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13. ABSTRACT *(Maximum 200 words)*

The efficacy of GPS data-processing algorithms with the RIBG model is demonstrated, as is the problem with low latitude ionospheric models, by comparison of predictions from GPS-updated RIBG predictions with independent Topex, and incoherent scatter (ISR) data.. Alternate plans are developed to solve the low-latitude model problem, and still retain a practical program for real-time processing of GPS data for ionospheric specification. In this regard, the GPS data-processing algorithms have been revamped for efficiency, now being an order of magnitude faster than before. This enables our program to meet high data throughput requirements for processing and updating GPS data from a global network of GPS receivers for global, near-real-time ionospheric specification. Algorithms have been partially developed to process multistation data for th purpose. The implications of our work for radio systems, ionospheric model development , and other developments are discussed, as well as i relationship to other work in this field.

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Global Ionospheric Specification from GPS and Airglow Data

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Long-term Goals: (1) Develop environmental (ionosphere + troposphere) propagation models which can, in combination with remote and in-situ ionospheric sensor measurements, determine in real-time the global radio propagation environment for use with radio systems, (2) Establish the role of GPS, in combination with other sensors and the preceding models, for global specification of the electron density distribution, (3) Establish the functionality of this data fusion technique in the overall space weather computational system (SWCS). (4) Help determine the functionality of the SWCS for solar-terrestrial physics development and for atmospheric compensation in radio systems, thus enhancing system performance.

Scientific Objectives: (1) Improve the equatorial model representation in the RIBG model, thereby enhancing low latitude performance of the data processing algorithms, (2) enhance the speed of these algorithms, (3) devise a method to combine the results from multi-station data, i.e., from a network of GPS receivers, and (4) determine the best use of both airglow and GPS data.

Approach:

Scientific Objective (1): We have developed a technique to specify driving parameters of a global climatological ionospheric propagation model (RIBG) from phase pseudorange data from two-frequency GPS receivers [Reilly and Singh, 1997]. These driving parameters for the RIBG model [Reilly, 1993] and an upgraded model ITRAY developed from it by Geoloc, are a sunspot number (SSN) for foF2, SSN for M3000, and CFAC, which determine maximum density in the F layer, height and width of the maximum, and rate of falloff of the topside electron density with height, respectively. The formulation also includes the rates of change of these parameters, as additional driving parameters, although these additional parameters have not been used to any appreciable extent. The GPS data processing algorithms have been tested on independent measurements of vertical TEC along orbital paths of the Topex/Poseidon satellite (Topex for short) and by incoherent scatter radar (ISR) determinations of overhead electron density vs. height profiles (EDPs). The testing compares GPS-updated RIBG computations of these observables with the independent measurements. Topex measurements indicate close agreement (within a few TEC units (1 TECU = 10^{16} electrons/m^2), which is is also the extent of Topex data noise) with updated RIBG predictions out to 10° or more in latitude (or longitude) separation from the GPS receiver in the mid-latitude region. On the other hand, the corresponding extension in latitude from the GPS receiver position is often

limited to a few degrees for the equatorial and high latitude regions. This is related to the local ionospheric dynamics in these two regions, which are not properly included by climatological models, like RIBG. In the equatorial region, the electrons at the magnetic equator are lifted by $E \times B$ forcing in the "fountain effect" and diffuse along magnetic field lines to lower latitudes on both sides of the magnetic equator, thus creating the "equatorial anomaly" electron density or total electron content (TEC) peaks on either side of the magnetic equator. These peaks are often asymmetrically distributed. The major contributing factor for this asymmetry in the equatorial anomaly peaks is the neutral wind, particularly the meridional (N-S) component. The high latitude ionosphere consists of even more complicated processes, including particle precipitation and effects of magnetospheric dynamics. The agreement with incoherent scatter radar EDPs, where RIBG is updated by nearby GPS receivers, is very good, especially when GPS data is used to determine all three driving parameters of the EDP model in RIBG.

