ROUTINE PRODUCTION OF IONOSPHERE TEC MAPS AT ESOC

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ABSTRACT

The first version of ESOC's Ionosphere Monitoring Facility (IONMON) software is now in operational use since January 1998. Since summer 1998 ESOC contributes with ionosphere products the IGS ionosphere pilot project. An external user interface needed for the support of other ESA missions, like ERS and ENVISAT, with IONMON products is close to completion.

This paper gives an overview over the results obtained from the routine ionosphere processing at ESOC since January 1998. Comparisons made with Total Electron Content (TEC) maps and GPS satellite Differential Code Bias (DCB) values from other IGS Analysis Centers (Feltens, 1999) and with TOPEX data allow for the identification of weaknesses and deficiencies in the ESOC ionosphere modeling and give ideas on what should be improved.

Based on the knowledge earned since January 1998 and regarding the results that came out from the comparisons with the products of the other Analysis Centers and with TOPEX data, the conception of new more sophisticated ionosphere modeling to be implemented at ESOC will be made.

INTRODUCTION

It is the task of this paper to give an overview over the routine ionosphere processing at ESOC, to present results obtained so far and to describe future plans.

The paper will start with a short summary of the ionosphere processing done at ESOC: observation data used, mathematical models, geographical extent, time resolution, delay of availability.

Next the paper will as example present for one day the results of different variants of the ESOC ionosphere modeling and explain the differences.

In order to achieve an objective quality assessment of ESOC ionosphere products, comparisons with external data are essential. This paper presents comparison results with VTEC data derived from TOPEX altimeter observables and for the GPS satellite DCBs with corresponding values from DLR Fernerkundungsstation Neustrelitz. Also comparisons with ionosphere products from the other IGS Analysis Centers are done regularly. A special project report (Feltens, 1999) was dedicated to these activities, which is also part of these 1999 IGS Analysis Centers Workshop Proceedings. This paper will thus restrict on comparisons with TOPEX data for the TEC and with Neustrelitz data for the DCBs.

Finally this paper will give an overview over future plans with regard to improve and extend ionosphere modeling at ESOC and then conclude with a condensation of the progress achieved so far.

ROUTINE IONOSPHERE PROCESSING AT ESOC

When starting with the operational evaluation of ionosphere products at ESOC in January 1998, it was coupled to the final orbit processing, i.e. ionosphere models were evaluated with a delay of about 11 days after the last observations. The main reason for this was not that the accuracy of the rapid orbits would not be sufficient, but the fact that the number of available ground stations is significantly higher in final processing. It is well known that a dense net of ground stations is needed for appropriate ionosphere modeling. However, in order to find out the capabilities under the condition of a reduced number of ground stations in rapid processing, operational evaluation of ionosphere products in rapid mode were started in the middle of March 1998 and did run parallel to the final ones until the end of April 1999. Since the beginning of May a new operational ionosphere processing commenced which uses the rapid orbits of the GPS satellites, but a number of ground stations, that even exceeds the one used in final orbit processing. Instead of a final and a rapid run per day, only one of these new runs is made daily now. It provides ionosphere products of an accuracy comparable to former final processing, but in a strongly reduced time.

The kind of modeling used in daily routine ionosphere processing at ESOC is described in detail in (Feltens et al., 1998). - So only some basics are presented here:

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

2) Currently 5 IONMON runs are made per day, using TEC observables collected from a global net of about 60 stations (an increase of the station number is planned to be done shortly after this 1999 IGS Analysis Centers Workshop). 24 hours of observation data enter into each fit. For the IGS ionosphere pilot project from these 24 hours TEC maps 2 hours TEC maps are currently established with time interpolation. The 4 daily

runs are (for more details see Feltens et al., 1998):

a) Low degree and order spherical harmonic fit with nighttime TEC data to determine a daily set of receiver/satellite differential code bias (DCB) values. It is the intent of the spherical harmonic single layer to absorb the nighttime TEC, which is assumed to be low. The DCB values thus obtained serve then as reference values for the other 4 fits of that day.

b) **GE**: global single layer model with a shell height of $450\ km$ using a GE-function (Feltens et al., 1996) to represent ionospheric TEC. The main sense of these GE runs was support of interpretation of results of the **CP**, **C1** and **C2** fits listed next; it is intended to exclude these GE single layer runs from routine processing in the near future.

c) **CP:** global 3-d Chapman Profile based model. The Chapman Profile's maximum electron density N_0 is represented with a GE-function, and the height of maximum electron density h_0 is modeled with an extended sin-function with a pre-defined allowed height range of $350\ km \leq h_0 \leq 450\ km$. For more details about the model see (Feltens, 1998). The TEC maps are then obtained by vertical integration over the electron density along the Chapman Profile. The output of these runs is used to interpolate the 2 hours TEC maps for the IGS ionosphere pilot service.

d) **C1:** global 3-d Chapman Profile model. The maximum electron density N_0 is represented with a GE-function, and h_0 is estimated as global constant. The reason of daily runs of this type is to better understand the Chapman Profile model performance.

e) And since end of September 1998 **C2:** global 3-d Chapman Profile model. The maximum electron density N_0 is represented with a GE-function, h_0 is kept fixed as global constant at $450\ km$, and the so called $sec\chi$-term (for more details see next chapter) is not included. The reason of daily runs of this type is to better understand the Chapman Profile model performance.

