitudes greater than 50°N with a time resolution of up to 10 min in the DLR routine processing mode. To ensure the reliability of the generated TEC maps we have developed a specific polar TEC model (NTCMP-1) which, again—working as a background model—is being combined with numerous actual observations by a weighting procedure. Since 1995, the above assimilation technique has been successfully applied to routinely generate GPS-based TEC maps over the European area. Nevertheless, further validation work is needed, indicating that the currently produced TEC maps still have an experimental status. Vertical TEC values are computed for a grid consisting of768 grid points within the latitude range between 50 and 90° N enabling the imaging of large scale perturbations in the auroral zone (http://www.kn.nz.dlr.de/daily/tec-np/). In analogy to the ionosphere monitoring (via TEC measurements) of the Northern polar region, we started also to monitor the ionosphere over the Southern polar region at latitudes greater than 50°S. Due to the rather low number of ground stations available, these data currently have a provisional character.

3. Space-based GNSS measurement techniques

The GPS data measured onboard CHAMP are received at the DLR Remote Sensing Data Centre

Neustrelitz and subsequently processed at DLR by an operational data processing system (Wehrenpfennig et al., 2001). Thus, the electron density profiles retrieved from the IRO measurements may be available within 3 h after data dump hence fulfilling operational requirements of potential users in science and space weather applications (Jakowski et al., 2002a, b, c). Subsequently, the computed IRO data products are submitted to the international science community via the Information System and Data Centre (ISDC) of GFZ Potsdam.

In addition to the IRO measurements also the 10s sampled navigation data measured with the zenith viewing antenna can effectively be used for probing the ionosphere (Heise et al., 2002). The topside electron density reconstruction is not yet operationally processed.

3.1. The IRO retrieval technique

To overcome the spherical symmetry assumption in retrieving electron density profiles from IRO measurements based on the Abel inversion technique, a tomographic solution is required. The established tomographic approach (Jakowski et al., 2002b) has the advantage that additional information 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 post-processing. The measured differential GPS phases provide the total electron content along the ray paths through the spherically layered voxel structure (Fig. 1). Since the ray path elements within voxels are known from the ray path geometry, the electron density in the different voxels can successively be derived from the 1s sampled measurements when the tangential point of occultation rays comes closer and closer to the Earth. Due to the rather low orbit height of CHAMP (~430 km) which is close to the peak electron density height, 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. The adaptive model consists of a Chapman layer whose topside is extended by a slowly decaying exponential term with a scale height of 10,000 km (Jakowski et al., 2002b). Crucial model parameters such as the peak density NmF2 and the plasma scale height H_{TS} are determined by six retrieval iterations at the upper boundary in order to ensure a smooth transition between model and measurements. A smooth transition indicates a reasonable initial guess of the plasmaspheric model and the retrieval procedure continues down to the bottom side.

For practical using of IRO retrieved electron density profiles their accuracy has to be evaluated under different geophysical conditions. This has been done by comparing the data with measurements obtained by quite different techniques, such as in situ measurements (Jakowski et al., 2002b), incoherent scatter radar (Stolle et al., 2003), or vertical sounding (Jakowski et al., 2005). Although, due to the operational requirements, a spherical symmetry of the ionospheric layers was assumed, the validation results are rather promising. Systematic studies established within the European COST 271 action (http://www.cost271.rl.ac.uk/) revealed a positive bias of about 0.5 MHz and a standard deviation of up to 1 MHz throughout the entire vertical profile. Also the comparison that has been made with tomographic reconstructions using the MIDAS technique has demonstrated a good agreement between these quite different approaches (Spalla et al., 2003). Additionally, first attempts have been made to compare the profiles with those derived from ionospheric models such as IRI 2001 (Jakowski and Tsybulya, 2004) to get some information concerning accuracy and reliability of the retrievals.

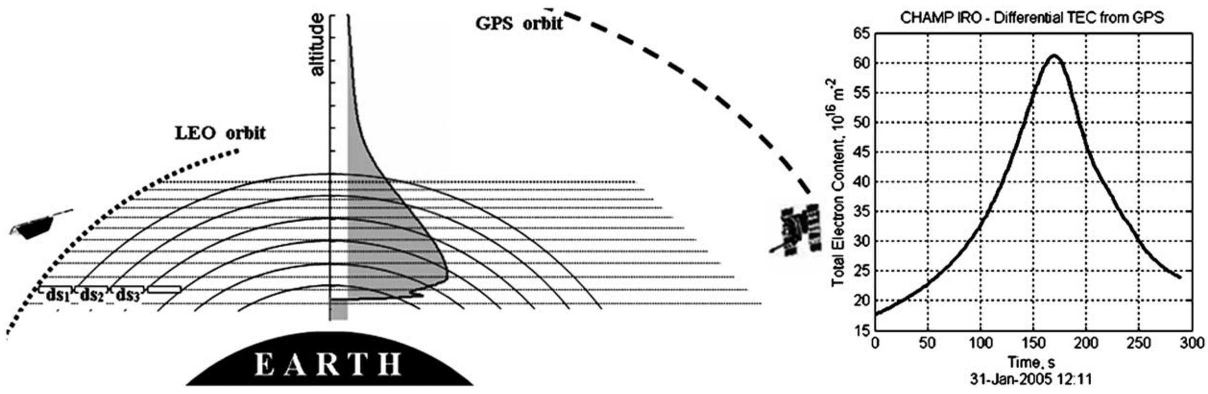

Fig. 1. Schematic view of the retrieval procedure (left panel) and a measurement sample of the relative TEC (right panel) along the radio occultation ray path used for the electron density profile inversion.

