

USING GPS FOR IONOSPHERIC CORRECTIONS OF ESA TRACKING DATA

J. Feltens¹, J.M. Dow², T.J. Martín-Mur², C. García Martínez³
 F. Martínez-Fadrique³, R. Piriz³

1. EDS, currently based at European Space Operations Centre (ESA/ESOC),
 Flight Dynamics Division,
 Robert-Bosch-Straße 5, D-64293 Darmstadt, Germany
 phone: +49 6151 902078, fax: +49 6151 902271
 E-mail: jfeltens@esoc.esa.de
2. ESOC
3. GMV, currently based at ESOC

ABSTRACT

An Ionosphere Monitoring Facility (IONMON) has been developed at ESOC, using globally collected dual-frequency GPS data to establish Total Electron Content (TEC) information models. With an external user interface these TEC information models can be used to apply ionospheric corrections to other satellite tracking data, namely to S-band and altimeter data. The intention is that the IONMON should support other ESA-missions, e.g. ERS and ENVISAT.

A first analysis of results obtained and accuracies achieved, was done in the form of an intercomparison of TEC models that were computed by - and exchanged between the different Analysis Centers of the International GPS Service for Geodynamics (IGS): TEC models were used to derive TEC maps in the form of grid data, i.e. comparison was done between these maps at grid points or at interpolated points. Beyond the TEC data, values of associated GPS satellite and receiver hardware delays were also compared. Four IGS Analysis Centers (ESOC included) contributed with results to this intercomparison.

Before taking the GPS-derived TEC models for routine application to ESA tracking data, a final verification was done with data extending over a five weeks period. For verification ERS S-band and altimeter data were corrected for ionospheric effects using GPS-derived TEC models. These verification results are presented in this paper.

1. INTRODUCTION

Since June 1992 ESOC participates as an Analysis Center in the IGS. ESOC's activities within the IGS include the routine provision of rapid and precise GPS orbits, earth orientation parameters, GPS satellite and station clock parameters, and ground station coordinates, as well as GPS data tracking and retrieval from ESOC tracking sites (Kiruna, Kourou, Malindi, Maspalomas, Perth and Villafranca).

As IGS member the ESOC Analysis Center has also access to GPS dual-frequency data provided daily by a net of about 80 globally distributed ground stations. Since

ionospheric effects that are acting on satellite transmitted signals, are frequency-dependent, the idea arose that these globally collected dual-frequency GPS data could also be used for the parameter estimation of some simple models to represent the ionosphere's TEC. These TEC models could then in turn be used to correct other satellite tracking data. Since the most recent GPS data can be retrieved daily from IGS, the provision of actual TEC models could be done daily too. This was the basic idea in the conception of an Ionosphere Monitoring Facility (IONMON) at ESOC.

The IONMON is a collection of main programs which can be subdivided into 3 major parts:

- 1) Preprocessing part: Derivation of TEC observables from the dual-frequency GPS data.
- 2) Processing part: Evaluation of the parameters of ionospheric TEC models from the TEC observables.
- 3) Postprocessing part: Model verification and analysis and external user interface.

The IONMON is part of the GPS Tracking and Analysis Facility (GPS TDAF) software, and its dedication within the GPS TDAF is the evaluation and provision of ionospheric TEC models on operational basis.

2. MATHEMATICAL REPRESENTATIONS AND PROCESSING OF TEC MODELS

The current IONMON version provides TEC information in the form of so called "single layer models" which assume the whole ionosphere to be condensed within an infinitesimal thin layer surrounding the Earth in form of a hollow sphere at an altitude of about 400 km. The IONMON uses spherical harmonics, Gauss-type exponential (GE) functions and polynomials as mathematical models to represent this ionospheric shell [Refs. 2 & 3]. - However, the IONMON software structure allows for the inclusion of more sophisticated models, e.g. ionospheric profiles, in future.

