Comparison of electron density profiles in the ionosphere from ionospheric assimilations of GPS, CHAMP profiling and ionosondes over Europe

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ABSTRACT

GPS integrated Total Electron Content measurements received at the ground or in space are used for tomographic reconstruction of the ionospheric electron density distribution. The IRI/GCPM model is used as initialisation of the tomographic MART algorithm. During the procedure GPS TEC data are iteratively assimilated to the model. To test the potential of the reconstruction, electron density profiles from IRI/GCPM and the assimilation are compared with ionosonde measurements and CHAMP radio occultation profiles for dates during the HIRAC campaign in April 2001. All profiling methods show electron density values of similar magnitude. It is shown that including TEC GPS data corrects the model towards the ionosonde measurements.

ZUSAMMENFASSUNG

Integrale Messungen der Elektronendichte aus GPS-Boden- sowie Radio-Okkultations-Messungen bilden die Datenbasis der hier vorgestellten 3-dimensionalen Tomographie der ionosphärischen Elektronendichteverteilung. Zur Initialisierung des verwendeten iterativen MART Algorithmus wird das IRI/GCPM Modell verwendet, wobei das Modell während der Iteration sukzessiv an die Messdaten angepasst wird. Um das Potential des Verfahrens abzuschätzen, werden Elektronendichteprofile des IRI/GCPM Modells und der Rekonstruktion mit Ionosondenmessungen und CHAMP-Okkultationsprofilen verglichen. Dafür wurden Messungen während der HIRAC Kampagne im April 2001 genutzt. Alle hier gezeigten Profilableitungen geben Elektronendichtewerte der selben Größe wieder. Eine Annäherung des IRI/GCPM Modells an die Messwerte der Ionosonde durch die Assimilation der TEC GPS Daten wird gezeigt.

INTRODUCTION

Ionospheric remote sensing can be realised by various methods. Phase shift and travel time observations of signals from the Global Positioning System (GPS) state a newly developed application for ionospheric electron content measurements. GPS information can be used to derive the integrated Total Electron Content (TEC) along the link between GPS satellite and receiver. Different analyses allow [0] the monitoring of the two-dimensional vertical integrated TEC distribution, [1] the retrieval of one-dimensional electron density profiles, or [3] the imaging of the three-dimensional electron density distribution. Scientific modelling [2] represents a further method to image three-dimensional electron density fields. A well established ionospheric profiling method is given by radio soundings using ionosondes [4]. In the following, numbers in brackets refer to the respective remote sensing.

[0]: By the combination of many TEC measurements from GPS received at the ground and organised by services like the International GPS Service (IGS), two-dimensional TEC maps are build (see, Jakowski et al., 2002a). Analyses of the horizontal behaviour of the electron content are an important tool for investigations of the ionosphere (e.g., Förster and Jakowski, 2000).

[1]: In July 2000, the Low Earth Orbiter (~ 430 km orbit altitude) satellite CHAMP has been launched by the GFZ Potsdam/Germany. Among other instruments, it carries a GPS receiver.

During an occultation with a GPS satellite TEC is monitored along quasi horizontal rays. This specific ray constellation allows the retrieval of ionospheric electron density profiles (see, Jakowski et al., 2002b). The monitoring of ionospheric profiles is a step towards an improved investigation of the vertical electron density distribution of the ionosphere. During one day, up to 200 profiles are recorded which are distributed globally.

[2]: As a possibility for imaging the ionospheric electron density distributions in three dimensions (in horizontal and vertical scale) ionospheric modelling is performed. A prominent model is the empirical International Reference Ionosphere (IRI) (e.g., Bilitza, 2001). Among a variety of ionospheric parameters, it also returns electron density in altitude ranges between 60 and 1000 km. To reduce the known overestimated density prediction in the topside ionosphere (above the F2-peak height, which is at about 300 km) by IRI and for an extension to the modelling of the plasmaspheric electron content IRI is combined with electron density outputs of the plasmaspheric parameterised Global Core Plasma Model (Gallagher et al., 2000).

[3]: Empirical modelling is a climatologic representation of ionospheric parameters, whereas ionospheric monitoring by GPS represents a measurement of the instantaneous state of the ionosphere. Therefore, three-dimensional ionospheric imaging over wide regions (as provided by scientific models) can be improved by GPS TEC data assimilations into the model (Schlüter et al., 2003). For this purpose, electron density outputs of the IRI/GCPM model and ground- as well as space-based (CHAMP) TEC records are combined through a tomographic inversion algorithm (Stolle et al., 2002).

