Ingesting GPS-Derived TEC Data into the International Reference Ionosphere for Single Frequency Radar Altimeter Ionospheric Delay Corrections

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Abstract

At the University of New Brunswick (UNB), we have developed the capability to independently produce hourly global total electron content (TEC) maps from Global Positioning System (GPS) data. UNB's hourly GPS-derived global TEC maps can be ingested directly into a modified version of the International Reference Ionosphere 1995 (IRI-95) model and augmented with a plasmaspheric electron content model to update its coefficient sets. We present a technique to provide improved IRI-95 predictions by using the modified model as a sophisticated interpolator between hourly GPS-derived TEC updates. The updated IRI-95 coefficient sets will make it possible to provide ionospheric delay corrections for various applications including single frequency radar altimeter missions such as the upcoming Geosat Follow-On mission. Since the spacecraft will be orbiting "inside" the ionosphere, our GPS-updated IRI-95 electron density profile will allow us to integrate the electron densities up to the spacecraft altitude to remove the bias imposed by the ionosphere. This would not be possible using GPS-derived TEC alone since it provides integrated electron content up to the altitude of the GPS satellites (20,200 km).

In this paper, we present results based on 3 days' worth of global GPS data (33 International GPS Service for Geodynamics (IGS) stations) at a medium solar activity time (year 1993) and 3 days' worth of global GPS data (74 IGS stations) at a low solar activity time (year 1995). We also compare our updated IRI-95 predictions using UNB's global TEC maps and the original IRI-95 predictions, against TOPEX/Poseidon (T/P) dual frequency altimeter-derived TEC data. Based on 3 days' worth of global GPS data during the medium solar activity time in 1993, the results show that there was better than a 9 TECU level (1 sigma) agreement in the total electron content on a global scale with the T/P-derived TEC data using the UNB technique. For the 1995 low solar activity time, our results agreed with the T/P data at better than the 5 TECU level (1 sigma). These results suggest that our method may be viable for providing ionospheric delay corrections for future single frequency altimeter missions.

Introduction

Current and planned satellite missions such as the European Remote Sensing satellites (ERS-1, ERS-2), the upcoming Geosat Follow-On, and ENVISAT missions are or will be equipped with single frequency radar altimeters to obtain ocean

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height measurements for study of ocean circulation and its variability. Unlike with dual frequency altimeters the path delay due to the ionosphere cannot directly be removed from the altimeter range measurements. For a radar altimeter operating at a frequency of 13.6 GHz, such as the one to be carried by the Geosat Follow-On, this path delay can be as much as 20 cm at solar maximum or during solar storms (1 cm path delay at 13.6 GHz corresponds to 4.6 TECU; 1 Total Electron Content Unit, TECU, corresponds to 10^{16} electrons/m^2). Therefore, to be able to maximize the accuracy of ocean height measurements obtained with single frequency radar altimeters, it is necessary to use alternative means to remove the propagation delay imposed by the ionosphere (Born and Katzberg, 1996).

The Geodetic Research Laboratory of the University of New Brunswick participated in an experiment organized by the University of Colorado - Colorado Center for Astrodynamics Research and NASA to characterize the impact of ionospheric delay on the ocean science conducted with single frequency radar altimeter data. The purpose of the experiment was to find out what state-of-the-art techniques are currently available for mitigating such effects. Using data from GPS satellites, global maps of TEC have been produced to update the IRI-95 coefficient sets. Furthermore, comparisons have been made with reference TEC data obtained from T/P dual frequency altimeter to confirm the accuracy of the technique.

UNB Ionospheric Mapping Technique

The UNB global ionospheric mapping technique is based on the regional ionospheric mapping technique. The interested reader is referred to Komjathy (1997) and Komjathy and Langley (1996a) for a detailed explanation of the technique. Here, we only give a brief description of the model. During preprocessing of the data, synthesized raw P1 minus P2 pseudorange GPS observations are used to adjust the level of the L1 minus L2 raw GPS observations. This is followed by the main processing stage to estimate three stochastic parameters in a Kalman filter approach for each of the IGS network stations used. The model is parameterized by the mean solar longitude and geomagnetic latitude. The global ionospheric modelling algorithm uses a varying ionospheric shell height separately computed for each IGS station taking into account the geographic and temporal variations of the shell height as described by Komjathy and Langley (1996b). The varying ionospheric shell height for each station is used as an input parameter when mapping the line-of-sight total electron content into the vertical using a commonly adopted geometric mapping function. During the postprocessing stage, the hourly global 5 degree by 5 degree TEC maps are constructed by using the three stochastic parameters defining a local ionospheric model for each station that is tied to a solar-geomagnetic coordinate system. The TEC estimates for any grid node are computed by using the models of the four nearest IGS stations weighted by the inverse node-station distance squared.