RESULTS

TEC Maps

First of all it is interesting to inspect the long-term behavior of two key parameters over the whole period of routine processing since January 1998. The first one is the daily *rms* obtained for the GE, CP and C1 fits:

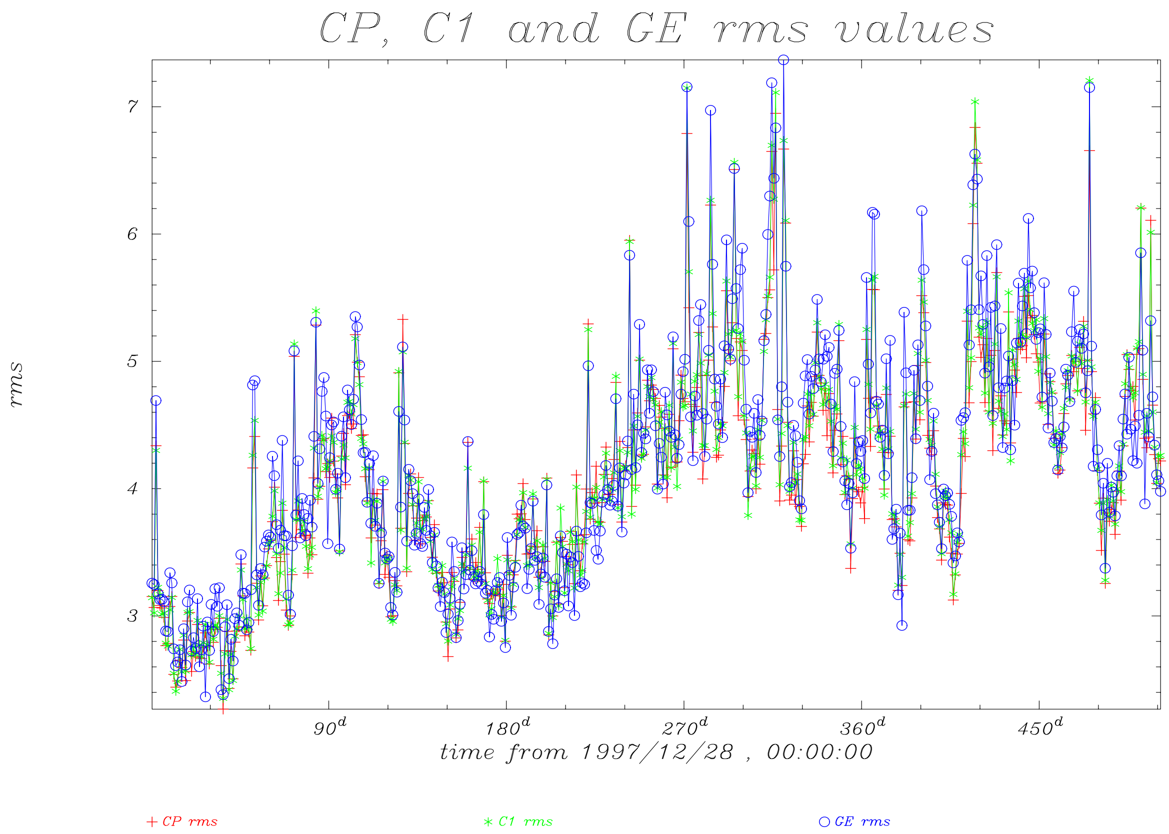

Figure 1: Daily *rms* obtained for the GE, CP and C1 fits.

Figure 1 indicates that the *rms* values of all three types of modeling are always close together. At the same time an overall increase of the *rms* level from about *3 TECU* in January 1998 up to about *5 TECU* currently can be recognized, superimposed by peaks up to *7 TECU* at some places. The reason for this can be explained by the fact that the ionospheric activity is continuously increasing since January 1998 (the next solar maximum is expected to be in the year 2000), and the high peaks in the *rms* level could always be observed when the ionosphere was particularity disturbed. At such events the models had sometimes problems to fit.

The other interesting parameter is the daily variation of the estimated height h_0 of maximum electron density from the **C1** fits. This height corresponds (more or less) to the height of the electron density distribution peak (typically *350 - 400 km*) of an equivalent

Chapman layer with the solar zenith angle referred to the vertical. This height is not identical with the centroid height of the Chapman Profile; the centroid height can be much higher ($550\ km$), see e.g. (Bertiger et al., 1997).