[4]: Ionospheric soundings from ionosondes return parameters of the vertical electron density distribution above the sounding stations. They deliver the electron density values of the F2-peak (NmF2) and, for good quality data, F2-peak height (HmF2) or even entire electron density profiles up to the F2-peak.

To evaluate the potential of the GPS TEC data assimilation into the combined IRI/GCPM model, this paper will compare the assimilation results [3] with following data sets: CHAMP ionospheric profiling [1], pure IRI/GCPM model predictions [2] and ionosonde data [4]. The interdisciplinary comparison is performed for dates during the HIRAC (HIgh RAte / Solar Max Campaign) campaign from April 23 to April 28, 2001. The presented dates were chosen in accordance to CHAMP data availability.

APPLIED METHODS AND DATA

[3]: The tomographic 3-dimensional reconstruction of the ionospheric electron density distribution (Schlüter et al., 2003) is based on the Multiplicative Algebraic iterative Reconstruction Technique (MART) Therefore, integrated TEC retrieved from GPS observations at ground-based receivers from the IGS network and space-based GPS TEC data received at the CHAMP satellite are used. The discrete assimilation process requires the discretisation of the model space (3d electron density distribution) as well as of the GPS ray paths into a 3-dimensional voxel system. The area of reconstruction is situated over Europe as it is indicated by the black solid lines in Fig.1. Initially, the voxels are filled with electron density values predicted by the IRI/GCPM model. By use of MART and the application of simple filtering techniques, the voxel's densities are iteratively adapted to the data. For this study, the number of iteration steps has been set to 30 for all selected dates. Before entering the assimilation process, ground- as well as the space-based TEC have to be calibrated (Sardón et al., 1994; Heise et al., 2003).
Only occultation rays situated entirely in the European region are considered for this study. We performed reconstructions at times within HIRAC, where at least one CHAMP occultation occurred. In Fig.2, the ray geometries for all available dates are shown.

[1]: The CHAMP profile retrieval using solely data collected during one CHAMP occultation with a GPS satellite is applied to derive ionospheric electron density profiles at the mean tangential point of the occultation (see, Jakowski et al., 2002b). The tangential point is the nearest point of one GPS-CHAMP link to the Earth surface. The CHAMP profiling procedure is based on a spherical layered shell structure of the ionosphere. The quasi horizontal rays give information on the electron content summed along the ray paths inside the shells. The electron densities of the different shells are successively derived, while the tangent point of the occultation rays comes closer to the Earth surface. For our comparison three CHAMP profiles are available. Their location is shown by the triangles in Fig. 1.

[4]: As has been mentioned in the former section, electron density outputs of the CHAMP profiling [2], of ionospheric models [3] and of the GPS assimilation process [4] will mostly be shown in reference to ionospheric F2-peak parameters measured by ionosondes. The applied ionosonde data have mainly been accessed from the SPIDR network (http://spidr.ngdc.noaa.gov). SPIDR data deliver electron density F2-peak value (NmF2) and height (HmF2). Data of the Juliusruh ionosonde have kindly been provided by the IAP Kühlungsborn and give also information of the whole electron density profile up to the F2-peak. The measured parameters are products of automatic inversion programs which do not underlie permanent human supervision. This needs to be taken into account when comparing especially HmF2 and profile features. The locations of included ionosondes for the comparative study are shown by the asterisks in Fig.1.

Ionosondes as well as the pure CHAMP data retrieval returns electron density profiles, or at least electron density F2-peak parameters as it is the case for SPIDR ionosonde data. To compare these outputs with results of the IRI/GCPM model and the GPS TEC data assimilation, electron density profiles has been selected out of the respective three-dimensional analyses near locations of the ionosondes or the pure CHAMP data profile.

