Monitoring The Ionosphere Using A Global GPS Network: Applications and Validation

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Biographies

Brian Wilson, a member of the GPS Networks and Ionospheric Systems Development Group at JPL, has been studying the ionosphere using GPS for six years and is a co-developer of the GPS-based global ionospheric mapping (GIM) technique. His current work is focused on improving and validating GIM, global ionospheric calibration of single-frequency ocean altimetry missions, real-time global WADGPS, and other remote sensing applications of GPS. He holds a M.S. in physics from Caltech.

Anthony J. Mannucci is a Member of the Technical Staff in the GPS Networks and ionospheric Systems Development Group at JPL. He specializes in developing and applying ionospheric calibrations systems for deep space tracking and Earth science applications. He holds a B.A. in physics from Oberlin College and a Ph.D. in physics from UC Berkeley.

Dah-Ning Yuan is a member of the Tracking Systems and Applications section at JPL. He joined a team to develop a system for monitoring global ionosphere using Total Electron Content (TEC) data derived from a world-wide network of dual-frequency GPS receivers. He is also involved in implementing SLR (satellite laser range) and DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellite) data processing techniques for 10 PEX/Poseidon project in the Navigation System section at JPL. He obtained his Ph.D. in Aerospace Engineering from tbc University of Texas at Austin in 1991.

Byron Iijima is a member of the GPS Networks and Ionospheric Systems Development Group at JPL. For the last 8 years he has been developing technology for deep-space and GPS tracking applications. He is currently focused on GPS-based ionospheric maps, especially in real-time applications. He holds a Ph.D. in physics from MIT.

Xiaoqing Pi is a member of the GPS Networks and Ionospheric Development Group at JPL. He holds a Ph.D in Astronomy from Boston University, and has been involved in the research and development areas of ionospheric modeling, computerized optical imaging tomography for airglow and aurora, ionospheric storms, and ionospheric scintillation. He is currently focused on ionospheric applications of GPS, particularly the nowcasting of ionospheric storms and ionospheric scintillation using a global GPS network.

Christian M. Ho joined the GPS Networks and Ionospheric Development Group at JPL in 1995. Currentl y, he is performing ionospheric storm studies using global ionospheric TEC maps generated from the global GPS network. He received his B .S from Peking University of China in 1981 and his Ph.D from UCLA in 1993, and has been in the field of space physics for 20 years.

Ulf J. Lindqwister obtained his Ph.D. in physics from Princeton University in 1988. Dr. Lindqwister is supervisor of the GPS Networks and Ionospheric Systems Development group at the Jet Propulsion Laboratory (J PL). The group operates the al I of NASA's stations in the GPS Global Network and the group also routinely produces ionospheric calibrations for NASA's deep space and near Earth missions. Recent activities include development of applications for global ionospheric specification and monitoring.

Abstract

A globally distributed network of dual-frequency GPS receivers currently exists and enables the monitoring of ionospheric total electron content (TEC) on global scales. By using spatial interpolation and temporal smoothing between tbc GPS-based TEC measurements, combined with model information from a climatological ionospheric model, wc are able to produce global ionospheric maps (GIM) of vertical TEC every 15 minutes. Comparisons to independent ionospheric measurements indicate that the global TEC maps are accurate globally to 5-10 TECU (1016 electrons/meter^2) and enable a continuous, global ionospheric specification which is more accurate than any