For investigation of our technique and the model at low latitudes, we have acquired Jicamarca (Peru) (11.9 S, 76 E) ISR data for the 7-12 October 1996 MISETA campaign. A Faraday double-pulse technique was used to obtain EDPs at 15 minutes intervals, without the need for external calibration. We have compared some of the EDP results with climatological model predictions from RIBG, ITRAY, and IRI-90. The GPS station selected to update the effective sunspot number (ESSN) input to these models, where the foF2 and M3000 sunspot numbers for RIBG are equal to this number and the value of CFAC is set to its default value 0.86, was Arequipa (16.46 S, 71.49 E) in Peru. A typical comparison of the observed EDP data for 9 Oct., 1996 with the ITRAY model (an extension to RIBG developed by Geoloc) prediction is shown in Figure 1. The calculated value of ESSN was 2.5. The dots are observed data between 1400-1600 LT and the two lines are the model values at 1400 LT and 1600 LT. The results show that ITRAY predicts both foF2 and the bottom-side region quite well. With the default value of CFAC (0.86) the model overestimates the topside density, but does better than IRI-90 and is comparable with RIBG in this regard. Solving for the three adjustable EDP parameters in RIBG or ITRAY would produce a very good topside fit, based on our experience with Millstone Hill ISR data [Reilly and Singh, 1997]. One of the most interesting and persistent features of the data, up to now, has been the extraordinarily high values of foE, even exceeding foF2. At this time, no climatological model exhibits this feature. This is of interest for low latitude model development.