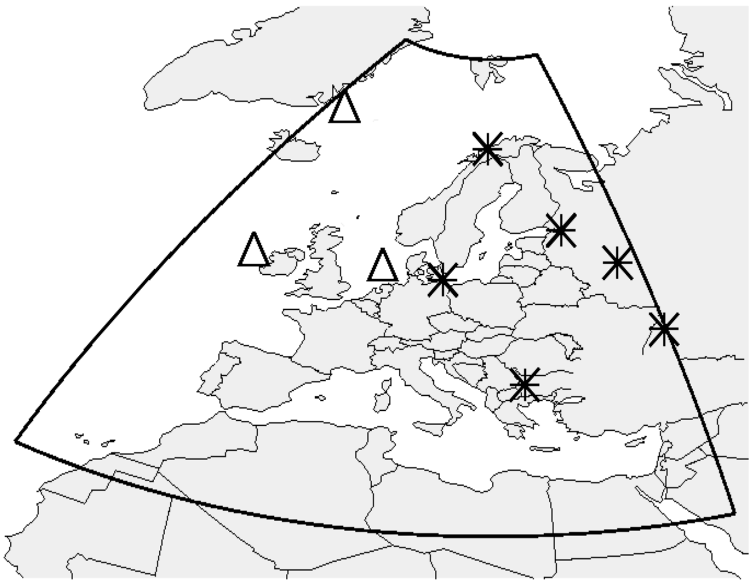


Fig. 1: The boundaries of the reconstruction area are shown by the black solid line. Asterisks present the location of the ionosondes and the triangles show the locations of the CHAMP retrieved profiles.