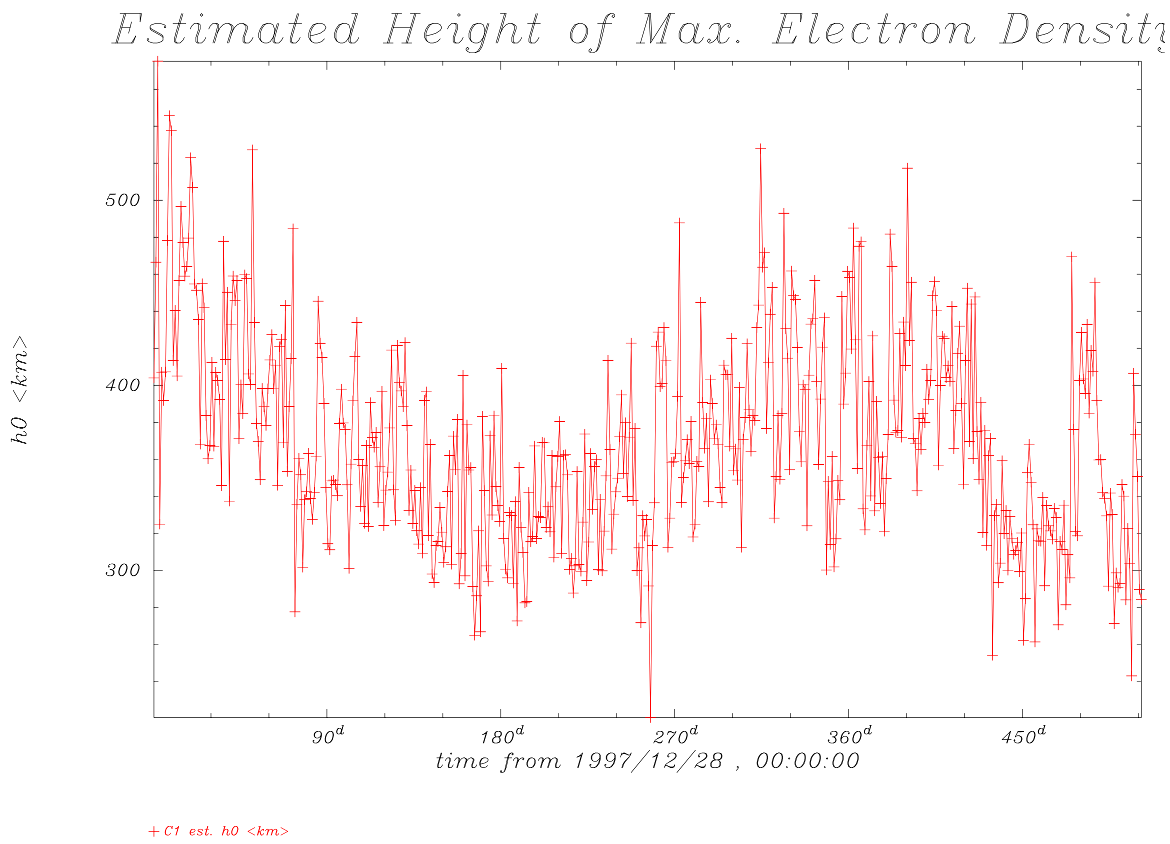

Figure 2: Daily estimated h_0 values from the **C1** fits [km].

Figure 2 shows quite clearly an opposite behavior than Figure 1. While the rms is growing with increasing solar activity, the electron density distribution peak height h_0 is decreasing. A significant peak can be recognized at the far right of the curve: h_0 reached higher values during a short time period when the ionospheric activity went down - and also the rms went down during that time, as can be seen on the far right of Figure 1. What also can be seen from both figures is that the ionospheric activity did not increase continuously but with at least one local minimum period.

As was already pointed out in the introduction of this paper, comparisons with TEC maps from other IGS Analysis Centers are the task of a dedicated IGS Ionosphere Working Group Project Report (Feltens, 1999) which is also part of these proceedings. Here the analysis will concentrate on ESOC-internal results and try to explain the differences that can be observed between the daily **CP**-, **C1**-, **C2**-fits. Figures 3a,c,d present the **CP**-, **C1**-, **C2**-TEC maps for 15 May 1999 (doy 99135), and Figure 3b shows the h_0 map from the **CP**-fit:

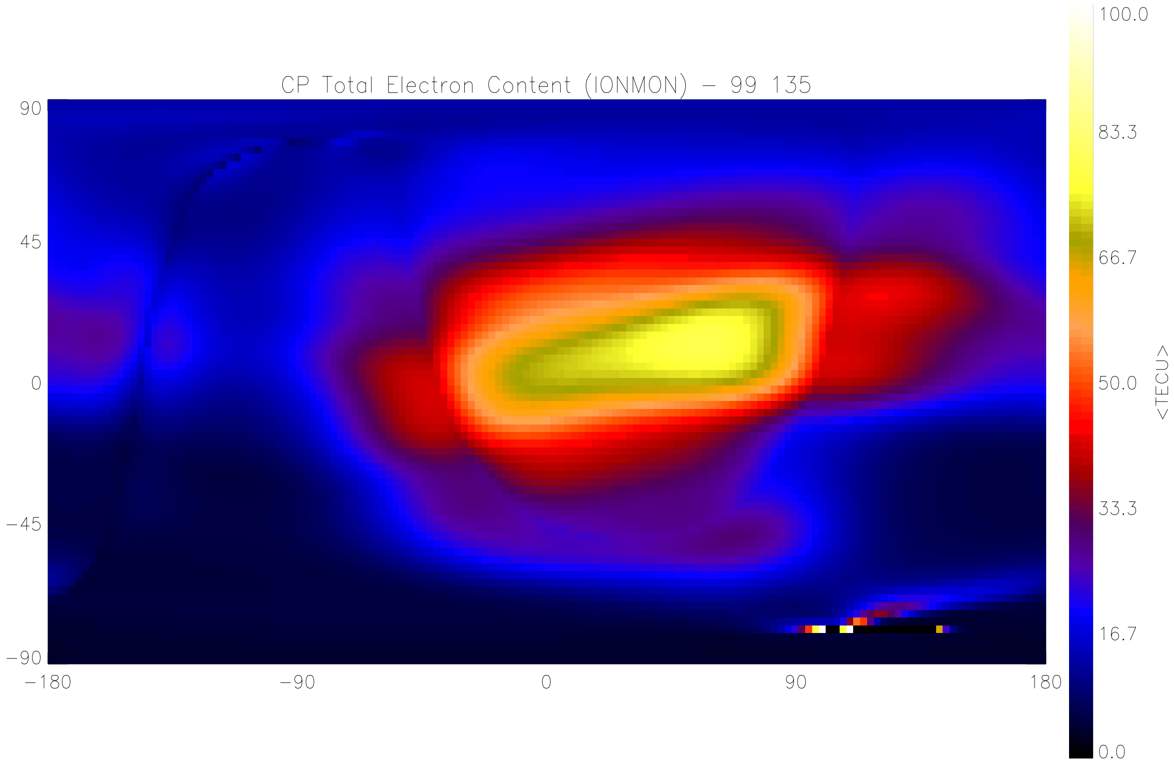

Figure 3a: Global *TEC* map from ESOC CP fit for doy 99135.