A global TEC information model is evaluated once per day by fitting the GPS-derived TEC observables of the

day before to degree and order 8 spherical harmonics and/or to degree 10 and order 8 GE-functions using the data of all available stations. The mathematical algorithm of the GE-functions is as follows:

$$VTEC = \Xi + G \cdot e^{-a_1 x - a_2 x^2 - a_3 x^3 - \dots - a_{2n} x^{2n}} \cdot e^{-b_1 y - b_2 y^2 - b_3 y^3 - \dots - b_{2m} y^{2m}} \cdot e^{-c_1 xy - c_2 x^2 y - c_3 xy^2 - \dots - c_{l-k+2} x^{k-1} y - \dots - c_l xy^{k-1}}$$

with

Ξ = constant offset

G = amplitude

a_i = coefficients in local time (x) direction

b_j = coefficients in geomagnetic latitude (y) direction

c_l = mixed coefficients

$k = \text{minimum}(2n, 2m) \quad l = k \cdot (k-1)/2$

GE-function: development $2n = 10$ in local time,
 $2m = 8$ in geomagnetic latitude.

Local polynomial TEC representations are evaluated for the day before in 6-hour intervals for each of the ESA tracking sites Kiruna, Kourou, Malindi, Maspalomas, Perth and Villafranca.

An "IONosphere Map EXchange (IONEX)" format to distribute the TEC models via IGS to the general community has been developed [Ref. 6]

3. CORRECTION OF ESA TRACKING DATA WITH GPS-DERIVED TEC MODELS

Users can access the IONMON TEC models via the IONMON's external user interface. This interface consists of a collection of subroutines, each processing one of the mathematical models listed above, and data files containing the single layer model coefficients from the GPS data fits. Each TEC model coefficient file is referred to a reference epoch which is the center epoch of the data that entered into the fit of this TEC model.

Epoch and earth-fixed cartesian ground station - and satellite position vectors are the input of each subroutine. At the first call, the invoked subroutine looks for those two TEC model coefficient data files whose reference epochs are closest to that epoch which was entered into the subroutine and reads their model coefficients and stores them internally into arrays. In this way the subroutine initializes itself at the first call. Then it evaluates a TEC value individually and independently with both of the two models. The final TEC value is then obtained by combining these two TEC values with a linear interpolation/weighted mean scheme, depending on how the actual epoch lies between the reference epochs of the two TEC models. This final TEC value is then the output of the subroutine. It is a slant range TEC, and the external user can calculate from this value an appropriate correction to the observation, e.g. range, doppler, etc.

For all subsequent calls the subroutine checks whether the input epoch is still lying between the reference epochs of the two TEC models. If not, it re-initializes by reading a new set of coefficients.

4. IONOSPHERIC CORRECTIONS OF ESA TRACKING DATA - RESULTS

4.1 Intercomparison between IGS Analysis Centers

To make a first verification and with a view to including ionospheric TEC data as new product into the IGS palette, an intercomparison of ionosphere products provided by different IGS Analysis Centers was organized in preparation of the IGS workshop in Silver Spring in March 1996 [Ref. 4]. Four Analysis Centers contributed to this comparison.

GPS-derived TEC data were evaluated over a time interval covering the last two weeks of October 1995 and the first three weeks of November 1995. The reason for the selection of this time period was the occurrence of a major solar flare at the middle of October 1995. The comparison was done by means of TEC maps in the form of grid data. Differences between pairs of TEC maps were computed at identical grid points resulting in residual TEC maps. These residuals were then analyzed to obtain a mean offset between the two TEC maps compared and a sigma with respect to this mean offset. The procedure continued with the calculation of the sigmas in sub-parts of the residual TEC map with respect to the overall mean. These sigmas were then arranged in matrices to identify parts of better and worse agreement between the two compared TEC maps. The detailed procedure is described in [Ref. 4], and in summary it came out from this intercomparison that in areas with tracking data of sufficient density the different TEC models seemed to show a general agreement of 5 TECU and better, normally about 3 TECU.