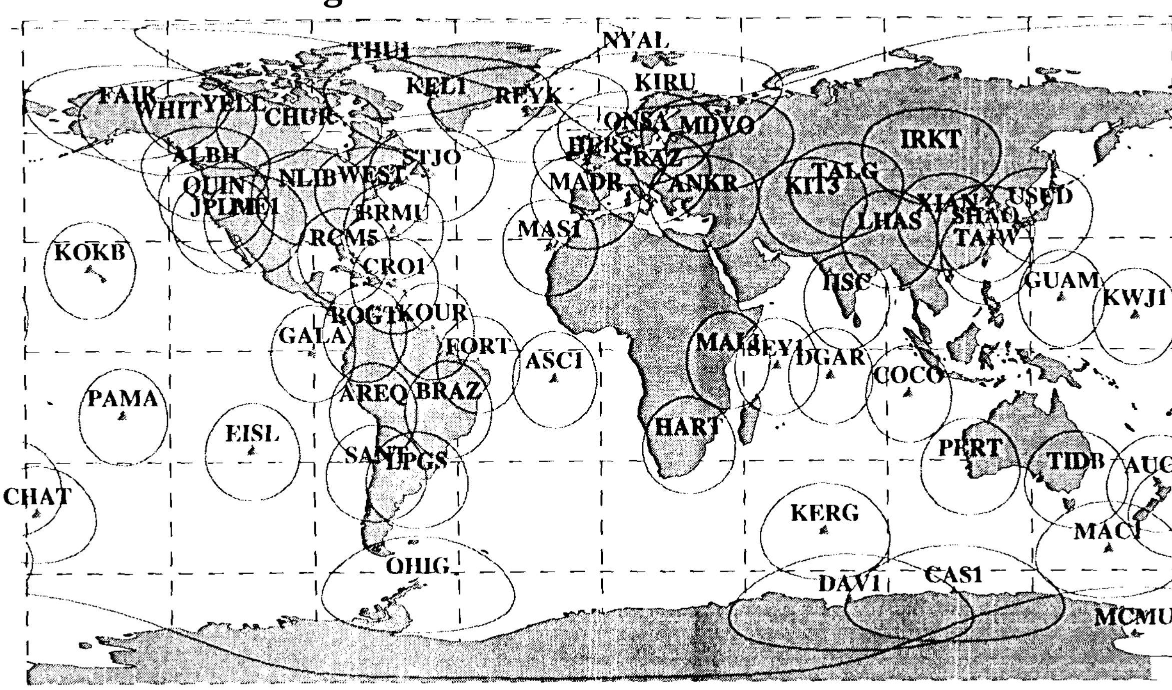
of the existing empirical models. The GIM technique is currently being used as the basis for three operational capabilities: (I) daily global ionospheric calibration for a single-frequency ocean altimetry mission (GFO), (2) hourly global ionospheric monitoring in support ot'the 50th Weather Squadron of the Air Force, and (3) real-time ionospheric correction over the continental U. S. for usc in wide-area differential GPS (WADGPS) applications.

Introduction

A globally distributed network of 80+ dual-frequency GPS receivers currently exists and enables the monitoring of ionospheric total electron content (TEC) worldwide. Global maps of TEC are useful for calibrating propagation delays or monitoring the solar-terrestrial environment, and can be produced continuously using this operational network. Potential applications include global and regional wide-area differential GPS (WADGPS) systems, global calibration for single-frequency satellite ocean altimetry missions, monitoring and prediction of space weather conditions, delay corrections at single-frequency satellite tracking stations and astronomical observatories, regional ionospheric studies, and Iong-term monitoring of environmental change. The rapidly growing international GPS network currently contains 80+ globally-distributed sites, with some notable gaps in the equatorial region and southern latitudes being filled in during the past year (see Figure. 1). In addition to this GPS resource, the TEC data set can be augmented using other dual-frequency tracking systems, such as the DORIS and PRARE systems.

By using spatial interpolation and temporal smoothing between the TEC measurements, combined with model information from a climatological ionospheric model, wc arc able to produce global ionospheric maps (GIM) of vertical TEC daily, hourly, or more frequently (Mannucci, *et al.*,1993 and Mannucci, *et al.*, 1994). The instrumental biases in the GPS receivers and satellite transmitters arc also estimated simultaneously (Wilson, *et al.*, 1994). A Kalman-type filter optimally combines the absolute and relative TEC measurements with model information, yielding a map of absolute ionospheric delay and a formal error map.

Tracking Mask of Fiducial GPS Global Network



(Elevation Cutoff =10 deg & Shell Height= 450 km)

Figure 1. Site map for the global GF'S network as of 1997, showing the coverage region assuming a 10 degree elevation cutoff. Coverage in the equatorial region and the southern latitudes has improved dramatically in the last year.

Several improvements to GIM have recently been implemented: an improved parameterization of the TEC grid using hi-cubic splines, optimized stochastic estimation strategy, several new strategies for constraining the maps using model information, and a real-time capability (Mannucci, *et* al., 1995). The accuracy of the global maps has been extensively validated by comparisons to independent ionospheric measurements: vertical TEC data from the dual-frequency altimeter on TOPEX, slant TEC data from a wide-spectrum instrument on the ALEXIS satellite, Faraday rotation, and ionosonde measurements. Current comparisons indicate that the GPS-driven maps arc accurate globally to 5–1 O TECU (1016 electrons/meter^2) and enable a continuous, global ionospheric specification which is more accurate than any of the existing empirical models (Mannucci, *et al.*, 1995). An extension of GIM to the 3-D ionosphere, in which the GPS data arc used to optimally adjust model-derived electron density profiles, is also currently under development.