The results of Figure 1 demonstrate that our technique can reproduce ionospheric conditions in the vicinity of a GPS station, except for unusual features, like the anomalous E layer at low latitudes. The extendibility of GPS updates to low latitudes may be investigated from Topex data. Figure 2 shows Topex orbital tracks for 7 November, 1997 and the global two-frequency GPS stations are also marked on it. The local times for Topex observations near equatorial crossings are between 1200 and 1300 (near local noon). We choose two orbits marked # 1 and # 2 on Figure 2 for analysis. The two orbits are approximately 2 hours apart in universal time. We choose the Kokee GPS data in Hawaii to update a single ESSN input to ITRAY. The effective sunspot number calculated from GPS data is 6.7 for the time period of the two orbits. Figure 3 shows the TEC observed by Topex (jagged line) and that predicted by GPS-updated ITRAY (thick solid line). The results show that TEC is well predicted at latitudes close to the GPS receiver and toward midlatitudes, whereas the prediction tends to break down further into the equatorial anomaly.
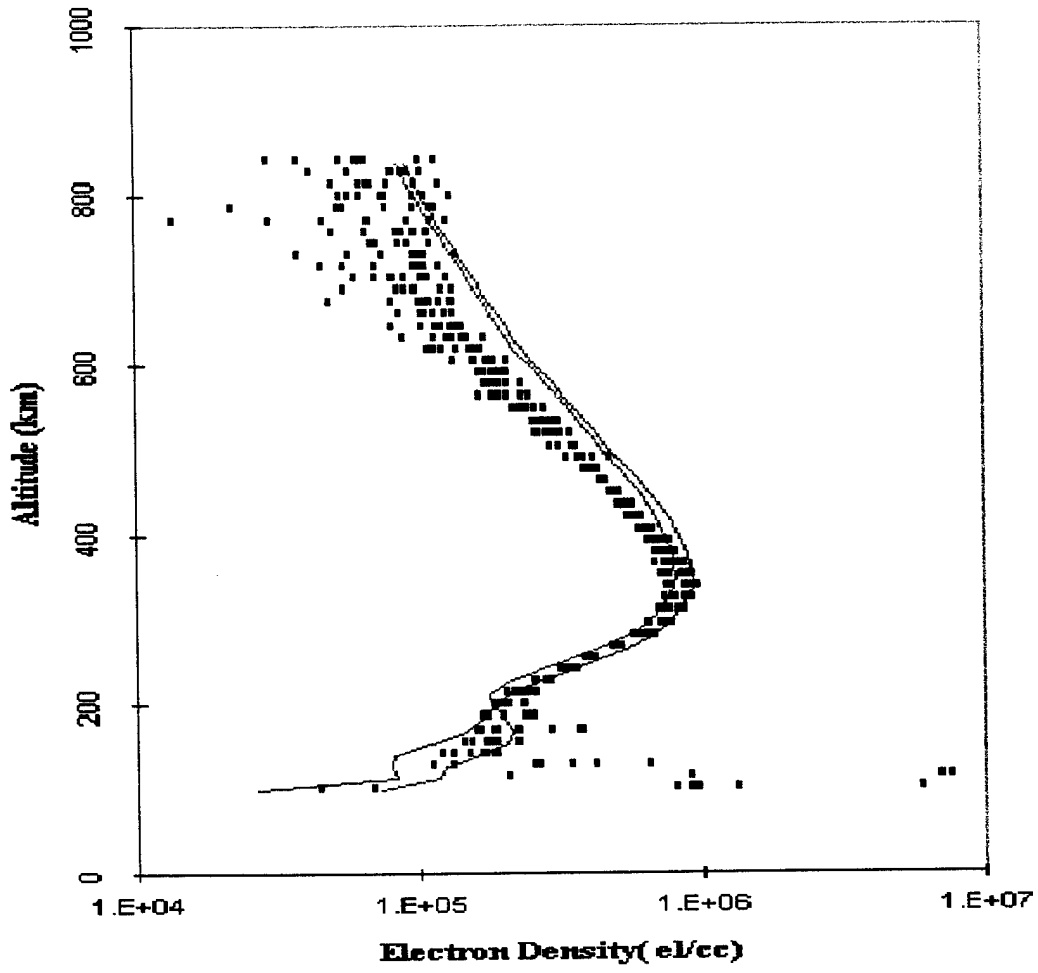
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Figure1 Jicamarca radar electron density profiles for 9 Oct.,1996 during 1400 - 1600 LT (dots) and ITRAY prediction at 1400 LT (upper line in topside) and 1600 LT (lower line)
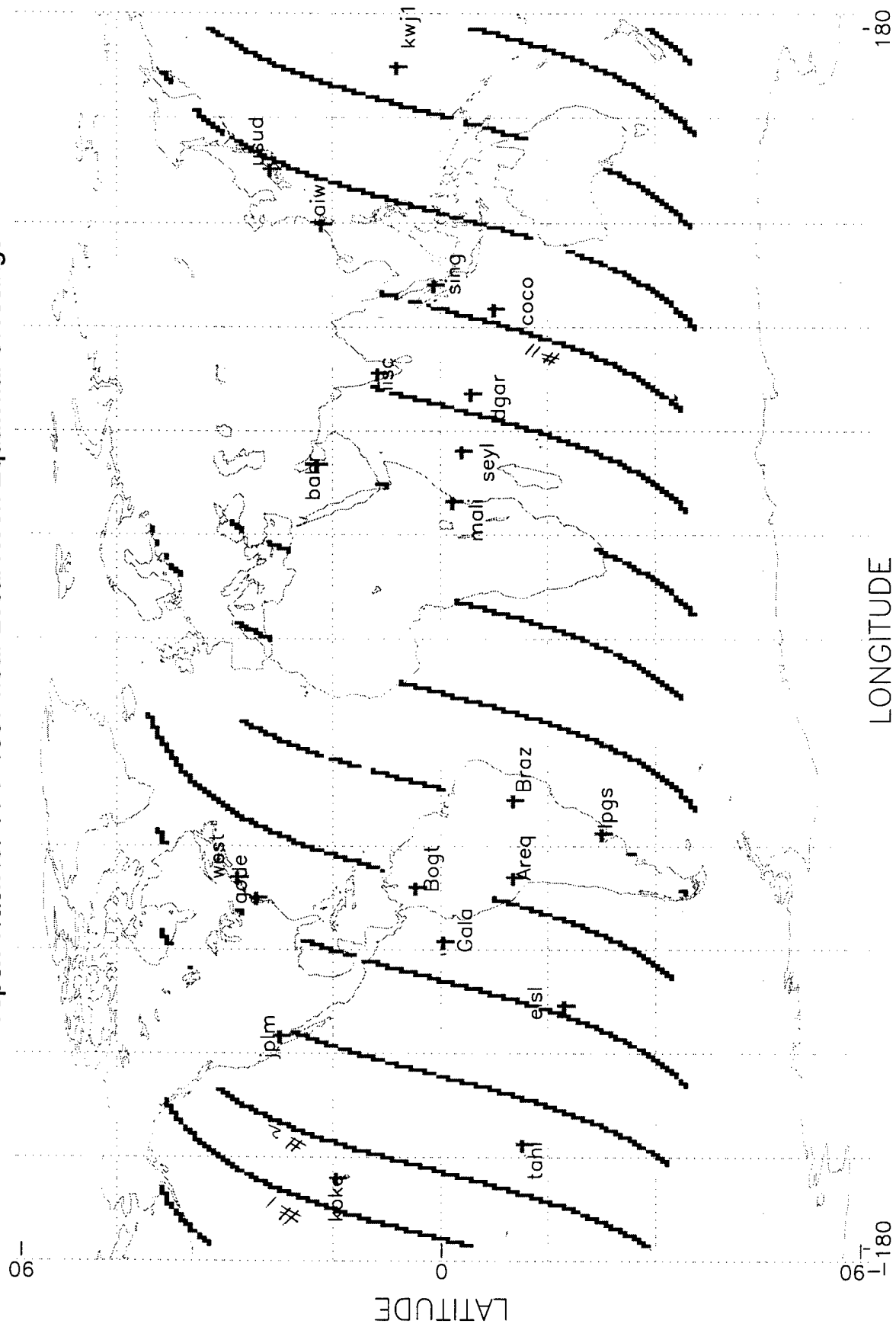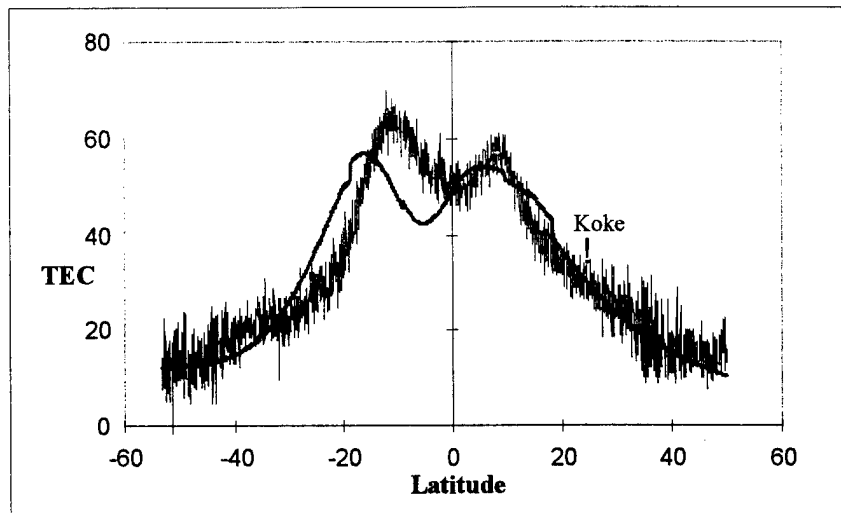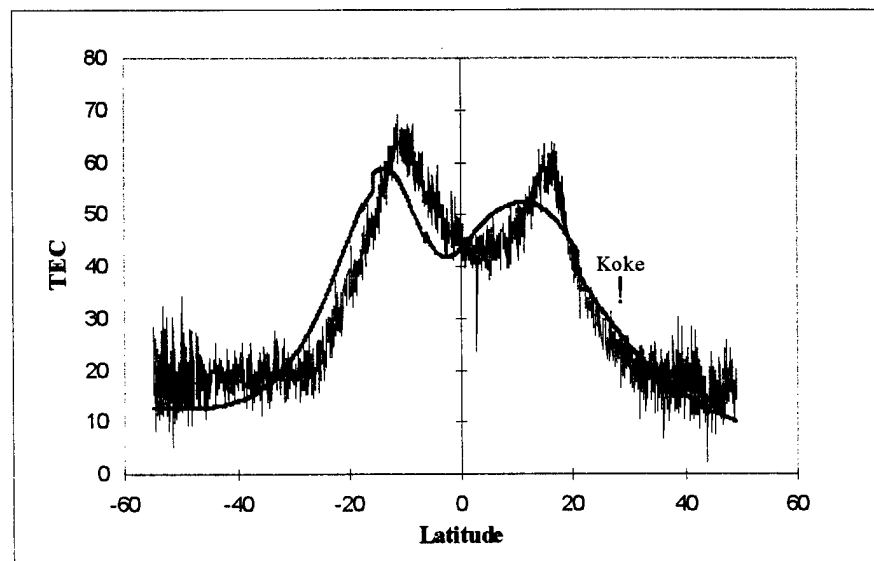
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Figure 2 Topex tracks for 11-7-97. Equatorial crossings occur near local noon .GPS
receivers are indicated by + marks.