As consequence of the results that came out of this intercomparison, the IGS ground station net used by ESOC was densified around the equator and at the southern hemisphere in order to close gaps in station coverage in weakly observed areas. Additionally the degree and order of single layer development was enlarged a bit.

4.2 Verification with ESA tracking data

For a period of 5 weeks in February/March 1997 global and local TEC models were produced in time intervals as stated in the above Section 2, covering the complete period. These TEC models were then used to correct ERS tracking data for ionospheric effects and to see whether this improved the ERS orbit determination. For comparison the same processing was repeated with application of ionospheric corrections from a modified version of the Bent model [Ref. 5].

The ionospheric corrections obtained from the spherical harmonic TEC models were so far away from the values of the Bent model, that they were not included into this comparison. The problem with spherical harmonics is that they fit bad in areas where no observation data are available, and areas like the southern Pacific or the far East are not so well covered by the IGS network. On the other hand the IGS intercomparison showed [Ref.4] that spherical harmonics behave good in regional areas which are well covered with GPS receivers, e.g. Europe.

The analysis was done with global ERS altimeter data and with ERS MPTS (S-band 2-way range) data recorded at the ESA tracking site Kiruna. Altimeter and MPTS data were processed in 4-day arcs. Besides the ERS orbital state and dynamical parameters an altimeter bias, and in the case of MPTS data, a range bias and a time bias were estimated.

The results presented in the following cover the time interval from 2 to 13 February and are representative for the whole 5 weeks period.

Altimeter Data

Global GE-function models were used to correct ERS altimeter data for ionospheric effects. For comparison the same processing was repeated using an improved version of the Bent model implemented at ESOC [Ref. 5] and with the IRI-95 model, which is an enhancement of IRI-90 [Ref. 1]. As an example Figure 1 shows the altimeter corrections obtained from the different models over a time interval of a half day, i.e. about six ERS orbital revolutions. Plots made for other time intervals show basically the same behavior as presented in Figure 1.

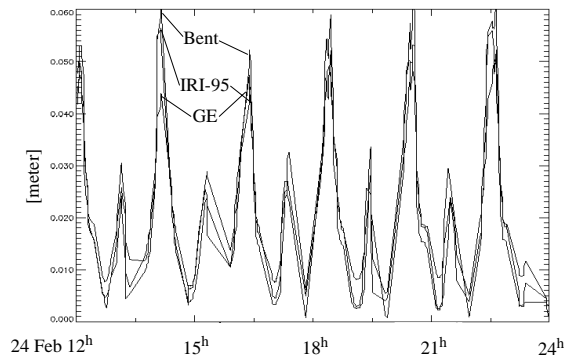


Figure 1. Altimeter corrections obtained from GPS/GE, improved Bent and IRI-95.

	<i>4-day statistics</i>		
	<i>mean offset</i>	σ	<i>rms</i>
GE - Bent	-2.9 mm	± 4.0 mm	± 4.9 mm
Bent - IRI-95	+4.6 mm	± 2.5 mm	± 5.2 mm
GE - IRI-95	+1.7 mm	± 3.9 mm	± 4.2 mm

Table 1. Statistics of the differences of the altimeter corrections obtained from GE, Bent and IRI-95.

As Figure 1 shows, all three curves are very close together, and the range corrections obtained from the three models differ only by 2 cm in the maximum. Also the statistics condensed in Table 1 confirm the closeness of the three models. According to Table 1 the GPS/GE-

function model and IRI-95 seem to be those two being closest together.

The *rms* of the ERS orbit fits seems also to be a bit smaller when calculating ionospheric corrections with the GE-functions than with the Bent model. The estimated altimeter bias shows changes in the order of 1 cm when one or the other of these two models is used.

