Improvement of a Global Ionospheric Model to Provide Ionospheric Range Error Corrections for Single-frequency GPS Users

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BIOGRAPHIES

Attila Komjathy received his M.Sc.Eng. degree (1989) from the Department of Geodesy and Mining Surveying of the University of Miskolc, Hungary, and subsequently worked as a research assistant for the Hungarian Academy of Sciences. In 1991, he enrolled as a Ph.D. student in geodesy in the Department of Geodesy and Geomatics Engineering of the University of New Brunswick (UNB), Canada. Komjathy specializes in extraterrestrial positioning techniques for high precision geodesy and navigation. His current research focuses on the Global Positioning System (GPS) and its applications, concentrating on the study of the ionospheric effects on GPS signals using various modelling techniques.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. After obtaining his Ph.D., Dr. Langley spent two years with the Department of Earth and Planetary Sciences of the Massachusetts Institute of Technology where he carried out research in the applications of lunar laser ranging and very long baseline interferometry to geodesy and geodynamics.

Dr. Langley has worked extensively with GPS. He is a co-author of the best-selling Guide to GPS Positioning published by Canadian GPS Associates and is a columnist for GPS World magazine. He has helped develop and present a number of seminar courses on GPS for both Canadian GPS Associates and the American-based Navtech Seminars Inc. Dr. Langley has consulted extensively in the field of GPS with private companies and government agencies both in Canada and abroad.

ABSTRACT

The electromagnetic waves propagating from the satellites of the Navstar Global Positioning System (GPS) to a GPS receiver on or near the earth's surface must travel through the earth's ionosphere. GPS receiver users must correct for the carrier phase advance and pseudorange group delay imposed on the signals by the ionosphere to achieve the highest possible positioning accuracies. Since a new solar cycle has just begun, this effect will become increasingly important.

It is possible to use global empirical and/or physics-based ionospheric models to account for the ionospheric effect using single-frequency GPS receivers. Moreover, dual-frequency GPS observations can also allow us to take advantage of the dispersive nature of the ionosphere and compute the total electron content (TEC). The permanent network of GPS receivers administered by the International GPS Service for Geodynamics (IGS) may be used to determine the spatial and temporal variation in TEC. Several analysis and processing centers of the IGS are currently developing the capability to make TEC maps available to users as an official IGS product. In this paper, we report on the use of five weeks' worth of dual-frequency GPS pseudorange and carrier phase observations from 6 European IGS stations to derive regional TEC values.

Furthermore, we have investigated the use of a modified version of the latest International Reference Ionosphere model enhancement of IRI-90, also designated as IRI-95, to provide ionospheric range error corrections for single-frequency GPS users. We used our GPS-derived TEC maps to provide updates to the IRI-95 model on an hourly basis. After updating IRI-95 for each hour, we used the updated coefficient set of IRI-95 to compute TEC predictions between two updates. The updated IRI-

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95 model was then used to compare the model performance against the GPS-derived TEC. The predictions provided by the original version of IRI-95 were also compared with our GPS-derived TEC maps. After updating IRI-95, we found that the original model performance was improved overall by 32.5 percent. We also made modifications to the model and to the code to increase the efficiency of the code's execution. We tested the practicability of the model and found that it takes about 0.03 seconds (using an 85 MHz MicroSparc II processor) to execute the IRI-95 model for computing TEC or ionospheric range error corrections for one epoch at any geographic location. We believe that such a short execution time will make the updated IRI-95 model suitable for both post-processing and *real-time* applications for providing TEC estimates which can be used for ionospheric range error corrections for single-frequency GPS users.

INTRODUCTION

In accounting for the effect of the ionosphere using a single-frequency GPS receiver, it is possible to use global ionospheric models [Langley, 1996]. Numerous studies have been undertaken using different empirical and physics-based ionospheric models for such a purpose. At UNB, we are conducting an on-going study to assess the accuracy and efficacy of such models. We decided to include the IRI-90 model [Bilitza, 1990] in our ionospheric research after Newby [1992] investigated the International Reference Ionosphere 1986 (IRI-86) model's performance. Recently, Jakowski and Sardon [1996] have improved the IRI-90 model performance by using ionosonde data input. Hakegard [1995] also investigated the practicability of IRI-90 for real-time TEC predictions. Earlier we compared the Broadcast model of the GPS navigation message [Klobuchar, 1986] and the IRI-90 model with vertical ionospheric range error corrections inferred by using Faraday rotation data. We concluded that the IRI-90 model appeared to be more accurate than the Broadcast model, both for day-time and night-time periods, during a low solar activity period, for mid-latitude conditions [Komjathy et al., 1995; 1996]. The Faraday rotation measurements for use as "ground-truth" provided by GOES geostationary satellites are no longer readily available. We have, therefore, decided to use dual-frequency pseudorange and carrier phase GPS measurements to infer ionospheric TEC.

