Monitoring of a polar plasma convection event with GPS

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ABSTRACT

When L-band radio waves of space based systems such as Global Positioning System (GPS) travel trough the ionosphere and plasmasphere their ray paths are perturbed due to the free electrons. Since the last decade these integrated measurements are used to map the ionosphere for navigational and scientific investigations. In November 2001 a polar plasma convection like ionospheric event has been recognised in vertical TEC maps produced with GPS data. This event on the one hand is shortly compared with the behaviour of the Interplanetary Magnetic Field (IMF) to which it may be related according to former publications. On the other hand the 3-dimensional tomography applying also GPS data is tested on its capability to reconstruct this ionospheric event in the European sector. The different mappings of the two monitoring methods are compared.

ZUSAMMENFASSUNG

Wenn L-Band-Radiowellen raumgestützter Navigationssysteme wie das Global Positioning System (GPS) die Ionosphäre oder Plasmasphäre durchlaufen, werden Ihre Strahlwege durch die freien Elektronen verändert. Seit dem letzten Jahrzehnt verwendet man diese integrierten Messungen, um die Ionosphäre im Interesse der Navigation und der Wissenschaft abzubilden. Am Beispiel eines Ereignisses vom November 2001 wurde eine polare Plasmakonvektion in der Ionosphäre durch vertikale TEC –Karten (Total Electron Content), die ebenfalls mit Hilfe von GPS Daten erstellt werden, abgebildet. Einerseits wurde das Ereignis der Plasmakonvektion mit dem Verhalten des Interplanetaren Magnetischen Feldes (IMF) kurz verglichen und auf ihren Zusammenhang hin untersucht. Auf der anderen Seite wurde anhand dieses Ereignisses die Methode einer über den europäischen Raum aufgespannten auf GPS–Daten basierenden 3-dimensionale Tomographie auf ihre Reproduzierbarkeit hin geprüft. Die zwei verschiedenen Methoden des Ionosphärenmonitorings werden verglichen.

INTRODUCTION

Since the ionosphere has an impact on GPS L-band radio waves (Global Positioning System) by its free electrons, increased knowledge on the ionospheric structure is of important interest for precise positioning. Especially during perturbed geomagnetic conditions when the ionosphere differs from its undisturbed state quasi real time data assimilation would be useful. At the other hand, these perturbations on the GPS signals are taken as scientific information to investigate ionospheric scenarios.

During the last decade GPS has become an interesting tool for ionospheric investigations. Hereby 1-dimensional profiling (*Schreiner et al., 1999, Jakowski et al., 2002*) allows to retrieve information on the vertical structure of the ionosphere. For this purpose, signals from GPS satellites orbiting the Earth at about 20,000 km are received during so-called occultations at LEO (Low Earth Orbiter) satellites at orbit altitudes lower than 800 km. A great advantage of this occultation technique lies in the global distribution of the retrieved profiles. Regarding the present amount of satellites profile coverage is still sparse although promising. 2-dimensional mapping of GPS data to vertical TEC (*Jakowski, 1995*) pose another application. Hereby, the vertical integrated measurements of the electron content is mapped to the Earth's surface. This method is based on ground received data and allows a regional continuous monitoring of the ionosphere. Data gaps are combined with a model.

In November 2002 a plasma convection like event has been recognized in north polar TEC maps, which are produce by the DLR Neustrelitz. This will be discussed in this paper. Here a tongue of air with high electron density is convected from the sunward to the antisunward side over the polar cap. There it is spreading and seems to be transported back to the dayside at auroral latitudes.

The inversion of the integrated TEC values to 3-dimensional electron density patterns is a third possibility of monitoring the ionosphere with GPS data. This method is expected to be a tool for retrieving vertical and horizontal information that will be discussed in the following section. In this paper the algebraic iterative method MART is applied as inversion algorithm. A relatively well-distributed amount of GPS receivers of the IGS (International GPS Service), which are the input data for tomography is located over the European sector. Electron density reconstructions have been placed in this region. During the above mentioned plasma convection event the air of enhanced electron density is also reaching Europe and therefore this time interval has been chosen to test the tomographic program on its capability to reconstruct this process.