After producing hourly global TEC maps, we use them to update the CCIR and URSI coefficient sets of the International Reference Ionosphere (IRI-95) model (Bilitza, 1990) as described later in this paper (see also Komjathy and Langley, 1996c). The IRI-95 model with the updated coefficient sets is then used as an interpolator between two TEC-derived hourly TEC maps. Regional TEC maps such as those produced by Jakowski et al. (1996) or global TEC maps such as those generated by Ho et al. (1996) and Schaer et al. (1996) could also be used to update the modified IRI-95 model.

Hourly Global TEC Maps

To demonstrate the global ionospheric TEC mapping technique, we processed GPS data from a global network of 33 measurement stations contributing to the IGS (Figure 1) spanning 3 consecutive days in 1993 (13 to 15 March, medium solar activity period) and data from 74 such stations giving much improved geographical coverage, particularly so in the equatorial region (Figure 2), spanning 3 consecutive days in 1995 (6 to 8 April, low solar activity period). A total of 321 station-days of GPS data were processed for the data analysis described in this paper. The raw GPS data were provided by the Scripps Orbit and Permanent Array Center (SOPAC, 1998). The IGS stations used are indicated with triangles in Figures 1 and 2. Also displayed are two T/P ground trajectories used for illustration later in this paper.

When comparing the spatial distribution of the IGS stations between 1993 and 1995 (Figures 1 and 2 respectively), it can be seen that the distribution of the stations for the 1995 data set is superior to that for 1993. This is especially true for the equatorial region where the station coverage is much poorer in 1993. From the ionospheric research point of view, it is unfortunate that there were fewer IGS stations

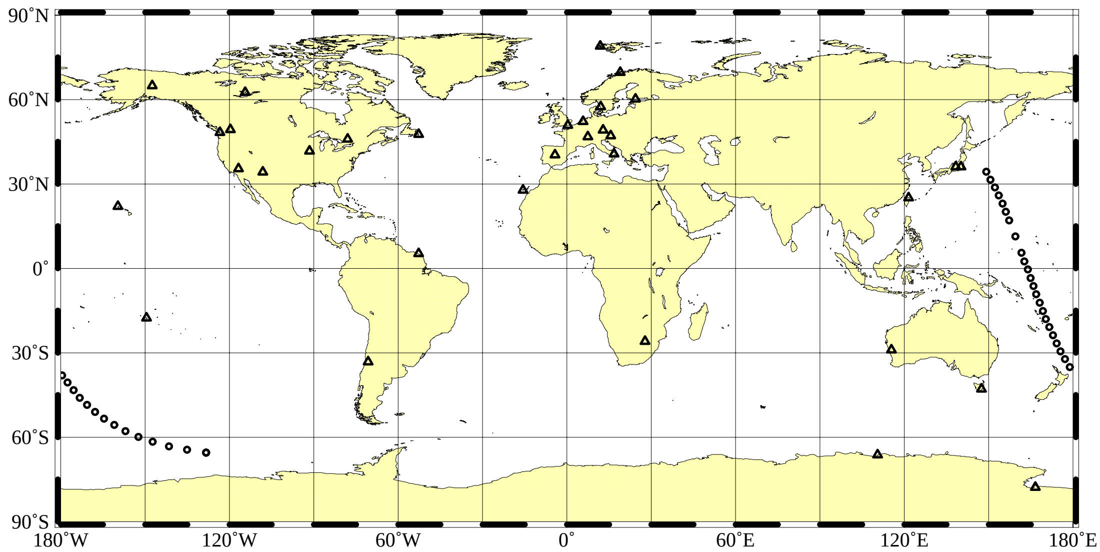

Fig. 1. Stations used for the 1993 global ionospheric data processing.