Recently, UNB participated along with several other research groups in an experiment to assess the capabilities of GPS dual-frequency observations to provide TEC values. The measurement campaign was organized by the Orbit Attitude Division of the European Space Agency's European Space Operations Centre (ESA/ESOC) Darmstadt, Germany, under the auspices of the IGS. The initial results of the comparison of ionospheric products between different processing centers were reported at the IGS Workshop in Silver Spring, MD, 19-21 March 1996. The experiment involved the processing and analysis of a 5 week long data set of dual-frequency GPS data from stations of the IGS network (GPS weeks 823 through 827). UNB analysed GPS data sets from 6 of the European IGS stations. The European region was chosen so that UNB and the IGS processing and analysis centers producing regional ionospheric maps would have a common region for comparison. Our regional model uses the following stations: Madrid, Grasse, Matera, Brussels, Wettzell, and Onsala. In the context of geomagnetic latitudes, three distinct latitude regions can be identified in our test network (1. Madrid, Grasse, Matera; 2. Brussels, Wettzell; 3. Onsala). All 6 stations use Allen Osborne Associates Inc. TurboRogue receivers.

Some of the results of the processing have been reported previously by Komjathy and Langley [1996a], where we concluded that after processing data from the 6 European stations collected over a 7 day period (the first 7 days of the ionospheric experiment organized by ESA/ESOC), we were able to detect highly varying ionospheric conditions associated with a geomagnetic disturbance. After investigating the effect of using different elevation cutoff angles and ionospheric shell heights on the TEC estimates and satellite-receiver differential delays, we discovered that using different elevation cutoff angles had an impact on TEC estimates at the 2 TEC unit (total electron content unit - TECU) level. We also concluded that using different ionospheric shell heights has an effect on the ionospheric TEC estimates also at about the 2 TECU level depending on geographic location and time of the day. We discovered that there are no significant changes in the satellite-receiver differential delay estimates computed using different elevation cutoff angles. We also compared our TEC estimates with TEC predictions obtained by using the latest IRI model enhancement also known as IRI-95. The results of this comparison are similar to those of other studies (e.g., Newby [1992]), which also investigated data sets at low solar activity times and for mid-latitude conditions.

As a continuation of this initial study, we used 21 days' worth of data with a more rigorous approach for ionospheric shell height determination as derived from IRI-95. The results of this study have been reported in Komjathy and Langley [1996b]. In the case of TEC estimation using dual-frequency GPS data, the ionospheric shell height determination is one of the potential error sources that could bias our estimates. We introduced the notion of using varying ionospheric shell heights derived from the IRI-95 model as opposed to using an ionospheric shell height fixed at a commonly adopted altitude (400 km). We found differences in the differential delays between the two approaches of up to the 0.3 ns ($\approx$1 TECU) level and differences in the TEC estimates up to the 1 TECU ($\approx$ 0.16 m delay on L1) level. We also found that with an inappropriate setting of the ionospheric shell height, it is possible to introduce a 0.5 TECU level error for every 50 km error in the shell height. In the case of differential delays, the equivalent error is about 0.14 ns. After comparing our differential delay estimates with those obtained by other research groups participating in the experiment, we found agreement in the differential delays between the three participating analysis centers which are involved in analysing regional ionospheric maps, at the 1 ns level. The relatively large bias differences were also confirmed by Feltens et al. [1996] and Wilson et al. [1996]. These differences may be caused by the use of different ionospheric mapping functions by the different analysis and processing centers. The comparison of the TEC maps performed by the Deutsche Forschungsanstalt für Luft und Raumfahrt (DLR) Fernerkundungsstation, Neustrelitz, Germany concluded that there was a good agreement between DLR's and UNB's results for 12 of the 21 days under comparison [Jakowski and Sardon, 1996]. However, for the rest of the data, 2 to 4 TECU level differences were reported. An analysis performed by ESA/ESOC showed a 1 TECU mean bias between ESA/ESOC and UNB results with a standard deviation of about 2 TECU [Feltens et al., 1996].

The ionospheric estimation technique currently used at UNB is described in detail in previous publications such as Komjathy and Langley [1996a and 1996b]. A brief description of the model is as follows: we estimate three stochastic parameters for each IGS station in a network mode tied to a solar-geomagnetic coordinate system assuming a Gauss-Markov stochastic process. The three parameters use a spatial linear approximation of TEC above each IGS station. The L1-L2 phase-levelled geometry-free observable is used to estimate the stochastic parameters along with other biases such as the satellite-receiver differential delays using a Kalman filter approach.

