A method, system, and apparatus provide the ability to estimate ionospheric observables using space-borne observations. Space-borne global positioning system (GPS) data of ionospheric delay are obtained from a satellite. The space-borne GPS data are combined with ground-based GPS observations. The combination is utilized in a model to estimate a global three-dimensional (3D) electron density field.
References Cited

OTHER PUBLICATIONS


References Cited

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Sparks, L. (2013), Ionospheric Slant TEC Analysis Using GNSS-based Estimation (IonoSTAGE), JPL D-34117, Jet Propulsion Laboratory, Pasadena, CA.


* cited by examiner
FIG. 2

Plasmasphere contribution to bias measurements

TECU
Plasmasphere contribution to bias measurements by day

FIG. 3
FIG. 4
FIG. 6
OBTAIN SPACE-BORNE GPS DATA

COMBINE SPACE-BORNE GPS DATA WITH GROUND-BASED GPS DATA

UTILIZE COMBINATION TO ESTIMATE A 3D ELECTRON DENSITY FIELD

FIG. 8
CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. Section 119(e) of the following co-pending and commonly-assigned U.S. provisional patent application(s), which is/are incorporated by reference herein:

Provisional Application Ser. No. 61/596,406, filed on Feb. 8, 2012, by Philip Stephens, Attila Komjathy, Brian D. Wilson, and Anthony J. Mannucci, entitled “Processing COSMIC/FORMOSAT-3 Data for Slant Total Electron Content Measurements”.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to ionospheric modeling, and in particular, to a method, apparatus, and article of manufacture for including ionospheric radio occultation data between satellites and global positioning system (GPS) transmitters to improve ionospheric modeling.

2. Description of the Related Art

(Note: This application references a number of different publications as indicated throughout the specification by names and years of publications (e.g., Author [2006]). A list of these different publications ordered according to these references can be found below in the section entitled “References.” Each of these publications is incorporated by reference herein.)

Ionospheric remote sensing is in a rapid growth phase driven by an abundance of ground and space-based GPS receivers, new UV (ultraviolet) remote sensing satellites, and the advent of data assimilation techniques for space weather. The success of the GPS/MET (Global Positioning System/Meteorology) experiment in 1995 inspired a number of follow-on radio occultation missions for profiling the atmosphere and ionosphere. Such processing provides ionospheric observables that can be used (e.g., in combination with other systems) to estimate a global 3D electron density field.

SUMMARY OF THE INVENTION

Ionospheric modeling can be improved by the inclusion of occultation data between satellites and GPS transmitters. COSMIC/FORMOSAT-3 provides a large dataset of such occultations. In order to utilize these absolute measurements in an assimilative model, the data must be carefully processed; the level of the ionospheric combination and the differential biases must be accurately determined. The COSMIC GPS receivers operate in a high multipath environment; a phase leveling algorithm, utilizing the information in the multipath, improves the leveling errors by at least 0.4 TECU.

Receiver biases are then computed from the leveled data by making some simplifying assumptions about the structure of the ionosphere and plasmasphere. Such ionospheric modeling provides occultation measurements as slant total electron content to an accuracy of 2.1 TECU (total electron content unit).

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIG. 1 illustrates an example of a PI combination versus a leveled LI combination for many arcs of data for a site in Australia on Nov. 16, 2010 in accordance with one or more embodiments of the invention;

FIG. 2 shows a histogram of the total plasmasphere contribution for all COSMIC measurements that were upward looking (>70°) and above 60 degrees latitude for all 6 COSMIC satellites between Jan. 1, 2009 and March 1, 2009 in accordance with one or more embodiments of the invention;

FIG. 3 illustrates the daily variations of the plasmasphere contributions in accordance with one or more embodiments of the invention;