Figure 3 Topex TEC data on 11-7-1997 and model predictions. The marker (!) identifies
the latitude position of the Kokee GPS station. #1 and #2 refer to orbits in Figure 2.

We have done extensive comparisons of Topex data and GPS- updated model predictions.
The result is that climatological models at equatorial latitudes presently do not
satisfactorily reproduce the shape of equatorial anomaly ($\pm 20^{0}$ magnetic latitude). To
improve the accuracy of our ionospheric model at equatorial latitudes, we collaborated
with Dr. Michael Keskinen of Naval Research Laboratory to adapt his low latitude model
to the RIBG or ITRAY models. To compensate for asymmetry in the equatorial anomaly
on the two sides of the magnetic equator, we tried to specify one or more additional
driving parameters (e.g., meridional component of neutral wind velocity and an electric
field component), which would help to reproduce observed equatorial anomaly
characteristics. The effort has not produced satisfactory results. Dr Keskinen has since
opted to develop a physical model, instead of a modified empirical model, to handle the

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equatorial ionosphere. It is a complicated matter to adapt this to RIBG, but Geoloc has discussed a method for doing it with Dr. Keskinen.

The RIBG values of ESSN that are needed to reproduce Topex TEC data in Figure 3 for Orbit #2 are shown in Figure 4. The variability of sunspot number as a function of geomagnetic latitude suggests a different technique for computing GPS updates of RIBG, when the receiver is fairly near the equatorial anomaly. One may assume that a driving parameter, like the sunspot number ESSN, for the two-hour processing interval for GPS data is a constant plus a Gaussian dependence on magnetic latitude on each side of the magnetic equator, where the constant and the Gaussian parameters are slowly varying functions of magnetic local time. This requires the solution for more driving parameters from discrete inverse theory [Menke, 1989], but this may produce a satisfactory result in the region of the equatorial anomaly, at least the nearer portion of it, independent of physical model assumptions and approximations. This is a subject for future research.

Scientific Objective (2): In order to improve the GPS data processing algorithm code speed, we have modified the old code to run faster by at least a factor of 20 over the initial software implementation delivered to Jet Propulsion Laboratory (JPL), without sacrificing accuracy. The old code was too slow for operations with a large number of receivers, but with the recent modification this drawback has been remedied.

