ROUTINE PRODUCTION
OF
IONOSPHERE TEC MAPS AT ESOC - FIRST RESULTS

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ABSTRACT

The first version of ESOC's Ionosphere Monitoring Facility (IONMON) software has become operational. The routine production of TEC maps and receiver/satellite differential code bias values has started in January 1998. ESOC intends to contribute with these products to an IGS ionosphere service as well as to use the ionosphere maps for the support of other ESA-missons, e.g. ERS and ENVISAT.

This paper condenses the results obtained from the first month of routine IGS ionosphere processing at ESOC with different kinds of TEC modeling. A comparison between TEC maps obtained from these distinct mathematical TEC models is made in order to assess the internal accuracy that can be achieved. A verification with TEC maps provided by other Analysis Centers will be possible when the IONEX format (Schaer et al., 1997) has been commonly implemented. The ESOC TEC maps are available in IONEX format. Verification of satellite differential code biases was done by comparison with values obtained from some other centers.

Based on the experiences made with the first month of operational ionosphere maps production, a fine-tuning of the models and last improvements could be made in order to optimize routine ionosphere processing.

INTRODUCTION

It is the task of this paper to give an overview on how routine IGS ionosphere processing is done at ESOC and to present an analysis of the first results obtained.

The paper will start with an overview over ESOC's ionosphere processing under the aspects of observation data used, geographical extent, mathematical models invoked, number of TEC maps produced daily, time resolution and delay of availability.

The main part of the paper will thereafter concentrate on the results achieved during the first month of routine ionosphere processing at ESOC. Until now, validation had to be restricted to internal comparisons only. The implementation of the IONosphere Map EXchange Format (IONEX) (Schaer et al., 1997) at the other Analysis Centers will enable an easy exchange of ionosphere products and thus allow for intercomparisons. The assessment of internal accuracy was done by the comparison of TEC maps obtained from different mathematical models. For the verification of estimated satellite differential code biases, corresponding values from some other Analysis Centers were available and could be used.

Finally this paper will conclude with an outlook on intended future activities and software extensions planned at ESOC in the area of the ionosphere.

ROUTINE IONOSPHERE PROCESSING AT ESOC

The operational evaluation of ionosphere products at ESOC is currently coupled to the final orbit processing. If a certain routine and experience has been achieved, the provision of ionosphere products in rapid mode can be taken into consideration. The software's structure and environment allows principally for a rapid processing.

Carrier phase leveled to code measurements - so called “TEC observables” - enter into the Ionosphere Monitoring Facility (IONMON) software. The sampling rate is 6 minutes.

Currently 4 IONMON runs are made per day, using TEC observables collected from a global net of about 50 stations. 24 hours of observation data enter into each fit. The 4 daily runs are:

1) Determination of a set of receiver/satellite differential code bias values. In order to cleanly extract the influence of the differential code biases from the TEC observables, only nighttime tracking data is enter into that fit. The ionosphere's part (which is expected to be quite small over nighttime) is absorbed by a low degree and order spherical harmonic of $n = 4$, $m = 2$, with the degree and order 1 coefficients kept fixed to zero. The differential code bias values thus obtained serve then as reference values for the other 3 fits of that day, and are introduced with a constraint of $0.5\ ns$ there.
2) Global TEC model by fitting a GE-function (Feltens et al., 1996) of degree and order $n = 10$, $m = 8$ to the TEC observation data. In the GE-function fit the ionosphere's electron density is assumed to be condensed within an infinitesimal thin layer enclosing the Earth as hollow sphere in a height of $450\ km$. The mapping function is $1/\cos Z$. In the analyses of next chapter this fit will be denoted as “**GE**”.
3) Global 3-d Chapman Profile model (Feltens, 1998). The maximum electron density N_0 is represented by a degree and order $n = 10$, $m = 8$ GE-function, and the height of maximum electron density h_0 is modeled with an extended $\sin$-function. The allowed height range is $400\ km \leq h_0 \leq 450\ km$. The output of this Chapman Pro-

file model are 6 maps: A TEC map obtained by integration over the Chapman Profile, a N_0 map, a h_0 map and maps of electron density at heights of 250, 500 and 750 km. In the analyses of next chapter this fit will be denoted as "**CP**".