Recently, we have finished processing all 5 weeks' worth of GPS data from the experiment and have produced hourly TEC maps at a 1 degree by 1 degree grid spacing for the European region spanning from -10 to 30 degrees in east longitude and 30 to 60 degrees in north latitude. In our current study we also investigated the practicability and efficacy of using the IRI-95 model to provide ionospheric range error corrections for single-frequency GPS users. The above described GPS-derived TEC maps have been used as "ground-truth" to provide updates to the IRI-95 model on an hourly basis. Once the IRI-95 update is completed, the new (updated) coefficient set for the IRI-95 is used to compute TEC predictions between two updates. For validation purposes, the updated IRI-95 model was used to compare the model performance with the GPS-derived TEC. We also compared predictions by the original IRI-95 with the GPS-derived TEC values.

IRI-95 MODEL MODIFICATIONS

In this section, we will give an overview of the latest IRI model enhancement which is also designated by the ionospheric community as IRI-95, followed by the description of our modifications we have made to the model. The backbone of the model is the numerical maps describing the F2-peak plasma frequency foF2 and the propagation factor M(3000)F2. The latter is closely related to the maximum usable frequency MUF(3000) which is the highest frequency that can be received at the distance of 3000 km after refraction in the ionosphere [McNamara, 1991]. The temporal and spatial variation of foF2 and M(3000)F2 are described by the Comité Consultatif International des Radiocommunications (CCIR) coefficients. More recently, the International Union of Radio Science (URSI) numerical map coefficients have been developed for use in describing the foF2 distribution. Both CCIR and URSI coefficients use a sixth order Fourier representation for the diurnal and seasonal variation of the foF2 whereas CCIR uses a fourth order Fourier series for the description of the M(3000)F2 propagation factor. From the numerical description point of view, both foF2 and M(3000)F2 quantities are represented by a function $\Omega(\varphi,\lambda,t)$ with geographic latitude, φ, longitude, λ, and Universal Time (UT), t, as variables. In $\Omega(\varphi,\lambda,t)$, the parameter h is the order of the Fourier series (h = 6 for foF2 and h = 4 for M(3000)F2) representing the diurnal variation of foF2 and M(3000)F2 parameters [Davies, 1990]:

$$\Omega(\varphi,\lambda,t) = a_0(\varphi,\lambda) + \sum_{j=1}^{h}\left[a_j(\varphi,\lambda)\cos jt + b_j(\varphi,\lambda)\sin jt\right] \qquad (1)$$

where

$$a_j(\varphi,\lambda) = \sum_{k=0}^{n} U_{2j,k} G_k(\varphi,\lambda) \qquad (2a)$$

$$b_j(\varphi,\lambda) = \sum_{k=0}^{n} U_{2j-1,k} G_k(\varphi,\lambda) \qquad (2b)$$

are the Fourier coefficients. $G_k(\varphi,\lambda)$ in equations (2a) and (2b) contains the geographical coordinate functions in the form of spherical Legendre functions up to a harmonic order of nine (foF2) and seven (M(3000)F2) in longitude. They are represented by the expressions $\sin^q \mu \cdot \cos^m \varphi \cdot \cos m\lambda$ and $\sin^q \mu \cdot \cos^m \varphi \cdot \sin m\lambda$ respectively, where q is the highest degree in latitude for each longitude harmonic m and μ is the modified dip latitude

$$\tan \mu = \frac{\psi}{\sqrt{\cos \varphi}} \tag{3}$$

where ψ is the geomagnetic dip latitude. The presence of the F2 layer is controlled not only by the geographic latitude and longitude but also the geomagnetic dip latitude, and hence the parameter ψ must be included in the model [Bilitza, 1990]. The variable n is related to the sum of the highest degrees of latitude for each longitude harmonic (n = 76 for foF2 and n = 49 for M(3000)F2). The global description of Legendre functions $G_k(\varphi, \lambda)$ is applied to each Fourier coefficient. The numerical maps that have been derived using some 180 ionosonde stations wordwide, are defined by two sets of coefficients representing low and high solar activity times for each month (n·(2h+1) = 988 coefficients for foF2 and 441 for M(3000)F2) [NSSDC, 1996a]. To obtain values for intermediate levels of solar activity for a particular day of a month, linear interpolation is used [McNamara and Wilkinson, 1983].

For computing foF2 using the CCIR/URSI numerical maps, the IRI-95 model uses the 12-month-smoothed global effective sunspot number (IG_{12} index) as an indication of solar activity [Davies, 1990]. The IG_{12} index is recommended as an alternative to 12-month-smoothed sunspot numbers R_{12} when predictions are made with the aid of the numerical map coefficients of ionospheric characteristics [NSSDC, 1996b]. In our approach, we included an additional scaling factor $K(\varphi, \lambda, t)$ that we use to determine an inferred effective sunspot number (inferred IG_{12} index) which is defined as the product of the IG_{12} index and the scaling factor. We implemented an efficient search technique to find the correct scaling factor that results in the best match between the IRI-95 model predicted TEC and the GPS-derived TEC. The search technique includes a change of the initial value for the scaling factor (K = 1) by a small amount and continuous monitoring of the difference between the IRI-95 prediction and the "ground truth" value (GPS-derived TEC). The search for the correct scaling factor is carried out until the difference between the IRI-95 predictions and the GPS-derived TEC values are less than a predefined value (0.5 TECU). The search is efficient because the change in K depends on the difference between the IRI-95 predictions and the "ground-truth", and optimizes the number of runs required to arrive at the 0.5 TECU level difference.