3.2. Topside ionosphere reconstruction technique

Whereas the IRO retrieval technique uses non-calibrated TEC data (Jakowski et al., 2002b), the topside assimilation reconstruction technique requires calibrated TEC along the numerous radio links between the GPS satellites and the topside GPS antenna onboard CHAMP (Fig. 2). Two types of input are required for the reconstruction algorithm: GPS navigation measurements from CHAMP (0.1 Hz) and orbit data for CHAMP and the involved GPS satellites. The data processing and retrieval method (Heise et al., 2002) 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 phases is used to derive the TEC value. TEC is consistently calibrated for receiver and satellite differential code biases.

The calibration of numerous link-related TEC values for instrumental biases is performed with the help of the Parameterized Ionospheric Model, PIM (Daniell et al., 1995). Considering that GPS differential code biases are reliably estimated by GPS processing centers, the calibration procedure is focused on the estimation of the CHAMP receiver bias only. Results show (Heise et al., 2005) that the estimated bias is quite stable—RMS does not exceed 1 TECU (1 TECU = $10^{16}\,m^{-2}$). After calibration, the absolute TEC data are assimilated into the PIM model applying a method described by Heise et al. (2002). The assimilation results provide for each CHAMP revolution a 3D reconstruction of the electron density from CHAMP up to GPS altitudes on a vertical plane close to the CHAMP orbit plane.

Validation of the derived electron density distribution at the CHAMP orbit height i.e. the lower boundary of the reconstruction volume has been made by comparison with in situ plasma density measurements of the Planar Langmuir Probe (PLP) installed onboard CHAMP. Compared with the PLP data the assimilation results have no significant bias and agree within a standard deviation of $2 \times 10^{11}\,m^{-3}$ (Heise et al., 2002). Good agreement was also found with topside profiles deduced from incoherent scatter measurements (Heise, 2003).

Considering the good global coverage of the space based GNSS data it becomes evident that this type of measurements can provide essential contributions to a space weather monitoring of the ionosphere.

4. Observations and discussion

The first IRO measurements were carried out onboard CHAMP on 11 April 2001. Since that time we have obtained more than 140,000 vertical electron density profiles which provide a huge data pool for comparative ionospheric studies. Although not yet completely validated, this tremendous data set enables already a preliminary data analysis to find out whether well-known physical ionospheric features become visible or not.

The high latitude magnetosphere and ionosphere react very sensitively to solar wind increases due to strong coupling mechanisms. TEC maps have been shown to image large scale ionization processes quite well even

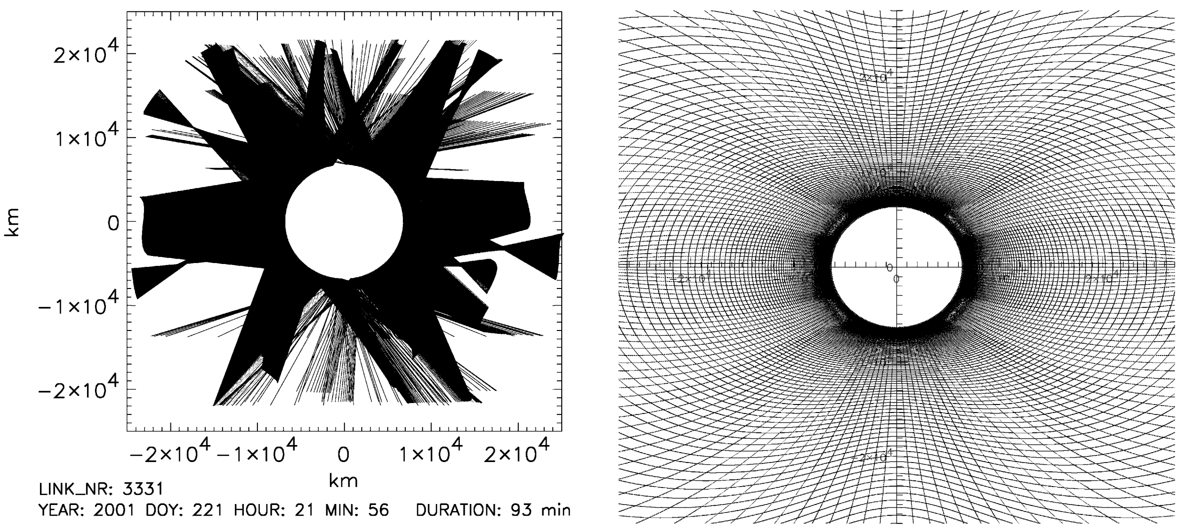

Fig. 2. Ray path structure during one revolution of CHAMP (left panel) and the defined voxel structure (right panel) utilized for the electron density reconstruction.

during ionospheric storms (Jakowski, 1996; Jakowski et al., 1999, 2002a). Therefore, it should be interesting to see whether there is a correlation of the different data sources providing a different view on the same subject. The accuracy of both the IRO measurements as well as the topside reconstruction have shown to be sufficient to image severe ionospheric perturbations due to strong space weather events.

