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Ionospheric Calibration for Single Frequency Altimeter Measurements

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Abstract

This report investigates the potential of using Global Positioning System (GPS) data and a model of the ionosphere to supply a measure of the sub-satellite TEC of the required accuracy (10 TECU rms) for the purpose of calibrating single frequency radar altimeter measurements. Since climatological (monthly mean) models are known to be in error by as much as 50 %, this work focused on the Parameterized Real-Time Ionospheric Specification Model (PRISM) which has the capability to improve model accuracy by ingesting (adjusting to) in situ ionospheric measurements. A set of globally distributed TEC measurements were generated using GPS data and were used as input to improve the accuracy of the PRISM model. The adjusted PRISM TEC values were compared to TOPEX dual frequency TEC measurements (which are considered truth) for a number of TOPEX sub-satellite tracks. The adjusted PRISM values generally compared to the TOPEX measurements within the 10 TECU accuracy requirements when the sub-satellite track passed within 300 to 400 km of the GPS TEC data or when the track passed through a night time ionosphere. However, when the sub-satellite points were greater than 300 to 400 km away from the GPS TEC data or when a local noon ionosphere was sampled, the adjusted PRISM values generally differed by greater than 10 TECU rms with data excursions from the TOPEX TEC measurements of as much as 40 TECU (an 8 cm path delay error at K band). Therefore, it can be concluded from this analysis that an unrealistically large number of GPS stations would be needed to predict sub-satellite TEC at the 10 TECU level in the day time ionosphere using a model such as PRISM. However, a technique currently being studied at the Jet Propulsion Laboratory (JPL) may provide a means of supplying adequate TEC data to meet the 10 TECU ionospheric correction accuracy when using a realistic number of ionospheric stations. This method involves using global GPS TEC data to estimate a global grid of vertical ionospheric TEC as a function of time (i.e. every one half hour) in a sun-fixed longitude frame. Working in a sun-fixed longitude frame, one is not limited by the spatial decorrelation distance of the ionosphere, but instead is limited more by the temporal correlations of the ionosphere in the sun-fixed frame which are a smaller effect. It is the opinion of the authors that using the global sun-fixed TEC grid data, in particular, ingesting it into PRISM, offers the best possibility of meeting the the 10 TECU ionospheric correction accuracy requirement, and should be the subject of further study.

1 INTRODUCTION

1.1 Background

Satellite altimetry has become a very powerful tool for the study of ocean circulation and variability, and it may provide the best chance of understanding the important issues related to climate and global change. Sea surface height measurements are computed by combining the radar altimeter measurement with knowledge of the orbit height of the satellite. Thus, any errors in the altimeter and orbit height measurements map directly into the sea surface height observables and reduce the ability to separate the desired ocean signal from the data. One of the many error sources in altimetry, and the subject of this report, is the delay in the altimeter measurement caused by the charged particles in the Earth's ionosphere. For a K band (13.6 GHz) altimeter, a total electron content (TEC) of 1 TECU (1×10^{16} electrons/meters^2) corresponds to approximately 0.2 centimeters of range delay. A maximum expected TEC (at solar maximum or during solar storms) of near 100 TECU will create 22 centimeters of range delay. Since some ocean signals have centimeter level magnitudes, it is necessary to eliminate to within a few percent the ionospheric delay from the altimeter height data. For example, to measure basin-scale (10,000 km wavelength) oceanographic features, an ionospheric correction accurate to 2 cm root mean square (rms) is required. At 13.6 GHz, this 2 cm range uncertainty corresponds to a TEC uncertainty of approximately 10 TECU.

If a radar altimeter transmits two frequencies, a method involving linear combination of the two signals (good to first order) can calibrate the ionospheric delay to a sufficient level. The TOPEX/POSEIDON dual frequency altimeter is currently supplying ionospheric corrections with precision near the 3 TECU rms (6 mm at K band) level (Calahan, personal communication, 1993). However, dual frequency altimeters are expensive and substantially increase weight and power consumption on the satellite. Because of these issues, several future altimetric missions, including the Navy's Geosat Follow-On (GFO) and NASA's TOPEX Follow-On (TFO), are using or are considering using single frequency radar altimeters. Use of only one frequency, however, eliminates the preferred dual frequency mode of ionospheric calibration, and thus. requires an independent measurement of sub-satellite TEC that is accurate to 10 TECU rms. Thus, calibration of the ionospheric delay for altimeter height measurements when using a single frequency altimeter is a subject of considerable interest.

This report has investigated techniques with the potential of supplying a measure of the sub-satellite TEC of the required 10 TECU accuracy. Since climatological (monthly mean) models are known to be in error by as much as 50 %, this work has focused on the Parameterized Real-Time Ionospheric Specification Model (PRISM) which has the capability to improve TEC model accuracy by ingesting (or adjusting to) in situ ionospheric measurements. The Global Positioning System (GPS), to be declared operational by the end of 1993, transmits dual frequency L band signals that can be used to generate TEC measurements. The current International GPS (IGS) tracking network consists of almost 35 globally distributed stations and thus, is providing an unprecedented global data set of ionospheric TEC which is ideal for adjusting the PRISM model to improve sub-satellite TEC prediction (Melbourne et al., 1991).

1.2 Objectives and Approach

Because GPS is the only measurement system to offer a truly global data set of the ionosphere, this work has concentrated on evaluating the PRISM model when using global GPS TEC data as input. Thus, the primary objectives of this effort were to: 1) determine if adjusting the PRISM model with global GPS TEC data can supply sub-satellite TEC predictions that are accurate to 10 TECU rms and 2) if the method can't supply the required accuracy, determine the reason and investigate other techniques that could be used to improve the model prediction.

To meet the above objectives, it was first necessary to obtain a TEC data set that could be considered as truth for comparison to the PRISM adjusted TEC values. Next, a set of globally distributed GPS TEC measurements had to be generated. With these data available, it was then possible to effectively evaluate the accuracy of the PRISM model when using the GPS data as input by comparing the adjusted PRISM TEC values to the TOPEX dual frequency TEC measurements for a number of TOPEX sub-satellite tracks.

The next section discusses the PRISM ionosphere model and its data adjustment procedure. The following two sections discuss the method of generation and the expected accuracy of the global GPS TEC data and TOPEX dual frequency TEC data sets that were used in this analysis. Then, the results of the study are presented. Finally, the conclusions discuss promising alternatives which may improve sub-satellite TEC prediction accuracy.

2 The PRISM Model

2.1 General Overview

The Parameterized Real-time Ionospheric Specification Model (PRISM) was developed for the United States Air Force (USAF) Air Weather Service by Computational Physics, Inc. of Newton, MA. The goal of the model is to provide a near real-time specification of the ionosphere over the entire globe. PRISM is not based on climatological (monthly mean) models, but rather on parameterized physical models. It also uses both ground based and satellite based measurements of the ionosphere to adjust the parameterized models to obtain a more accurate prediction of the ionosphere. This adjustment procedure can correct eight profile parameters at the data locations. It also uses a weighting function. that is dependent on distance, to specify a global correction field for the ionosphere. For single frequency altimeter calibrations, the goal is to use ionosphere data to adjust the base PRISM model to be closer to the actual sub-satellite TEC.

2.2 The Parameterized Physical Models

There are four separate models that are used in PRISM to predict the state of the ionosphere. They are: a low latitude F layer model, a mid latitude F layer model, a combined low and mid latitude E layer model, and a high latitude E and F layer model. For more details on these models see the PRISM 1.2 algorithm description (Daniell, Whartenby, and Brown, 1993). These four models have been parameterized in terms of geophysical parameters to achieve reasonable computational speeds. This parameterization process involved generating a set of databases for various values of the geophysical parameters. It also required the generation of semi-analytic representations of the databases. The authors of PRISM felt a model based on the theoretical physics of the ionosphere would perform better than climatological models when ingesting ionospheric measurements.