Numerically, the coefficient sets for equations (2a) and (2b) can be described by

$$U_{2j,k} = \left[U_{2j,k}^{low} \frac{IG_{12}}{100} + U_{2j,k}^{high} \left(1 - \frac{IG_{12}}{100} \right) \right] \cdot K(\varphi, \lambda, t) \tag{4a}$$

$$U_{2j-1,k} = \left[U_{2j-1,k}^{low} \frac{IG_{12}}{100} + U_{2j-1,k}^{high} \left(1 - \frac{IG_{12}}{100} \right) \right] \cdot K(\varphi, \lambda, t) \tag{4b}$$

where the coefficient sets for the high and low solar activity can be distinguished. (The original versions for equations (4a) and (4b) do not contain the scaling factor K but are otherwise identical to equations (4a) and (4b) shown here.) For the coefficient sets used to compute M(3000)F2, the 12-month-smoothed sunspot number R_{12} is used by the IRI-95 model. For every IRI-95 run during the search, a new value for parameter $\Omega(\varphi, \lambda, t)$ (i.e, foF2 and M(3000)F2) is used to compute the F2 layer peak electron densities and peak electron density heights to help in constructing a new IRI-95 profile. The computation of peak electron densities and peak density heights of different layers (D, E, F1, and F2) is described by Bilitza [1990]. The next step is the integration of the electron densities along the IRI-95 profile up to an altitude of 1,000 km. Above this altitude, we did not consider the plasmaspheric electron content, which has an effect primarily on the night-time TEC predictions. The effect can be as much as about 50 percent (around 2 to 3 TECU) of the night-time TEC near sunspot minimum [Davies, 1990]. For the integration to obtain TEC predictions, a step size of 1 km was used. Upon finding the correct scaling factor K, modified foF2 and M(3000)F2 coefficient sets are produced allowing us to construct the updated IRI-95 profile, and consequently obtain the updated TEC value.

RESULTS OF DATA ANALYSIS

We used our hourly TEC maps each consisting of 1,271 (31 by 41) gridded TEC values for the European region encompassing 5 weeks' worth of GPS data for the data analysis. We computed hourly scaling factors for 1 degree by 1 degree spacing according to the modifications described in the last section. This resulted in the computation of 1,054,930 scaling factors using our search technique. The scaling factors for every other UT hour were then used subsequently to compute a scaling factor for the UT hour in between using a linear interpolation. Following that, the modified IRI-95 model was used to predict the TEC for this hour and a particular geographic location. For verifying our results, we also evaluated the original version of IRI-95 for computing TEC at each grid point for the whole data set.

For illustrative purposes, we chose three stations from the 6 European stations used to create ionospheric maps to display the different ionospheric modelling techniques currently used and implemented at UNB. The three stations are Madrid, Brussels and Onsala, encompassing three different geomagnetic latitude regions used for the European data processing. In Figure 1, we have plotted TEC predictions and estimates for the period of 15 to 22 October 1995 (GPS week 823) using 4 different ionospheric modelling techniques. These are the original IRI-95-predicted TEC, the updated IRI-95 using the GPS-derived TEC maps, the Parameterized Ionospheric Model (PIM) predictions [Daniell et al., 1995], and the GPS-derived TEC values. On the right-hand y axis, we also plotted the 12-month-smoothed IG_{12} indices as well as the inferred IG_{12} indices using our computed scaling factor. In Figure 1, we can see that the global empirical ionospheric model IRI-95 and the physics-based numerical model PIM predict different shapes for the diurnal TEC variation.