DATA AND METHODICAL ASPECTS

IGS holds nearly 300 GPS receivers worldwide. About 60 of them are located in the European sector. They are receiving 24 active GPS satellites that are orbiting the Earth at about 20,000 km height. As mentioned above the positioning signal is perturbed by free electrons in the ionosphere and plasmasphere. Since GPS transmits bifrequent signals the disperse ionospheric influence on the measurements can be separated. The resulting TEC value is therefore available as integrated input for 3-dimensional ionospheric electron density distribution reconstruction.

The use of radio signals for ionospheric electron density imaging was first proposed by *Austen et al., (1988).* In the first time mainly TEC data from the NNSS (Naval Navigation Satellite System) were taken for 2D reconstructions (e.g. Pryse et al., 1995). The idea to apply GPS data as input for ionospheric monitoring is based on the continuous and relatively low cost data achievement.

Since the amount of GPS data still does not correspond to the desired scientific resolutions of inversion results many research groups are faced with resolving underdetermined mathematic problems. Different methods are used in 3D monitoring using GPS data. Spherical harmonics (*Spencer et al., 2002*) are based on the application of defined base functions. This method is fast and can be applied globally but its results are relatively smooth. *Mitchell et al., (2001)* extended the data input by averaging over one hour and included also limb sounding data from LEO satellites. Abel transform found application (*Ruffini et al., 1998*) by monitoring the ionosphere for positioning correction aspects. This program works globally and the problem of underdetermination is reduced by relatively low resolution, which is sufficient for its purpose.

This paper deals with the iterative algebraic algorithm MART (*Schlüter et al, 2002*), which is voxel orientated. The sparse matrix is inverted ray by ray and does not pose problems for computational memory. The calculation starts from the tomographic equation:

$$TEC = \int_{ray} r\,dl \ ,$$

which is discretised and voxels of electron densities are corrected iteratively (k - iteration step number) according to the data:

$$r_j^{k+1} = r_j^k \cdot \left[\frac{TEC_i}{\sum_j l_{ij} r_j^k} \right]^m \qquad \text{with} \qquad m = l \frac{l_{ij}}{\sum_j l_{ij}}$$

where ñ is the electron density of voxel j, l is the partial ray path of ray i in the voxels, TEC is the measured integrated value and λ is the relaxation parameter to reduce artefacts. The iteration is initialised by a combination of the IRI and Gallagher model (*Bilitza, 1990; Gallagher et al., 2000*). Results are therefore model dependent that is a weak point here.