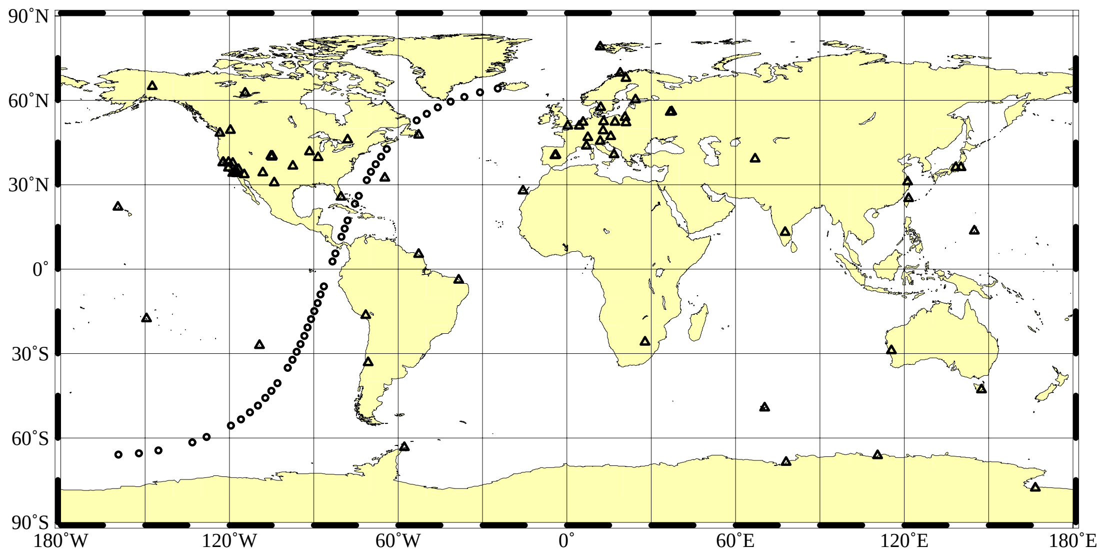

Fig. 2. Stations used for the 1995 global ionospheric data processing.

available in 1993 during the period of medium solar activity. It is very important to realize that the number of IGS stations in coastal regions has also increased making it possible to provide better ionospheric corrections for the single frequency altimeter measurements over the oceans. Nevertheless, the very fact that there were more than twice as many IGS stations available in 1995 than in 1993 does not imply that the spatial coverage usable for altimetry had increased by a factor of two, since most of the new stations were established deep inside the continental regions improving the coverage over land and having very little or no contribution to the spatial coverage over the oceanic region.

Figure 3 is an example of an hourly snapshot of the global ionosphere produced by the above technique, referring to Universal Time (UT) 17h of 6 April 1995. TEC is greatest in the equatorial region with values up to 55 TECU. The equatorial anomaly and the equatorial trough are evident.

In Figure 4, another example of an hourly TEC map is displayed for UT 13h of 15 March 1993.

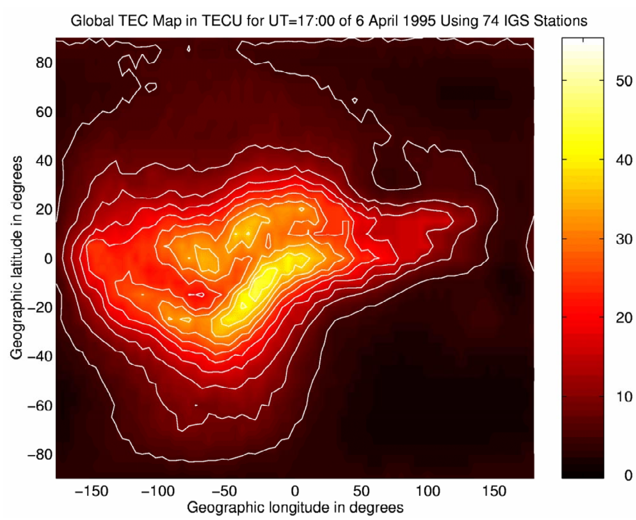

Fig. 3. An example of an hourly snapshot of the global ionosphere for 17h UT on 6 April 1995.

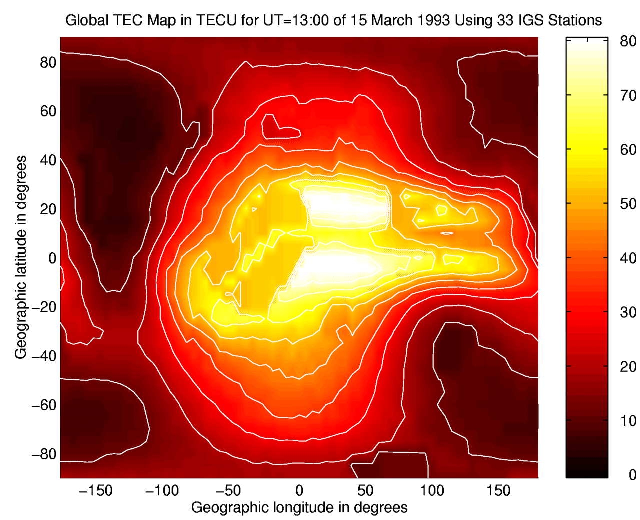

Fig. 4. An example of an hourly snapshot of the global ionosphere for 13h UT on 15 March 1993.