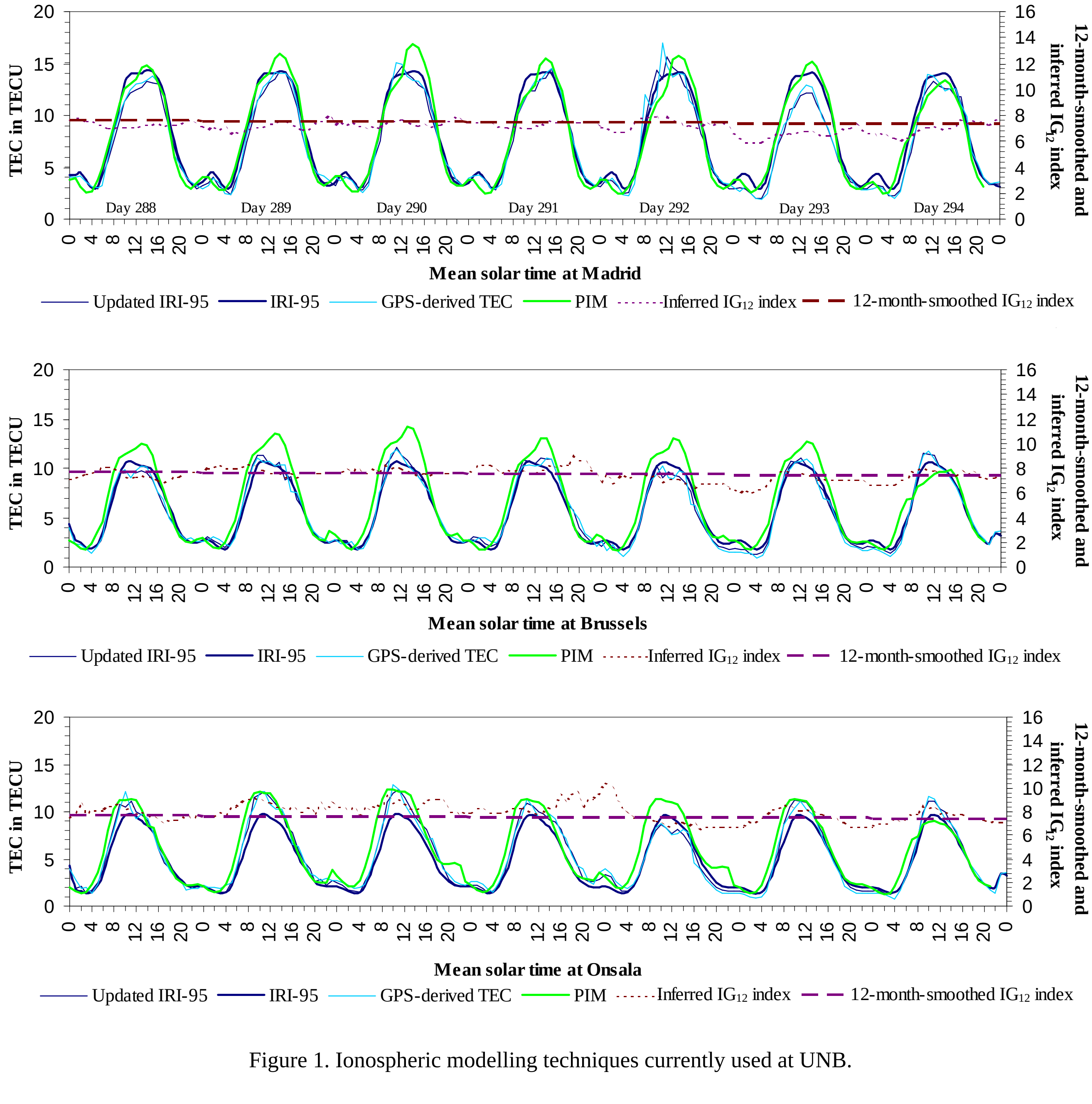

Figure 1. Ionospheric modelling techniques currently used at UNB.

None of the models could predict the effect of the geomagnetic disturbance which occurred on day 292 on the TEC variation. This is despite the fact that the PIM model uses both solar flux and geomagnetic data as input parameters as opposed to the IRI-95 models where only 12-month-smoothed IG_{12} index and sunspot number R_{12} are used as input.

The GPS-derived TEC values and the updated IRI-95 predictions seem to agree well, indicating that under quiet geomagnetic conditions the updating technique seems to be successful. On day 292, when the geomagnetic disturbance started, the differences are much larger suggesting that the updating process was less successful. The larger variations in the inferred IG_{12} index during the geomagnetically disturbed days (on days 292 and 293) suggest that under disturbed ionospheric conditions, finding the correct scaling factor may be more difficult. The inferred IG_{12} index shows fluctuations during the week that vary with the geomagnetic latitude region and seem to start in the north with station Onsala (on day 291) and subsequently move south to station Madrid (on day 292). This could be explained by the fact that the magnetic disturbance has its commencement phase for different geomagnetic latitudes at different times. It appears that the geomagnetic disturbance was moving equatorward which is a well described phenomenon [Davies, 1990].

For high latitude stations such as Onsala, the PIM model seems to provide closer agreement with the GPS-derived TEC values. The reason for this is that the PIM model is composed of a high latitude model for predicting electron densities above 51 degrees geomagnetic latitude [Daniell et al., 1995].

Since the TEC maps produced by the IGS analysis and processing centers may become official IGS products in the foreseeable future [Feltens, 1996; Schaer et al., 1996], our technique could become an efficient method of providing ionospheric range error corrections for single-frequency GPS receivers. Our technique could be used to update IRI-95 on an hourly basis (depending on the availability of the TEC maps) and could use the updated CCIR/URSI coefficient sets for computing predictions between two updates. In this paper, we used two-hourly updates to be able to compare the updated IRI-95 with the GPS-derived TEC in between. In Komjathy and Langley [1996b], we provided a short description of other research centers' ionospheric estimation techniques whose products could also be potentially used for updating the IRI-95 model.