4) Global 3-d Chapman Profile model. The maximum electron density N_0 is represented by a degree and order $n = 10$, $m = 8$ GE-function, and h_0 is estimated as global constant. The output are also a TEC map, a N_0 map and maps of electron density at $h = 250, 500, 750\ km$. A h_0 map does not make sense in this case, since h_0 is constant. In the analyses of next chapter this fit will be denoted as "**CP1**".

All fits use a 20^o elevation cutoff, and elevation-dependent weights are applied to the observables. The internal evaluation of all these models is done in the solar-magnetic reference frame.

Polynomial models to represent the TEC within the local area around a single ground station can be evaluated upon special request and over limited time for ESOC-internal use only. It is not intended to deliver these local polynomial models to the IGS. 6 hours of observation data enter into such a polynomial fit.

Once a certain routine has been achieved, the ionosphere products processing can be enhanced, e.g. every 6 hours a global model with 24 hours of TEC data.

FIRST RESULTS

TEC Maps

As already pointed out above, no access to TEC maps from outside ESOC was available for the analysis of the first results of operational processing. So only an ESOC-internal verification between the TEC maps originating from the different mathematical models could be done so far. An application of GE-function TEC models to ERS altimeter and S-band data during a period covering February'97 provided corrections for ionospheric signal delays with accuracies comparable to that obtained from the IRI-95 model (Feltens et al., 1997). The GE-functions shall thus serve here as reference with respect to which the 3-d Chapman Profile models shall be compared. The results presented here were obtained over the period from 28 December 1997 (97362) to 23 January 1998 (98023).

One indicator of accuracy is the daily repeatability of statistical parameters, such as %-age of measurements used and rms, in the one and in the other TEC model fit. Figures 1a and 1b show these two parameters for the three fits **GE**, **CP** and **CP1**:

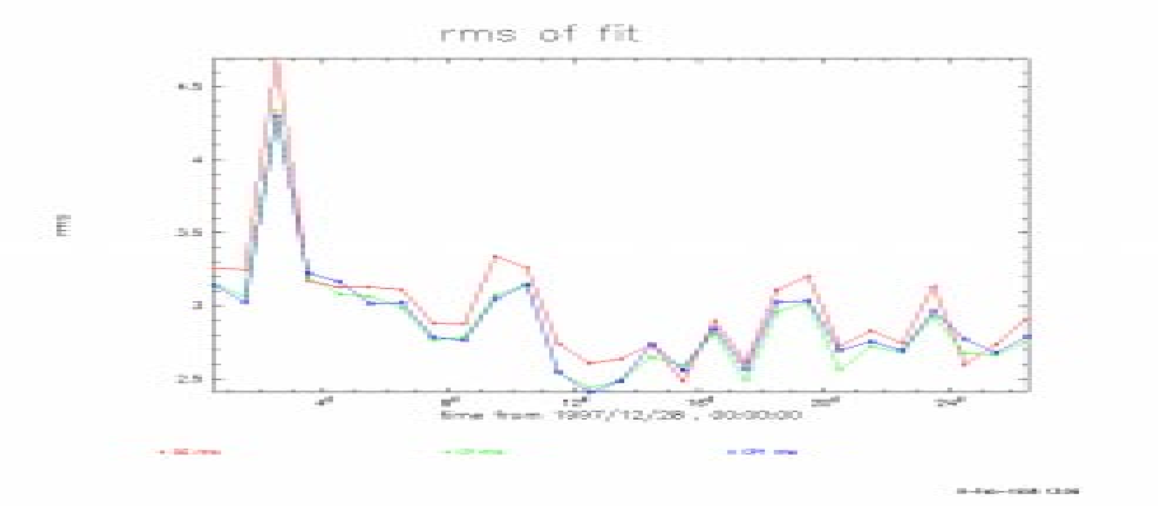

Figure 1a: Daily rms obtained for the GE, CP and CP1 fits.