Scientific Objective (3): Techniques for combining the observations from several GPS receivers for ionospheric specification over a large region have been investigated. Because there are different models in RIBG for different latitude regions (equatorial, mid-latitude, auroral, and polar) some care must be exercised in combining receivers from different latitude regions. Combining mid-latitude receivers is straightforward. The data from GPS stations at California sites (Pasadena at 34.20N,118.173W, Harvest at 34.469N, 120.68W, and Goldstone at 35.425 N,116.889 W) has been processed to yield sunspot numbers which merge smoothly with each other from station to station. We have tried to extend the baseline at mid-latitudes to few thousand kilometers by using GPS stations at Pasadena, CA (34.20 N,118.173 W), PieTown, NM (34.301 N ,108.119 W), and Fort Davis, TX (30.68 N,104.015 W). Under most cases the Pie Town sunspot number can be obtained from the other two by a simple weighted average, based on distance. Such a simple scheme is not successful at equatorial latitudes. We tried to repeat similar analysis for stations at Coco Is, Australia (12.188S, 96.834E) and Singapore (1.345 N,103.679 E) for orbit # 11 in Figure 2. The sunspot numbers at the two stations do not exhibit any significant correlation. The main reason for this appears to be the sensing of different portions of the anomaly region by the two receivers. Even at one station, the extendibility in time rapidly becomes a problem if we compute sunspot number to fit data for a particular time. It will be of interest to repeat this study for the sunspot number extension suggested at the end of the discussion for Scientific Objective (1).

Scientific Objective (4): We have not yet been able to locate coincident UV airglow and GPS data at this point, but an opportunity will be available in the near future with the launch of airglow sensors on ARGOS and DMSP satellites.
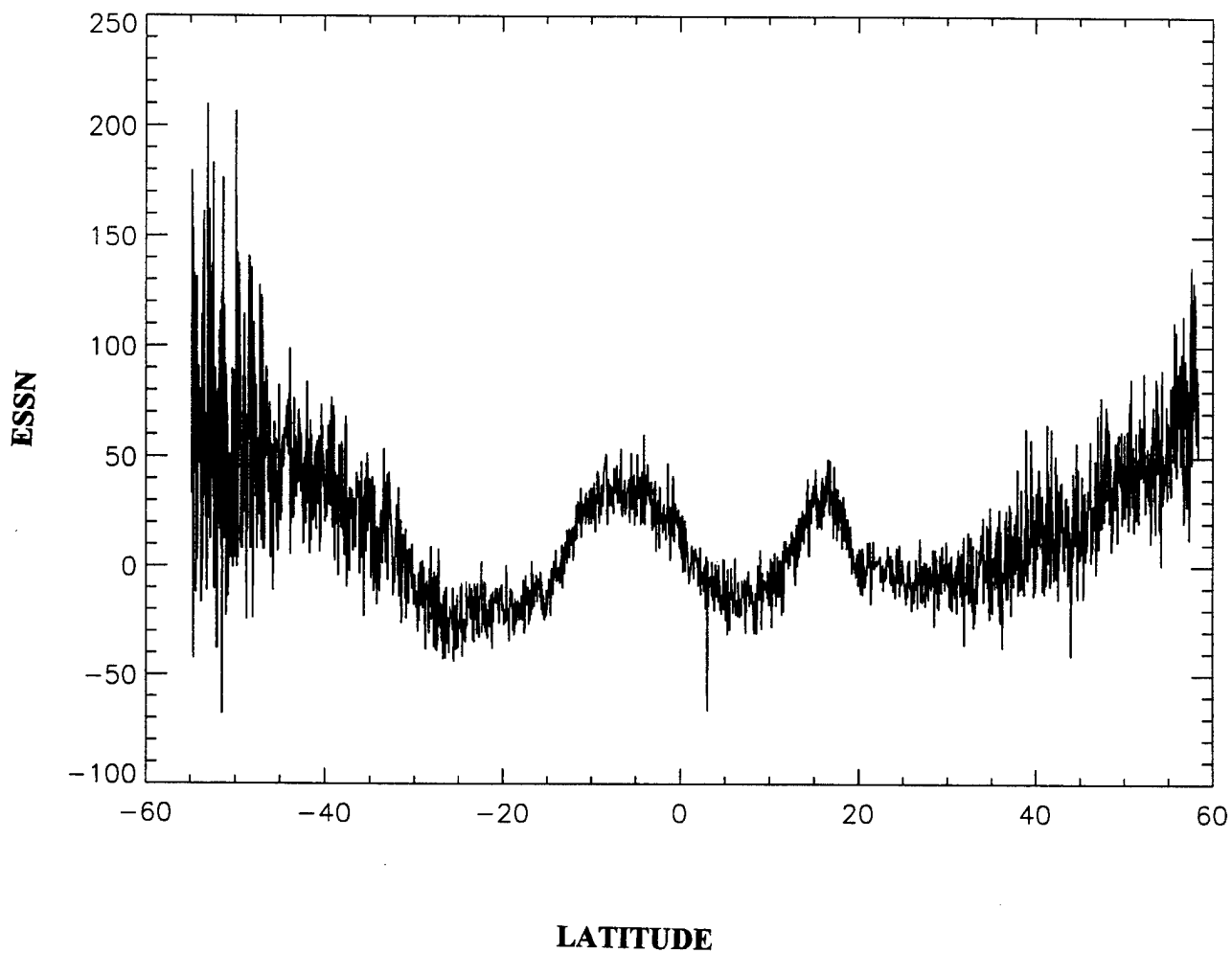
Figure 4 RIBG values of effective sunspot number (ESSN), required to fit the Topex data
in Figure 3, orbit 2