A more frequent update interval (e.g., one hour) would provide more precise scaling factors, therefore more reliable updated IRI-95 predictions. The reason we used two-hourly updates was to verify our results using GPS-derived TEC values already available for each hour. We modified the source code of the IRI-95 model such that it can be used for different post-processing software packages such as UNB's DIfferential Positioning Program (DIPOP) package to provide ionospheric range error corrections when only single-frequency GPS observations are available. In a post-processing scenario, updating of IRI-95 could be performed by using hourly TEC observations before and after the epoch for which we require TEC predictions. This would be followed by a linear interpolation between the two scaling factors computed for every hour.

Assuming that our GPS-derived TEC maps are free of error, we computed the r.m.s. differences between the updated IRI-95 predictions and the GPS-derived TEC maps as well as the original IRI-95 predictions and the GPS-derived TEC maps. For computing statistics we used all GPS data and scaling factors computed. We computed hourly r.m.s. differences as well as daily and overall r.m.s. differences between the updated and non-updated IRI-95 with respect to the GPS-derived TEC values.

In Figure 2, we show the hourly r.m.s. differences for the first week under investigation. The hourly r.m.s. differences have been derived using all 1,271 observations pertaining to each hourly map. From the figure we can see that the updated IRI-95 model provides smaller r.m.s. differences than the original one in all cases. It is also interesting to note that on day 292, the geomagnetic disturbance resulted in the update to IRI-95 model using our technique being less successful. The rate of change of the TEC may have been so rapid that we were unable to compute a valid scaling factor that could be used for updating IRI-95. A more sophisticated approach than the linear interpolation procedure is needed when the ionosphere is disturbed. This argument seems to be supported also by the fact that during day-time hours, the updated IRI-95 seems to show larger r.m.s. differences than the night-time ones. This is due to the rapid changes in the TEC during day-time hours.

We also computed the daily r.m.s. differences for all 35 days' worth of GPS data. In Figure 3, we display these differences. The peak on day 292 represents the large r.m.s. difference caused by the geomagnetic disturbance that we can also see in Figure 2. There are 3 more peaks which are apparent in the time series. This could be due to the daily variation in the TEC which is not modelled by global empirical models such as the IRI-95. Its coefficient set is based on the monthly median diurnal variation of the foF2 and M(3000)F2 parameters. After updating IRI-95, these peaks have been reduced indicating that the updating procedure was successfully completed. Figure 3 gives a clear indication that for all 35 days investigated we achieved improvement in TEC predictions over the original IRI-95 model predictions.

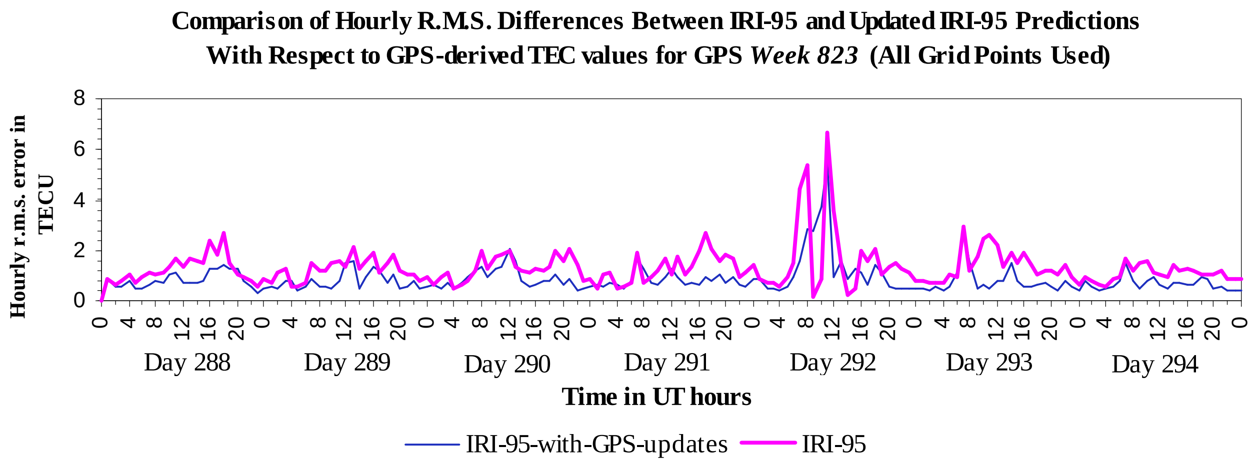

Figure 2. Hourly r.m.s. statistics.