The purpose of this paper is to briefly describe three applications of the GIM technique in the field of ionospheric specification. The three applications arc: (1) daily global ionospheric calibration for a single-frequency ocean altimetry mission (GEOSAT follow-on or GFO), (2) hourly global ionospheric monitoring in support of the 50th Weather Squadron of the Air Force, and (3) real-time ionospheric correction over the continental U. S. (CONUS) for use in wide-area differential GPS (WADGPS) applications. It must be emphasized that these three applications are not simply research projects, but are operational capabilities that have been demonstrated and arc or will soon be functioning continuously. In particular, the third capability, WADGPS corrections over the CONUS (including ionospheric corrections), is currently being demonstrated in conjunction with an operational 14-site GPS network developed by SATLOC corporation of Tcmpc, AZ (see Bertiger et al., 1997 at this conference).

The GIM Technique

'f'he GIM ionospheric correction algorithms have been described in previous Institute of Navigation Proceedings (Mannucci *et al.,* 1993 and Mannucci, *et al.,* 1995), and so only a fcw recent improvements will be summarized here.

Briefly, the GIM technique employs a "shell" model of the ionosphere to estimate a map of vertical TEC on a 2-dimensional ionospheric shell. The ionospheric delay is assumed to be well approximated by a thin shell of electron density concentrated at a fixed height of 450 km. Although the maximum electron density as a function of altitude occurs between 350-450 km, the centroid of the distribution falls somewhat higher than the maximum due to the extended topside ionosphere. Accuracy comparisons of GIM to independent ionospheric measurements (TOPEX and others) indicate that the typical centroid height of 450 km is a good choice for the ionospheric shell height.

The vertical delay on the shell is modeled using linear or hi-cubic splints connecting a set of vertex points which are uniformly distributed over the sphere. The vertex grid is fixed in a solar-geomagnetic coordinate system in which latitude is measured from the geomagnetic equator and the longitude is nearly Sun-fixed. Since the two main drivers of the ionosphere arc the solar extreme ultraviolet flux and the Earth's magnetic field, the ionospheric delays arc more slowly varying in this coordinate frame.

The ionospheric mapping process makes extensive use of stochastic estimation. For each measurement update, the vertical ionospheric delay is re-estimated at every grid point. The vertex parameters are modeled as "random walk" stochastic processes, so that the updated values at each grid point arc correlated with their values at the previous time step; i.e., they are not estimated entirely independently at each step, so that a brief history of measurements contributes to the current estimate. Since a distance weighting function (splint) is also used, the vertex TEC values arc also correlated spatially with the values at adjacent grid points. This results in stable and smoothly varying ionospheric fits or maps.

In order to span spatial and temporal gaps in the GPS data coverage, GIM also makes use of *a priori* information from climatological ionosphere models such as the Bent model (Bent et al, 1976), the International Reference Ionosphere (IRI), or the Parametrized Ionosphere Model (PIM). PIM is the climatological database inside the Parameterized Real-Time Ionospheric Specification Model (PRISM). PRISM is a 3-dimensional ionosphere model which can use ground-based ionosonde and TEC data, and *in situ* electron density measurements from satellites to update its electron density versus altitude profiles (Anderson, 1993 and Daniell *et al.,* 1995). GIM can incorporate model information either as a value constraint or a difference constraint (i.e., constraining the TEC di fference bet wccn two adjacent vertices). Current analysis indicates that incorporating the difference constraints leads to improved accuracy, while the value constraints do not. Since the climatological models represent average behavior, they are not quantitatively correct for local conditions but rough knowledge of the smooth spatial and temporal gradients (slopes) does lead to an overall improvement in accuracy.

Validation using TOPEX

To assess the global accuracy of GIM, independent ionospheric measurements from the radar altimeter on-board the TOPEX/Poseidon satellite were used. (Comparisons to other independent ionospheric measurements—Faraday rotation, ionosonde, integrated

GPS/MET profiles-will not be discussed here.) The TOPEX dual-frequency altimeter, which measures vertical range from the sca level to satellite altitude, also provides vertical TEC information with an accuracy of 2–3 TECU (Callahan, 1993 and I me], 1994). Smoothed 10-second TOPEX TEC data arc available over the ocean areas covering the entire geographic latitude range from -66 to +66 degrees. 'I'he TEC maps from the GIM solutions can be compared with sub-satellite TEC measurements derived from TOPEX altimeter. Thus, TOPEX is an ideal source of independent measurements for validating the **global** accuracy of GIM, particularly in the dynamic equatorial region.

TOPEX orbits at an average altitude of 1330 km altitude, above the bulk of the ionosphere. The GPS measurements up to 20,000 km contain an additional contribution from the plasmasphere. (Model analysis and measurements from GPS/MET indicate that the additional delay is usually small, 1–2 TECU). Thus, neglecting the plasmasphere and assuming that TOPEX is unbiased, one can use the direct measurements from TOPEX as ground truth in evaluating the accuracy of the interpolated TEC maps. The altimeter measurements arc only available over the oceans, where GPS sites arc particularly sparse, hence these comparisons represent a stringent test of GIM interpolation accuracy.