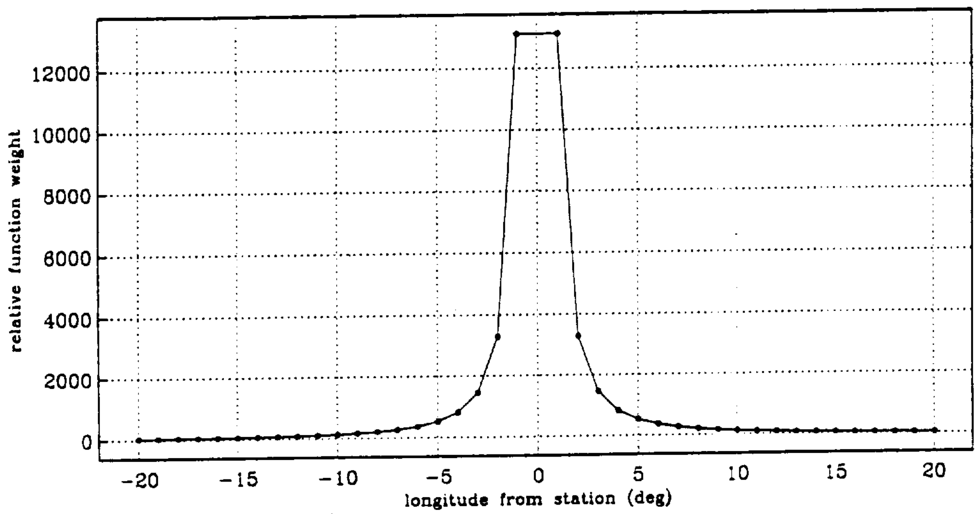

Figure 1: PRISM weight function versus longitude at the equator. This function essentially de-weights any data more than three degrees away from the measurement site.

2.3 Real-Time Adjustment Procedure

The PRISM real-time adjustment procedure is able to adjust the PRISM parameterized physical model with a variety of ionosphere data. These data types include: bottomside soundings (f_oF_2, h_mF_2, f_oE, h_mE) of the Digital Ionosphere Sounding System (DISS), TEC data from any source, in situ plasma and auroral electron and ion fluxes from the DMSP satellites. Before any real-time adjustment, PRISM uses linear interpolation on $F_{10.7}$ and K_p to obtain the best prediction of the ionosphere from the parameterized databases. Once the most accurate state of the ionosphere is generated from the databases, the real-time adjustment procedure uses the available data to correct for eight profile parameters at each data site. In between each measurement site, as will often be the case for the altimeter application, a weighted average based on distance is used to interpolate the eight adjustment parameters. Figure 1 shows the weight function used in the PRISM adjustment procedure. This function ensures that PRISM will match the data at each measurement site and will vary smoothly between sites. The large drop off of this function also ensures that information from a site will not be used relatively far ($>$ 500 km) from a site.

Since GPS TEC data were used to adjust the PRISM model in this analysis, the use of TEC data by the adjustment procedure will briefly be discussed. Because PRISM uses parameters that apply to a specific point on the ionosphere profile to adjust its profile, and TEC is an integrated parameter, PRISM converts the TEC measurement to an equivalent value of f_oF_2, the reflection frequency at the peak ionospheric electron density. This conversion utilizes the TEC measurement and the electron density profile shape to derive an estimate for f_oF_2.

3 Global GPS TEC Data

The current International GPS Service (IGS) tracking network consists of nearly 35 globally distributed stations and is providing an unprecedented global data set of ionospheric TEC which will undoubtedly contribute to a better understanding of the Earth's ionosphere (Melbourne et al., 1991). However, this 35 station network, as with most tracking networks, does have a shortage of stations in the southern hemisphere, near the equator and also over the ocean. Fortunately, the IGS plans to add over 15 additional stations to the network in the next two years which will fill in some of these holes (see Figure 2).

Deriving GPS TEC data that is suitable for input into the PRISM model is a rather complicated process. Measurements from the Global Positioning System consist of two L band signals (L1 at 1575.42 and L2 at 1227.6 MHz) that in theory can be linearly combined in a straight forward manner to compute a measure of the TEC between the GPS satellite and the GPS receiver. In practice, however, this computation is complicated by the presence of hardware biases between the L1 and L2 channels in both the GPS satellite and the GPS receiver. Thus, to derive an absolute measure of line-of-sight TEC, these biases must be solved for (or calibrated if possible) and removed from the data. Once an absolute measurement of line-of-sight TEC if formed, it must be mapped to an equivalent vertical TEC which is the measurement expected by PRISM. The following section describes in more detail how the GPS TEC data were generated in this analysis. Then an assessment of the accuracy of these data is given.

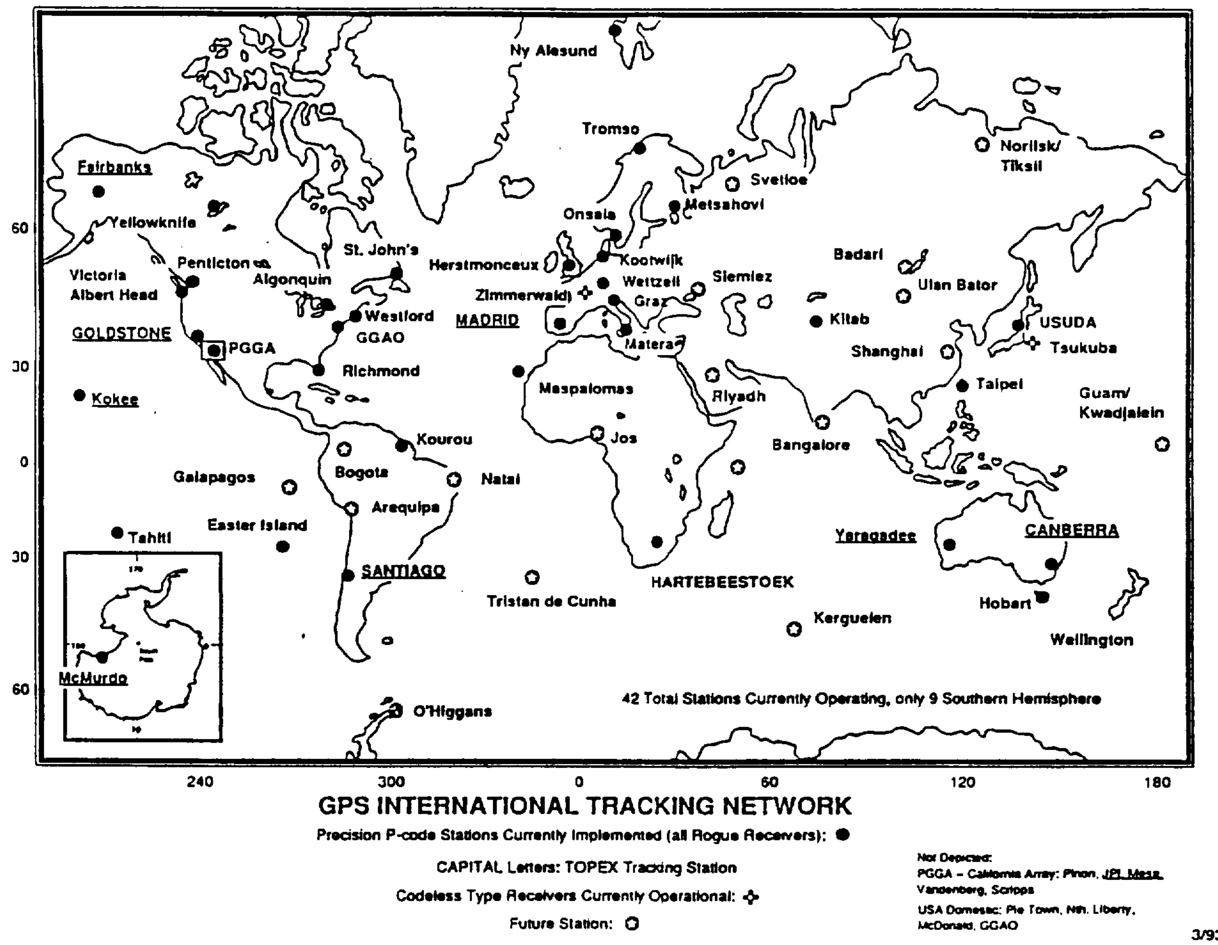

Figure 2: Current IGS tracking network with future planned stations.