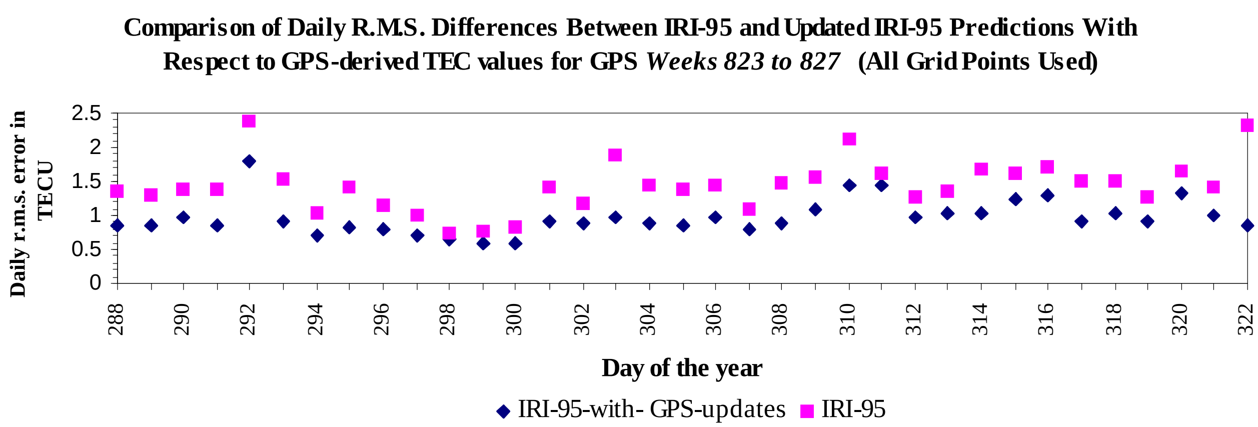

Figure 3. Daily r.m.s. statistics.

GPS week	R.m.s. of differences between **original IRI-95 predictions** and GPS-derived TEC values in units of TECU	R.m.s. of differences between **updated IRI-95 predictions** and GPS-derived TEC values in units of TECU	Improvement in %
823	1.5	1.0	31.4
824	1.1	0.7	32.0
825	1.4	0.9	37.4
826	1.6	1.2	26.1
827	1.6	1.1	35.5
Average	1.5	1.0	32.5

Table 1. Summary of the weekly statistics.

We also computed overall statistics. It was found that after updating IRI-95 using the GPS-derived TEC values, r.m.s. differences were reduced by an overall 32.5 percent as opposed to not updating it (i.e., using the original IRI-95). The weekly and overall statistics have been summarized in Table 1. The summary of the weekly statistics shows that the r.m.s. differences between the original IRI-95 and the GPS-derived TEC are at the 1.5 TECU level compared to the differences between the updated IRI-95 and GPS-derived TEC which are at the 1 TECU level. The weekly improvements range from 26 to 37 percent with an overall average of 32.5 percent.

After extensive testing, and making IRI-95 more efficient to run, we found that it takes about 0.03 seconds of CPU time for computing TEC or ionospheric range error corrections for one epoch at any geographic location using our modified version of the IRI-95 model with or without the GPS updates. We used an 85 MHz MicroSparc II processor for all our processing.

GPS week	CPU time	CPU time in seconds	Number of runs	Seconds/run
823	3h 28m 12.4s	12,492.4	421,972	0.0296
824	3h 30m 49.7s	12,649.7	421,972	0.0300
825	3h 30m 43.1s	12,643.1	421,972	0.0300
826	3h 30m 24.2s	12,624.3	421,972	0.0299
827	3h 30m 35.0s	12,635.0	421,972	0.0299
Sum	17h 30m 44.5s	63,044.5	2,109,860	0.0299

Table 2. Summary of CPU times.

In Table 2, the CPU time and the number of runs are indicated for each GPS week processed. The values in the table include running the model with the pre-computed scaling factors as well as without the scaling factors for each grid node under investigation encompassing all 5 weeks' worth of GPS data. Over two million runs were completed to compute the hourly, daily and overall statistics.

We also measured the time it takes to compute the scaling factors for the hourly TEC maps. We counted the number of runs needed to arrive at the 0.5 TECU level difference between our GPS-derived TEC values and the IRI-95 predictions. In Figure 4, the average number of IRI-95 runs for a grid point are plotted against UT hours for GPS week 823. On the right-hand y axis, the required time to compute the scaling factors for an hourly map is displayed. It is clear that it takes more IRI-95 runs to compute the scaling factors for a daytime observation since the ionosphere is more variable during daytime. For computing scaling factors, we did not start the iteration process using scaling factors from previous hours which would make it less time consuming (since they are correlated) to compute the correct scaling factor for the subsequent hour.