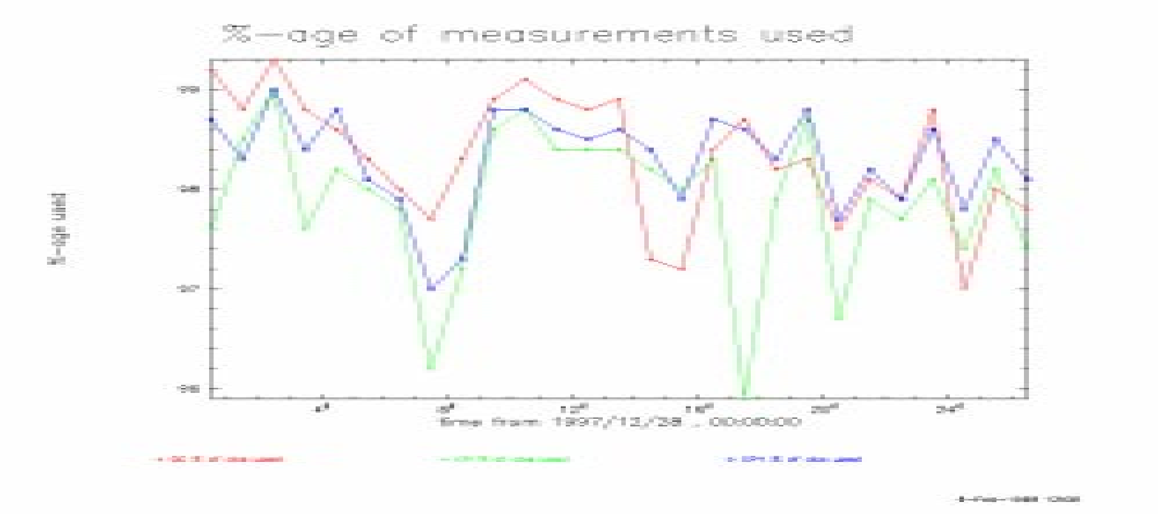

Figure 1b: Daily $\%\text{-}age$ of measurements used in the GE, CP and CP1 fits.

The curves of Figures 1a and 1b seem to indicate that GE-function fits and Chapman Profile fits are of comparable accuracy, with the Chapman Profile models showing a tendency to be slightly better. The **CP** fits show the lowest rms, but also the lowest %-age of measurements used. The rms of the **CP1** fits are slightly higher, but more observations were taken. When comparing GE-functions with Chapman Profile models it must be kept in mind, that the Chapman Profile models show more flexibility because of more unknowns that are estimated.

The next Figure 2 presents the daily variation of estimated height h_0 of maximum electron density from the **CP1** fits.

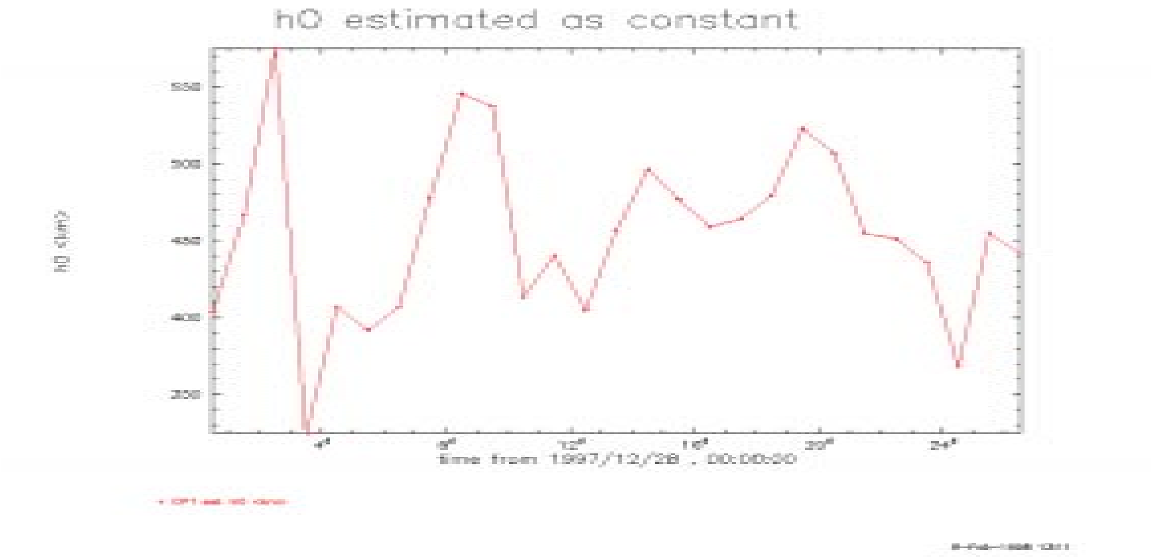

Figure 2: Daily estimated h_0 values from the CP1 fits [km].