MPTS Data

MPTS tracking data from ESA ground site Kiruna were used to verify the GPS-derived TEC models on local base. Additionally to the global GE-function models, local polynomial models, derived from fits of GPS data recorded at Kiruna, were included into this analysis. Comparisons were made with the Bent model. Table 2 condenses the results obtained:

<i>arc / model</i>	<i>used meas.</i>	<i>rejected meas.</i>	<i>rms</i>
<u>Feb 2 - Feb 5</u>			
GE	955	53	0.98 m
Polynomial	955	53	0.98 m
Bent	954	54	0.98 m
<u>Feb 6 - Feb 9</u>			
GE	961	49	1.08 m
Polynomial	961	49	1.09 m
Bent	961	49	1.10 m
<u>Feb 10 - Feb 13</u>			
GE	931	60	1.14 m
Polynomial	931	60	1.14 m
Bent	931	60	1.14 m

Table 2. Verification of GPS/GE and /polynomial models with Kiruna MPTS data (S-band 2-way range).

The results obtained from the processing with the different ionosphere models are so astonishingly close together that the suspicion arises that there might be something wrong in the processing. So the behavior of some of the estimated parameters was analyzed. First of all the differences in the ionospheric range corrections obtained with the different models were plotted and are

shown in Figures 2 - 4:

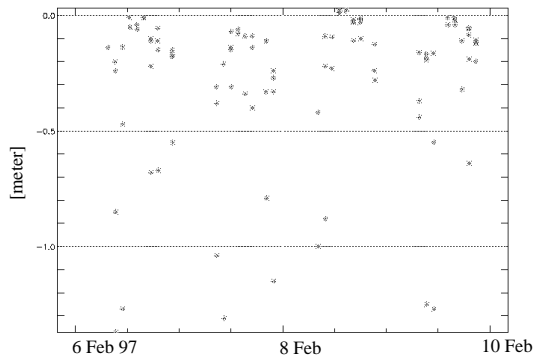


Figure 2. Differences in ionospheric range corrections GE - Bent.

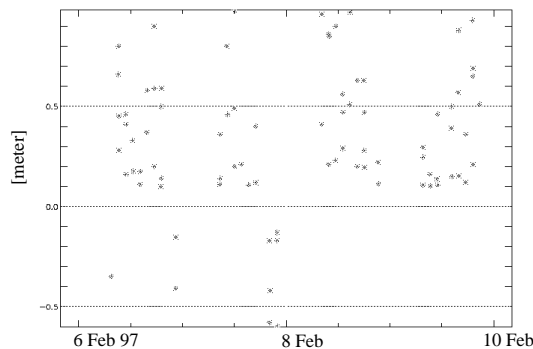


Figure 3. Differences in ionospheric range corrections Polynomial - Bent.

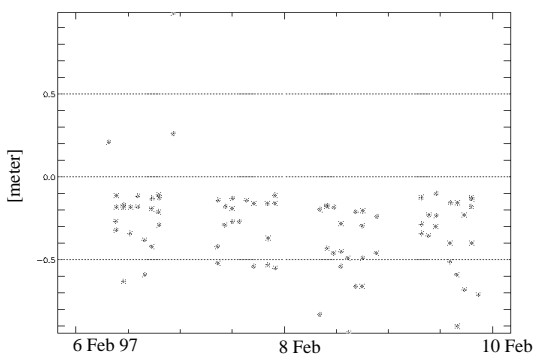


Figure 4. Differences in ionospheric range corrections GE - Polynomial.

As the above Figures 2-4 show, in the mean differences of less than 50 cm can be observed in the ionospheric range corrections obtained from the three models, sometimes values up to 1 m appear. The range corrections from the GPS/GE-function model are systematically smaller than the ones from the Bent model and the ones from the GPS/polynomial model. This can be seen from

Figures 2 and 4 in which the differences are systematically negative. And as Figure 3. shows, the range corrections from the polynomial model are systematically larger than the ones from the Bent model. Such systematic offsets between different ionosphere models were also observed at the IGS intercomparison [Ref. 4].