3.1 Data Generation

The first step in the procedure to generate absolute vertical TEC data is to form the biased line-of-sight TEC data from the raw dual frequency measurements. A dual frequency GPS receiver outputs pseudorange (less precise) and carrier phase (very precise) on both the L1 and L2 frequency at each observation time step. A biased measure of TEC can be computed from the pseudorange data with the following first order relationship:

$$TEC = \frac{(\tau_{L1} - \tau_{L2}) f_{L1}^2 f_{L2}^2}{k(f_{L2}^2 - f_{L1}^2)} \tag{1}$$

where τ_{L1} and τ_{L2} are the corresponding pseudorange L1 and L2 measurements (in meters), f_{L1}^2 and f_{L2}^2 are the L1 and L2 frequencies (in Hertz), and k is a constant (in meters^{3}Hertz^2/-electrons). Since the pseudorange is an absolute (but noisy) range measurement, the pseudorange derived TEC is a noisy measure of TEC with the satellite and receiver L1/L2 hardware biases included. The carrier phase gives only a very precise measure of change in TEC over an arc, because it is biased by an unknown number of L1 and L2 cycles. This first order relationship for change in TEC, ΔTEC, is shown below:

$$\Delta TEC(t_i, t_0) = \frac{([\Phi_{L1}(t_i) - \Phi_{L1}(t_0)] - [\Phi_{L2}(t_i) - \Phi_{L2}(t_0)]) f_{L1}^2 f_{L2}^2}{k(f_{L2}^2 - f_{L1}^2)} \tag{2}$$

where $\Phi_{L1}(t_i)$ and $\Phi_{L2}(t_i)$ are the corresponding carrier phase L1 and L2 measurements at time t_i (in meters). One should note that the carrier phase cycle ambiguities cancel out in the above subtraction operation between measurement times. By performing a least squares fit (or leveling) of the carrier phase TEC data to the pseudorange TEC data over a pass, a precise TEC measurement biased by only the receiver and satellite hardware biases (and not the carrier cycle ambiguities) can be generated and is shown below

$$TEC_{measured} = TEC_{true} + b_{sat} + b_{rcvr} \tag{3}$$

where b_{sat} and b_{rcvr} are the satellite and receiver biases, respectively.

The next step of this procedure is to remove the L1/L2 receiver and satellite hardware biases, b_{sat} and b_{rcvr}, from equation (3). Some of the IGS network GPS Rogue receivers have the capability to perform a calibration measurement of their receiver bias. However, many of the receivers don't have this capability, and furthermore, the GPS satellites can not perform this type of calibration. Fortunately, a technique currently being studied at the Jet

Propulsion Laboratory provides a means of estimating both the satellite and receiver L1/L2 biases. However, the primary goal of this method is to estimate a global grid of vertical ionospheric TEC as a function of time (i.e. every one half hour) in a sun-fixed longitude frame by using global GPS TEC data. The global grid consists of a network of stochastic (random walk) grid points that are updated in time (along with their covariance) as new GPS TEC data are acquired. The biases are estimated as constants along with the grid and are necessary to obtain absolute TEC ionosphere maps. These estimated hardware biases or receiver calibrated biases can be subtracted from the biases TEC measurements to obtain absolute measurements of line-of-sight TEC from the receiver to the GPS satellite.

Once the absolute line-of-sight TEC have been formed, they are mapped to the vertical using an infinitely thin ionosphere shell assumption found in Lanyi and Roth (1988). This mapping function, $M(E)$, is shown below

$$M(E) = (1 - [cos(E)/(1 + h/R)]^2)^{-1/2} \tag{4}$$

where E is the elevation of the GPS satellite, h is the height of the assumed ionospheric shell, and R is the distance from the center of the Earth to the station. The value of $M(E)$ ranges from 1.0 at the zenith to near 2.2 at an elevation angle of 20 degrees. The line-of-sight TEC is mapped to the vertical direction at the intersection of the measurement and the thin ionosphere shell. Thus, for a given receiver, and a given time, there will be a number of vertical TEC measurements that have been mapped to varying sub-ionospheric latitude and longitude intersection points. This is the form of the TEC data that was input into PRISM in this analysis.

3.2 Accuracy Assessment

The uncertainties in the derived vertical GPS TEC data are composed of both random and systematic effects. The first component that can actually be ignored, is due to the random measurement noise of the original carrier phase data. The carrier phase measurement precision is near the millimeter level which corresponds to less than 0.01 TECU at L band. The next effect can be considered systematic in nature and arises from the uncertainties of the least squares fits between the pseudorange and carrier phase data. These fits are generally performed with rms differences of between 0.5 and 1.0 TECU. These uncertainties could more

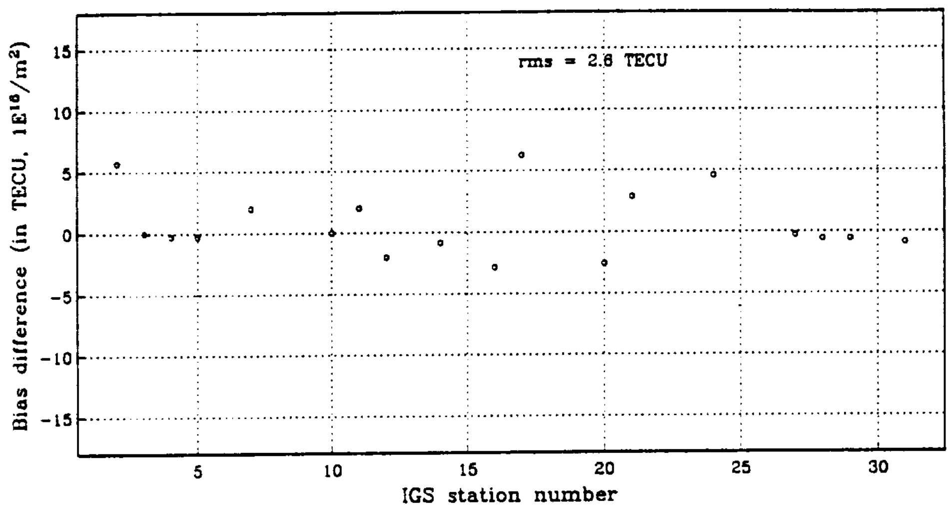

Figure 3: Differences between receiver calibrated L1/L2 biases and receiver biases that were estimated in a March 12. 1993 global TEC map solution by JPL. The rms difference between the biases is 2.6 TECU.

than double due to the increase in pseudorange measurement precision if the Department of Defense policy of anti-spoof is enabled. The next source of error arises from the uncertainties in the L1/L2 receiver and satellite bias values that are subtracted from the biased TEC data. The formal errors of the receiver biases that are estimated with the JPL technique range from 0.8 to 1.4 TECU. The formal errors of the satellite bias estimates are generally smaller and range from 0.8 to 0.9 TECU. These formal uncertainties do not include errors due to mismodeling such as mapping errors, and thus are somewhat optimistic representations of the bias uncertainties. If GPS receiver hardware calibrations were available, they were used instead of the bias estimates. The hardware calibrations are believed to be accurate at the 0.3 TECU level. Figure 3 shows the difference between the receiver bias estimates and all the available receiver hardware calibrations which has an rms difference of 2.5 TECU. Thus, if the hardware are considered perfect, this 2.5 TECU uncertainty may be a more representable value of the uncertainties in the receiver bias estimates.

An estimate of the uncertainty in the line-of-sight absolute GPS TEC measurements depends on whether receiver hardware calibrations or estimates of the receiver biases are used. If a receiver hardware calibration is used, a GPS TEC measurement uncertainty can be obtained by performing a root sum square (rss) operation on the pseudorange and carrier phase least squares fit uncertainty (0.5 to 1.0 TECU), the GPS satellite bias estimate formal uncertainty (0.8 to 0.9 TECU) and the expected uncertainty of the hardware calibration (0.3 TECU). Performing this operation gives the combined rss uncertainty which ranges from 1.0 TECU to 1.7 TECU. If an estimate of the receiver bias is used, a total GPS TEC measurement uncertainty can again be obtained by performing the rss operation on the pseudorange and carrier phase least squares fit uncertainty (0.5 to 1.0 TECU), the GPS satellite bias estimate formal uncertainty (0.8 to 0.9 TECU) and the uncertainty of the receiver bias estimate (0.8 to 2.5 TECU). This operation gives the combined rss expected uncertainty which ranges from 1.2 TECU to 2.8 TECU. The maximum expected vertical GPS TEC data uncertainties can be obtained by multiplying the line-of-sight uncertainties by a maximum mapping function value of 2.2 at 20 degrees elevation (lanyi and Roth, 1988). This gives maximum uncertainties of 3.7 TECU rms when using receiver hardware calibrations, and 5.5 TECU rms when using estimates of the receiver biases. These worst case maximum vertical GPS TEC data uncertainties are still well below the desired ionospheric correction requirement of 10 TECU rms.