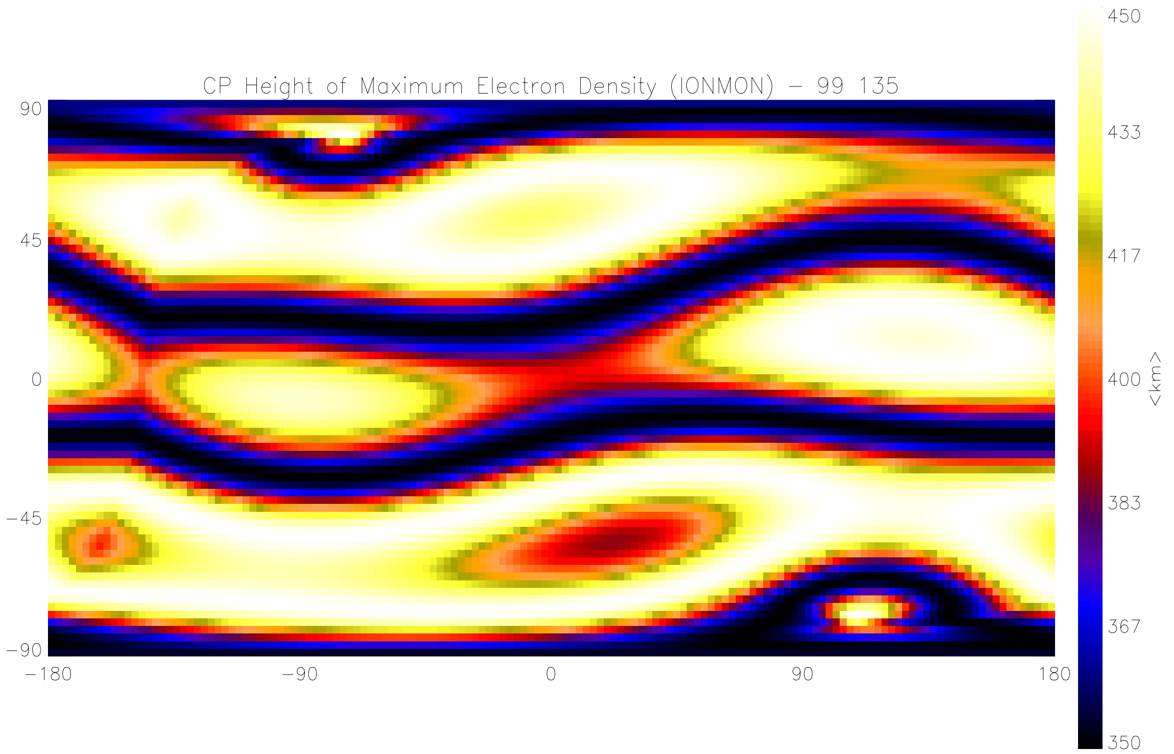

Figure 3b: Global h_0 map from ESOC CP fit for doy 99135.

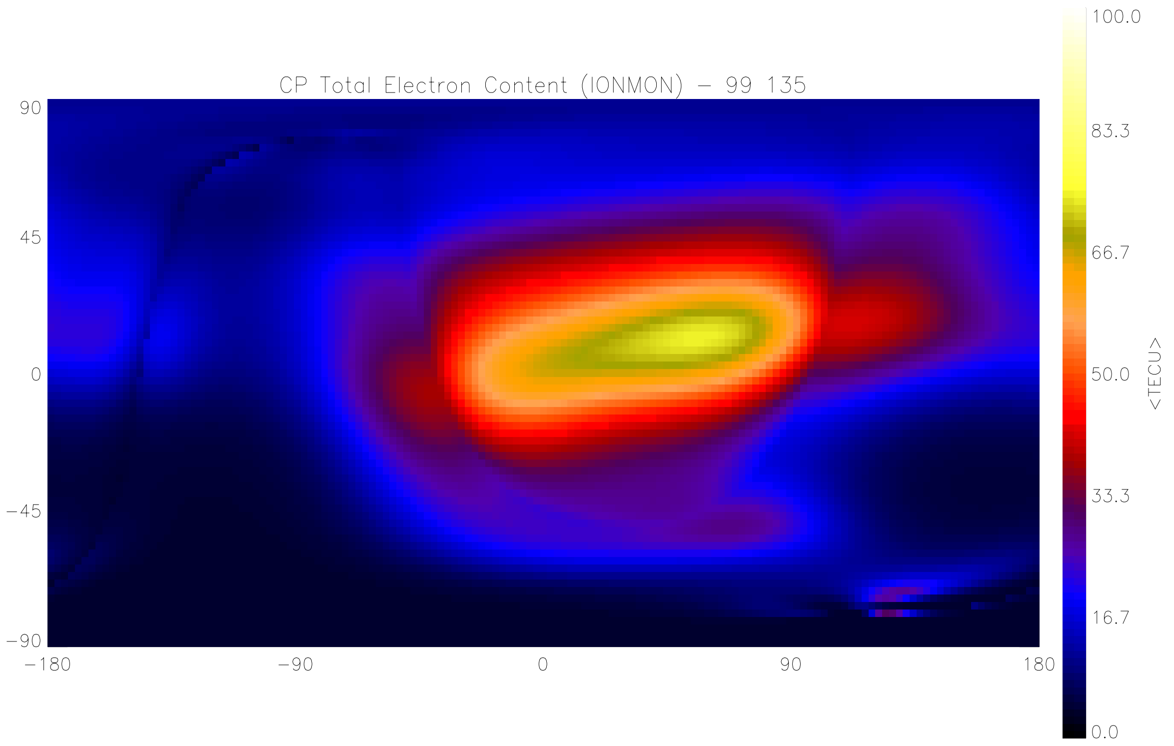

Figure 3c: Global *TEC* map from ESOC C1 fit for doy 99135.