To demonstrate the capabilities of both techniques we have selected the severe geomagnetic storms that occurred on 5/6 November 2001 and at the end of October 2003. The geomagnetic activity reached extreme high values (Kp = 9/Ap = 300) in the night from 5 to 6 November 2001 (Fig. 3, upper panel). Intense proton showers, accompanying this storm, led also to other space weather phenomena. Thus the remote sensing satellite BIRD that is operated by the German Aerospace Centre (DLR) went into the safe mode due to safety reasons. High energetic particles may generate additional ionization in the bottom-side ionosphere. Whereas the polar TEC maps indicate a strong enhancement of the polar ionisation at midnight and a tongue-like pattern indicating strong horizontal plasma drift due to storm-enhanced convection electric fields, the corresponding radio occultation retrieval results (right panel) show a strong enhanced ionisation in the E-layer heights. To mark the region where the radio occultation observation originates, the IRO traces are indicated by strips in the TEC maps. In agreement with the polar map the IRO data measured over the night-side area at 02:02UT where obviously the negative storm phase has been started already, show strongly reduced electron density values at F2 layer heights and above. Thus, both completely independent data sources and measuring techniques provide a consistent and more comprehensive view on the same subject.

Strong perturbations in the high latitude topside ionosphere may be deduced also from topside data assimilation results (Fig. 4). The vertical reconstruction up to about 3000 km yields enhanced topside electron densities in the polar region where also the corresponding TEC map at 06:00UT shows strong TEC variations along the satellite trace crossing the polar ionosphere. Both reconstructions/maps complement each other to get a valuable insight into the horizontal and vertical ionisation in the polar region. Although a more detailed discussion of the corresponding physical processes would require a more comprehensive data set, the given example demonstrates the capabilities of GPS measurements onboard CHAMP to provide valuable data for monitoring space weather effects in the ionosphere.

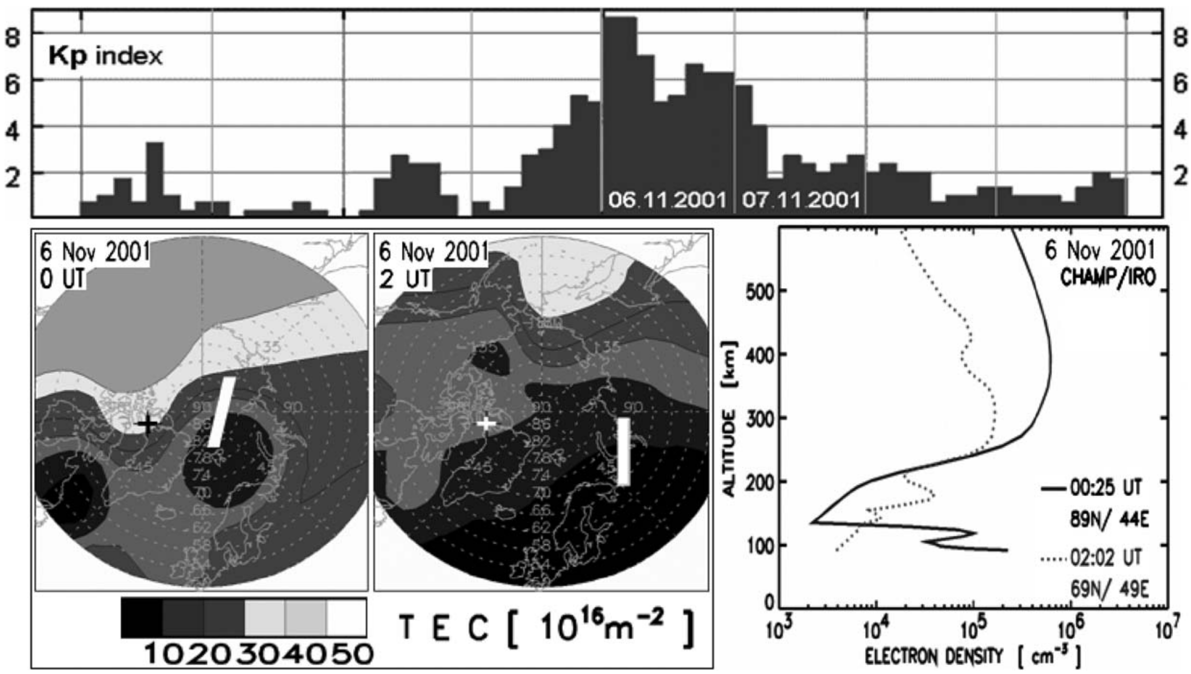

Fig. 3. Ionospheric storm behaviour during the main phase of the geomagnetic storm on November 5–6, 2001. Horizontal ionization distribution shown on the polar TEC maps for 00:00 and 02:00 UT (bottom left panels) and corresponding IRO derived vertical electron density profiles (bottom right panel). The geomagnetic Kp index is provided on the upper panel. The geomagnetic pole is indicated by a cross.