Figure 2 shows a quite strong variation of the daily estimated h_0 values. But, as is pointed out in (Feltens, 1998), h_0 is only weakly estimable from pure TEC observables. The inclusion of satellite-to-satellite tracking (SST) data into the Chapman Profile model fits might improve this situation. Because for lack of such data, this could not be done yet. A combination of TEC data with other kinds of data, e.g. ionosonde data, might improve the situation too.

Figures 3 to 5 show a sequence different maps obtained for one day from the **GE**, **CP** and **CP1** fits. All Figures have a vertical range from $+90^o$ to -90^o in geographic latitude and a horizontal range from 0^h local time (-180^o) to 24^h local time ($+180^o$) and are centered at 12^h local time (0^o).

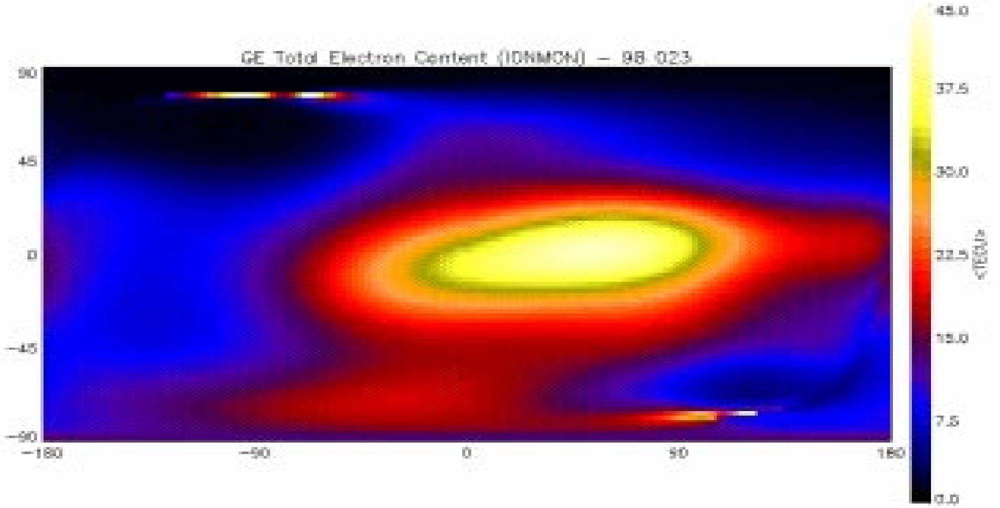

Figure 3: Global TEC map from GE fit for doy 98023.

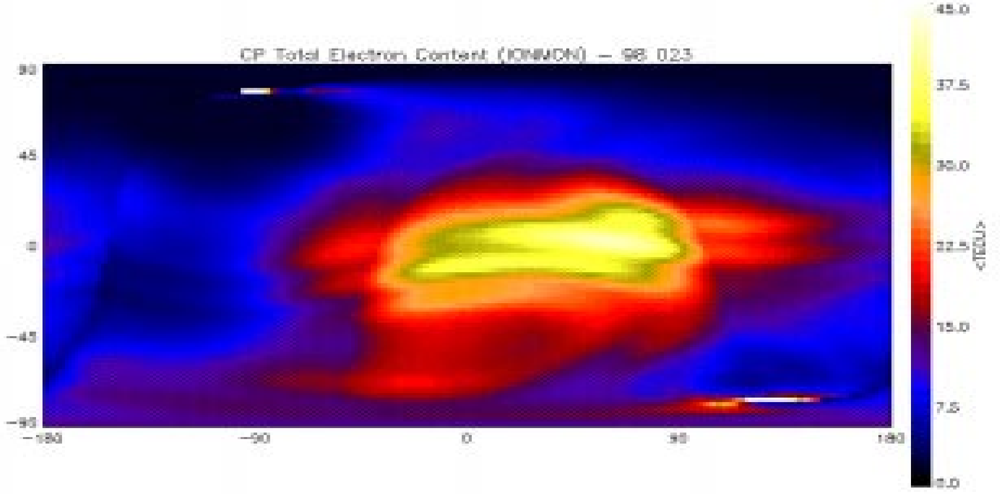

Figure 4a: Global TEC map from CP fit for doy 98023.