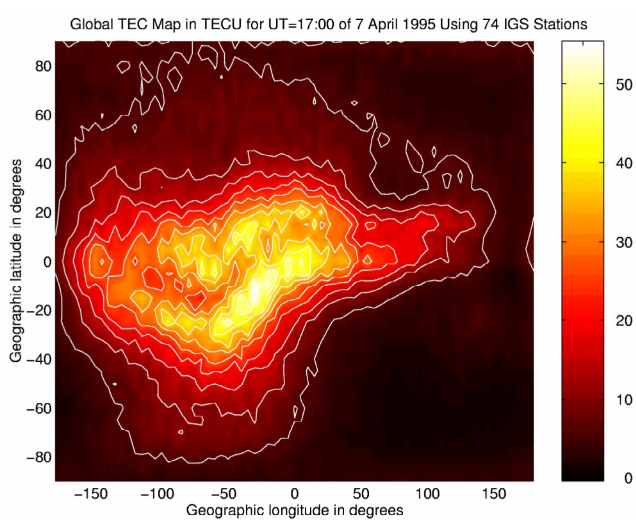

Fig. 5. An example of an hourly snapshot of the global ionosphere during geomagnetic storm conditions for 17h UT on 7 April 1995.

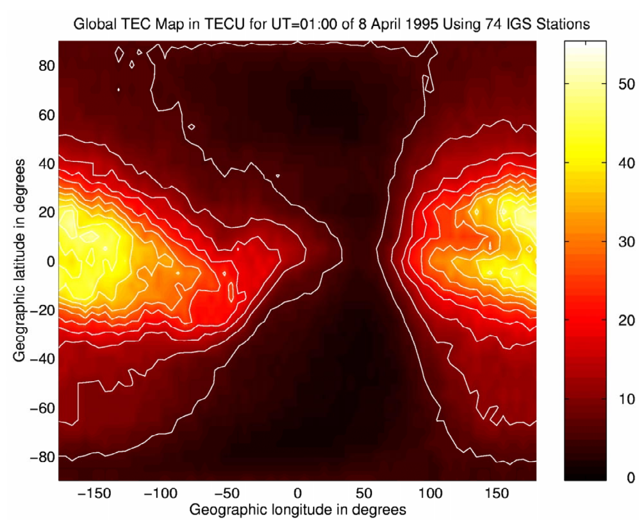

Fig. 6. An example of an hourly snapshot of the global ionosphere during geomagnetically quiet period for 1h UT on 8 April 1995.

For the 1993 data, note the "colorbar" indicates that the largest TEC value, which occurs in the equatorial region, amounts to about 80 TECU. In order for the maps not to look too crowded, we used 10 contour levels for all maps included in this paper. That is, in the case of the 1993 global TEC map, the contours correspond to the levels 8, 16, 24, ... ,80 TECU. In the figure, we can see that the lack of coverage of stations in the low latitude region causes apparent discontinuities and large gradients in the equatorial region. Despite the problems due to the spatial coverage of the stations in the equatorial region, the data and algorithms were still able to recover the general form of the equatorial anomaly using only 33 stations.

In Figure 5, another example for UT 17h of 7 April 1995, it is interesting to note that the global ionosphere appears to have become disturbed which might be indicative of a severe geomagnetic storm (Ap = 207) which occurred at about that time (NGDC, 1997). The disturbed contour lines in the map are apparent. A few hours later (see the map in Figure 6), the ionosphere seems to have become quiet again with a corresponding Ap index of 27. No such disturbances were found in our maps for the 1993 three day period which is not surprising since this was a period of low Ap indices (no geomagnetic storms).

Updating IRI-95 with GPS-derived TEC Maps

The IRI-95 uses the 12-month-smoothed global sunspot number and IG index as an indication of solar activity. In our updating procedure, we include an *inferred* IG index which is defined as the product of the IG index and a scaling factor. We implemented an efficient search technique to find the scaling factor that results in the best match between the IRI-95 model predicted TEC and the GPS-derived TEC. A new inferred IG index is computed for each hourly GPS-derived TEC grid point taking into account that the inferred IG index is a function of geographic latitude, longitude and Universal Time (UT). We use an empirical plasmaspheric electron density model of Gallagher et al. (1988) to account for the plasmaspheric part of the total electron content between the ground and the GPS satellites. For further explanation of the IRI-95 update procedure, the reader is referred to Komjathy (1997).

We produce updated IRI-95 TEC predictions based on the GPS-derived TEC maps on a 5 degree by 5 degree spaced grid. To determine TEC at an arbitrary geographic location within a grid, we use a weighting function approach for modelling irregular surfaces (Junkins et al. 1973). The weighting function approach approximates an irregular surface from regularly spaced data.