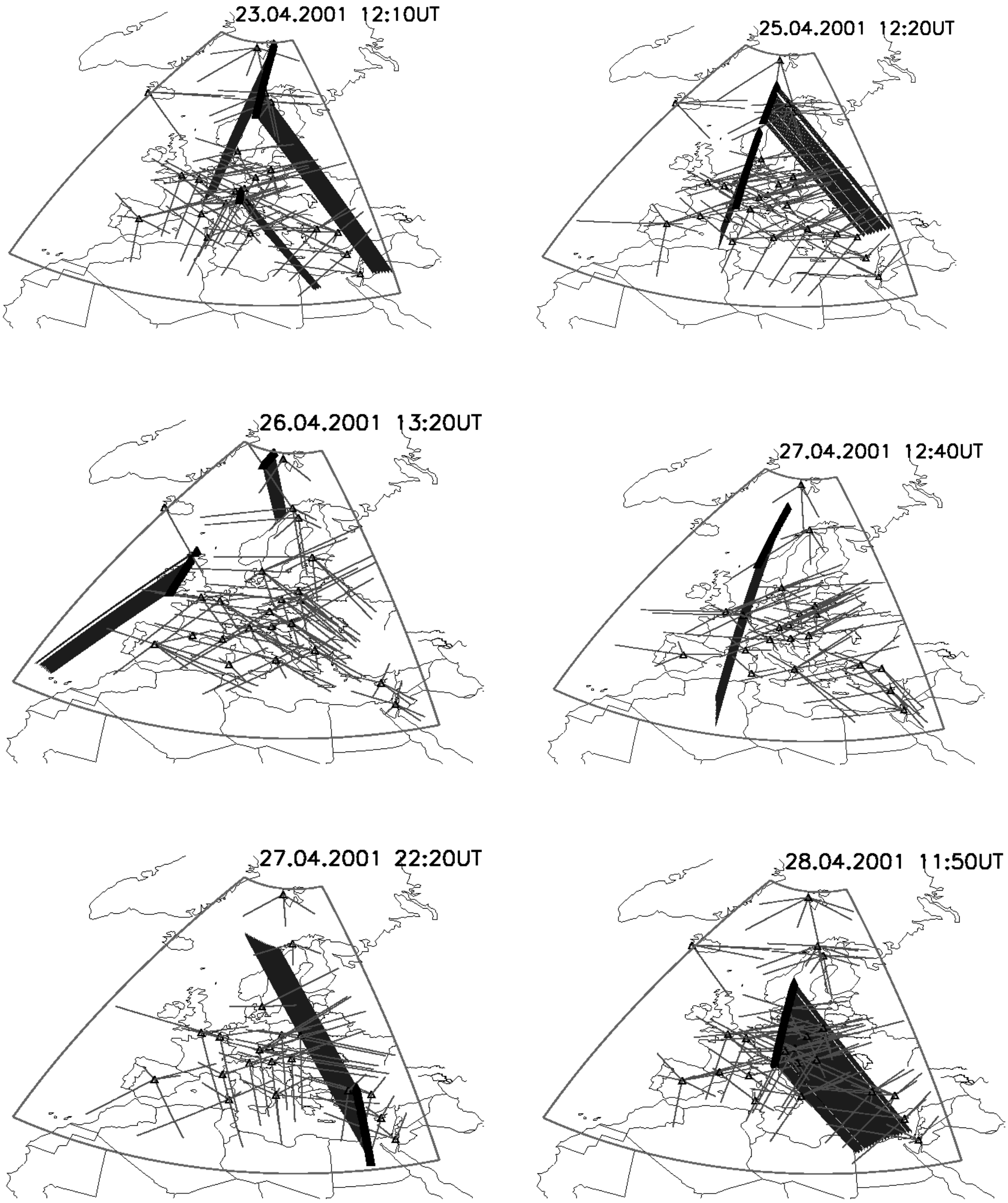


Fig. 2: Ray distribution of the GPS TEC measurements as input for the reconstruction dates. Dates and times are shown at the top of each panel. Small triangles show GPS receiver locations. Separate appearing lines are ground-based GPS rays. Solid black columns represent the densely aligned recorded GPS rays along the CHAMP ray path.

RESULTS

In Fig. 3(a)-(l) ionospheric electron density profiles are plotted for specific dates during the HIRAC campaign. The profiles have been retrieved by following methods:

[1] ionospheric profiling using solely CHAMP data,
[2] combined IRI/GCPM model,
[3] ground-based and CHAMP TEC data assimilation into the IRI/GCPM model, and
[4] ionospheric soundings by ionosondes.

All presented electron density profiles show good agreements to each other for the respective date. Electron density values are of equal order of magnitude. A rough overview immediately reveals that the reconstruction procedure adapts the model prediction towards ionosonde or CHAMP profiles.

However, the quality of the reconstruction profiles varies for the different dates. This is contributed to characteristics of the method: the results of the 3-dimensional GPS data assimilation [3] are expressed as data induced adaptation of the IRI/GCPM model [2] to the GPS TEC measurements. This adaptation should be important for high data availability as it is the case, e.g., in Fig. 3(l). Also equipped with relatively dense GPS rays, the model modification through TEC data was low in Fig. 3(h), even though the ionosonde shows a somewhat higher value of NmF2 than the model predicted. This might indicate that the initial electron density predictions from IRI/GCPM were close to available GPS data information in this case.

Correspondences between assimilation [3] and CHAMP retrieved profiles [1] are excellent for peak densities, e.g., Fig. 3(d) and Fig. 3(f). Note, that in Fig. 3(f) the same CHAMP data was applied in both methods. Here, rays of that occultation used for CHAMP profiling [1] lay entirely in the area of reconstruction. For the results presented in Fig. 3(d) almost no GPS data were available for assimilation near the location of the CHAMP profile. For this date, rays of that occultation used for CHAMP profiling [1] lay partly out of the reconstruction area and were not assimilated [3]. However, peak values are similar. This again shows the satisfactory density prediction of IRI/GCPM for moderate ionospheric conditions, as it was the case during the entire HIRAC campaign. Nevertheless, both figures reveal the dependence of the assimilation results on the initial model through the profile shape. This aspect of model dependence of the reconstruction results needs to be considered for all dates.

It has to be annotated that steps in the profiles of the topside ionosphere appear sometimes (e.g. Fig. 3(f)). They are attributed to vertical smoothing parameters, which do not seem to be sufficient for the present data densities in the respective cases, but are applicable for other situations.