Near Real-Time Applications

Single-frequency altimetry calibration

GEOSAT follow-on (GFO) is a single-frequency radar altimetry mission (launching May 1997) that will provide continuous measurements of sea surface height under its ground track (see Figure 2). The accuracy of the measured sea surface height is limited by orbit accuracy and uncalibrated ionospheric delays. JPL has been tasked to provide sub-satellite ionospheric calibrations to the Navy within 24 hours in order to support daily generation of GFO data products. Data-driven GIM is expected to provide vertical TEC accuracies of 5– 10 TECU or 1–2 cm at the altimeter frequency of 13.5 GHz, which is a vast improvement over the 30–S0'% errors observed in calibrations based on climatological models (during the prior GEOSAT mission).

GFO has an orbital altitude of 800 km so the integrated TEC maps from GIM need to be supplemented with electron density profiles from climatological models. Figure 2 illustrates the problem schematically. The TEC above 800 km must be computed and removed from the total in order to generate the calibration for the altimeter. Fortunately, the super-satellite TEC is usually no more than 10% of the total TEC delays so even if the models are in error by 30-50?% the resulting errors will be small. We have compared super-satellite TEC computed from three climatological models—Bent, IRI '90, IRI '95, and PIM—and preliminary results indicate that except for Bent they arc fairly consistent and that IRI '95 is a good candidate model. Preliminary comparisons of GIM-based calibrations to independent slant TEC measurements from the ALEXIS satellite (also at 800 km altitude) showed agreement at the level of 2–3 TECU in the mid-latitudes.

To assess the global accuracy of GIM and other models, wc have compared them to TOPEX measurements over several 10-day cycles. Figure 3 shows a histogram of residuals (model - TOPEX) for several models during March of 1993, when the ionosphere was more active than the current solar minimum conditions. A full discussion of the results for the various models is beyond the scope of this paper, but the results for March, 1993 illustrate several points. First, GIM has smaller residuals than any of the climatological models and they are evenly distributed about zero; 819k of the GIM residuals are within ±10 TECU and the RMS error is 8.0 TECU. In contrast, the climatological models exhibit much larger noise tails and the distributions arc not symmetric about zero. All of the climatological models systematically underestimate the TEC, particularly in the equatorial region, and even for the best model only 70% of the residuals are within ±10 TECU. The March 1993 period represents almost a worst-case accuracy for GIM since only 34 GPS sites were available. For a more recent cycle in April 1995 when 60+ sites were available and the ionosphere was less active, 85% of the GIM residuals were within ±5 TECU.

Global Ionospheric Specification for the Air Force

JPL has performed a 30-day test of a system designed to deliver hourly GPS-based TEC data from a global network of 24 stations to the Air Force's 50th Weather Squadron (SOWS) at Falcon AFB. The near real-time TEC data will be fed into PRISM, an ionospheric specification model which is operational at 50WS, and other ionosphere models. The intent is to improve the near real-time accuracy of global ionospheric specification for a variety of Department of Defense customers.

To support this project, JPL has upgraded the communications at numerous sites in the global GPS network to enable hourly downloads from the receivers. The GPS data from all 24 sites is collected at JPL every hour, next absolute TEC data is computed from the GPS observables, and then the TEC data is passed to 50WS. This system also enables hourly GIM solutions at JPL, although the accuracy will be somewhat less than the daily GIM solutions using the full network with 80+ sites.

A previous accuracy study using PRISM and GIM has demonstrated the value of the near real-time TEC data in improving the accuracy of ionospheric specification. Vertical TEC from two data-driven models, GIM and PRISM, and two climatological models, Bent and PIM, were compared to TOPEX measurements during three different TOPEX cycles. Figure 4 shows the RMS error