Figures 7 and 8 show comparisons of the T/P TEC measurements with the TEC determined from the original IRI-95, the updated IRI-95, the UNB TEC maps, the Jet Propulsion Laboratory (JPL) Global Ionospheric Maps (GIMs) and the Gallagher's plasmaspheric model. The T/P data set was provided as 60 second smoothed data. Anomalous data points such as those over land masses and ice cover were removed. The accuracy of such T/P data is considered to be better than 3 TECU (Yuan et al., 1996). There are 26 T/P passes for each of the 6 days investigated. For each T/P pass, we computed the original IRI-95 predictions and the updated IRI-95 TEC using our TEC maps. Note that we only plotted TEC values for each technique where we had T/P data values available. This is the explanation for the unevenly spaced data values plotted. We have chosen to plot two representative examples showing the TEC versus latitude (Figures 7 and 8), with the corresponding T/P pass ground trajectories superimposed on the world maps shown earlier in Figures 1 and 2.

In Figure 7, we display a day-time T/P pass of 13 March 1993 representing medium solar activity conditions with a maximum T/P TEC measurement of about 75 TECU in the equatorial region at 10 degrees either side of the geomagnetic equator. The original IRI-95 underestimates the TEC over the entire region whereas the UNB and GIM estimates follow a

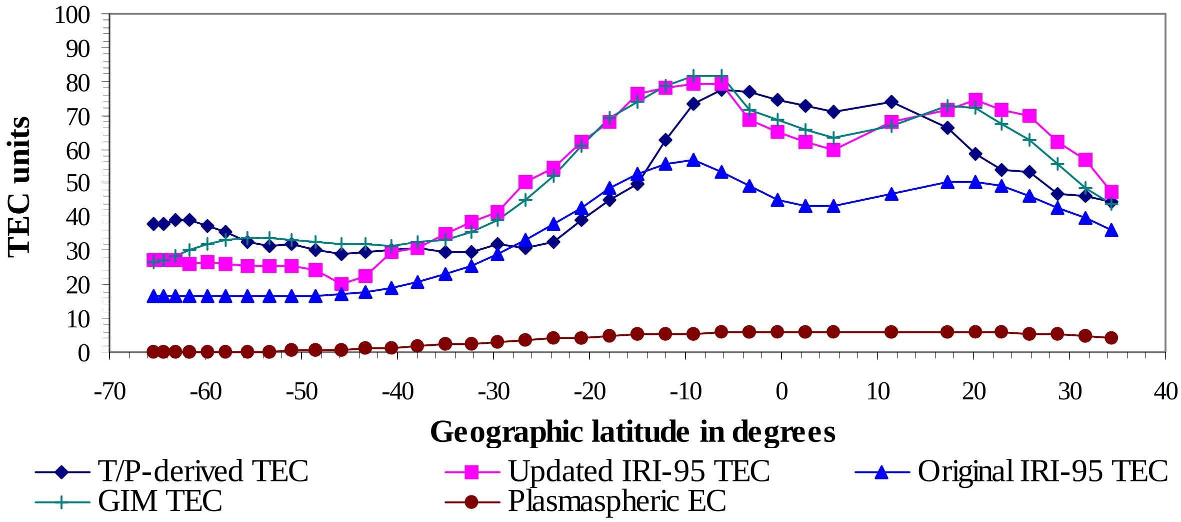

Fig. 7. An example of the comparison of different techniques with T/P pass 02 between UT 0h 46m and 1h 24m of 13 March 1993.