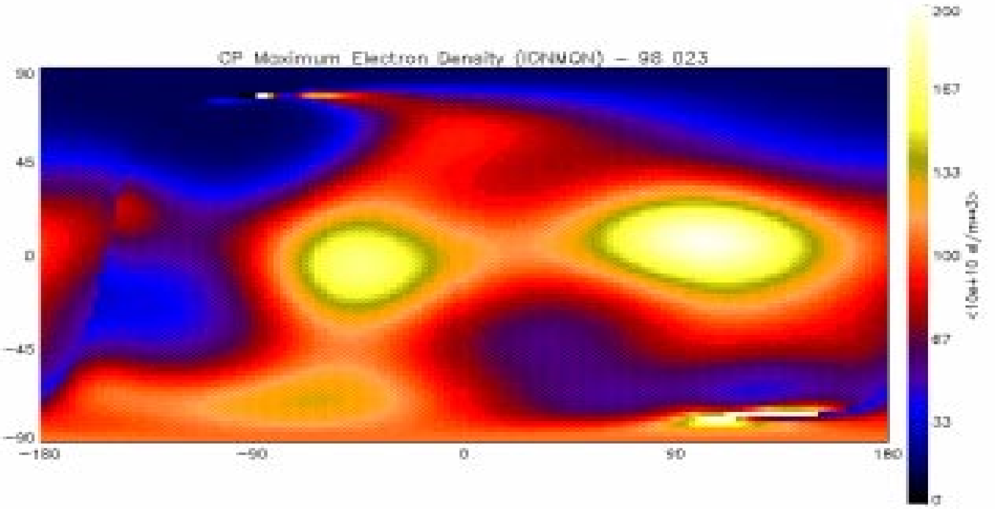

Figure 4b: Global N_0 map from CP fit for doy 98023.

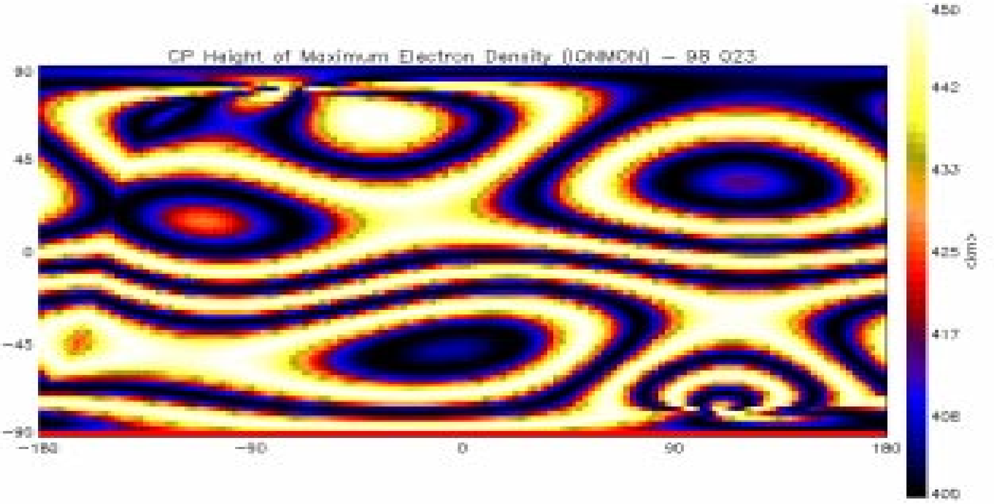

Figure 4c: Global h_0 map from CP fit for doy 98023.