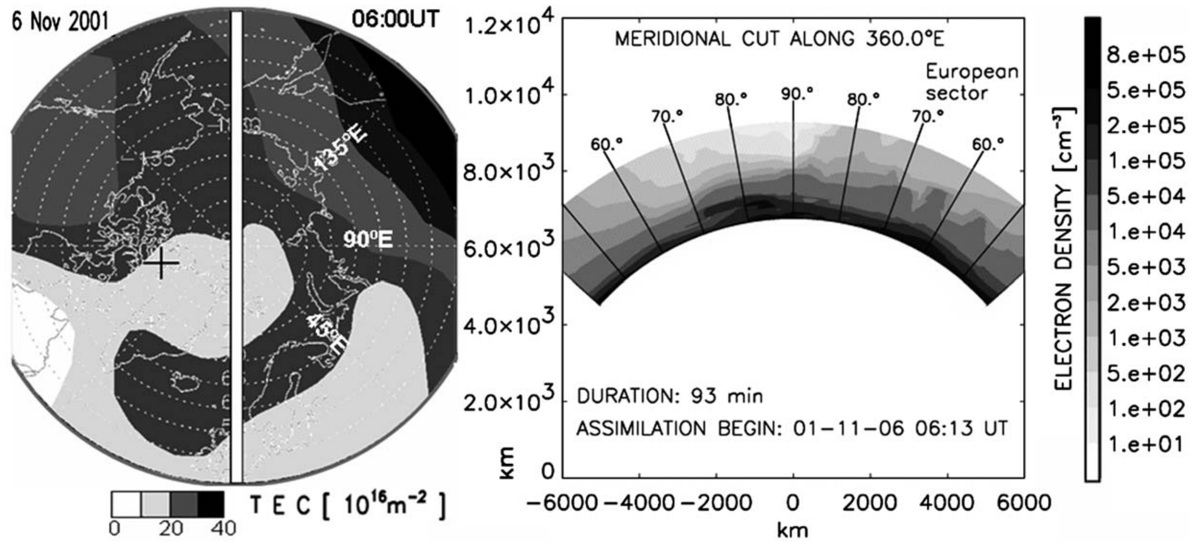

Fig. 4. Polar TEC map (left panel), generated for 06:00UT on 6th November 2001, compared with the topside reconstruction (up to about 3000 km height) of the vertical electron density distribution mapped near the CHAMP orbit plane (right panel). The ground projection of the CHAMP orbit is indicated by a white line on the TEC polar map. The geomagnetic pole is indicated by a cross.

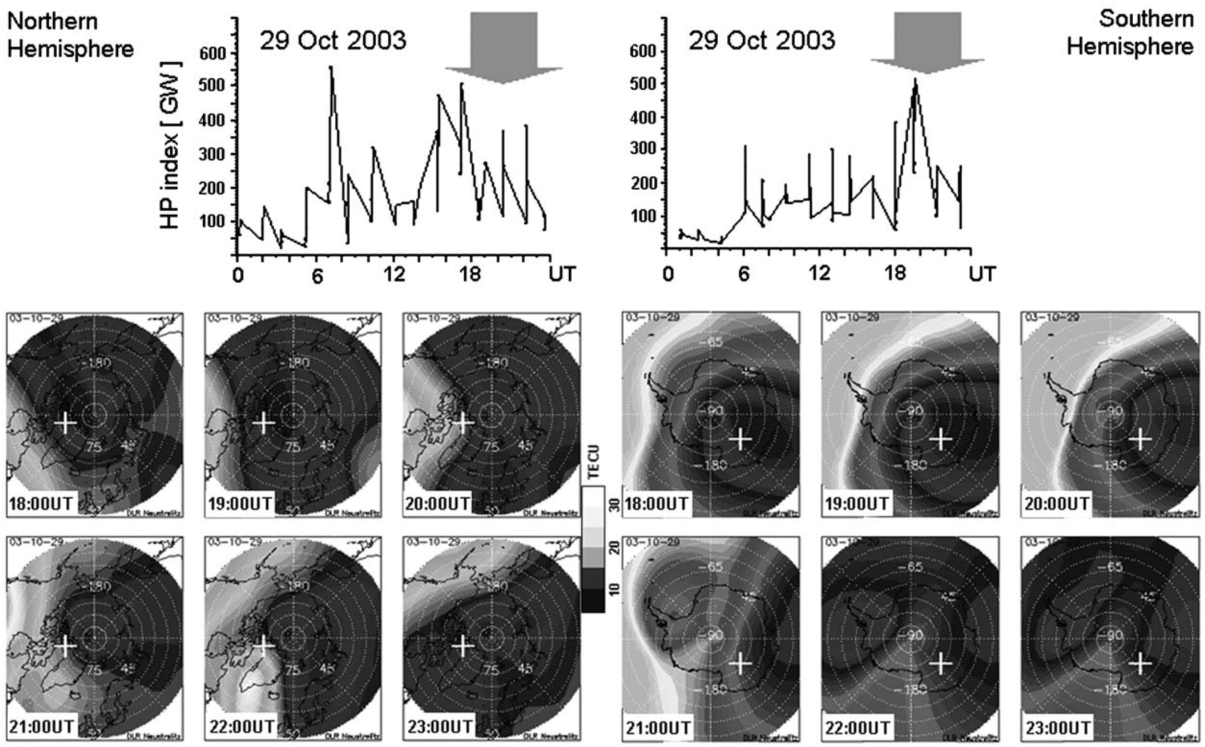

Fig. 5. Polar TEC maps, Northern (bottom left panel) and Southern (bottom right panel), from 29th October 2003. The top panels show the Hemispheric Power Index (http://cedarweb.hao.ucar.edu/instr/ehp.html) for both hemispheres. The selected time interval is marked by the width of the arrows in the index plots. The geomagnetic pole is indicated by a cross.