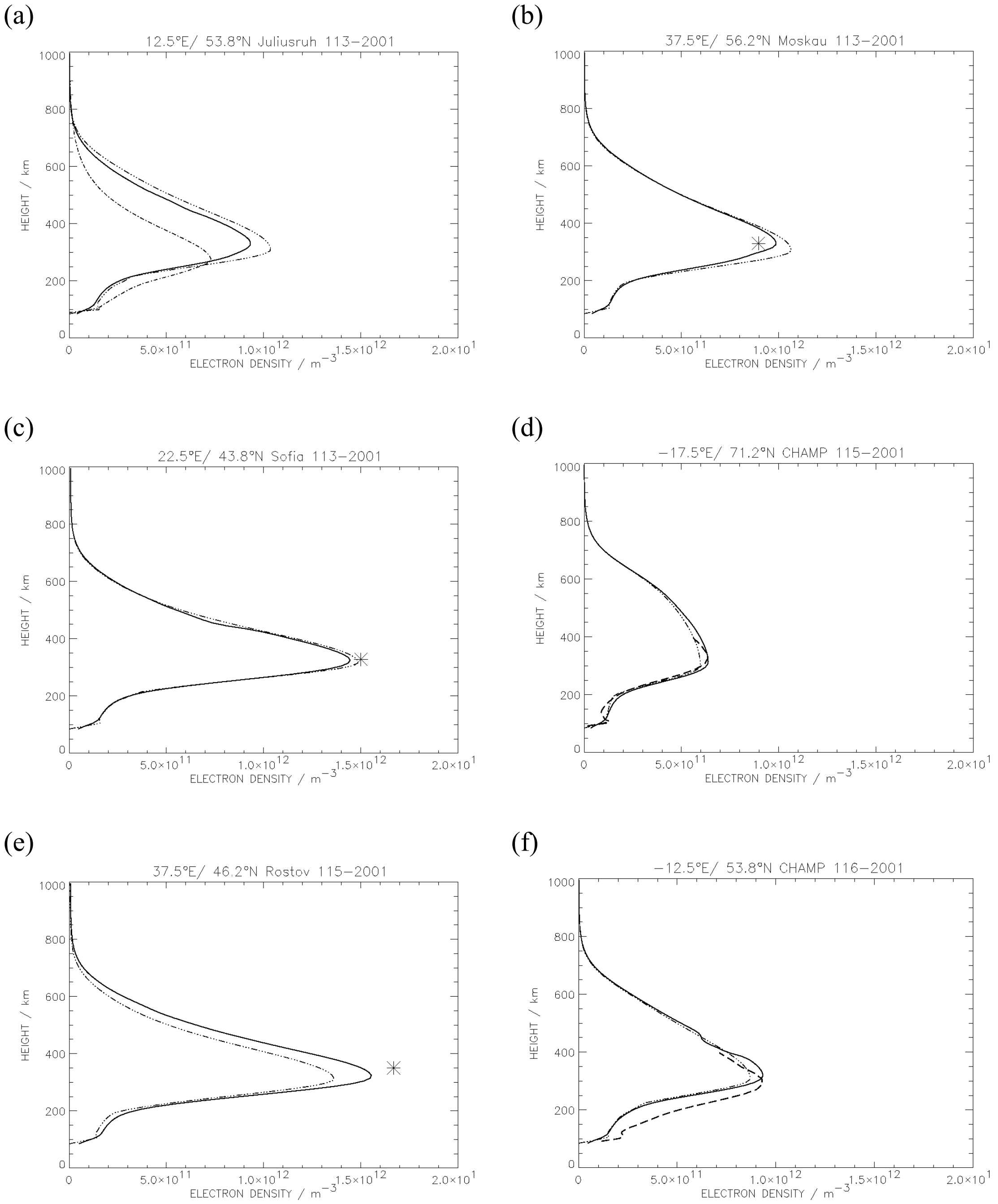
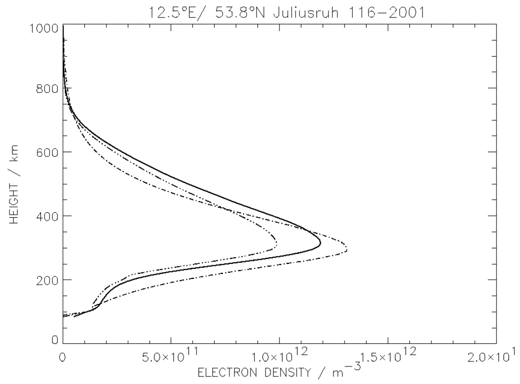
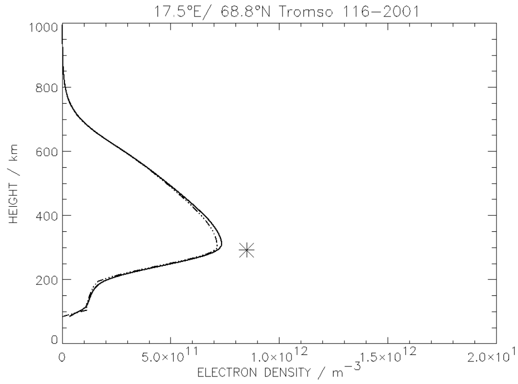