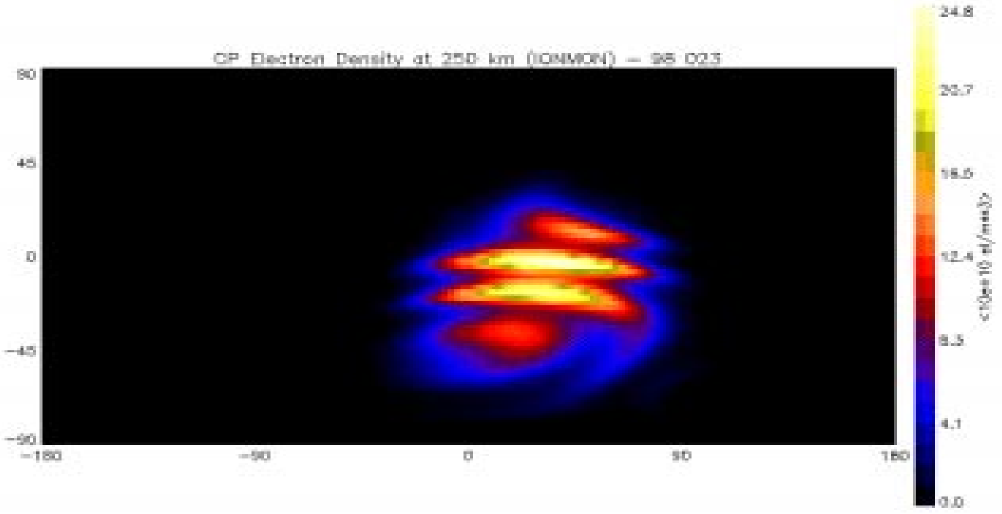

Figure 4d: Global electron density map at $h = 250\ km$ from CP fit for doy 98023.

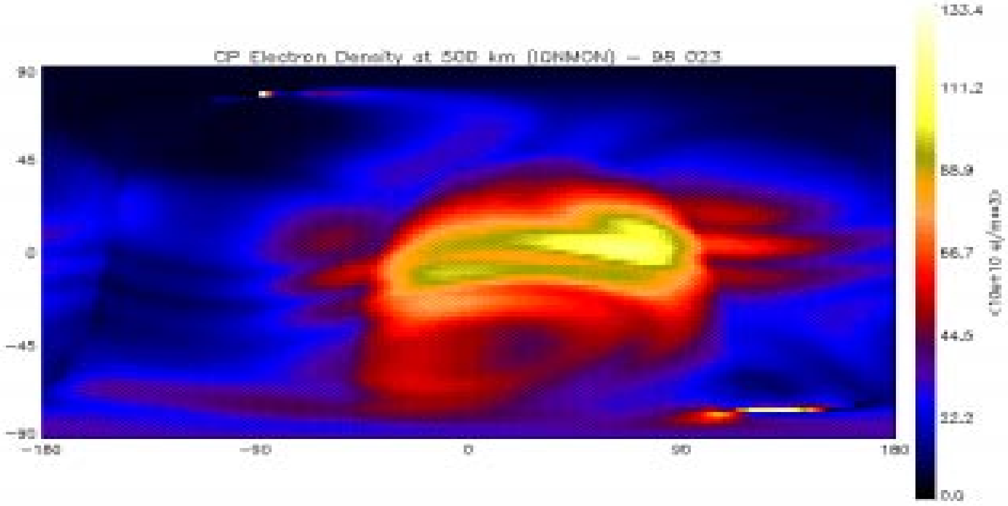

Figure 4e: Global electron density map at $h = 500\ km$ from CP fit for doy 98023.

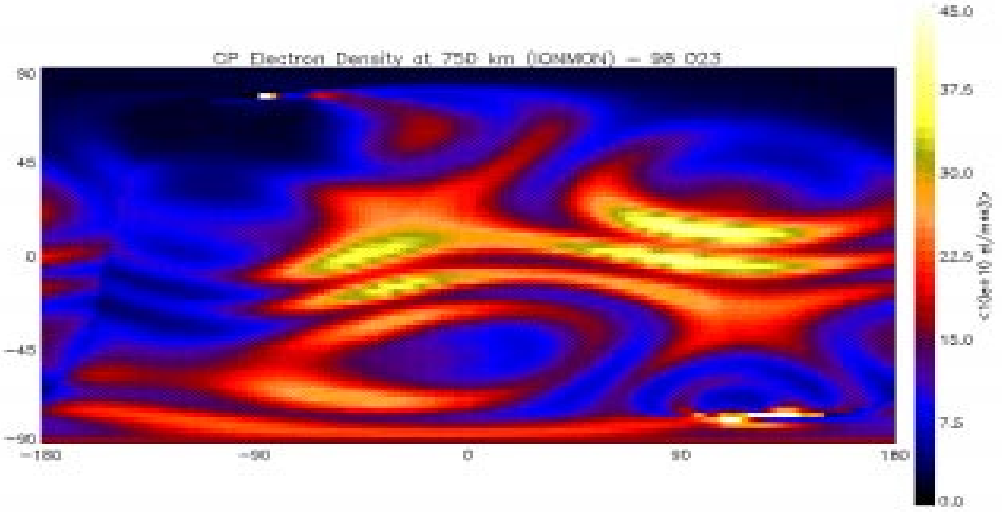

Figure 4f: Global electron density map at $h = 750\ km$ from CP fit for doy 98023.