4 TOPEX Dual Frequency TEC Data

The TOPEX altimeter may be the most precise TEC measurement system available. Deriving sub-satellite TEC data from the TOPEX/POSEIDON dual frequency altimeter is less complicated than deriving GPS TEC data, but is still not straight forward. Measurements from the TOPEX altimeter consist of round trip light times of both the K and C band signals (13.6 and 5.3 GHz) off the ocean surface. In theory, these measurement can be combined with equation (1) to compute the TEC between the altimeter and the ocean surface. However, similar to the GPS TEC procedure, this computation is complicated by the presence of a hardware bias between the K and C band channels. Thus, to derive an absolute measure of line-of-sight TEC, this bias must be removed from the data. The following section describes in more detail how absolute TOPEX TEC are generated. Then an assessment of the accuracy of this data type is given.

4.1 Data Generation

The TOPEX project at the JPL distributes geophysical data records (GDRs) that contain all relevant altimetric data including the dual frequency ionospheric TEC measurements. Many corrections are applied to the TEC measurements to compute the most accurate data possible. The first step in generating the TOPEX TEC data is to combine the K and C band range measurements with equation (1). As stated, this measurement does contain a bias due to an offset between the K and C band channels. Fortunately, this K and C band relative offset was estimated (at about 10 cm, and 8 TECU effect) by the TOPEX project at the JPL using histograms of the ionosphere TEC data (Calahan, personal communication, 1993). Other corrections that are applied to the TEC data consist of pointing angle errors and varying K and C band sea state (i.e. electromagnetic bias) effects . CCAR possesses all GDRs and thus will eventually have access to all of the TOPEX TEC data released by the TOPEX project office.

4.2 Accuracy Assessment

The uncertainties in the derived TOPEX TEC data are composed of both random and systematic effects. The random measurement noise in the TOPEX TEC data is due to the noise of the K and C band range measurements. Figure 4 shows a sample section of the TOPEX TEC data with a polynomial removed to obtain a measure of the random data noise of the measurement. The rms of the noise is 2.3 TECU, which is consistent with the noise on the K and C band range measurements. The magnitudes of the systematic error sources are more difficult to quantify. It is believed that the 10 cm relative K and C band offset of 10 cm was accurate to approximately 2 cm (Calahan, personal communication, 1993). This 2 cm offset uncertainty corresponds to an error about 1.8 TECU (0.4 cm at K band). The error caused by the differing K and C band electromagnetic biases (which vary with sea state) is difficult to bound and is not considered here. Thus, an optimistic estimate of the uncertainty of the TOPEX TEC data can be computed by taking the rss of only the random measurement noise and the uncertainty of the relative K and C band offset. This computation gives a value of 2.9 TECU which is much smaller than both the worst case GPS TEC data uncertainty (5.5 TECU) and the ionospheric correction requirement of 10 TECU.

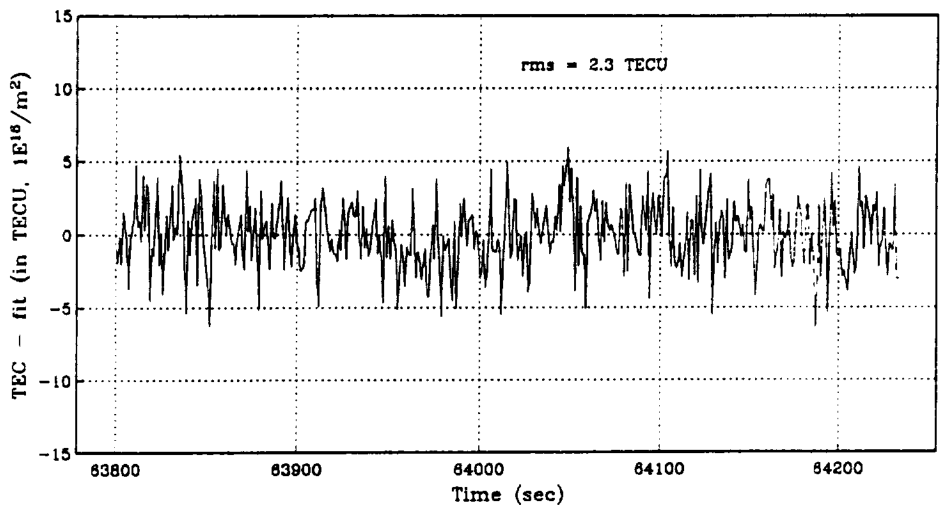

Figure 4: A sample of TOPEX TEC data (every second) minus a polynomial fit versus time. The rms of 2.3 TECU is an accurate measure of the altimeter data noise and is consistent with the measurement precision of the K and C band range measurements.

5 Results

The following results compare adjusted (with GPS TEC data) and unadjusted PRISM TEC values to TOPEX dual frequency TEC measurements (which are considered truth) for a number of TOPEX sub-satellite tracks (in cycle 18) on March 12, 1993. A set of globally distributed TEC measurements were generated using GPS data (acquired from JPL) from March 12. 1993 for input into PRISM. Post-processed estimates of solar and geophysical data were obtained from the National Geophysical Data Center in Boulder Colorado to make the PRISM unadjusted model as accurate as possible. March 12, 1993 was a moderately active day with an $F_{10.7}$ and sun spot number of 158.7 and 77.0, respectively.

The following results compare the PRISM adjusted and unadjusted values with the TOPEX TEC data at a one minute time step. The GDR TOPEX TEC 1 second data was smoothed over 20 seconds centered around each one minute time interval. The data is presented by showing the adjusted and unadjusted PRISM TEC values and the smoothed TOPEX TEC values versus time along the TOPEX ground track. The rms differences between the adjusted and unadjusted PRISM TEC curves and the TOPEX curve are also shown. The first two TOPEX tracks studied, passes 39 and 43, pass through a night time ionosphere. Figure 5 is a TOPEX groundtrack plot of pass 39 which shows the relative geometry between the passes and the closest GPS TEC sites. Figure 6 is a plot of the TOPEX and PRISM TEC values for pass 39 ans shows very little improvement when using GPS TEC data as verified by the 7.6 and 7.4 TECU rms differences for the adjusted and unadjusted PRISM values. The reason for this lack of improvement is due to the lack of GPS TEC data in the vicinity of the groundtrack. There is almost a direct overflight of the St. John's, Canada site and the PRISM value is adjusted to agree closely with TOPEX, but the TEC at this time is small (less than 10 TECU). The GPS site in Richmond, Florida is too far away to appreciably adjust the PRISM values. Figures 7 and 8 are similar to Figures 5 and 6 and show results for pass 43. Figure 8 shows no improvement for pass 43 when using GPS TEC data with identical 5.3 TECU rms differences. However, the PRISM values are adjusted significantly by the GPS TEC data. First of all, there is a jump in the adjusted PRISM TEC between the 6th and 7th minutes of the pass. This jump is caused by a change from the mid-latitude ionosphere adjustment procedure to the high-latitude adjustment procedure which uses the GPS TEC data differently. This jump in TEC is not understood completely, and will be looked at more closely in future analyses. The station in Tahiti does improve the PRISM TEC values near its closest approach, but it is too far away to help the TEC adjustments near (t = 32500 seconds) where the TOPEX TEC is near 35 TECU. There also is a near overflight of a California site, but the TEC at this time is again too small to notice a significant improvement. The rms differences for passes 39 and 43 are less than the 10 TECU correction requirement, but the passes are traversing through night time ionospheres with low TEC magnitudes.