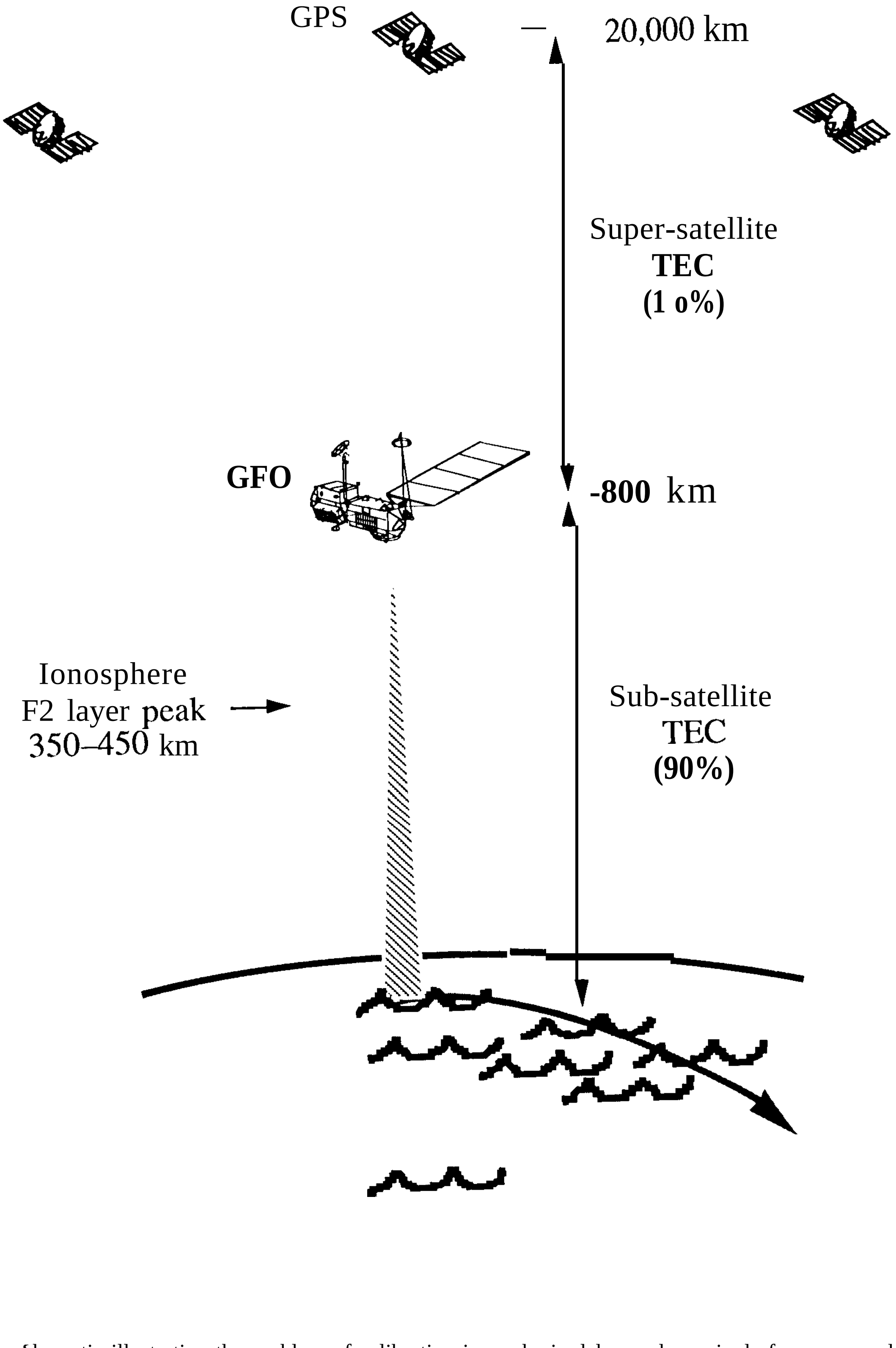


Figure 2. Schematic illustrating the problem of calibrating ionospheric delay under a single-frequency radar altimeter such as GEOSAT follow-on. GFO orbits at an altitude of 800 km so the super-satellite TEC represents a small fraction of the total TEC. Climatological ionosphere models can be used to estimate the super-satellite TEC and remove it.

for the various models expressed in TECU and as percentage improvement over the Bent model. The data-driven models performed significantly better than the climatological models. GIM performed the best in all three geomagnetic regions (low, mid, and high latitudes), with an overall RMS error of 6.1 TECU (31 % improvement over Bent). PRISM also showed increased accuracy over Bent (22%) when ingesting the TEC data. Further studies with the current, improved version of PRISM are being pursued.