Fig.3 (a)-(f): Electron density profiles of the assimilation [3] (solid line), the IRI/GCPM model [2] (dash-dot-dot-dashed line), CHAMP [1] (dashed lines) and ionosonde [4] profiles (dash-dotted line). If the ionosonde only gives NmF2 and HmF2 the F2-peak is indicated by an asterisk. The respective comparative profiling method ([1], or [4]) is noted on the top of each panel, as well as the location of the reconstructed and the modelled profile. Dates are marked as day of the year and respective year. For exact time of the day refer to the corresponding panels in Fig.2.

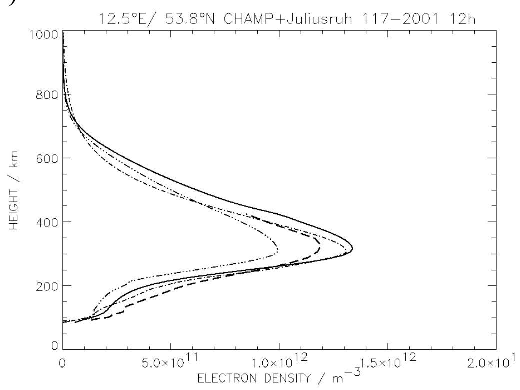
(g)



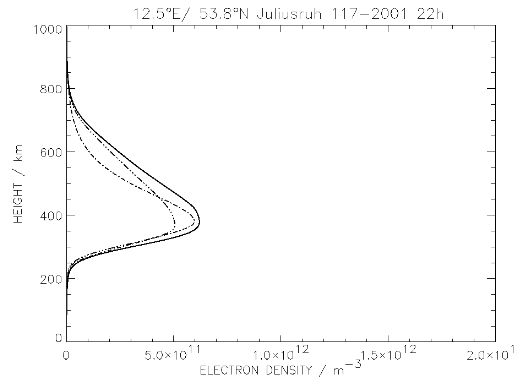
(h)



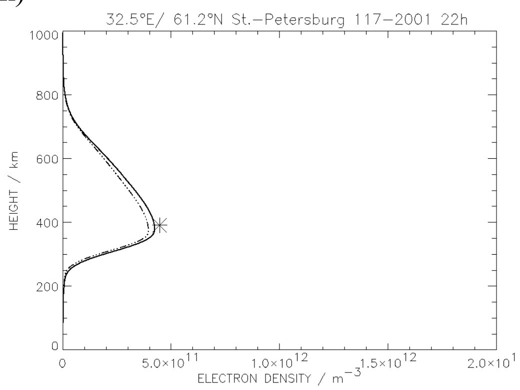
(i)



(j)



(k)



(l)

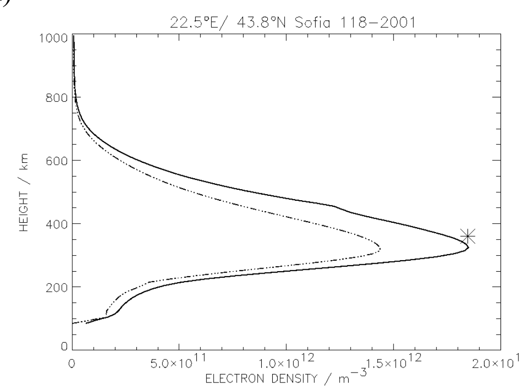


Fig.3 (h)-(l), continued.

CONCLUSIONS

We presented results of 3-dimensional ionospheric GPS TEC data assimilation into the IRI/GCPM model. Integrated TEC from ground- as well as from satellite-received GPS has been used as data input. To test the potential of the 3-dimensional electron density reconstruction beside other ionospheric remote sensing methods, comparisons of electron density profiles measured with different methods ([1], [2], [4]) have been performed. Dates for comparisons have been chosen during the HIRAC campaign in April 2001 and were accorded to CHAMP data availability.

The results of the electron density reconstructions show good agreement with ionosonde data and CHAMP profiling retrievals. Some aberrations appear, which can be attributed to characteristics of the method. All presented cases showed an improvement of the initial model IRI/GCPM towards ionosonde data after the assimilation of GPS TEC data.

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