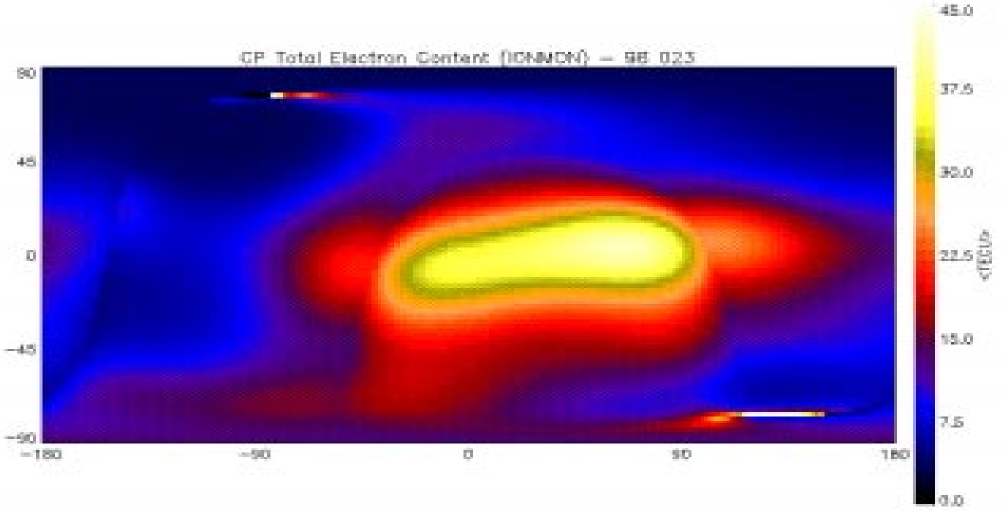

Figure 5: Global TEC map from CP1 fit for doy 98023.

When comparing the TEC maps in Figures 3, 4a and 5, one recognizes an overall good agreement between the **GE** , **CP** and **CP1** fit. Compared with the **GE** map, the two Chapman Profile maps present finer structures. This is especially valid for the map from the **CP** fit, since the height h_0 is not treated as constant but as extended sin-function single layer in this case. The estimation of both, N_0 and h_0, makes the Chapman Profile models more flexible than the GE-function, thus allowing a better adaption to the TEC observation data. Additionally the 3-d geometry being intrinsic in the Chapman Profile models may enhance this flexibility. This 3-d geometry is ruled by the Sun's zenith angle χ (see Feltens, 1998).

The h_0 map shown in Figure 4c should not so strongly be interpreted as the real h_0 distribution, but more as the result of absorbing unmodeled effects in the **CP** fit.

Figures 4d to 4f present the electron density at different heights. Apart from the N_0 map of Figure 4b, the map for $h = 500\ km$ shows the heighest electron density values, since it is closest to the height of maximum electron density. The lowest electron density can be seen in the map for $h = 250\ km$, indicating a strong decrease of ionization by the solar radiation after having passed h_0. The map for $h = 750\ km$ shows an overall lower niveau of electron density than the map for $h = 500\ km$, which can be expected from theory - but at the borders the electron density can be heigher at $750\ km$ than at $500\ km$. This effect is also explained by Chapman Profile theory: Close to the terminator the height of maximum electron density is larger than at noontime (Feltens, 1998), and this effect propagates upwards and can be felt in $750\ km$ altitude.

The above maps show abnormal peaks at high latitudes. Because of holes in the station net and the arrangement of orbital inclinations in GPS satellite constellation, there is a bad coverage around the poles. As consequence there are no observation data in these zones to which the TEC models could fix. This problem can only be overcome by densifying the station net in the polar regions (as far as new stations become available) - especially on the southern hemisphere.