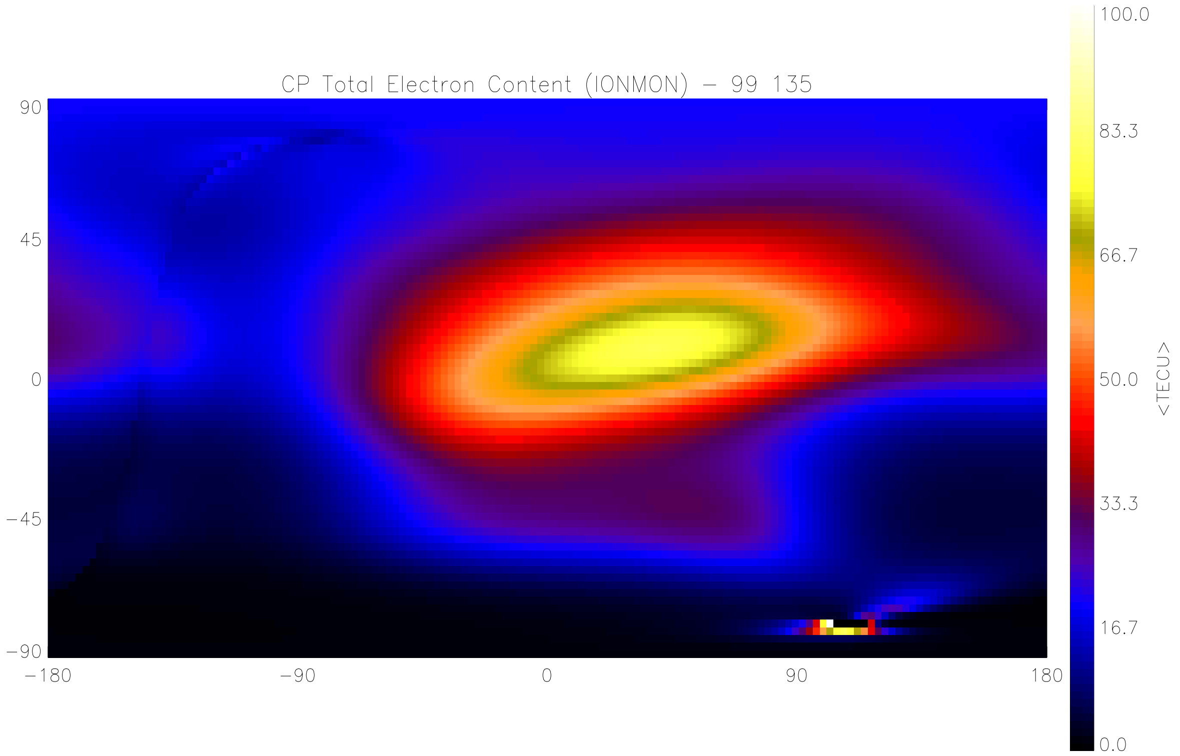

Figure 3d: Global *TEC* map from ESOC C2 fit for doy 99135.

The vertical axis of the Figures 3a-d is geographic latitude (deg) and the horizontal axis is geographic longitude at 12:00 UT.

The theory standing behind ESOC's ionosphere modeling based on the Chapman Profile concept is explained in (Feltens, 1998). In short summary, the two key parameters that can be estimated in a Chapman Profile are the maximum electron density N_0 and its height h_0. While N_0 is modeled as GE-function in all three approaches, **CP**, **C1**, **C2**, the height h_0 is handled in different ways:

In the **CP**-fit, whose output is delivered as official ESOC product to the IGS Ionosphere Pilot Service, it is assumed that h_0 is globally varying; h_0 is thus estimated as a special kind of surface function (extended sin-function, see Feltens, 1998) which is allowed to vary freely with geographic location - but in altitude only within the range of $350\ km \le h_0 \le 450\ km$.

In the **C1**-fit h_0 is assumed to be a global constant which is estimated as one unknown in the fit. This assumption corresponds of course not to the conditions in the real ionosphere, but, however, the above Figure 2 showed that with this approach h_0 values can be obtained, which look quite plausible with regard to the progress of solar activity. Since h_0 is treated as global constant, the GE-function to represent N_0 is now the only remaining surface function in the model causing the integrated vertical TEC to vary.

The basic difference of the **C2**-fit with respect to the other two is that here the so called $sec\chi$-term is not included. In principle the integrated vertical TEC is obtained as:

$$VTEC = N_0 \cdot \frac{H}{\sec\chi} \cdot \left\{ e^{(1 - \sec\chi \cdot e^{-z_i})} - e^{(1 - \sec\chi \cdot e^{-z_j})} \right\} \qquad , \qquad z = \frac{h - h_0}{H}$$

where (for more details see Feltens, 1998)

χ	solar zenith angle,
N_0	maximum electron density of the Chapman Profile referred to $\chi = 0^o$,
h_0	height of maximum electron density N_0 above Earth surface at $\chi = 0^o$,
h	actual height above Earth surface at $\chi = 0^o$,
H	scale height.

When regarding the solar zenith angle χ as global function of distance with respect to the sub-solar point, one sees that χ is 0^o directly at under the Sun and increases from there to 90^o at the dawn zones (in ESOC's IONMON processing the upper limit for χ is set to 70^o for the terminator and the whole nightside). The scaling factor $1 / \sec\chi = \cos\chi$ in the above equation represents thus a global function of χ which has its maximum value one at the sub-solar point and converges from there to $zero$ into all directions. The multiplication factor $1/\sec\chi = \cos\chi$ has thus a shape similar to the simplest GE-function $\exp\{-x^2\}$. On the other hand, the maximum electron density N_0 is modeled as GE-function too. So, why not to ignore the $sec\chi$-term at all (practically by setting $\chi = 0^o$ in the above equation) and to estimate this geometric effect together with the N_0 GE-function? Tests have shown, that the $sec\chi$-terms of the exponential functions in the braces play a minor role only. So the sense of the **C2**-fits is to find out how the N_0 GE-function is able to include this geometric effect.