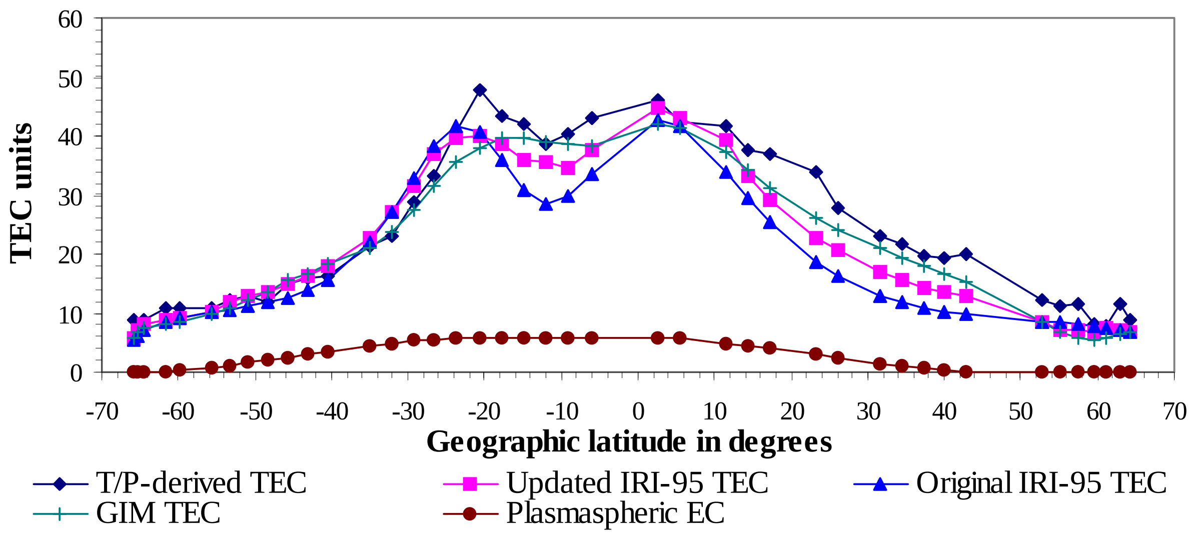

Fig. 8. An example of the comparison of different techniques with T/P pass 21 between UT 18h 32m and 19h 24m of 8 April 1995.

similar signature and are closer, on average, to the T/P values. The southern hemisphere mid-latitude region shows a 20-30 TECU level discrepancy from the T/P-derived TEC data. This might be due to the fact there are no IGS stations available in that region and that the UNB and GIM estimates are correspondingly affected. On the other hand, the northern hemisphere mid-latitude region shows an increasing agreement with the T/P data as the satellite passes over Japan (see Figure 1) indicating a 3 TECU agreement between the T/P-derived TEC data and the updated IRI-95 model using the UNB TEC map.

Figure 8 displays a day-time T/P pass of 8 April 1995 representing low solar activity conditions. A very good agreement among the different techniques in the southern hemisphere mid-latitude region is noted. In the northern hemisphere mid-latitude region, T/P TEC values are larger by about 5 TECU which might be due to the combination of uncertainties in T/P measurements and the UNB estimates. To validate the updated IRI-95 values, one can directly compare the T/P data with the updated IRI-95 values at times when the T/P ground tracks are near any of the IGS stations. One such example can be seen over Canada (see Figure 2) indicating a 4 TECU agreement (see Figure 8) between the updated IRI-95 values and the nearby T/P measurement.

Analysis of Results and Discussion

Figure 9 compares the original and the updated IRI-95 model performance with respect to all T/P passes for the three days in 1993 and three days in 1995. The data points in the figures refer to the mean, and the error bars correspond to the standard deviation of the differences between the updated and original IRI-95 predictions with respect to the assumed errorless T/P data. Based on 6 days' worth of T/P and GPS data, the final results in predicting TEC along the T/P ground tracks are displayed in Table 1. We can clearly see that the mean differences for the three days in 1993 were reduced to 1.7, 0.5, and -1.2 TECU from 10.8, 9.1 and 6.5 TECU by updating IRI-95. The ranges of the mean standard deviations have also been reduced following the update procedure. In the case of the 1995 data, we also achieved an improvement for 2 of the 3 days in reducing the mean differences with respect to the T/P data. The ranges of the mean standard deviations were reduced for all three days in 1995. The success of globally updating IRI-95 using GPS data strongly depends on the level of