The next six figures show TOPEX passes (50, 52, and 54) that traverse the day time ionosphere near local noon. Figures 9 and 10 show the groundtrack and results for pass 50. Figure 10 shows a small improvement for pass 50 when using GPS TEC data as shown by the 9.8 and 10.4 TECU rms differences for the adjusted and unadjusted PRISM values, respectively. This is primarily due to the near overflight fo the GPS site in Kourou. French Guiana. Figures 11 and 12 show the groundtrack and results for pass 52. A significant improvement for pass 52 is shown in Figure 12. The decrease from 12.7 TECU to 8.5 TECU when using the GPS TEC data is caused by close TOPEX overflights with the GPS sites. The

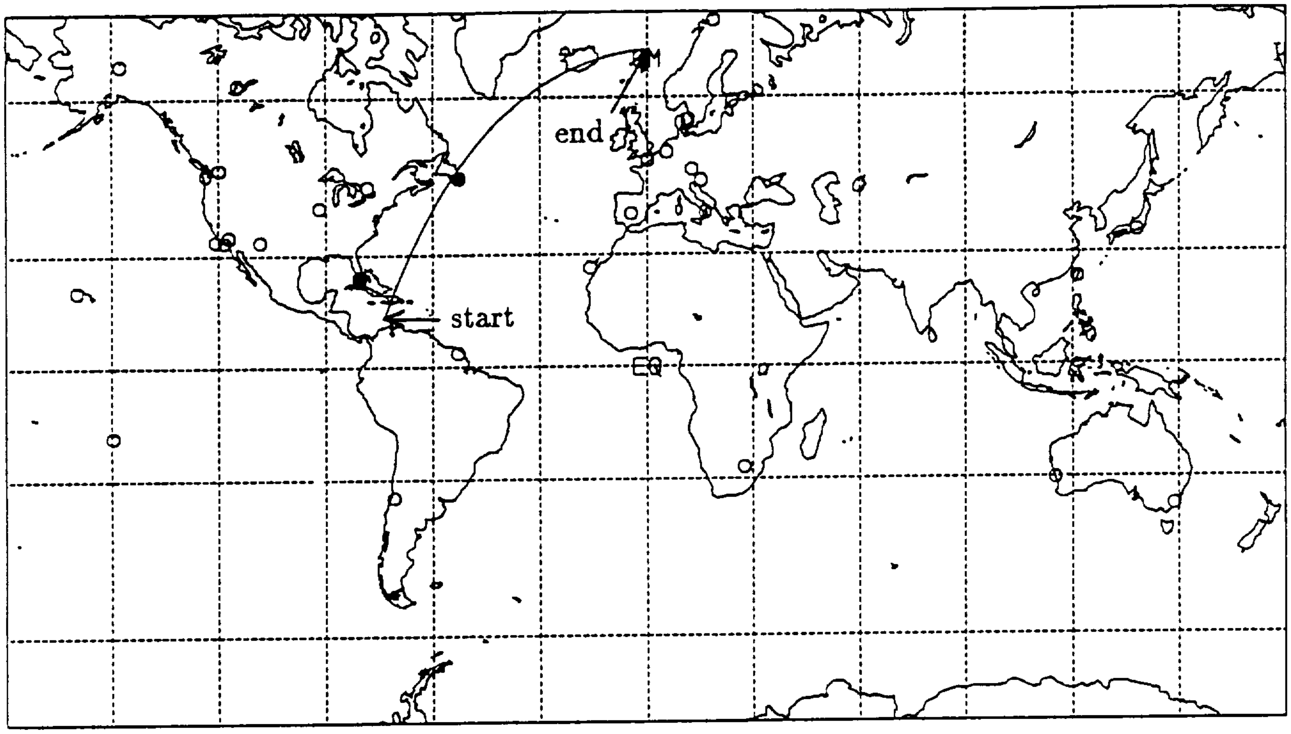

Figure 5: TOPEX groundtrack for pass 39 (cycle 18) with near by IGS GPS stations (black dots).

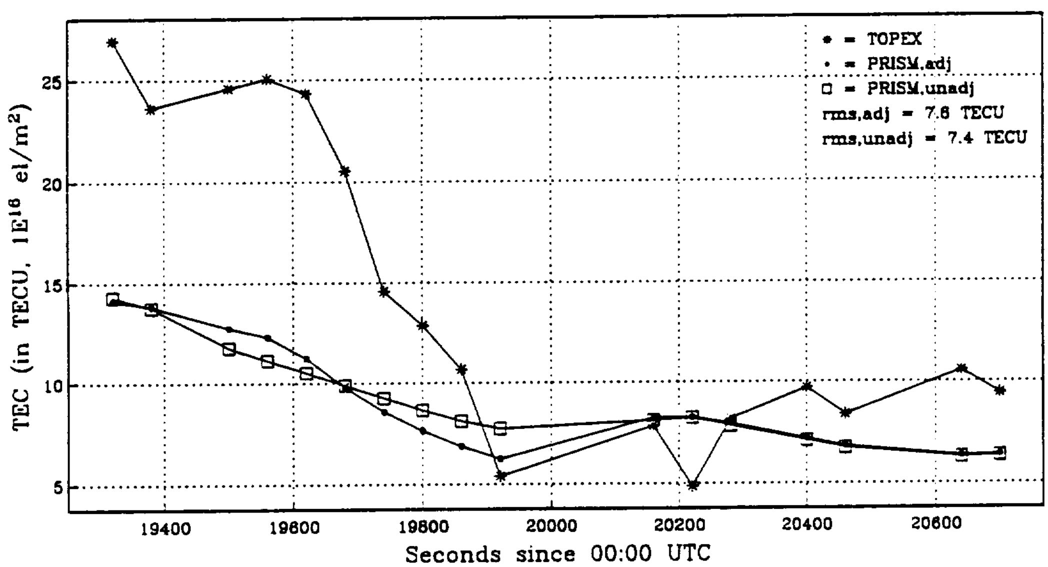

Figure 6: TEC Data (12 Mar 1993) for TOPEX pass 39 (cycle 18) versus time. The rms differences between the PRISM adjusted and unadjusted TEC values and the TOPEX TEC measurements are given above. Local time at the midpoint of the pass is approx. 1 am.

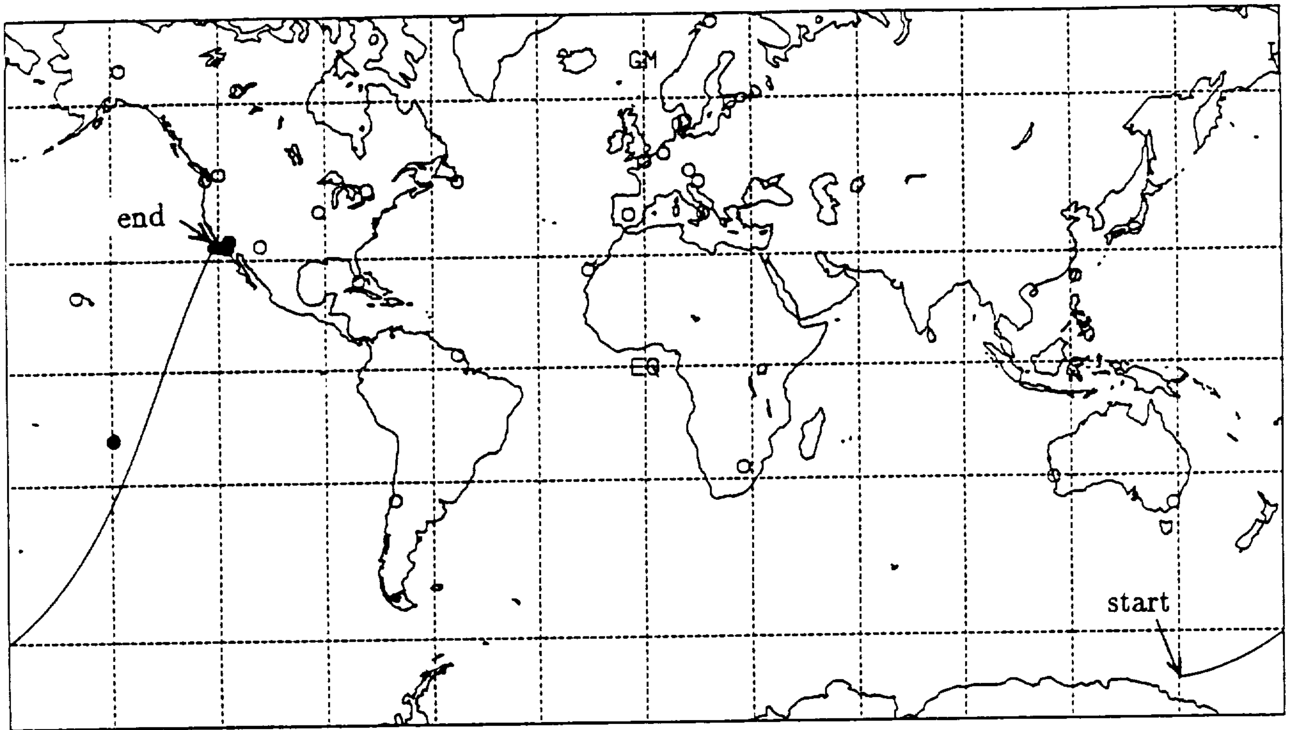

Figure 7: TOPEX groundtrack for pass 43 (cycle 18) with near by IGS GPS stations (black dots).