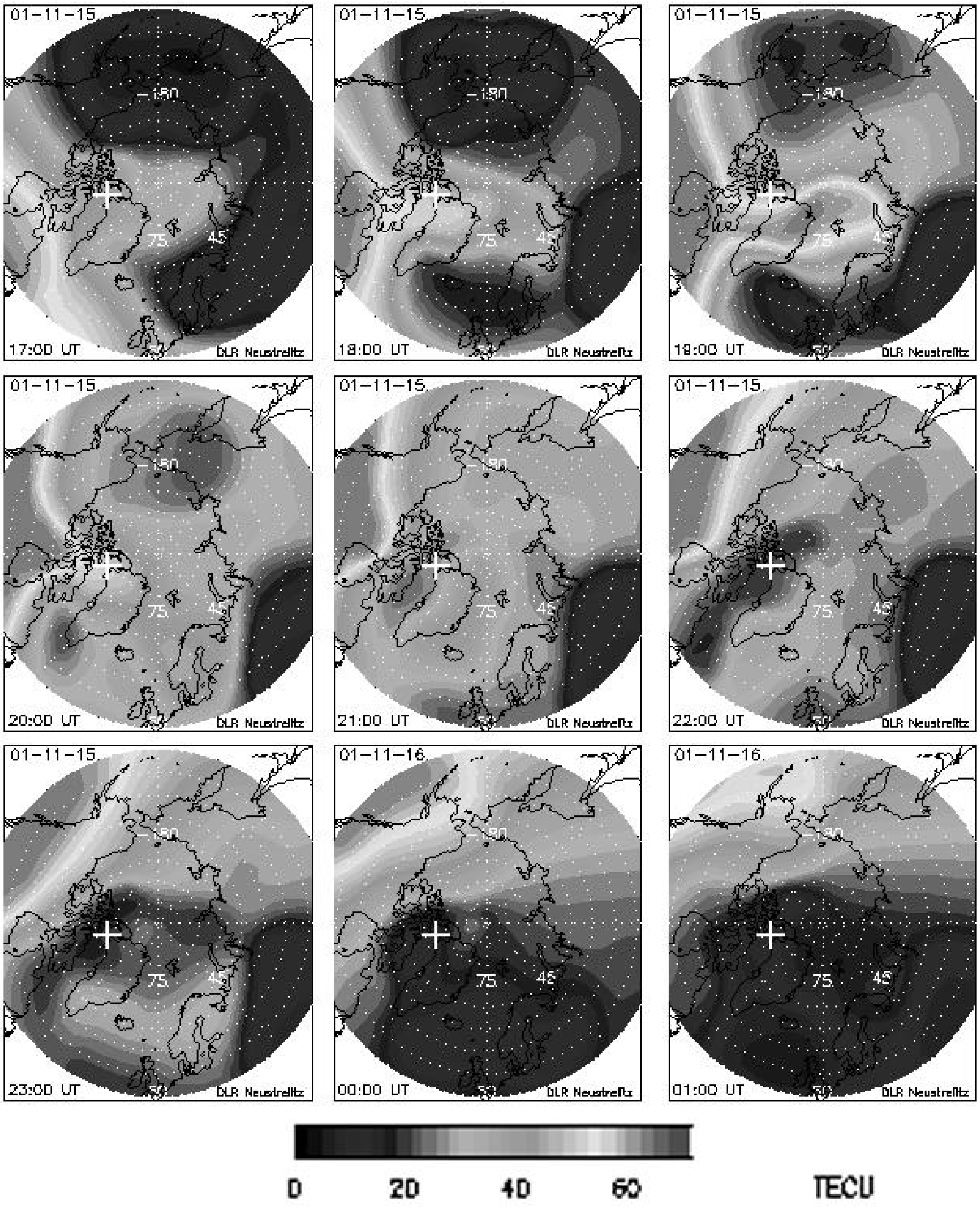

Fig 1: North Polar TEC maps from 15th of November, 2001, 17 UT to 16th of November, 2001, 01 UT

Since the GPS TEC readings include also the plasmasphere its portion has to be estimated and data are corrected by that before being used for ionospheric reconstruction. The extension of the reconstruction area ranges from 32.5°N to 80°N in latitude, from –20°E to 40°E in longitude and from 80 –1000 km in height. The resolution of the model is 2.5° in latitude, 5° in longitude and 10 km in height.

PLASMA CONVECTION EVENT IN POLAR TEC MAPS

From November 15th, 2001, 17 UT and November16th, 2001, 00 UT a polar plasma convection event has been observed in north polar vertical integrated TEC maps, which can be seen in Fig.1. At 17 UT of November 15th air of high electron density is convected antisunward. Between 18 and 19 UT the tongue continues to be transported to the night side. At 20 UT the pattern seems to spread and to form a two cell distribution while the plasma is convected back to the dayside at auroral latitudes. Antisunward convection might occur when the z-component of the IMF (interplanetary magnetic field) is southward directed, thus being negative. In this case, the IMF is oppositely directed to the geomagnetic field and their field lines can merge together and form geomagnetic open field lines out to the interplanetary space. Then, by so-called geomagnetic reconnection energy and momentum may be transferred across the magnetopause (*Dungey et al., 1961*) and reach near earth regions. For more detailed explanations see, e.g., *Kelley (1989)* or *Prölls (2001)*. Via the equation:

$$E = -V \times B\ ,$$

where B is the magnetic field, which points here southwards, V is the solar wind (particles transmitted from the sun), so directed from the sun to the earth, an electric field E directed from dawn to dusk builds up. By the $E \times B$ drift the ionospheric geoplasma is transported antisunward.