Tasks Completed:

(1) (a) Further demonstration of the efficacy of GPS data processing algorithms with RIBG and specification of the low-latitude problem, through comparisons of GPS-updated predictions with Topex data and low-latitude ISR data. **(b)** Demonstration from ISR data of an anomalous, large E-layer in the electron density profile (EDP), to be included in low latitude ionospheric model formulations and not part of present model formulations. **(c)** Development of alternate plans to solve the low-latitude problem, based on the formulation of a RIBG driving parameter representation as a constant plus a Gaussian dependence on magnetic latitude, or, by adapting computationally intensive physical ionospheric model results to the RIBG ionospheric propagation model.

(2) Improved GPS/RIBG data processing speed by a factor of twenty, so as to meet high data throughput requirements, such as in JPL's operations, where data from a global network of GPS receivers must be processed every hour, or fraction thereof, for global ionospheric specification products in near-real-time.

(3) Partial formulation of algorithms for combining multi-station GPS data for global updates of the RIBG model. Investigation of the implications of low-latitude model deficiency for this purpose.

Results/Conclusions:

(1) Low latitude models presently are not adequate for precise determination of the equatorial ionosphere, which is a major contributor of ionospheric effects for radio systems of interest, operating across this region. It remains to adequately describe the asymmetric equatorial anomaly and anomalous E layer contributions in this region. This was demonstrated through analysis of GPS, Topex, and ISR data. Alternate plans were formulated for overcoming the low-latitude problem for GPS data processing with the RIBG model, and these appear promising, in terms of approaching performance demonstrated for mid-latitudes. Processing GPS data with alternative ionospheric propagation models, based on a more complete description of low-latitude physical processes, was explored. Presently, the prospect of this is delayed, because such ionospheric models are not yet developed for radio systems implementation, and adequate radio propagation models have not yet been developed to go with them.

(2) Efficiencies introduced in the GPS data processing algorithms have speeded them up by an order of magnitude, thus making them suitable for use in high data throughput operations, such as will be required for global near-real-time ionospheric specification from GPS sensors.