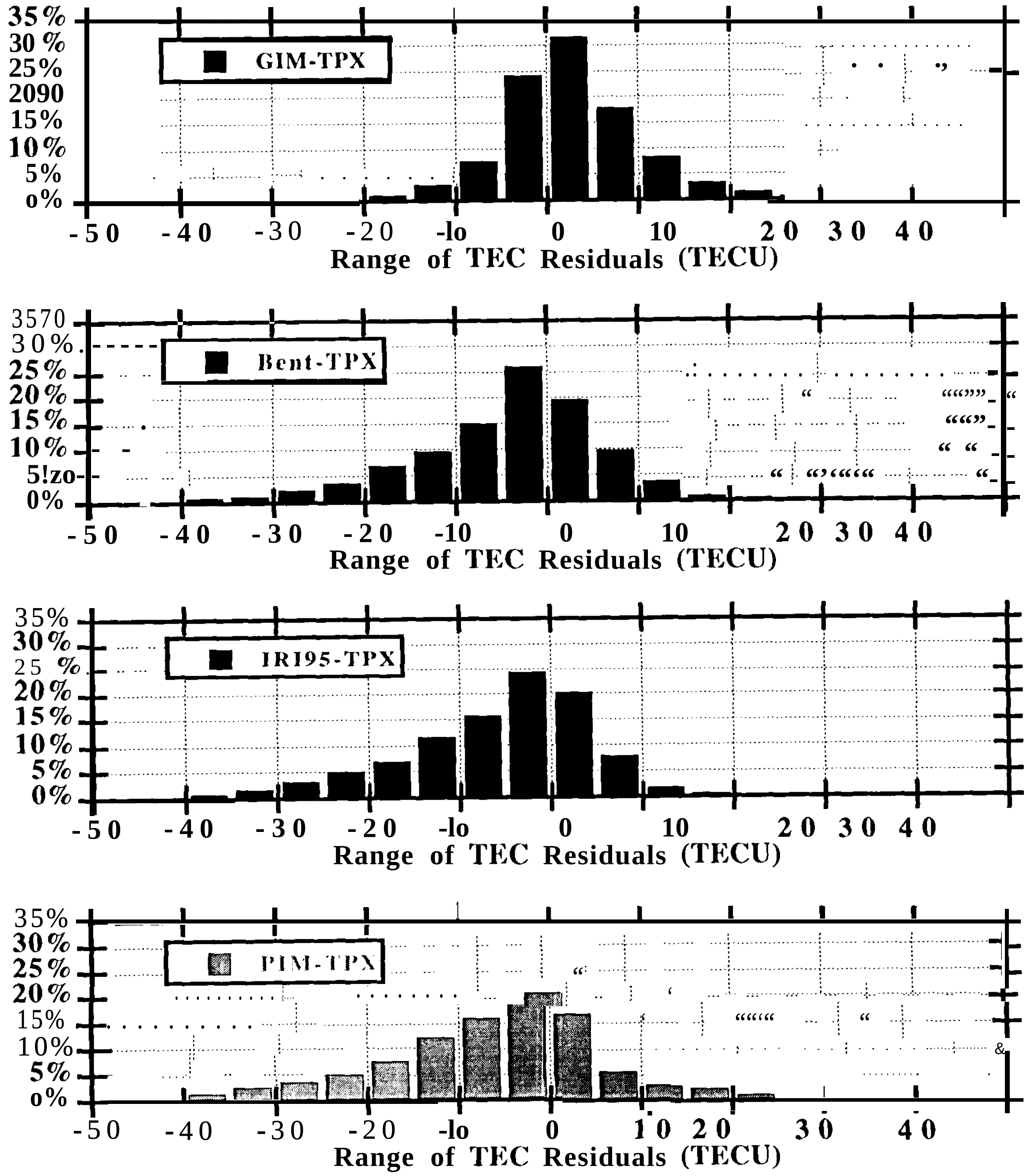


Figure 3. A comparison of GIM and three climatological models to TOPEX vertical TEC measurements during March, 1993. The GIM residuals exhibit the narrowest and most symmetric distribution; 85% of the GIM residuals are within ±10 TECU. In contrast, the climatological models all systematically underestimate the TEC (large negative noise tails).

Geomagnetic Region	Model	# of Points	RMS Error (TECU)	% increase in Accuracy over Bent
ALL	Bent	**5404**	8.9	--
ALL	PIM	5404	9.7	**-9%**
ALL	PRISM	5404	6.9	+22%
ALL	GIM	5404	***6.1 ***	+31 %
Low	Bent	2342	11.5	—
LOW	PIM	2342	11.7	-2%
Low	PRISM	2342	8.0	+30%
Low	GIM	2342	7.7	+33%
MID	Bent	2089	6.1	---
MID	PIM	2089	8.0	-31%
MID	PRISM	2089	6.0	+2%
MID	GIM	2089	4.5	+26%
HIGH	Bent	973	6.7	—
HIGH	PIM	973	7.5	-12%
HIGH	PRISM	973	5.7	+15%
HIGH	GIM	973	4.8	+28%

Figure 4. A comparison of two data-driven models, GIM and PRISM, and two climatological models, Bent and PIM, to vertical TEC measurements from TOPEX. GIM and PRISM, which can ingest TEC data, are significantly more accurate than the Bent model. The RMS residuals have been broken down into three geomagnetic regions. GIM performs best in all three regions, with an overall RMS error of 6.1 TECU.