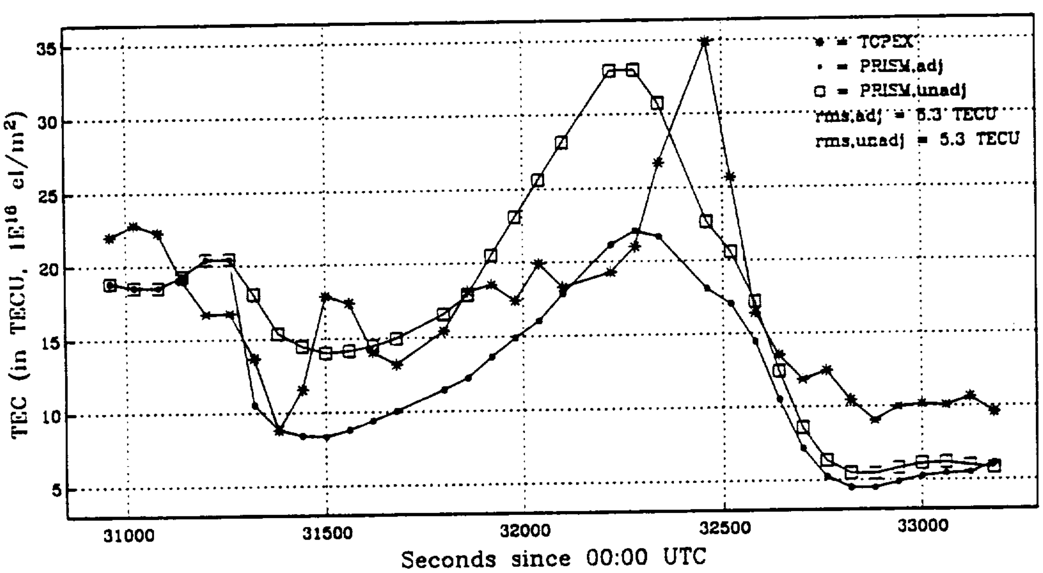

Figure 8: TEC Data (12 Mar 1993) for TOPEX pass 43 (cycle 18) versus time. The rms differences between the PRISM adjusted and unadjusted TEC values and the TOPEX TEC measurements are given above. Local time at the midpoint of the pass is approx. 1 am.

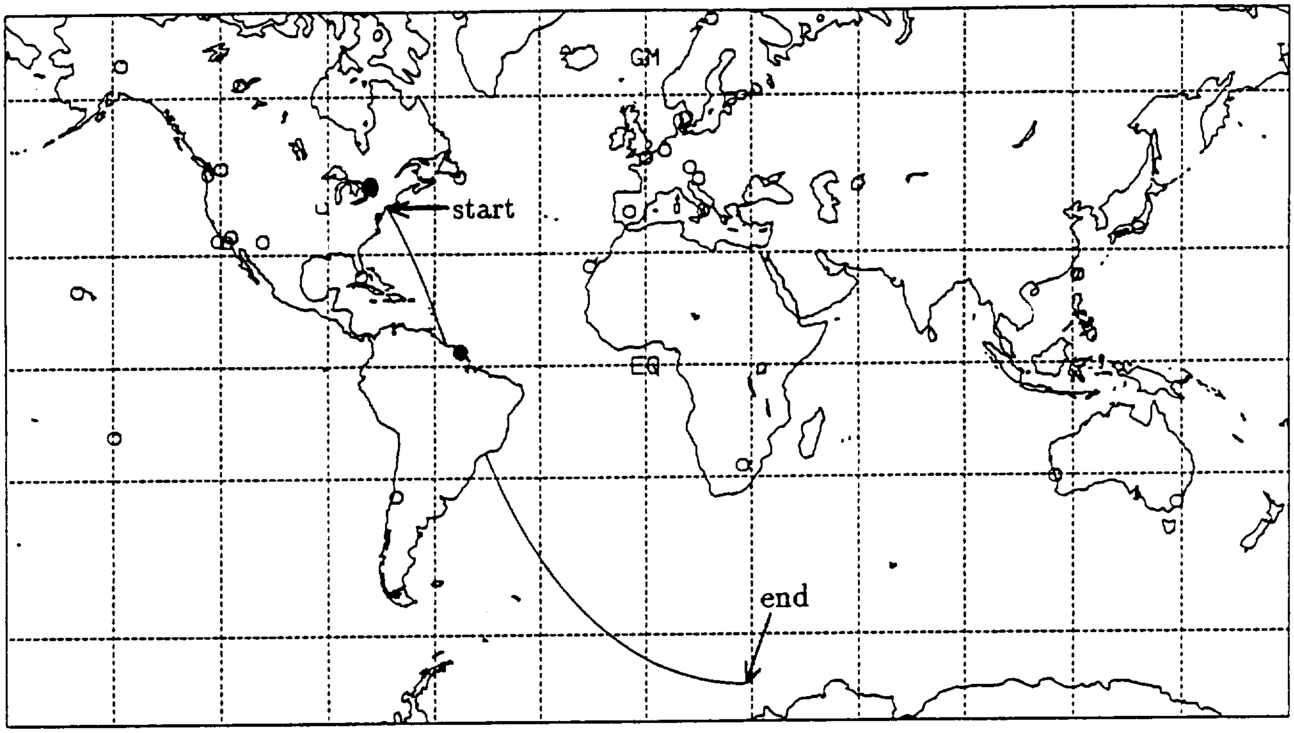

Figure 9: TOPEX groundtrack for pass 50 (cycle 18) with near by IGS GPS stations (black dots).

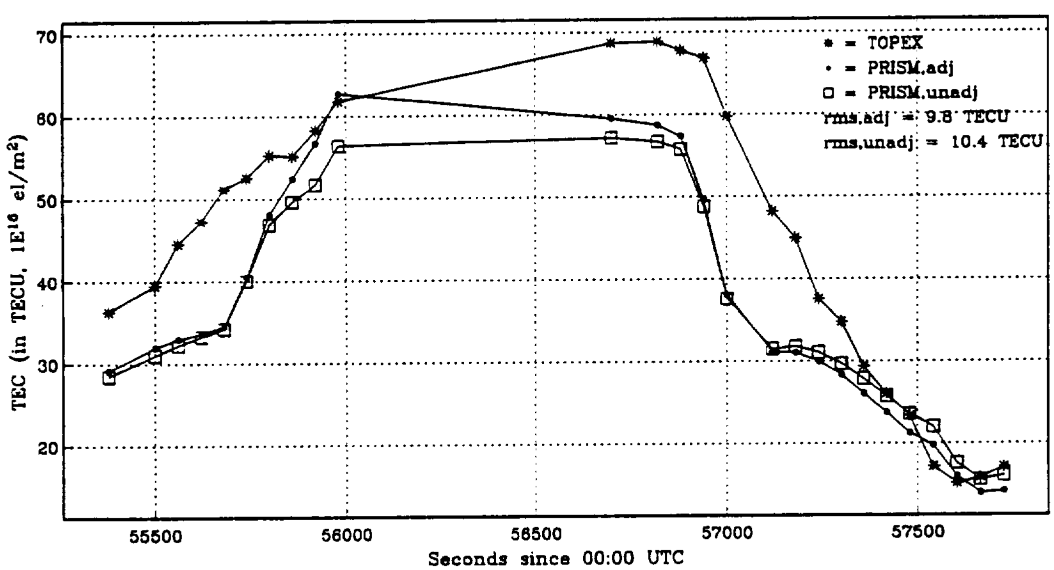

Figure 10: TEC Data (12 Mar 1993) for TOPEX pass 50 (cycle 18) versus time. The rms differences between the PRISM adjusted and unadjusted TEC values and the TOPEX TEC measurements are given. Local time at the midpoint of the pass is approx. 12 noon.