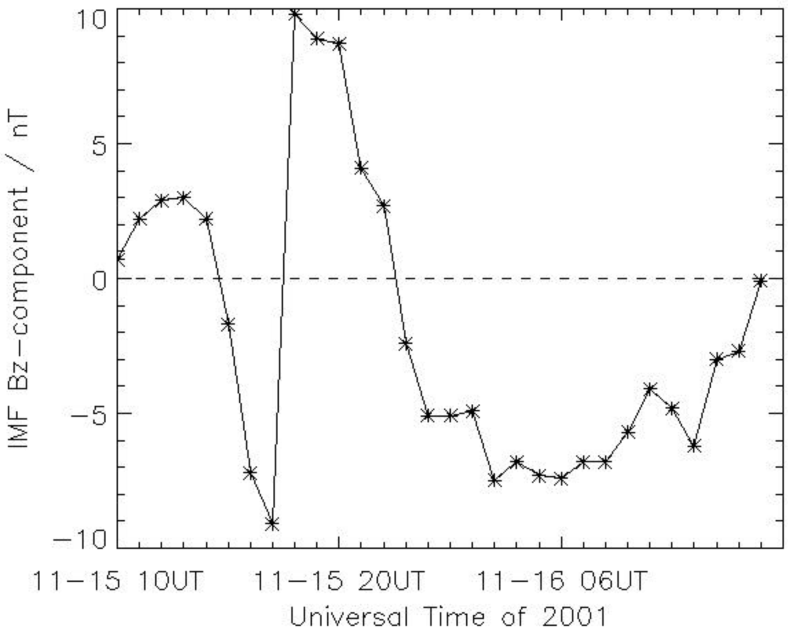

Fig 2: z-component of the Interplanetary Magnetic Field measured at the ace2 satellite at 15th of November, 2001 10 UT and 16th of November, 2001 15 UT

This process affects also F-layer regions where most of the ionospheric plasma is found. The plasma is often transported back to the dayside in lower auroral latitudes and forms a tow-cell-pattern. This effect may also be seen in the TEC maps at 20 UT. Nevertheless, many authors mention that the resulting convection pattern is strongly dominated by the y-component of the magnetic field. Localised perturbations, which cannot be ruled out (e.g. *Ruohoniemi and Greenwald, 2002*) may disturb the clear two-cell pattern. In fact, starting at 21 UT the plasma is largely distributed over the polar cap and no more clearly two-cell pattern of classical southward IMF induced polar convection can be recognised.

In Fig.2 the real time IMF measurements of the z-component of the ace2 satellite is graphically shown. Here we can see that the IMF is directed southward until 17 UT with a high amplitude more then -9 nT. At this time the antisunward convection is recognised at the polar TEC maps. At 18 UT a sudden south-to-north turning at a similar high magnitude occurs. Thus, thenceforward the pattern found in the polar TEC maps cannot be reconnected with an southward IMF anymore because the ionospheric response time on IMF changes is between 6 and 8 minutes at nighttimes (*Khan and Cowley, 1999*), which has been confirmed in between the same range by other authors. Meanwhile after 18 UT a strong northward directed z-component of the IMF has been measured. According to several investigation it has been noted that by this IMF conditions a more complicated three- or four-cell pattern may be built up, which is described in detail by *Kelley (1989)*. Roughly speaking, here a convection to the dayside might be formed over the pole and two or one cell of plasma transport pattern are formed at each of the dawn and dusk side of the sunward plasma motion. Taking the satellite IMF data as correct, the strong reverse of the z-component of the IMF could create turbulences in plasma motion and may favour local perturbations to dominate.

Nevertheless, as seen in the further development of TEC in Fig.1, the high plasma anomaly spreads widely over the polar cap and is almost reconciled at 00 UT at 16th of November, 2001.

TOMOGRAPHIC CASE STUDY

As a tomographic case study the plasma convection event in November 2001 described above has been chosen. In the TEC maps a remarkable, relatively well located electron density perturbation over the European sector can be realised and therefore it is suitable for testing the tomography lying in this region.

Reconstruction results at selected times are shown in Fig.3. One can see an electron density enhancement arriving from the North towards midlatitudes at 20 UT. At 22 UT the positive anomaly is developing and spreading on the Northern part of Europe around 23 UT. It starts to decrease at midnight.