The space weather event at the end of October 2003 was characterized by a series of large radiation bursts at the sun and huge coronal mass ejections (CMEs) causing severe perturbations in the geomagnetic field and in the geo-plasma environment formed by the magneto- and ionosphere. On 28 October, while the sunspot group 486

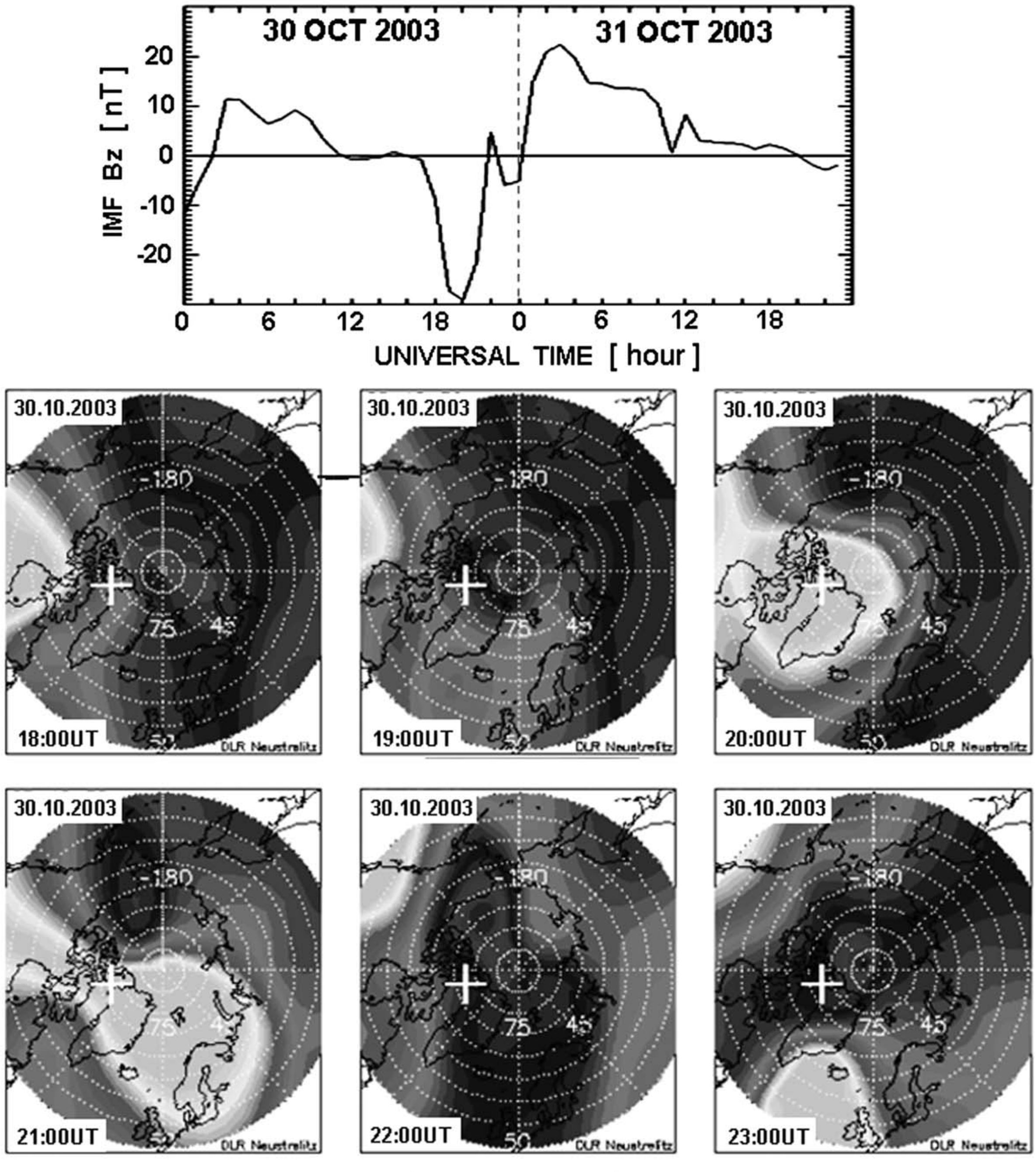

Fig. 6. Northern polar TEC maps (bottom panels) for 18:00–23:00UT on 30th October 2003. The geomagnetic pole is indicated by a cross. The dynamics of TEC correlates with the behaviour of the IMF Bz component (top panel).

faced directly toward Earth, a huge X-17.2 solar flare was observed which was the third largest on record since 1976. The corresponding CME left the sun at about 2000 km/s reaching the Earth magnetosphere already after 19 h around 06:00UT on 29th October. The subsequent geomagnetic storm was one of the largest in the past 40 years ending finally at Halloween.

The ionospheric ionization, represented here by TEC, is obviously (Fig. 5) well correlated with the corresponding Hemispherical Power Index (Foster et al., 1986). Whereas the Northern hemisphere is characterized by a rather low Power Index and a reduced TEC level, the Southern hemisphere indicates a high power index around 20:00UT which directly correlates with the variation of the TEC level at the day-time sector.

The TEC level is also highly correlated with the direction of the interplanetary magnetic field (IMF). The significant southward (negative) direction of Bz correlates directly with the generation of a strong increase of the high latitude ionospheric plasma density (Fig. 6). The enhanced TEC may be due to ionizing particle precipitation and a strong plasma drift from the day-side towards the night-side. The EISCAT derived vertical electron density profiles confirm the TEC map signatures and indicate additionally enhanced ionization at the bottomside ionosphere probably caused by the enhanced particle precipitation (Stolle et al., 2003). It is interesting to note that the enhanced ionization practically vanishes during the short northward turn of Bz at 22:00UT. This indicates extreme highly dynamically processes in the ionosphere from which only the large scale phenomena are visible in the TEC maps. It is remarkable that the strong ionization reappears very fast in the 23:00UT TEC map just in the same moment when Bz turns again southward. It is beyond the scope of this paper to give a comprehensive analysis of the Halloween storm. In this study we focus on the comparison of quite different types of GNSS measurements to evaluate their potential for more detailed studies in the future.