FIG. 4 shows the 10-day average biases for three of the COSMIC satellites between Oct. 1, 2010 and Oct. 24, 2010 in accordance with one or more embodiments of the invention;
The ionosphere combinations, 

\[ P_r = P_r(\gamma - 1)I_{[\text{L}]} - N + \text{Am} \delta_{\text{L}} + \text{Am}_{\text{p}} + \text{Am}_{\text{p}} + \text{Am}_{\text{p}}. \]

\[ L_z = L_z(\gamma - 1)I_{[\text{L}]} - N + \text{Am} \delta_{\text{L}} + \text{Am}_{\text{p}} + \text{Am}_{\text{p}}. \]

are dominated by the ionospheric contributions in the domain where the noise and carrier multipath contributions are low.
mize the variance of the $P_2 L_2$ combinations using the multipath to develop a weight. Since one may have no a priori knowledge of the distribution of the multipath, the method of maximum entropy (Cover and Thomas [1991]) suggests that only the mean and variance of the multipath should be taken and a normal distribution function should be used as the weighting function. This approach introduces the least amount of self-correlation between the weighted average and the sample of the distribution. Consider now the two multipath combinations (not to be confused with the $m_{pp}$ terms)

$$MP_1 = P_1 - \frac{a}{d} L_1 \lambda_1 + \frac{b}{d} L_2 \lambda_2,$$

$$MP_2 = P_2 - \frac{c}{d} L_1 \lambda_1 + \frac{d}{d} L_2 \lambda_2,$$

where $a$, $b$, $c$ and $d$ are frequency dependent combinations, for the given $f_1$ and $f_2$ these are:

$$a=5529, \quad b=7200, \quad c=11885, \quad d=2329.$$

It was shown in Estey and Meer tens [1999] that these combinations can be expressed as

$$MP_1 = \bar{e}_1 \left(1 + \frac{2}{\lambda - 1}\right) \bar{p}_{1} \lambda_1 + \left(\frac{2}{\lambda - 1}\right) \bar{p}_{2} \lambda_2 - \left(1 + \frac{2}{\lambda - 1}\right) m_{pp} \bar{p}_{2},$$

$$MP_2 = \bar{e}_2 \left(\frac{2}{\lambda - 1}\right) \bar{p}_{1} \lambda_1 + \left(\frac{2}{\lambda - 1}\right) \bar{p}_{2} \lambda_2 - \left(\frac{2}{\lambda - 1}\right) m_{pp} \bar{p}_{2},$$

where $\bar{e}_1$ are combinations of the carrier multipath, $m_{pp}$, and the noise, $\bar{e}_2, \bar{e}_p$. Therefore the difference

$$MP_1 - MP_2 = P_1 - \lambda_1 L_1 - \lambda_2 L_2,$$

$$= \Delta \bar{e} + \Delta m_{pp} \bar{p} + \lambda_1 N_1 - \lambda_2 N_2.$$

It has also been shown (Hofmann-Wellenhof [2001]) that the noise and carrier phase multipath are two (2) orders of magnitude smaller than the pseudorange multipath. For each connected arc, the ambiguities are constant, so Eqn. 11 is a distribution of the differential pseudo range multipath. This distribution may be used to derive the Gaussian statistics of the weighting function for the width of the differential multipath contribution to be used during the weighting. This implies that points in the arc that have large deviation from the mean of the differential multipath contribution will not have a large influence on the calculation of $\langle N \rangle$. This is what is desired to help reduce the variance in the weighted $P_2 L_2$ calculation. The weighting function is then the normal distribution of the difference in the multipath combinations with mean and variance

$$\mu = \frac{1}{N} \sum_{i=1}^{N} (MP_{1,i} - MP_{2,i}), \quad \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (MP_{1,i} - MP_{2,i} - \mu)^2.$$

The $w_i$ for each measurement is calculated as

$$w_i = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{\frac{(MP_{1,i} - MP_{2,i} - \mu)^2}{2\sigma^2}\right\}.$$

Using this one finds:

$$\langle \lambda \rangle = \Delta \bar{e} + \Delta m_{pp} \bar{p} + \Delta \bar{e}_L + \Delta \bar{e}_p \bar{p},$$

$$\langle \Delta \bar{p} \rangle = \langle \Delta \bar{e}\rangle + \langle \Delta m_{pp} \rangle \bar{p}.$$

This can be converted to slant TEC (STEC) by

$$\sum_{i=1}^{N} \frac{40.3 \cdot \text{TEC}}{f_i^2} \gamma - 1 = B_i + \Delta \sum_{i=1}^{N} \frac{40.3 \cdot \text{TEC}}{f_i^2} \gamma - 1,$$

where $B_j = \frac{40.3 \cdot \text{TEC}}{f_i^2} \gamma - 1$.

The determination of $B$, which is dominated by the satellite and station differential biases, is discussed in the following section.