Taken the combined initialisation IRI/Gallagher model (*Schlüter et al., 2002*) as an indication of climatologic average in the respective month, the amplitude of deviation from the model mean can be understood as disturbed ionospheric behaviour. This will allows us a more detailed interpretation of the tomographic reconstruction in comparison with the TEC map monitoring.

The deviation plots are produced at 12.5° longitude and show the whole latitude range of the tomographic region. Since the 12° longitude circle crosses Iceland, Norway and Germany it lies in the centre of the calculated region and in the centre of the European perturbation during this time.

The plots start at 18 UT of the November 15th where a small positive anomaly of $2x10^{11}$ electrons/m^3 can be recognised at polar and subpolar regions. This is in agreement with the TEC maps where the enhanced electron density arrive in Northern Europe at this time. It is thus of interest to see in Fig.4 that the perturbation arrives and disappears very quickly. While the model underestimates the electron content by about $2x10^{11}$ electrons/m^3 at 18 UT, this is enhanced to $8x10^{11}$ electrons/m^3 in the same regions just one hour later. This situation will las t until 23 UT with its maximum of $12x10^{11}$ electrons/m^3 deviation from the model at 22 UT. Compared to the predicted values, this marks an electron density enhancement of about 50% to the modelled mean. As fast as the convected plasma arrived, so quickly it seems to pull back. The underestimation of the model of still 10 $x10^{11}$ electrons/m^3 at 23 UT falls down to 4 $x10^{11}$ electrons/m^3 at 0 UT of the following day and notes only 2 $x10^{11}$ electrons/m^3 again at 01 UT.