In order to compare polar TEC maps with the result of the topside electron density reconstruction in the CHAMP orbit plane, we come back to the evening hours (18:00–23:00UT) on 29th October (Fig. 7). The CHAMP orbit traces are marked in the corresponding hourly polar map by white lines. It is evident that the reduced TEC level in the Northern Polar TEC map (left

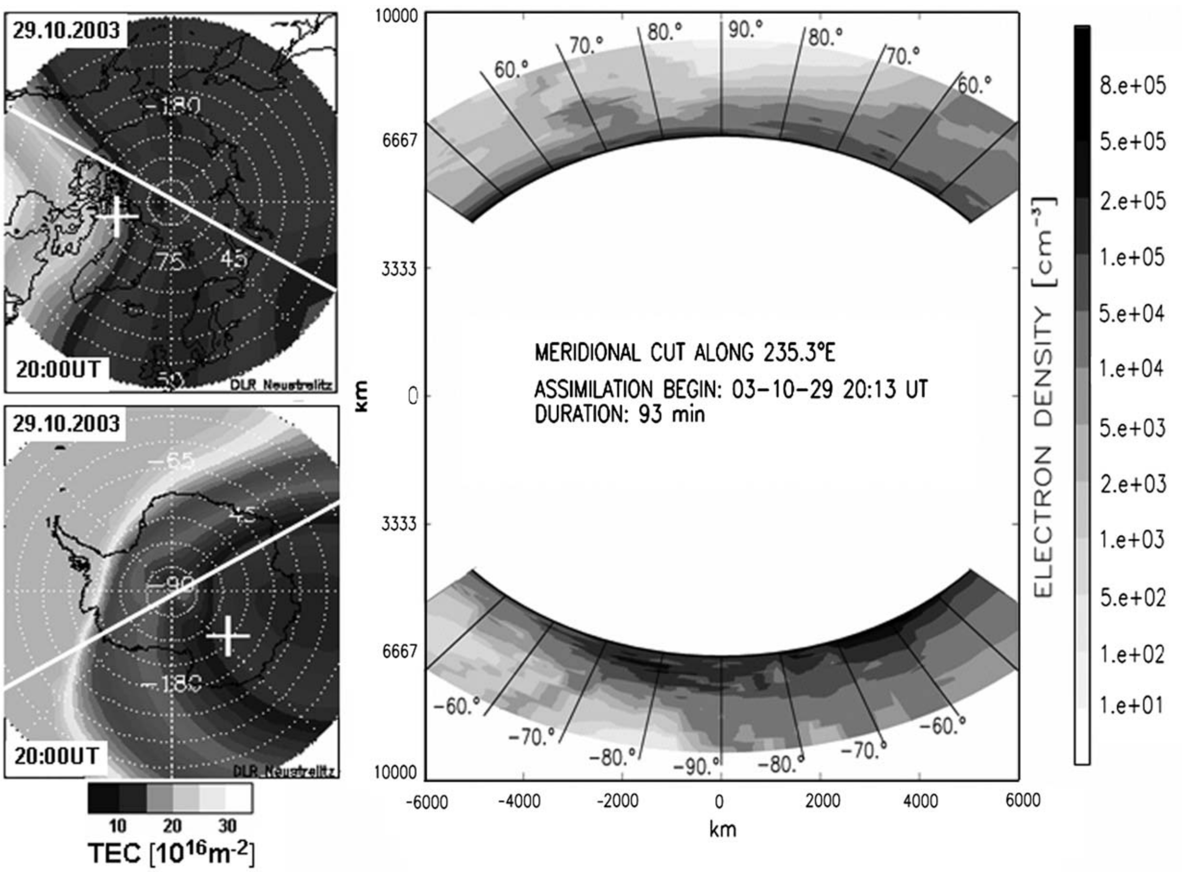

Fig. 7. Northern and Southern polar TEC maps (left panels), generated for 18:00–23:00 UT on 29th October, compared with the corresponding topside reconstructions (up to about 3000 km height) of the vertical electron density distribution mapped near the CHAMP orbit plane (right panel). The ground projection of the CHAMP orbit is indicated by a white line on the TEC polar maps. The geomagnetic pole is indicated by a cross.

panel) is well reflected in the corresponding topside reconstruction of the electron density (right panel). This good correlation is also visible at the Southern hemisphere where the enhanced ionization level is well reflected in the topside reconstruction.

To demonstrate the capabilities of the IRO technique, we have compared actual IRO derived electron density profiles of 30th October 2003 with electron density profiles averaged over the two-month period of October and November 2003 (Fig. 8). The deviations are helpful to get additional insight into the mechanism of ionospheric storms and corresponding vertical redistribution of the plasma due to perturbation induced meridional winds and /or electric fields (e.g. Foerster and Jakowski, 2000). Although the IRO measurements cannot provide a continuous data sequence over a selected site, a comparison with high resolution TEC maps can provide additional insights because the IRO profiles provide information about the vertical redistribution of the plasma. So it is possible to understand and to separate the action of dynamic forces such as perturbation induced meridional winds and electric fields. During the storm, major changes in the shape of the electron density profiles and large deviations of this profiles from the corresponding median values are observed (note: medians represent the average non-perturbed behavior). During storms, particularly in the considered period, processes of different nature occur. Whereas the F2 layer region shows plasma loss at 60°N, at 20°N the plasma peak density increases. This is probably due to perturbation induced southward directed neutral winds or due to an eastward directed electric field as it was indicated in former studies (Jakowski et al., 1999). The uplifting is confirmed by the lower density values at the bottom side. It is interesting to note that at 20°S a strong plasma depletion of the F2 layer is observed whereas the bottom side shows average behavior. At both hemispheres at 40° mid-latitudes the redistribution of the plasma is obviously from the topside to the bottom side indicating a complex interaction of competitive processes along the entire longitude sector.