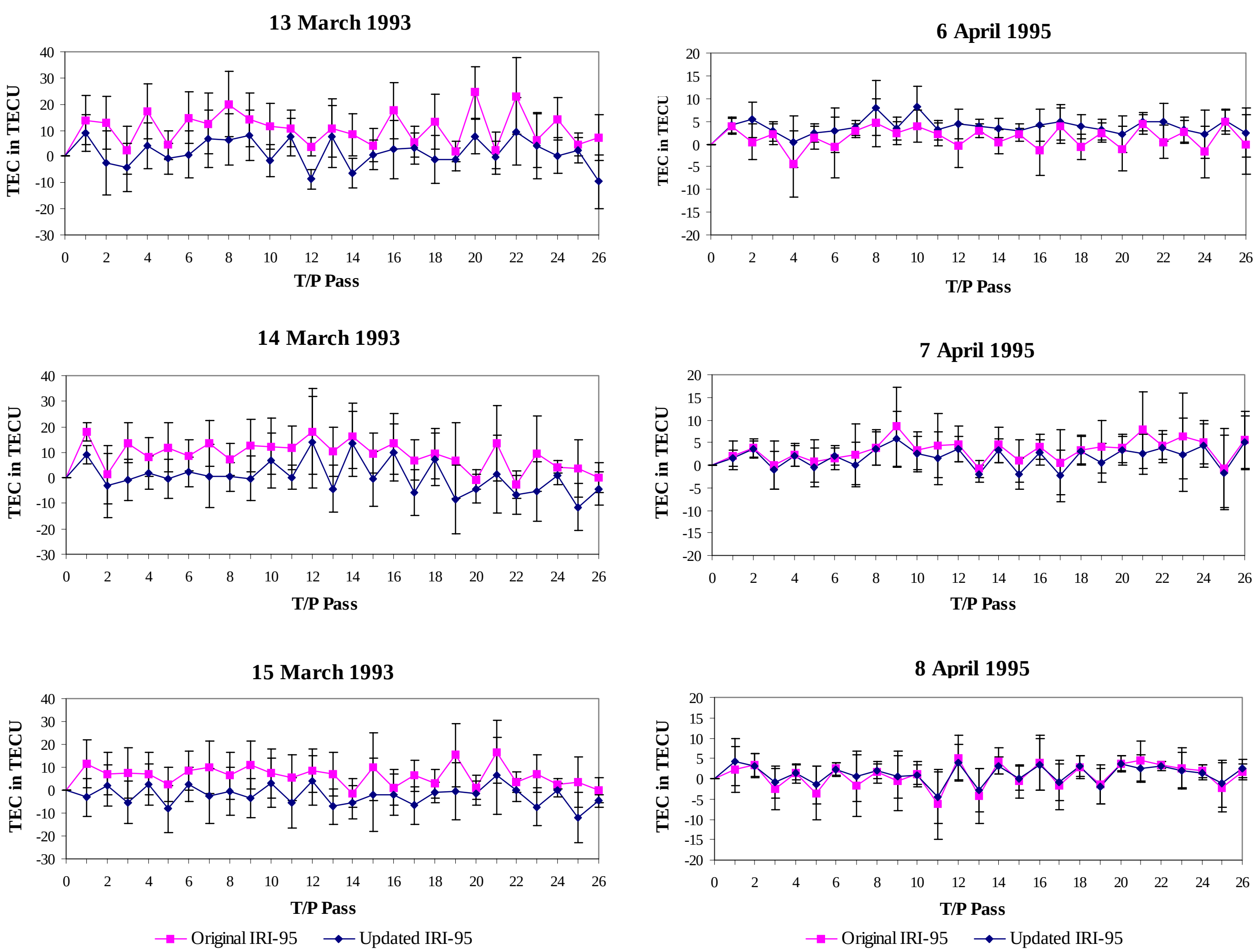

Fig. 9. Comparison of updated IRI-95 and original IRI-95 with T/P data for three days in 1993 and 1995.

Table 1. Summary of results from the comparison between updated IRI-95 and T/P-derived TEC data.

Day	Original IRI-95 (all units in TECU)			Updated IRI-95 (all units in TECU)		
	average mean	average s.d.	s.d. range (min, max)	average mean	average s.d.	s.d. range (min, max)
13-Mar-93	10.8	8.7	$3.5 \leq\sigma\leq 14.7$	1.7	7.7	$3.7 \leq\sigma\leq 12.1$
14-Mar-93	9.1	9.5	$2.5 \leq\sigma\leq 16.9$	0.5	8.8	$3.3 \leq\sigma\leq 16.1$
15-Mar-93	6.5	9.2	$2.1 \leq\sigma\leq 15.7$	-1.2	8.5	$2.6 \leq\sigma\leq 14.9$
06-Apr-95	1.4	3.6	$1.3 \leq\sigma\leq 7.3$	2.8	3.2	$1.5 \leq\sigma\leq 6.5$
07-Apr-95	3.3	4.9	$1.9 \leq\sigma\leq 9.3$	1.8	4.0	$1.7 \leq\sigma\leq 7.2$
08-Apr-95	1.2	4.4	$0.9 \leq\sigma\leq 8.6$	0.8	3.7	$1.1 \leq\sigma\leq 6.4$

solar and geomagnetic activity and the number of IGS stations used for deriving the UNB TEC maps. In the equatorial region, due to the paucity of GPS stations, limited success was achieved using the updating procedure (it could be better in the future if more stations were to be added). The effectiveness of the updating procedure also depends on the distance between the IGS stations and the T/P sub-satellite position.