(3) Assimilation of multistation data appears practical at mid-latitudes, but our results indicate that this is still problematic at low- and high-latitudes. The object is to use data sensor information, which is, for the most part, geographically and temporally distributed at points, in isolated regions, and along line segments. One needs a model to use this information to fill in the large spaces for determination of a global space-time distribution. The low- and high-latitude model deficiency are two of many significant roadblocks to this goal.

Impact for Science: A major objective is global real-time specification of the ionospheric electron density distribution for use in space weather forecasts and nowcasts for radio and electrical systems, ionospheric compensation in various types of radio systems, some requiring this information to meet ambitious performance goals, and as a database for developing solar-terrestrial physics. A major problem, because of its size and intensity, is the specification of the low-latitude ionosphere. Our approach has been to develop the technique of GPS-updated RIBG, to improve it as a practical solution for atmospheric compensation in radio systems of interest, as well as a relatively accurate technique for determining the background (minus irregularities) ionosphere in mid-latitude regions. Solution of the low-latitude problem rests on the development of computationally intensive physics-based ionospheric models, or on the use of clever data-driven techniques. We have considered both in this project, and it appears to us that much progress will be made in these areas of research in the relatively near future. The ability to solve for the background ionosphere also means that a long (so that irregularities can be essentially averaged out) time series of data can be processed to determine remote sensing system bias errors (e.g., receiver and satellite clock errors, as well as phase integer ambiguities for the GPS system), and when these are removed, the data may be used to determine ionospheric fluctuations (e.g., TEC fluctuations) for use in the development of physical models of ionospheric dynamics. These are the strengths of our approach with the data-driven model RIBG, or any other improved, practical ionospheric propagation model which may be forthcoming.

Relationship to Other Programs or Projects: JPL has an impressive facility to process data from its global network of two-frequency GPS receivers. Its routinely provides vertical TEC maps in near-real-time for CONUS, and at least on a delayed basis for global distributions. It also provides background clock error biases for GPS satellites. It could be tasked to provide simple driving parameter maps for a model like RIBG. We believe that our techniques are intrinsically more accurate than theirs for a single GPS receiver at mid-latitudes, and will be for low-latitudes, but we foresee a cooperative effort, whereby their processing capability will be combined with some of our techniques for a global data-driven RIBG (or other ionospheric propagation model) for the uses detailed above. In the meantime, there is a large effort to fuse all kinds of data in an Assimilating Physical Ionospheric Model (AIM), being developed by scientists from Utah State University (now also in private business), largely sponsored by ONR. It is hoped that some of our techniques will facilitate the development of AIM (e.g., through determination of slant TEC from GPS), through its use of GPS data to update it, and in its possible combination with a radio propagation model for atmospheric compensation, to enhance the performance of radio systems. The prospect of GPS-updated RIBG or GPS/airglow-updated RIBG would have appeal for use in DOD radio surveillance systems.

Transitions Accomplished and Expected:

It is expected that the GPS data-processing techniques will be of use for development of the AIM system, at least the component related to GPS data fusion. This is of interest to ONR. Further, GPS can be used as a sanity check and as a complementary data source, relative to other sources in the AIM data fusion effort. An efficient data-driven ionospheric propagation model is of interest for performance enhancement of DOD radio surveillance systems, and will probably be transitioned to these systems. Our techniques are relatively accurate for ionospheric compensation in GPS navigation systems and for providing relatively accurate corrections for DGPS systems. Hence, we expect commercial interest, as well as military interest, in our GPS techniques.

References:

Menke, V., Geophysical Data Analysis: Discrete Inverse Theory, Academic Press, New York, 1989

Reilly, M. H., A transionospheric radio propagation model, in *Proceedings of the Seventh International Ionospheric Effects Symposium, Doc. ITAD-730-MS-93-421,* pp. 400-408, edited by John M. Goodman, Natl. tech. Inf. Serv., Springfield, VA, 1993

Reilly, M. H. and M. Singh, Ionospheric specification from GPS data and the RIBG ionospheric propagation model, *Radio Science,* Volume 32, Number 4, Pages 1671-1679, July-August 1997