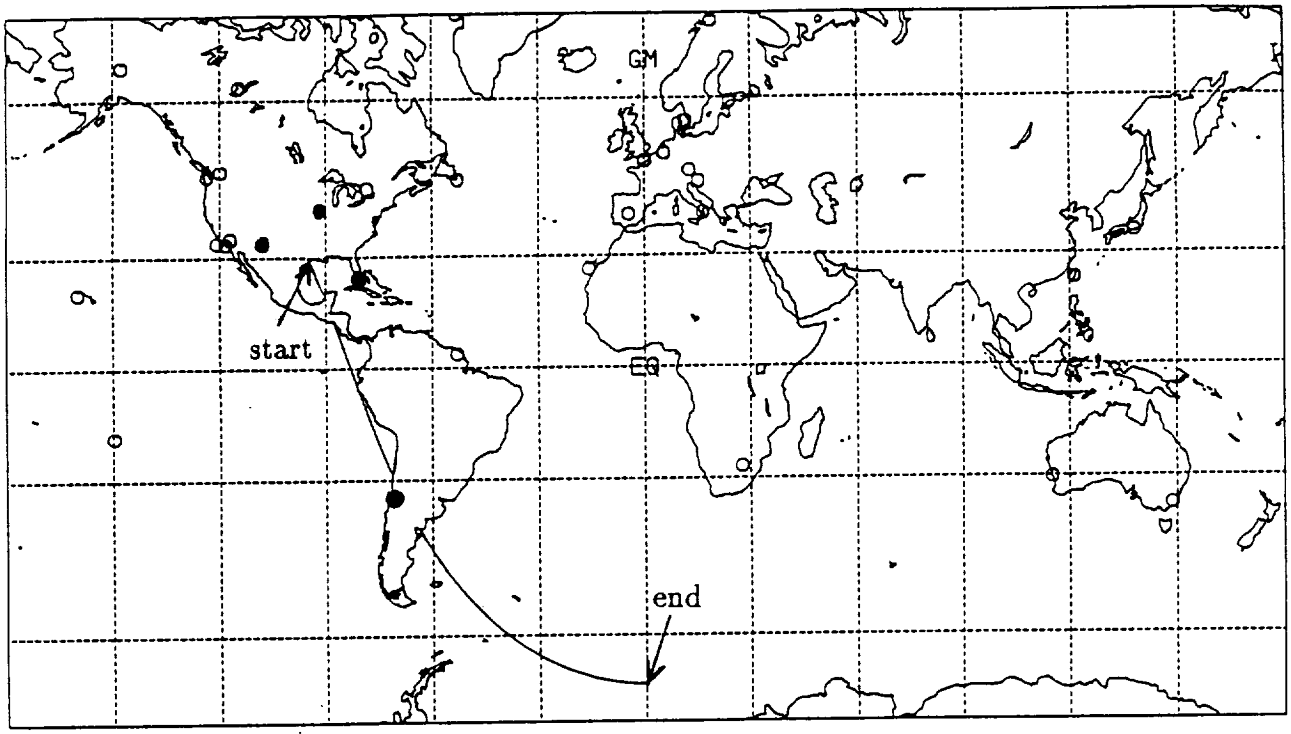

Figure 11: TOPEX groundtrack for pass 52 (cycle 18) with near by IGS GPS stations (black dots).

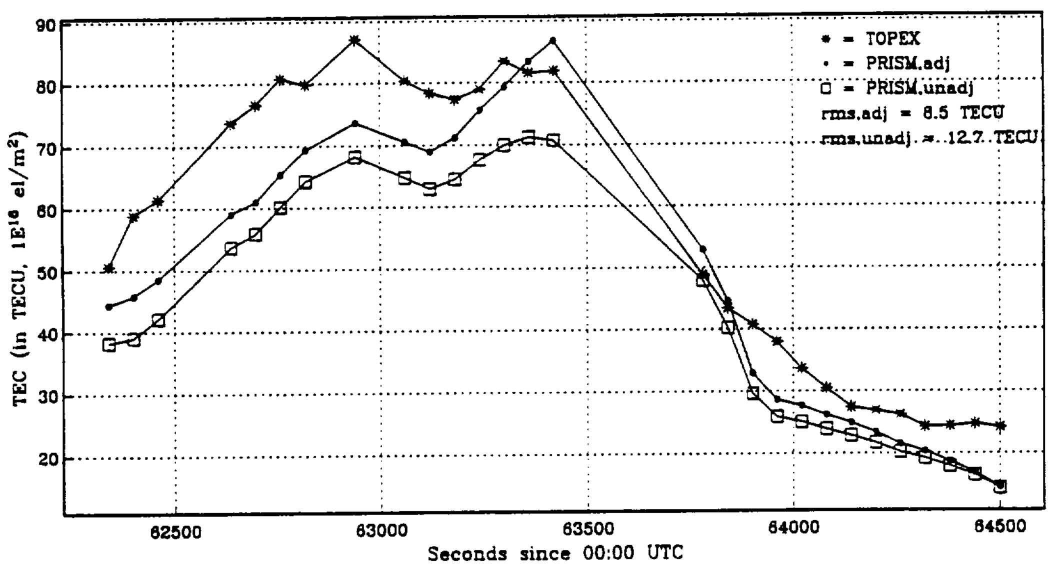

Figure 12: TEC Data (12 Mar 1993) for TOPEX pass 52 (cycle 18) versus time. The rms differences between the PRISM adjusted and unadjusted TEC values and the TOPEX TEC measurements are given. Local time at the midpoint of the pass is approximately 12 noon.

GPS site in Richmond. Florida helps the PRISM adjustment in the beginning of the pass, and the site in Santiago, Chile improves the adjustment in the middle of the pass. Figures 13 and 14 show the groundtrack and results for pass 54. Pass 54 appears to traverse the maximum of the daytime ionosphere where the TOPEX altimeter measured TEC's as high as 120 TECU. There is an improvement in the PRISM TEC values when using GPS TEC data, but the the rms difference (15.5 TECU) is still well above the 10 TECU requirement with data excursions of 40 TECU (8 cm at K band). Again, this is because there are no stations in the vicinity of the pass 54 TOPEX groundtrack when it passes through the maximum ionosphere.

The above results show that the PRISM adjustment procedure does well at matching the TOPEX TEC values when the TOPEX overflight point is near a GPS TEC measurement. This is because the PRISM weight function used in the adjustment procedure only incorporates information from a TEC measurement 300 to 400 km away from that measurement. Because of this, the authors used a modified weight function that incorporated the TEC measurement information at distances up to 1000 km away from the measurement, keeping in mind that this may have enabled some decorrelated information to be used. Passes 43, 52 and 54 were re-run with the modified weight function and generated rms differences of 7.1 TECU, 6.9 TECU and 14.4 TECU, respectively. The rms differences with the original PRISM weight function were 5.3 TECU, 8.5 TECU, and 15.5 TECU for passes 43, 52, and 54. Passes 52 and 54 showed little improvement while pass 43 degraded. These results are inconclusive, but they do show that using a weight function with a larger decorrelation distance does not give appreciably better results, and could make the adjustments worse in areas with high TEC gradients.

6 Discussion and Conclusions

The adjusted PRISM values generally compared to the TOPEX measurements within the 10 TECU accuracy requirements when the sub-satellite track passed within 300 to 400 km of the GPS TEC data or when the track passes through a night time ionosphere. However, when the sub-satellite points were greater than 300 to 400 km away from the GPS TEC data or when a local noon ionosphere was sampled, the adjusted PRISM values generally differed