Conclusions

The results presented in this paper were obtained from two sets of 3 days' worth of global GPS data during a) a period of medium solar activity, for which there was a better than 9 TECU level (1 sigma) agreement in the TEC on a global scale between the T/P-derived TEC data and UNB-TEC-maps-updated IRI-95, and b) during a period of low solar activity for which UNB's results agreed with the T/P data at a better than the 5 TECU level (1 sigma). The results show significant improvements in the mean differences after updating IRI-95 for the days in 1993. In the case of the 1995 data, we achieved improvements for 2 of 3 days under investigation. The typical formal errors for the UNB TEC maps for 1995 is about 2 to 3 TECU. This seems to be consistent with the better than 5 TECU level agreement with T/P we found in the case of the 1995 data considering a typical 3 TECU level measurement error on the T/P data. For the medium solar activity 1993 data, the typical error bars for the UNB TEC maps are about 3 to 4 TECU. The better agreement with the T/P data found in 1995 is at first sight surprising since April 6-8 1995 was a period of geomagnetic disturbance whereas March 13-15 1993 was a geomagnetically quiet period. However, this discrepancy is easily explained by the fact that the number of available ground stations in 1995 was more than double the number of stations available during the 1993 time period.

We have shown that the UNB GPS-data-updated IRI-95 coefficient sets are capable of providing a means for ionospheric delay corrections for future single frequency radar altimeter missions. The GPS-updated IRI-95 electron density profile would allow the integration of electron densities up to the spacecraft altitude to remove the bias imposed by the ionosphere.

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References

Bilitza, D. (ed.), International Reference Ionosphere 1990. Report Number NSSDC/WDC-A-R&S 90-22, National Space Science Data Center/World Data Center A for Rockets and Satellites, Lanham, MD (1990).

Born, G. and S. Katzberg, Introductory Remarks, Science Requirements, in the *Report of the Workshop for Ionospheric Delay Correction for Single Frequency Radar Altimetry*, Colorado Center for Astrodynamics Research of the University of Colorado, 24-25 September (1996).

Gallagher, D.L., P.D. Craven, and R.H. Comfort, An Empirical Model of the Earth's Plasmasphere, *Advances in Space Research*, Vol. 8, No. 8, pp. (8)15-(8)24 (1988).

Ho, C.M., A.J. Mannucci, U.J. Lindqwister, X. Pi, and B.T. Tsurutani, Global Ionosphere Perturbations Monitored by the Worldwide GPS Network, *Geophysical Research Letters*, Vol. 23, No. 22. pp. 3219-3222 (1996).

Jakowski, N., E. Sardon, E. Engler, A. Jungstand, and D. Klän, Relationships Between GPS-Signal Propagation Errors and EISCAT Observations, *Annales Geophysicae*, Vol. 14, pp. 1429-1436 (1996).

Junkins J.L., G.W. Miller, and J.R. Jancaitis, A Weighting Function Approach to Modelling of Irregular Surfaces, *Journal of Geophysical Research*, Vol. 78, No. 11, pp. 1794-1803 (1973).

Komjathy, A., *Global Ionospheric Total Electron Content Mapping Using the Global Positioning System*, Ph.D. dissertation, Department of Geodesy and Geomatics Engineering Technical Report No. 188, University of New Brunswick, Fredericton, New Brunswick, Canada (1997).

Komjathy, A. and R.B. Langley, An Assessment of Predicted and Measured Ionospheric Total Electron Content Using a Regional GPS Network, *The Proceedings of the National Technical Meeting of the Institute of Navigation*, Santa Monica, CA, 22-24 January, The Institute of Navigation, Alexandria, VA, pp. 615-624 (1996a).

Komjathy, A. and R.B. Langley, The Effect of Shell Height on High Precision Ionospheric Modelling Using GPS, in *Proceedings of the 1996 IGS Workshop*, Silver Spring, MD, 19-21 March, pp. 193-203 (1996b).

Komjathy, A. and R.B. Langley, Improvement of a Global Ionospheric Model to Provide Ionospheric Range Error Corrections for Single Frequency GPS Users, *The Proceedings of the 52nd Annual Meeting of the Institute of Navigation*, Cambridge, MA, 19-21 June, The Institute of Navigation, Alexandria, VA, pp. 557-566 (1996c).

National Geophysical Data Center (NGDC), Geomagnetic Database, ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/1994. Accessed 13 June (1997).

Schaer, S., G. Beutler, M. Rothacher, and T.A. Springer, Daily Global Ionospheric Maps on GPS Carrier Phase Data Routinely Produced by CODE Analysis Center, *Proceedings of the 1996 IGS Workshop*, Silver Spring, MD, 19-21 March, pp. 181-192 (1996).

Scripps Orbit and Permanent Array Center (SOPAC), SOPAC Data Browser, http://lox.ucsd.edu/docs/. Accessed 29 January (1998).

Yuan, D., B. Wilson, A. Mannucci, and U. Lindqwister, Using GPS for Single Frequency Altimeter Calibration, in the *Report of the Workshop for Ionospheric Delay Correction for Single Frequency Radar Altimetry*, Colorado Center for Astrodynamics Research of the University of Colorado, Boulder, CO, 24-25 September (1996).