5. Summary and conclusions

Presented was a review of the capabilities of ground and space based GNSS measurements for monitoring the space weather and its effects in the ionosphere. It is concluded that the combined use of ground and space based GNSS measurements can improve the insight into the dynamics of ionospheric perturbation processes mainly due to different characteristics of the different measuring techniques:

- high temporal and horizontal resolution of the plasma distribution by TEC maps,
- good vertical resolution of the electron density distribution from the LEO orbit height down to the bottomside ionosphere by IRO retrievals,
- overall vertical plasma distribution of the ionosphere and plasmasphere in the LEO orbit plane from LEO up to GNSS orbit heights by data assimilation or

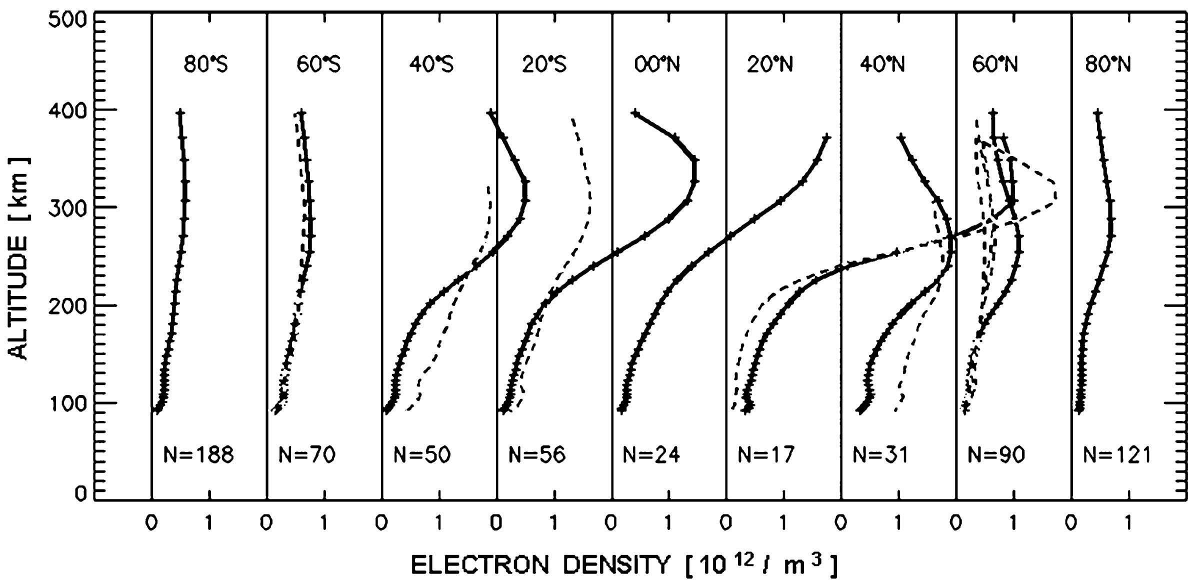

Fig. 8. IRO derived electron density profiles retrieved for 0°E longitude and different latitude ranges within the 11:30–13:00 UT time window on October 30, 2003 (dashed lines). Comparison is made with corresponding median profiles calculated over October and November 2003. The number N of profiles (used for calculation of the median) is provided in each 20° latitude interval.

tomographic reconstruction methods using the navigation data.

It is shown that the different data types usually reveal a consistent description of different aspects of ionospheric perturbation processes during severe space weather events on 5/6th November 2001 and at the end of October 2003. Furthermore, it is shown that geomagnetic storm related fluctuations of TEC are correlated with space weather parameters such as particle fluxes, the direction of the interplanetary magnetic field (Bz) and the hemispherical power index.

Polar TEC maps as well as corresponding reconstructions of the electron density from CHAMP measurements indicate rapid ionization changes which are probably caused by enhanced particle precipitation and plasma convection. To resolve the spatial structure and dynamics of polar irregularities improved temporal and spatial resolution is required.

The permanent densification of GNSS networks at the Earth surface and the growing availability of space based GNSS measurements at multiple LEO satellites will provide a unique opportunity for a comprehensive monitoring of the ionospheric state in particular if different methods are combined (Jakowski et al., 2002b; Stankov et al., 2003; Heise, 2003). If the data base is dense enough, there is a great potential for reconstructing the 3D electron density distribution in a self consistent form.

Because space weather induced irregular spatial and temporal gradients of the electron density distribution may seriously degrade the performance of Com/Nav systems, the GNSS based monitoring has a big potential to mitigate the space weather impact on related applications (Jakowski et al., 2002c, 2004).

Acknowledgements

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References

Daniell, R.E., Brown, L.D., Anderson, D.N., Fox, M.W., Doherty, P.H., Decker, D.T., Sojka, J.J., Schunk, R.W., 1995. Parameterized ionospheric model: a global ionospheric parametrization based on first principles models. Radio Science 30, 1499–1510.