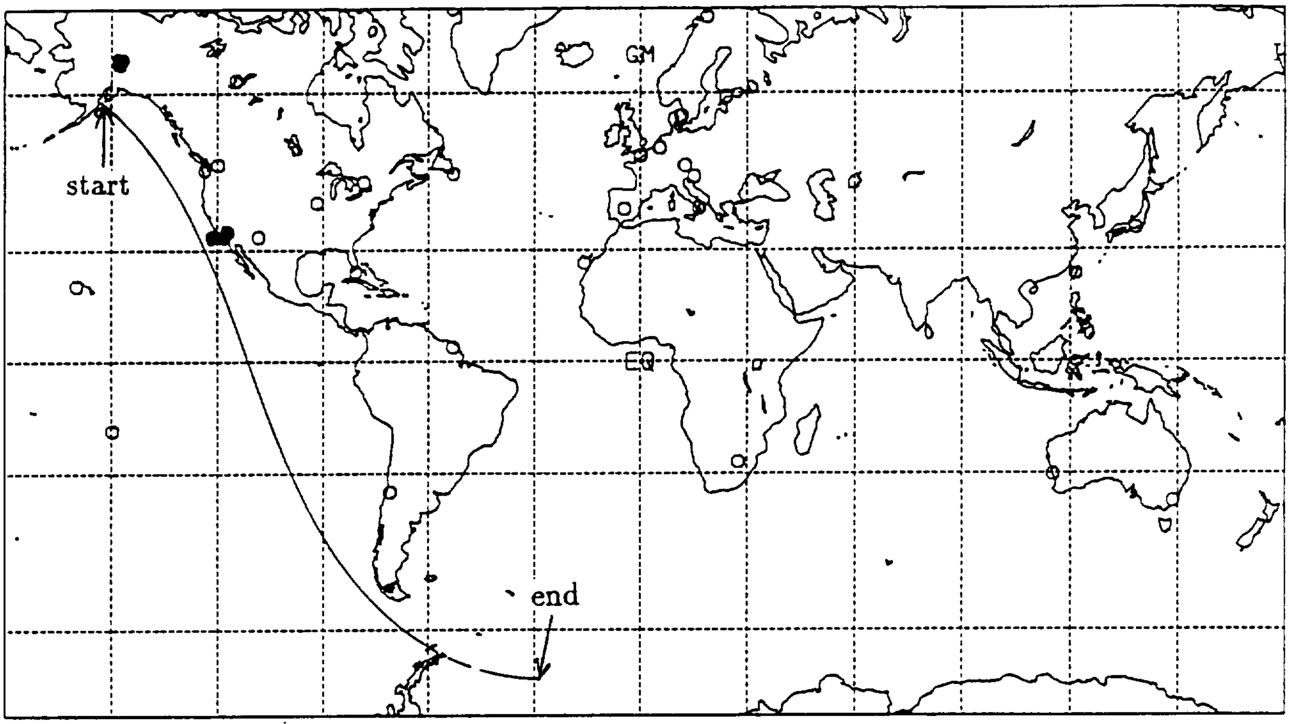

Figure 13: TOPEX groundtrack for pass 54 (cycle 18) with near by IGS GPS stations (black dots).

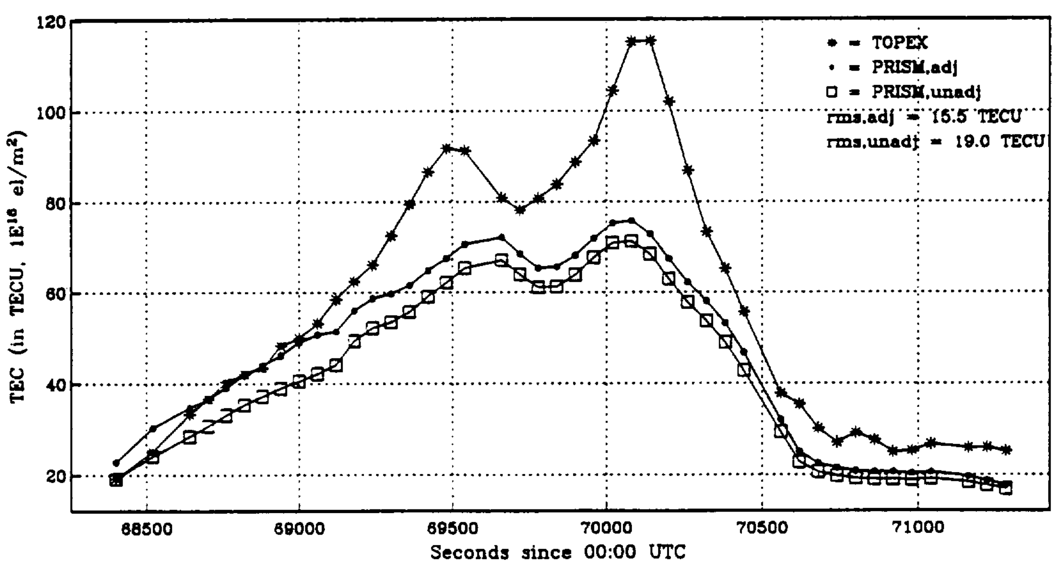

Figure 14: TEC Data (12 Mar 1993) for TOPEX pass 54 (cycle 18) versus time. The rms differences between the PRISM adjusted and unadjusted TEC values and the TOPEX TEC measurements are given. Local time at the midpoint of the pass is approximately 12 noon.

by greater than 10 TECU rms with data excursions from the TOPEX TEC measurements of as much as 40 TECU (an 8 cm error at K band). A modified weight function (using information at distances up to 1000 km away from the GPS TEC data) was studied, and showed no appreciable improvement in the PRISM adjustment procedure. Therefore, it can be concluded from this analysis that ingesting TEC data from GPS stations directly into PRISM will not predict sub-satellite TEC at the 10 TECU level in the day time ionosphere. Because the PRISM adjustment procedure only incorporates information from measurements that are within 300 to 400 km (derived from the inherent spatial decorrelation distance of the ionosphere) of the TOPEX overflight point, a prohibitively large number of ionospheric measurement sites would be needed as input to PRISM to meet the 10 TECU accuracy requirement.

However, there may be a method of ingesting TEC data into PRISM that would not be as sensitive to the spatial decorrelation of the ionosphere and thus would require a more realistic number of stations. For example, GPS TEC data from a previous or future time could be rotated in longitude (by an amount that the Earth has rotated in that time) to be closer to the altimetersub-satellite point. In essence, this technique would give TEC data in a sun-fixed frame that is old (or in the future) by some period of time.

A technique that takes better advantage of the sun-fixed longitude assumption, and that was used to estimate the L1/L2 receiver and satellite biases used earlier in this report, is currently being studied at the Jet Propulsion Laboratory. This method involves using global GPS TEC data to estimate a global grid of vertical ionospheric TEC as a function of time (i.e. every one half hour) in a sun-fixed longitude frame. Working in a sun-fixed longitude frame is not limited by the spatial decorrelation distance of the ionosphere, but is limited more by the temporal correlations of the ionosphere in the sun-fixed frame. The global grid consists of a network of stochastic (random walk) grid points that are updated in time (along with their covariance) as new GPS TEC data are acquired. If GPS TEC data are not present over a grid point, the estimate of the grid point will not be updated and its covariance will increase according to the noise assigned to the stochastic parameter. Thus, this technique gives both a grid estimate of TEC in a sun-fixed frame, and also a corresponding covariance (which reflects the uncertainty of the estimate) that can be used as a weighting function when ingesting GPS TEC data into PRISM.

There are two methods that may be able to utilize the JPL sun-fixed TEC grid data to meet the 10 TECU accuracy requirement. The first method would consist of using GPS TEC grid data directly by subtracting a measure of the TEC above the altimetric satellite from the total vertical TEC grid data to give the sub-satellite TEC. The TEC above the satellite should be obtained with good accuracy from dual frequency GPS measurements received at the satellite. Therefore, the accuracy of this method will be dependent primarily on the accuracy of the TEC grid data. The second technique, and the more hopeful, would use the TEC grid data, weighted by the grid covariance, as input to adjust the PRISM model. Thus, if the uncertainties of the grid parameters are small, the PRISM values will be adjusted toward the TEC grid data, and if the uncertainties are large, the values will be closer to the parameterized physics of the PRISM model. It is the opinion of the authors that using the global sun-fixed TEC grid data, in particular, ingesting it into PRISM, offers the best possibility of meeting the the 10 TECU ionospheric correction accuracy requirement, and should be the subject of further study.

Another area of study that requires further understanding is the consistent under prediction of TEC by the PRISM base model as compared to the TOPEX TEC and GPS TEC measurements. Both the TOPEX and GPS measurement systems obtained TEC values as high as 115 TECU on March 12, 1993, compared to 72 TECU for the PRISM model. A value of 115 TECU is considered high for the middle of a solar cycle, but the authors feel this is an accurate measure of ionospheric TEC since it was measured by two independent systems. A comparison of PRISM with a climatological model such as the International Reference Ionosphere model (IRI-90), could provide some insight into the consistently low TEC prediction of the PRISM base model. CCAR will have the IRI-90 model up and running soon, so this comparison would be relatively easy to perfrom.

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