Ionospheric Correction for WADGPS Applications

JPL and SATLOC arc currently operating a prototype WADGPS systcm over the CONUS. A complete description of the systcm appears in Bertiger *et al.*, 1997 and a study of the impact of ionospheric storms on the accuracy of the ionospheric correction map is considered in Mannucci ct al., 1997. As part of this WADGPS system, a new vertical TEC map is estimated in solar-magnetic coordinates every 15 minutes using GPS data from 14 reference sites. Ionospheric corrections on an Earth-fixed grid arc computed and broadcast every 5 minutes.

Since TOPEX measurements arc only available over the oceans, it is less useful for validation over the CONUS. Instead, the ionospheric correction map was validated using GPS measurements from indcpcndcnt test sites. In this paper, wc present validation results from November of 1996. Figure 5 shows a site map of the 11 available reference sites in the SATLOC real-time network and the 8 independent test sites. The validation tests were performed as follows. The vertical TEC map was formed using GPS data from the 11 reference sites. Then each GPS observation from the test sites (with an elevation of 50 degrees or higher) was scaled to equivalent vertical and compared to tbc correction map evaluated at the ionospheric pierce points of the observations. Figure 6 shows the RMS residuals for each of the 8 test sites expressed in units of cm at L1 (1 TECU = -16 cm at L1). The RMS error is better than 25 cm for all of the sites except JPLM. Note that both the JPLM and QUIN test sites arc outside the coverage region and the NLIB site is also distant from the nearest reference site (since the site at Lincoln, NE was not available). Accuracy in the CONUS is better than the global accuracy since the site coverage is denser and the ionospheric TEC is generally smaller and smoother in the mid-latitudes than in the low and high latitudes.

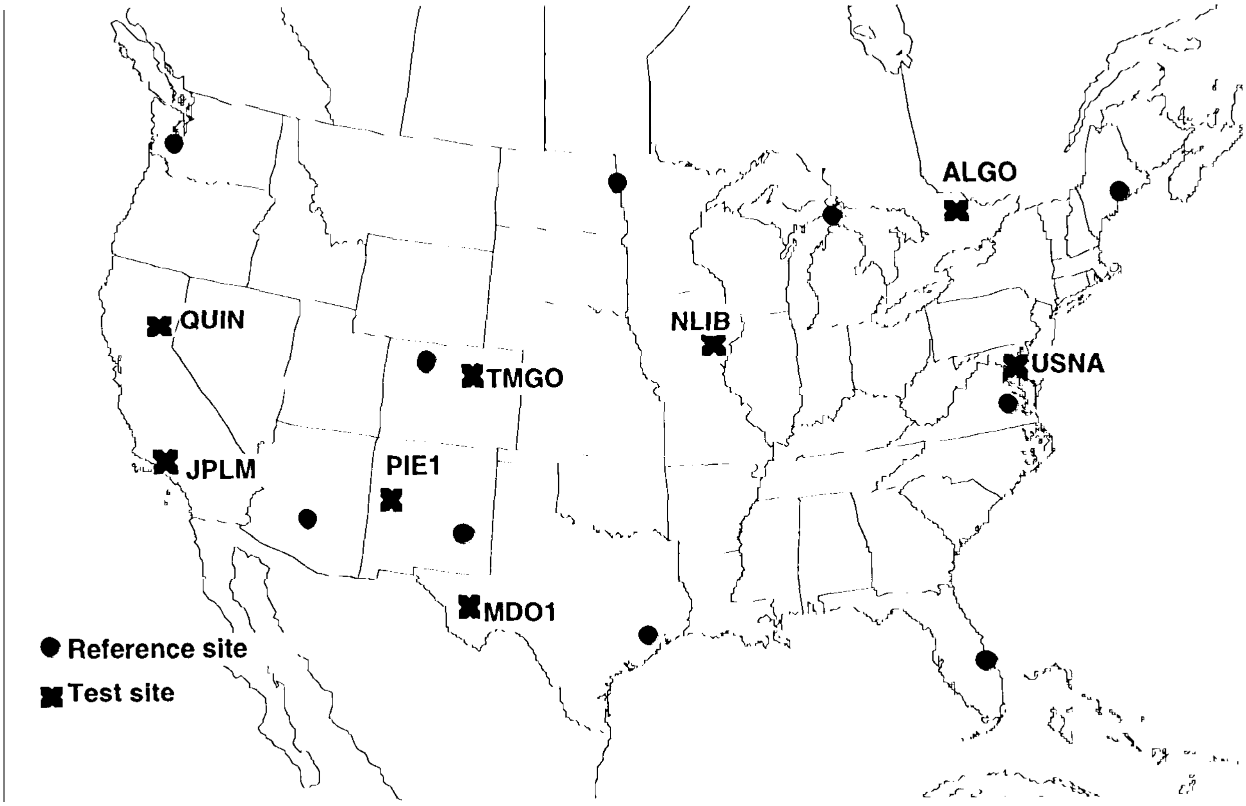


Figure 5. Site map for the operational SATLOC network and the independent test sites. SATLOC currently operates 14 real-time GPS sites, of which 11 were available during the test period in November of 1996. Eight independent GPS sites were used for post-processing validation.