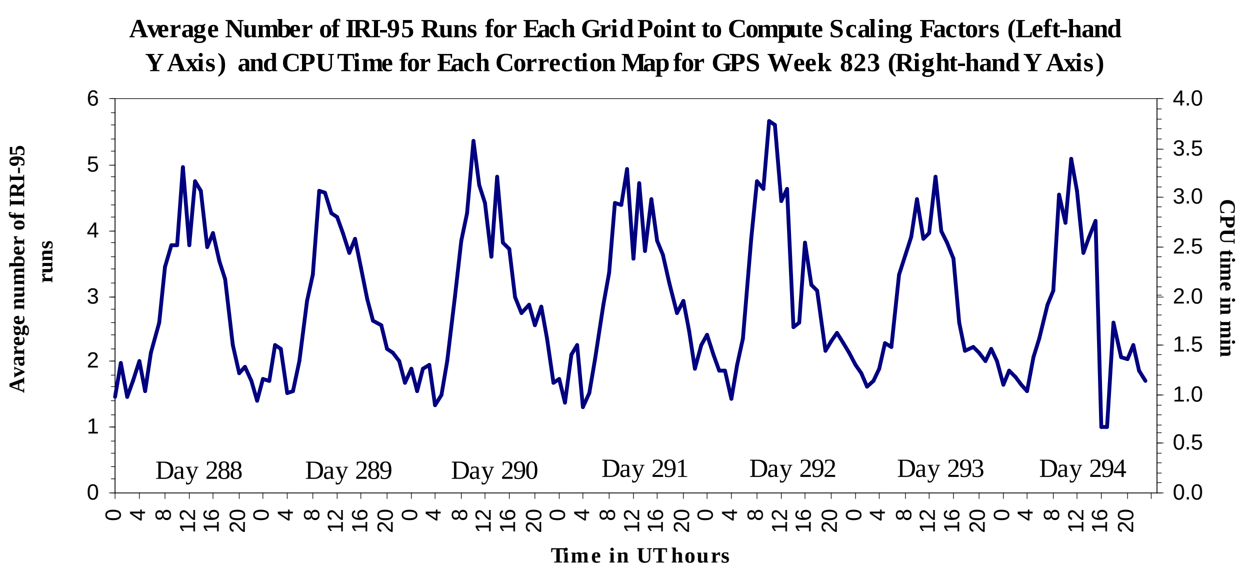

Figure 4. Number of IRI-95 runs required to arrive at the proper scaling factor.

The reason for this approach is that the purpose of using this technique is to make use of the availability of the hourly TEC maps only before and after an epoch (without having to process other maps) when a single-frequency user collects data to update the IRI-95 coefficient set in order to improve predictions between two updates. Also, a user is not required to compute scaling factors for each grid point but only those gridpoints that are of interest in the vicinity of the single-frequency user's geographic location. In this study, we used all grid nodes for the sake of completeness and for the development of the statistics.

Another potential application for our technique could be to provide *real-time* ionospheric range error corrections for single-frequency GPS users. Our technique provides TEC maps using a Kalman filter type estimation. Therefore, the technique could be used to process dual-frequency GPS data as they become available in near real-time. The frequency of producing TEC maps can easily be increased from 1 map per hour. Highly varying ionospheric and geomagnetic conditions may require more frequent TEC maps. Subsequently, our TEC maps (as the output of the Kalman filter type estimation) could be used to update the IRI-95 model coefficient set as described in this paper. In a real-time scenario, the updating could be performed by using the latest available scaling factor from the previous hour. Since our modified version of IRI-95 runs quite efficiently, it may be feasible to compute ionospheric range error corrections for each satellite at every observation epoch and geographic location. These ionospheric range error corrections could then be forwarded to the user in real-time.

CONCLUSIONS

In the research reported in this paper, we investigated the use of TEC estimates from dual-frequency GPS observations provided by 6 of the IGS stations to update the latest IRI model enhancement of IRI-90 (also designated as IRI-95). We used a 5 week long GPS data set from the European region to compute scaling factors to IRI-95's CCIR/URSI coefficient sets and to provide evidence that the update procedure has been successful.

The overall statistics revealed that after updating the IRI-95 model, the r.m.s. of the differences between the updated IRI-95 model and the GPS-derived TEC, as well as the original IRI-95 predictions and the GPS-derived TEC values, decreased by an overall 32.5 percent. These results are likely only valid for a mid-latitude region under low solar activity conditions. After extensive testing and modifications of the IRI-95 model, we found that it takes about 0.03 seconds on average to compute TEC or ionospheric range error corrections for each epoch at any location using our version of the IRI-95 model.

Our technique could be used as an alternative to the Broadcast model to provide ionospheric range error corrections for single-frequency users. Providing ionospheric range error corrections will become more and more important 2 or 3 years from now when we will again start experiencing increased solar activity. The relatively short execution time of the modified version of IRI-95 makes it possible to use this technique both for *real-time* and post-processing purposes. The backbone of this technique is the TEC maps that could become available either by using our Kalman filter type estimation or some other source such as ionospheric maps which may be produced by IGS in the near future.

So far in our studies, we have estimated regional ionospheric maps. We plan on extending the testing of our technique to low and high latitude regions under medium and high solar activity conditions.

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