Davies, K., 1980. Recent progress in satellite radio beacon studies with particular emphasis on the ATS-6 radio beacon experiment. Space Science Review 25, 357–439.

Foerster, M., Jakowski, N., 2000. Geomagnetic storm effects on the topside ionosphere and plasmasphere: a compact tutorial and new results. Surveys in Geophysics 21 (1), 47–87.

Foster, J.C., Holt, J.M., Musgrove, R.G., Evans, D.S., 1986. Ionospheric Convection Associated with Discrete Levels of Particle Precipitation. Geophysical Research Letters 13, 656–659.

Hajj, G.A., Romans, L.J., 1998. Ionospheric electron density profiles obtained with the Global Positioning System: Results from the GPS/MET experiment. Radio Science 33 (1), 175–190.

Heise, S., 2003. Rekonstruktion dreidimensionaler Elektronendichteverteilungen basierend auf CHAMP-GPS-Messungen, ISRN DLR Forschungsbericht 2003-07.

Heise, S., Jakowski, N., Wehrenpfennig, A., Reigber, C., Luehr, H., 2002. Sounding of the topside ionosphere/plasmasphere based on GPS measurements from CHAMP: initial results. Geophysical Research Letters 29, 14 doi: 10.1029/2002GL014738.

Heise, S., Stolle, C., Schlueter, S., Jakowski, N., 2005. Differential code bias of GPS receivers in low earth orbit: an assessment for CHAMP and SAC-C. In: Reigber, Ch., Luehr, H., Schwintzer, P., Wickert, J. (Eds.), Earth Observation with CHAMP—Results from Three Years in Orbit. Springer, Berlin, pp. 465–470.

Jakowski, N., 1996. TEC Monitoring by Using Satellite Positioning Systems. In: Kohl, H., Ruester, R., Schlegel, K. (Eds.), Modern Ionospheric Science. European Geophysical Society, Katlenburg-Lindau, pp. 371–390.

Jakowski, N., Tsybulya, K., 2004. Comparison of ionospheric radio occultation CHAMP data with IRI 2001. Advances in Radio Science 2, 275–279.

Jakowski, N., Schlueter, S., Sardon, E., 1999. Total electron content of the ionosphere during the geomagnetic storm on 10 January 1997. Journal of Atmospheric and Solar-Terrestrial Physics 61, 299–307.

Jakowski, N., Wehrenpfennig, A., Heise, S., Kutiev, I., 2002a. Space weather effects on transionospheric radio wave propagation on 6 April 2000. Acta Geodaetica et Geophysica Hungarica 37 (2–3), 213–220.

Jakowski, N., Wehrenpfennig, A., Heise, S., Reigber, C., Luehr, H., Grunwaldt, L., Meehan, T.K., 2002b. GPS radio occultation measurements of the ionosphere from CHAMP: early results. Geophysics Research Letters 29, 10 doi: 10.1029/2001GL014364.

Jakowski, N., Heise, S., Wehrenpfennig, A., Schlueter, S., Reimer, R., 2002c. GPS/GLONASS based TEC measurements as contributor for space weather forecast. Journal of Atmosphere and Solar-Terrestrial Physics 64, 729–735.

Jakowski, N., Stankov, S.M., Klaehn, D., Beniguel, Y., Rueffer, J., 2004. Operational service for monitoring and evaluating the space weather impact on precise positioning applications of GNSS. Proceedings of the European Navigation Conference, 17–19 May 2004, Rotterdam, The Netherlands, ABS No. GNSS2004-119.

Jakowski, N., Tsybulya, K., Mielich, J., Belehaki, A., Altadill, D., Jodogne, J.C., Zolesi, B., 2005. Validation of GPS Ionospheric Radio Occultation results onboard CHAMP by Vertical Sounding Observations in Europe. In: Reigber, Ch., Luehr, H., Schwintzer, P., Wickert, J. (Eds.), Earth

Observation with CHAMP—Results from Three Years in Orbit. Springer, Berlin, pp. 447–452.

Reigber, C., Luehr, H., Schwintzer, P., 2000, CHAMP mission status and perspectives, EOS Transactions—American Geophysical Union, 81 (Suppl. to No.48), F307.

Spalla, P., Jakowski, N., Wehrenpfennig, A., Spencer, P.S., Mitchell, C.N., 2003. Verification of CHAMP radio occultation observations in the ionosphere using MIDAS. In: Reigber, C., Lühr, H., Schwintzer, P. (Eds.), First CHAMP Science Mission Results for Gravity, Magnetic and Atmospheric Studies. Springer, Berlin, Heidelberg, New York.

Stankov, S.M., Jakowski, N., Heise, S., Muhtarov, P., Kutiev, I., Warnant, R., 2003. A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. Journal of Geophysical Research 108 (A5), 1164 doi:10.1029/2002JA009570.

Stolle, C., Jakowski, N., Schlegel, K., Rietveld, M., 2003. Comparison of high latitude electron density profiles obtained with the GPS radio occultation technique and EISCAT measurements. Annales Geophysicae 22 (6), 2015–2028.

Wehrenpfennig, A., Jakowski, N., Wickert, J., 2001. A dynamically configurable system for operational processing of space weather data. Physics and Chemistry of the Earth - Part C - Solar Terrestrial and Planetary Science 26 (8), 601–604.