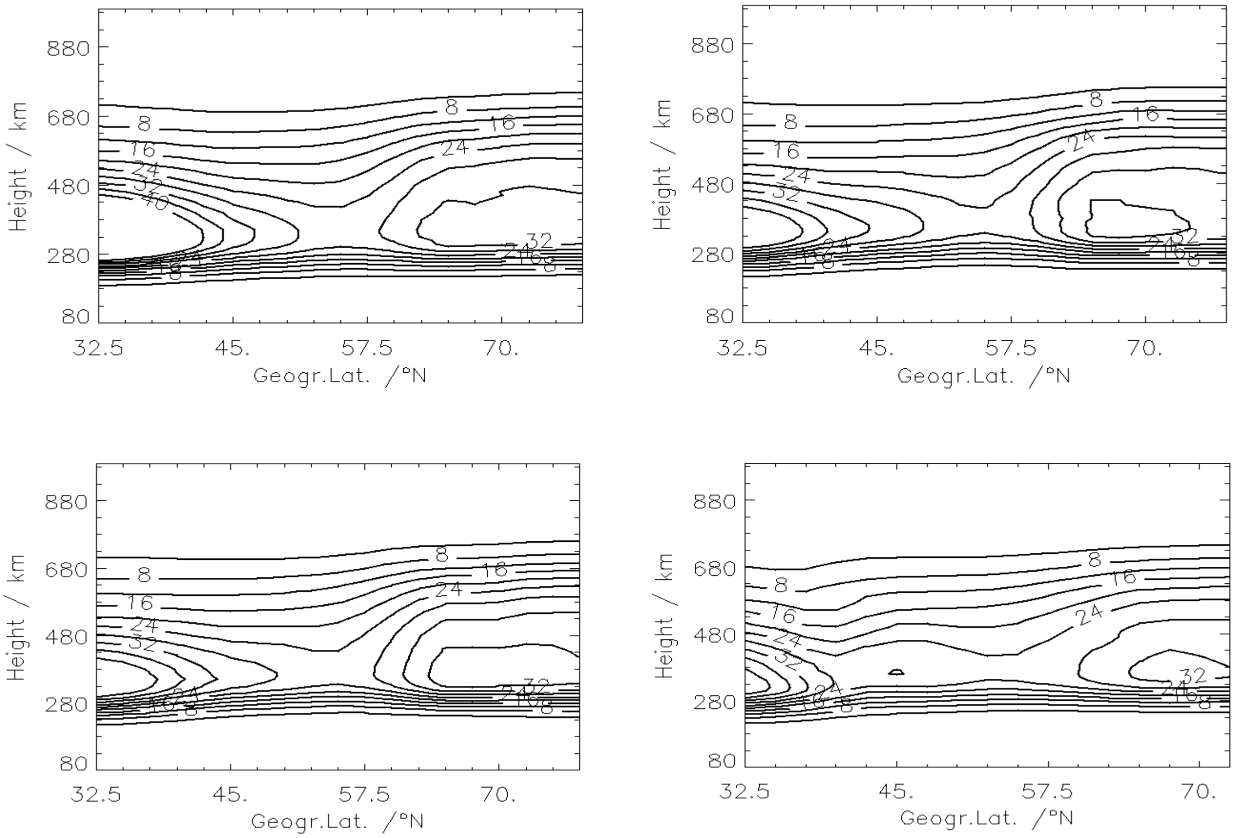

Fig.3: Tomographic electron density distributions at 12.5°E longitude on November 15, 2001 (a) 20 UT, (b) 22UT, (c) 23 UT and November 16, 2001 (d) 00 UT. Solid lines are marked in 10^{11} electrons/m^3.

It can be noted that also in the TEC maps the anomaly arrives very quickly but has its clear European maximum with about 40 TECU at 20 UT. Just one hour later at 21 UT it is pulled northwards and values between 20 and 30 TECU are measured.

Regarding the local extension the same time differences are found. While the widest extension of high electron density mass down to about 40°N is found at 20 UT in the polar TEC maps the tomographic results represent a maximum at 22 UT with positive correction about 4 $x10^{11}$ electrons/m^3 at these latitudes. At other, moderate perturbed times significant anomalies are going south to about 60°N in both presentations,. At 00 UT of the following day very less positive correction is seen in tomographic results and none anymore in the polar TEC maps.

Differences between the two methods of monitoring of the convection event can lie in the different method of data assimilation. Slant TEC is mapped to vertical TEC in the 2-dimensional TEC maps where the mapping function could produce errors especially in high gradient conditions around the GPS receiver. An advantage here is of course the wide range of observation over the whole polar cap and the relatively good data coverage compared to the 3-dimensional plotting where the height dimension imports additional grid points and the number of unknowns rises. For 3D reconstruction due to this lack of data coverage a model is applied as initial condition for tomographic iteration, which leads the results to a strong model dependency. The lower the data coverage, the more the results are similar to the initial model. During several hours the data reception is changing in number and distribution and this may influence the results. In addition, the restricted area of observation only allows interpretations of medium scale ionospheric processes. The advantage of 3D reconstructions lies in the redistribution of the electrons of the integrated measurement on the real ray path and that there is no need for spherical symmetric assumption around the receiver.