When comparing the TEC maps of the **CP**-, **C1**-, **C2**-approaches (Figures 3a,c,d) then one can see, that the **CP**-fit seems to provide the most details, probably because it allows the height h_0 to vary. The global h_0-map is given in Figure 3b and shows some structures along the geomagnetic equator. Whether this is the real geographic function the ionosphere's height of maximum electron density remains questionable, but this estimated h_0 surface seems obviously to account for some effects which could not be covered by the N_0 GE-function alone. The TEC map of the **C1**-fit looks smoother; since h_0 is treated as global constant, fine structures along the geomagnetic equator disappear. Both, **CP** and **C1**, show "ear-like" structures on the east- and westside of the maximum, indicating some kind of mismodeling. The **C2**-TEC map does not show these "ears". Since in **C2** the $sec\chi$-term has been excluded, the "ears" in **CP** and **C1** must be due to geometry reasons. This fact represents an inconsistency: For theoretical reasons the $sec\chi$-term should be included, and **C2** works only properly when h_0 is kept fixed and not estimated. On the other hand, when $sec\chi$ is neglected under certain conditions (h_0 is kept fixed), this kind of mismodeling disappears. Further effort must be undertaken to overcome this problem.

On the **CP** and **C2** TEC maps an abnormal peak can be seen in the deep south. This is due to lack for data in that region. The bad ground station coverage at high latitudes is a well known problem within the IGS. Since there are no data for the models to fit in this region, the N_0 GE-function tends to go to infinite there.

Another good check is to plot VTEC values computed from the IONMON models against VTEC numbers derived from TOPEX altimeter data and to inspect the agreement along TOPEX passes. Figure 4 shows an example for 2 September 1998 (doy 98245). The TOPEX data were kindly provided by JPL. The TOPEX pass went from North to South. The maxima on both sides of the geomagnetic equator can clearly be seen. For comparison reasons not only the VTEC curves of ESOC and TOPEX and the difference between them were put into the plot, but also the VTEC curves of JPL's GIM model and of the Bent ionosphere model. What can be seen from the curves is, that TOPEX, ESOC and JPL's GIM agree very good over the northern hemisphere and in the northern geomagnetic anomaly. South of the geomagnetic equator the situation is worse, especially for ESOC. A reason for this might again be the bad ground station coverage on the southern hemisphere, so that the models cannot fit properly. The Bent model reproduces the equatorial anomaly better than the ESOC and JPL models, but lies systematically below the other curves by about

20 TECU. What is described here, was also observed in comparisons with other TOPEX passes.

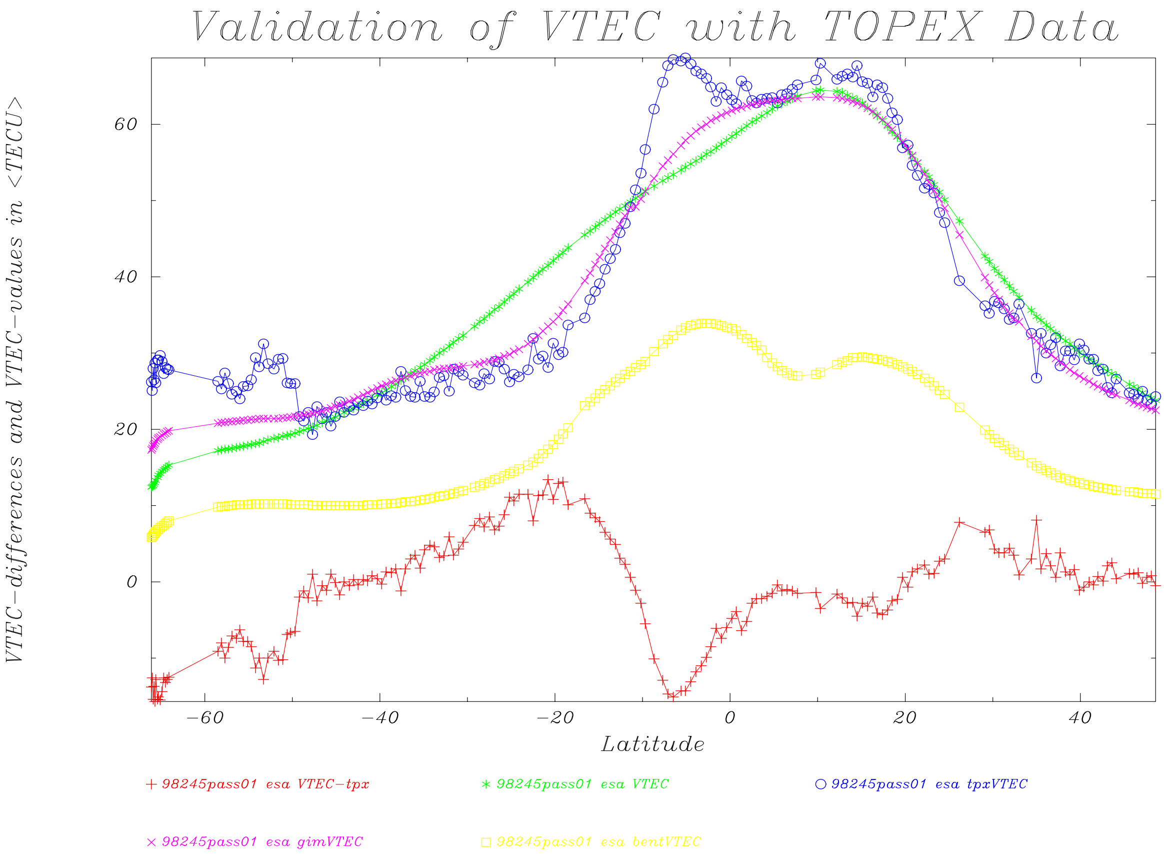

Figure 4: VTEC of ESOC versus altimeter VTEC for a TOPEX pass on day 98245.