Differential Code Biases

DLR Fernerkundungsstation Neustrelitz had provided differential code bias values with respect to which the ESOC/IONMON differential code biases could be compared. As example the values for four satellites are presented Figure 6 over the time span from 28 December 1997 to 23 January 1998:

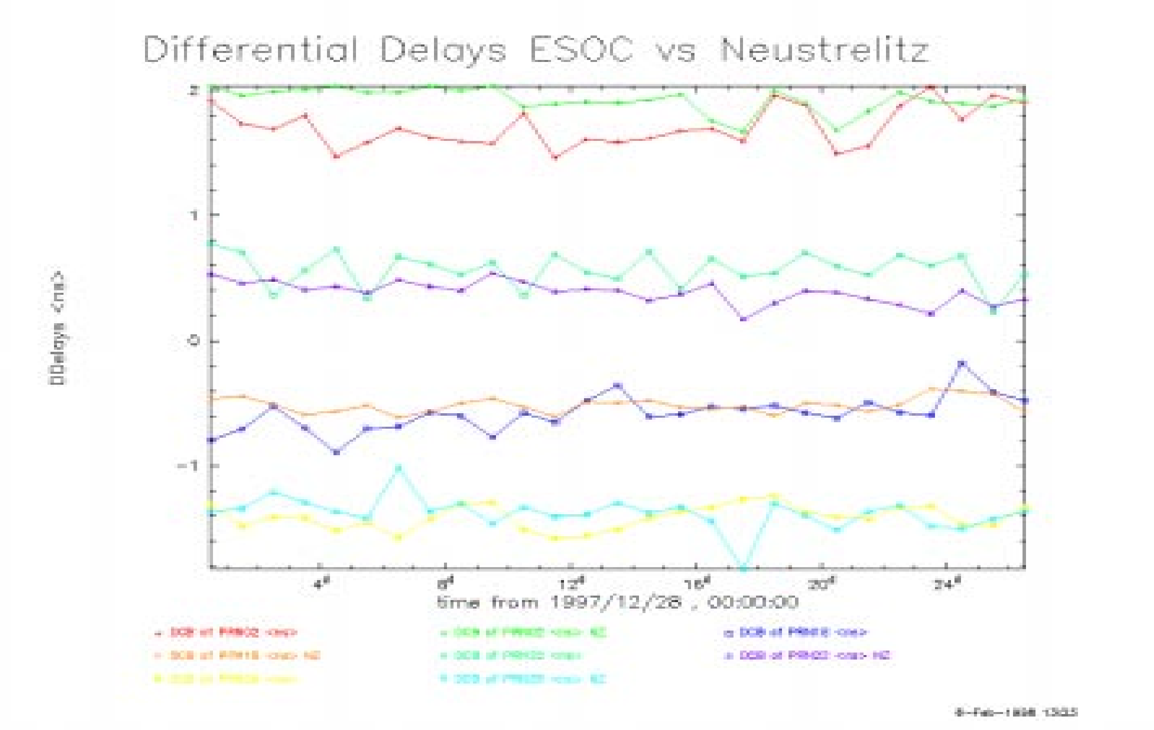

Figure 6: ESOC versus DLR Neustrelitz differential code bias values for PRNs 02, 18, 22, 26.

Figure 6. shows an agreement between the Neustrelitz and the ESOC values within $0.3\ ns$ over the whole period. An agreement of the same order was also found for the other GPS satellites. Additional comparisons with differential code bias values from the Astronomical Institute of the University of Berne comfirmed this order of agreement.

CONCLUSIONS

ESOC has started with the routine evaluation of ionosphere products at the beginning of this year 1998. Three different kinds of global TEC maps and a set of receiver/satellite differential code bias values are produced daily. Of the three TEC maps two are based on a

Chapman Profile approach, thus providing also information on the ionosphere’s electron distribution with respect to height.

Validation of achieved TEC map accuracy could so far only be done by analysis of ESOC-internal products. The common implementation of the IONEX software at all Analysis Centers will then allow for an easy and efficient intercomparison of ionosphere products.

Verification of internal accuracy was basically done with two methods:

1) By examination of the daily continuity of statistical parameters.
2) By comparison of TEC maps from different mathematical models for identical days.

Both methods confirmed stable and accurate IONMON model and software performance.

For the approval of estimated differential code biases, external values were available for comparison and showed an overall agreement in the order of $0.3\ ns$.

All in all ESOC’s operational ionosphere processing looks accurate and stable. The products are output in the IONEX format. ESOC is ready to contribute to an IGS ionosphere product.

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