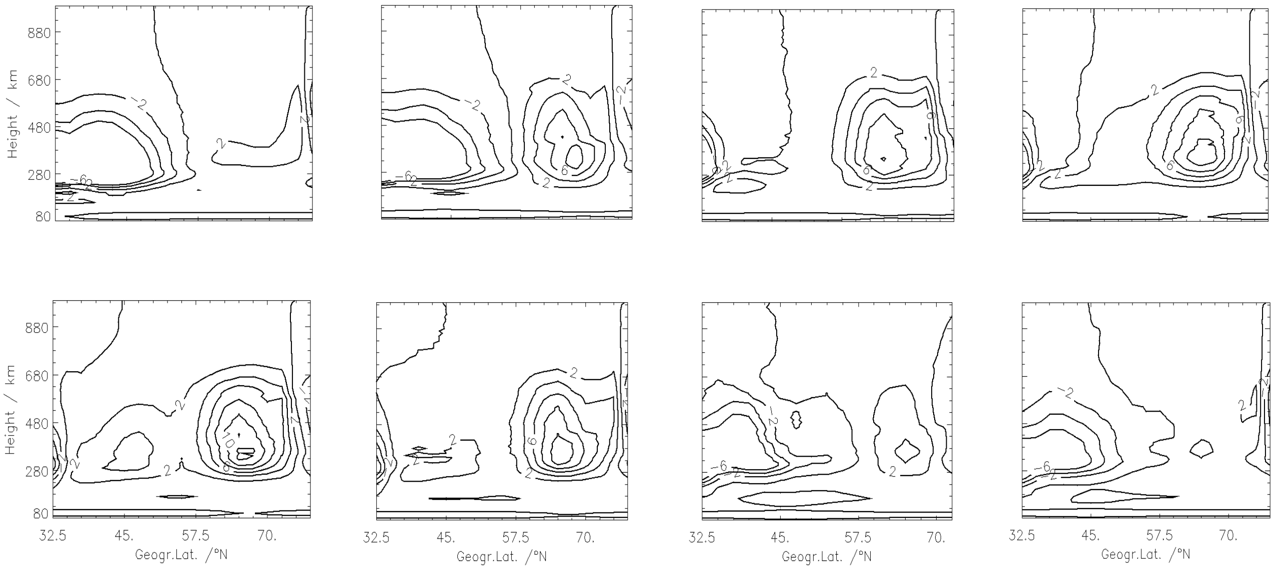

Fig. 4: Difference plots between tomography and initial model from November 15, 2001 18 UT (upper left panel) to November 16, 2001 01 UT (lower right panel).Time step between each figure is 1 h. Modelled electron densities have been subtracted from tomographic values. Solid lines are marked in 10^{11} electrons/m³. Longitude is 12.5°E

Fig.4 shows an inversion of the correcting trend to negative values above 75°N. It has to be mentioned that less GPS receivers are installed in polar regions than in the European midlatitudes, so less input data is available there. The constant correction can probably be referred to the known IRI-mismodelling of these regions.

In near equatorial regions a negative deviation to the model is recognised except for unusual enhanced electron densities (21–23 UT), which may be connected to a probable IRI overestimating in this regions, which are often seen during such studies, however, a detailed investigation of this effect is out of the scope of this paper.

CONCLUSION

In this paper a polar plasma convection event has been seen by north polar vertical TEC maps from the night of November 15th to November 16th, 2001. The behaviours of such ionospheric events may be connected to a southward z-component of the IMF. Since a strong south-north turning happened one hour after the onset of the convection, probably local perturbations dominate during the event.

This ionospheric scenario extending also in European regions is suitable for investigations of the reconstruction capability of the 3-dimensional monitoring. Herein a clear positive electron

density anomaly was seen arriving from northern latitudes and spreading over Europe. Compared to polar vertical TEC maps local extensions of the event are similar. The positive anomalies of electron density values reach down to 40° N during the time of maximum disturbance. The temporal development of the maximum anomaly arrives two hours later in the 3-dimensional monitoring than in the 2-dimensional TEC plots, even though the calculations do not indicate high perturbations in lower latitudes then 60°N.
We showed that 2-dimensional as well as 3-dimensional monitoring of TEC and the ionospheric electron density respectively can well reconstruct large scale ionospheric scenarios such as the presented polar plasma convection. The advantage of the 2-dimensional TEC maps lies in the wide region of mapping, which allows a very good regional overview on the event. The more dense data coverage in thanks to the 2-dimensional grid permits also results tending more toward reality than toward the therefore applied model.

Even if the extension of the event in 3-dimensional electron density mapping is shifted in time compared to the TEC maps the temporal evolution is as well reconstructed. In European regions it can be seen that the air mass of high electron density propagates very fast southwards in between 2 hours, lasts during about 3 hours and pulls back again highly fast in between 1 hour, the whole event happens during 7 hours approximately.

The tomographic reconstruction confirmed that the most important plasma motion is realised in altitudes of the F2-layer where the highest atmospheric ionisation level is found. Good insight into the interpretation of vertical distributions is expected when space based GPS data such as those from LEO satellites are integrated in the reconstruction. Until now it is difficult to capture occultations that lies completely in the reconstructing sector. An extension of the region e.g. over the north pole will help to accommodate this lack and could have the great advantage for better observation of the ionosphere especially in perturbed periods. However, data coverage is even worse in inhabited territories. Hereby occultation data would be useful at the present state even necessary.

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