A range bias is estimated in the MPTS data evaluation. This range bias (which is mainly the delay in the on-board transponder) is in the order of 1 km and shows, depending on the ionosphere model used, variations in the order on 1 - 2 m, i.e. the same order as the differences in the ionospheric corrections. From the modeling, range bias and ionospheric effects are directly correlated with each other. Obviously the change in ionospheric correction propagates directly into the estimated range bias value.

Additionally the consistency of the estimated tropospheric parameters was analyzed. Tropospheric parameters are estimated in 4-hour intervals. When using the GPS-derived TEC models, they show a variation from one 4-hour interval to the next of less than 1%, and for the Bent model this variation is less than 2%.

5. CONCLUSIONS

An Ionosphere Monitoring Facility has been developed at ESOC, using globally collected dual-frequency GPS data to establish Total Electron Content (TEC) information models on routine basis. To verify the performance of these TEC information models, ionospheric corrections were computed with them and applied to ERS altimeter and MPTS data. Comparisons with IRI-95 and Bent models show astonishing agreement - in spite of that the GPS-derived models consist of much more primitive algorithms. So it seems that for certain applications in orbit determination the same accuracy can be achieved with simple empirical models, which are updated daily or hourly by fitting them to fresh GPS data, as with sophisticated and complex ionosphere models. Another reason for the close agreement between the complex models and the simple GPS models might be the fact that ionosphere and solar activity are currently very quiet. Under more disturbed conditions in the ionosphere GPS solutions are likely to be more accurate, because they are always fitted to fresh TEC data in which the ionosphere's behavior under higher solar activity is inherent. Regarding potential application areas outside ESOC, and especially the IGS, the provision of such simple TEC models to users, which have such complex models like IRI-95 or Bent not available, either because they do not have access to them, or because they do not have the computer capacity to process them, the availability of such simple TEC models would also enable them to improve their results. Once the coefficients are known from a fit and are available, it is very easy to process ionospheric corrections with them also on a small computer. So for certain applications the usage of simple empirical ionospheric TEC representation models derived from GPS data fits could be an alternative to the usage of the complex ionosphere models like Bent or IRI-95.

6. REFERENCES

1. Bilitza, D. (ed.) (1990): 'International Reference Ionosphere 1990'. *National Space Science Center/World Data Center A for Rockets and Satellites, Lanham, MD. Report Number NSSDC/WDC-A-R&S 90-22.*
2. Feltens, J. (1995a): 'GPS TDAF Ionosphere Monitoring Facility, Mathematical Model Developments'. *GTDAF-TN-08* Iss 1/- 11 Sep-95 (ESOC-internal document).
3. Feltens, J. (1995b): 'GPS TDAF Ionosphere Monitoring Facility, Examination of the Applicability of Gauss-Type Exponential Functions to Ionospheric Modeling'. *GTDAF-TN-09* Iss 1/- 11 Sep-95 (ESOC-internal document).
4. Feltens J., J. M. Dow, T. J. Martín-Mur & C. García Martínez (1996): 'Verification of ESOC Ionosphere Modeling and Status of IGS Intercomparison Activity'. *Proceedings of the IGS 1996 Analysis Center Workshop*, Silver Spring, MD, U.S.A., March 19-21, 1996, pp 205 -219.
5. Rawer, K. & D. Bilitza (1985): 'Study of Ionospheric and Tropospheric Models'. *European Space Agency Contract Report, Contract No. 5375/83/D*, September 1985.
6. Schaer, S., W. Gurtner & J. Feltens (1997): 'IONEX: The IONosphere Map EXchange Format Version 1'. *Proceedings of the IGS 1997 Analysis Center Workshop*, Pasadena, CA, U.S.A., March 11-13, 1997, currently in press.