Conclusions

Using the GIM technique, wc are able to combine GPS-based TEC measurements with model information to produce global ionospheric maps of vertical TEC as often as every 5–15 minutes. We have discussed three applications of GIM: global calibration for a single-frequency altimetry mission, improved global ionospheric specification for the Air Force, and a WADGPS system over the CONUS. Figure 7 summarizes the current accuracies and turnaround times for the three applications. They vary in the number of GPS sites involved (80+, 24, and 14 respectively), the turnaround time (daily, hourly, and every 5 minutes), and in accuracy (3–8 TECU, 3–10 TECU, and 1–4 TECU). The differences (and the ranges) in RMS accuracy reflect the differences in the density of GPS sites and the dynamics of the ionosphere in the region of interest. Global accuracies of 3 TECU arc achievable in the mid-latitudes, but RMS errors increase to 5--8 TECU during disturbed periods and in the dynamic equatorial region. For regional maps over the CONUS and Europe, accuracies of 1–3 TECU arc possible since the site coverage is quite dense and the mid-latitude ionospheric gradients are more easily modeled.

Significant operational improvements have occurred over the last two years. For example, two years ago it took a week to collect and process the GPS data from the global GPS network; today it is being done in real-time for 14 sites in the CONUS. Global, real-time applications are limited only by the cost of installing the proper communications infrastructure at more of the globally - distributed GPS sites. Ionospheric specification accuracy will continue to improve, even in the dynamic equatorial region, as more sites arc installed and additional modeling improvements become operational.

The advent of a global, ground-based GPS network provides an unprecedented opportunity to use data-driven models to specify the ionosphere far more accurately than has previously been done. In addition to calibration applications, the global network enables nowcasting and forecasting of ionospheric storms, scintillation monitoring, space weather studies, and contributions to coordinated ionospheric and atmospheric science campaigns. In a fcw years, flight GPS data may be available from a constellation of LEO's, and the combination of ground and space-based observations will enable full 3-dimensional ionospheric tomography.

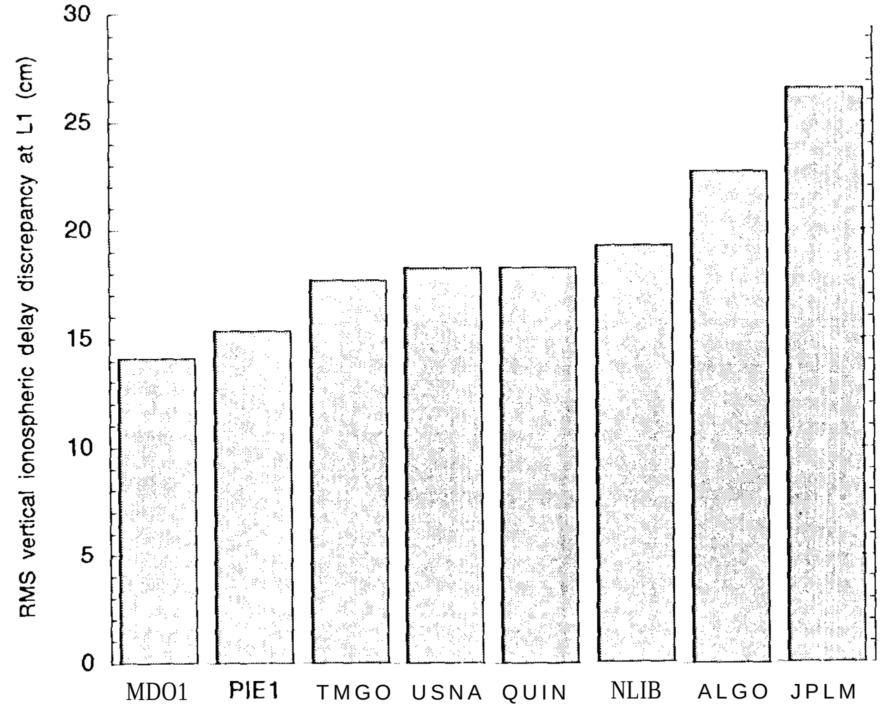


Figure 6. RMS crrors for cight independent test sitcs in the CONUS during Novcmbcr of 1996. GPS mcasurcments from the test sites were scalcd to equivalent vertical TEC and compared to a vertical TEC map gencrated from 11 reference sites. RMS residuals are better than 25 cm at 1.1, except for the JPL test site which is outside the coverage region.

Acknowledgments

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