Differential Code Biases

For the analysis of DCBs two things are of interest: 1) their long-term behavior and 2) the agreement with corresponding values from other Analysis Centers. Figure 5 shows the estimated DCB values for a selected set of GPS satellites over the whole time period of routine ESOC ionosphere processing since January 1998. The GPS satellite DCBs that were selected for this figure were chosen so that they distribute evenly over the whole plot.

What can be seen from Figure 5 is that the estimated GPS satellite DCB series show short-term variations of about 0.1 - 0.2 nanoseconds, while over the whole time span also long-term variations can be recognized. These long-term variations can be attributed to the limited capability of the TEC modeling to completely absorb effects due to changing ionospheric activity and thus propagating into the estimated DCB values.

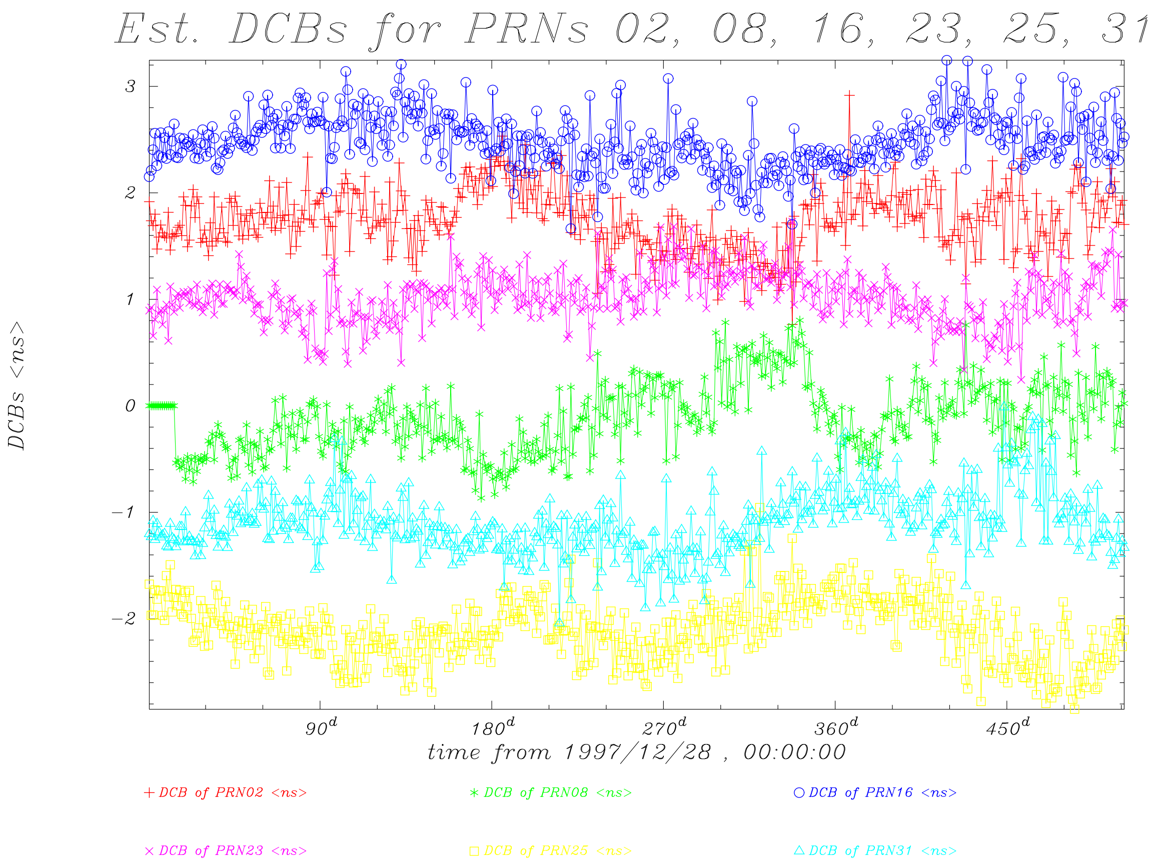

Figure 5: Long-term behavior of estimated ESOC DCBs for PRNs 02, 08, 16, 23, 25, 31.

Figure 6 presents a comparison between estimated ESOC DCB values and corresponding values from DLR Fernerkundungsstation Neustrelitz for the timespan 25 April to 15 May 1999 (doys 99115 - 99135).

Figure 6 shows an agreement between the Neustrelitz and the ESOC values within $0.2\ ns$ over the whole period, sometimes $0.3\ ns$ are reached. An agreement of the same order was also found for the other GPS satellites. Additional comparisons with DCB values from other IGS Analysis Centers can be found in the IGS Ionosphere Working Group Project Report (Feltens, 1999) and show the same order of agreement.

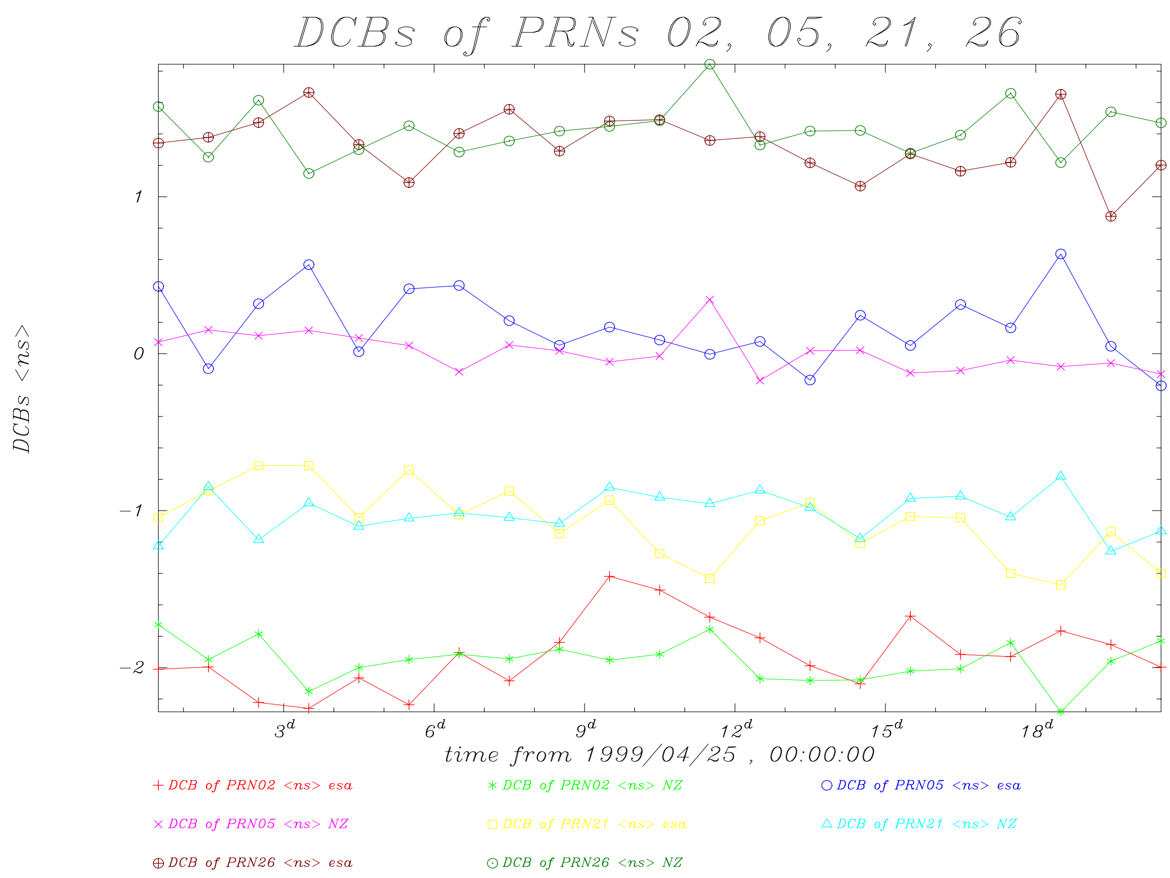

Figure 6: ESOC versus DLR Neustrelitz DCBs for PRNs 02, 05, 21, 26.

FUTURE PLANS

The ESOC Ionosphere Monitoring Facility (IONMON) software version 1 is now in operational use for more than one year. The analysis of results obtained so far and the comparison with ionosphere products from other Analysis Centers (Feltens, 1999) give ideas in which directions the current version 1 must be improved. Further requirements for an IONMON version 2 are defined by the needs for support of other ESA missions and/or are indicated by new trends, which can be followed when studying the actual publications. Regarding all these aspects, an extension of the current IONMON software to a version 2 will go into the following directions.

1) A very important task will be the enhancement of time resolution. The ionosphere is a rapidly changing medium, and 24 hours fits with 2 hours interpolations are clearly not sufficient. The current batch estimator will thus be replaced by a Kalman filter.

2) ESOC wants to have available models around ESA tracking sites, e.g. at Kiruna, providing very precise local ionosphere information. The routine processing of version 2

will thus also include routine local ionosphere modeling.

3) The inclusion of Satellite-to-Satellite (SST) tracking data will improve the estimability of ionosphere model parameters a lot, and the extension of the current GPS processing for GLONASS will densify the sky coverage. So, SST and GLONASS are two options that will also be included into version 2.

4) Very different approaches are used at the Analysis Centers to represent the ionosphere mathematically, and the comparison of TEC maps originating from different Analysis Centers show significant differences (Feltens, 1999). Regarding these results and studying the different algorithms provides valuable information and new ideas needed for the development of more sophisticated mathematical ionosphere models. It is intended to develop for the IONMON version 2 mathematical models which are physically based and supplemented with empirical approaches where appropriate.

CONCLUSIONS

ESOC has started with the routine evaluation of ionosphere products at the beginning of the year 1998. The Ionosphere Monitoring Facility (IONMON) version 1 software is used for this operational processing. Four different kinds of global TEC maps, one single layer GE-function map and three 3-d Chapman Profile approaches, and a set of receiver/satellite DCBs values are produced daily. The output of one Chapman Profile model is contributed to the IGS Ionosphere Pilot Project.

When routine ionosphere processing was started, it was coupled to final orbit processing. Processing in rapid mode commenced then 3 months later and ran in parallel to the final for something more than a year. Since about one month routine ionosphere processing is now based on a combined strategy using rapid orbits, which are sufficient with their accuracy, but a number of ground stations that is even larger as it was in the final processing. The significant benefit of this new strategy is that ionosphere products can now be produced with at least the same quality in shorter time.

Validation of achieved accuracy was done in several directions. The accuracy of TEC maps was basically verified with four methods:

1) by examination of the long-term behavior of statistical key parameters,

2) by ESOC-internal comparisons between - and analyses of the different modeling approaches,

3) by comparison of VTEC values computed from the IONMON with VTEC data derived from TOPEX altimeter observables,

4) by comparison with TEC maps from other Analysis Centers (Feltens, 1999).

The four methods confirmed stable IONMON model and software performance. As the comparisons with TEC maps from other Analysis Centers and with TOPEX data show, improvements in the IONMON mathematical models are desirable.

For the approval of estimated DCBs, also their long-term behavior was inspected and comparisons were done with corresponding external values from outside ESOC. The long-term curves indicate that, especially when the ionosphere is very active and/or disturbed, the mathematical algorithms are not able to absorb all these effects, which thus propagate to a certain extent into the estimated DCBs. With respect to external DCB values an overall agreement in the order of $0.2\ ns$ could be seen.

All in all ESOC's operational ionosphere processing looks stable and accurate within the limits set by the currently used mathematical models. An IONMON software version 2 will overcome to a considerable amount the deficiencies of the current processing.

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