**Bias Estimation**

One of the features of the GIM data processing system is the ability to estimate the satellite and receiver differential biases, $B_{pp}$, from Eqn. 16 by taking cross correlations between many different ground based GPS measurements. Each ground station has multiple satellite links which allow an algorithm to be developed for determining the bias between station i and receiver j in a relative sense. By fixing one of the relative satellite biases to be 0, the complete deconvolution of $\Delta \bar{e}_{pp}$ and $\Delta \bar{e}_{pp}$ is performed. This, of course, is done under the assumption that for some weighting function $g$, one can assume:

$$\langle \Delta m_{pp} \rangle_{g} = \langle \Delta \bar{e}_{pp} \rangle_{g} = 0,$$

where the subscript $g$ indicates a weighted mean using $g$ as the weighting function.

For an unbiased distribution, $g$, this is true for an unbiased noise (e.g. $\Delta \bar{e}_{pp}$). For the ground GPS receivers, it is also safe to assume that the multipath is small, thus the weighted mean of zero is also a fair assumption. Another assumption that leads to the same conclusion is that the global average multipath over all satellites and receivers is zero. Under these assumptions, for weighting function $g$, GIM provides

$$R_{i,j} = \frac{40.3 \cdot \text{TEC} \cdot \Delta \bar{e}_{pp}}{f_i^2} + \Delta \bar{e}_{pp} + \langle \Delta m_{pp} \rangle_{g},$$

where the $\delta$ represents the relative bias where each has been shifted in opposite directions by some constant value (this is the absolute bias of the GPS satellite fixed to 0).
For the space-platform, such as COSMIC, GIM is not suitable to estimate receiver biases. Instead, one can use the relative satellite biases produced by GIM and generate a relative COSMIC receiver bias. Thus one effectively computes:

$$B_r = B_p - \frac{40.3 \cdot TEC \Delta h_{1,2}^P}{f_1} \times \frac{1}{\gamma}$$

Unfortunately, the multipath in the COSMIC environment is larger than the ground case. As a result, one cannot make the same assumption about the unbiased distribution and therefore, cannot neglect the weighted mean. This will differ from arc to arc and introduces larger variances in the bias estimation for space-borne GPS data.

The GIM bias estimation relies on cross correlation between multiple sites measuring the same ionosphere. For the space-based GPS data, this data overlap is not available and an alternate method must be employed. One could use a background model, such as the International Reference Ionosphere (IRI) (Blitzr and Reinsch [2008]) but these models are not able to capture the space weather conditions that may be present.

Instead, embodiments of the invention employ a simple but effective approach. Since COSMIC is orbiting at around 800 km, above the F-region peak, one expects upward looking measurements to be passing through a minimal amount of the ionosphere. If the measurements are restricted to be in the high latitude regions, the contribution from the plasmasphere is expected to be very small. Under the assumption that the high-latitude and high elevation angle measurements pass through a minimal amount of TEC, these measurements can be used to derive a bias for the receiver. This is done by tabulating the smallest measurement of an arc that passes through the filtered region. Over the course of the day the measurements are averaged. From this average a small component due to the small ionosphere and plasmasphere contributions are subtracted. This average minus estimated contribution is the daily bias for the receiver.

A recent study by Yizengaw et al. [2008] showed that the plasmasphere contribution to the total ground based TEC in high latitude regions was about 25%. FIG. 2 shows a histogram of the total plasmasphere contribution for all COSMIC measurements that were upward looking (>70°) and above 60 degrees latitude for all 6 COSMIC satellites between Jan. 1, 2009 and Mar. 31, 2009. The plasmasphere contribution was computed by integrating the line-of-sight TEC through the Sheeley-Tu (Sheeley et al. [2001]; Tu et al. [2006]) plasmasphere model. The total contribution appears to be at the 0.1 TECU level.

FIG. 3 illustrates the daily variations of the plasmasphere contributions. The lines represent the means of the plasmasphere contribution and the error bars represent the 1-sigma range of the plasmasphere contributions. Thus, it can be seen from FIG. 3 that the daily variation of the mean is minimal and the 1-sigma variation each day is similarly of order 0.1 TECU. In a simplistic model, it may be assumed that the background TEC between COSMIC and the GPS satellite in the upward looking, high-latitude measurements, is 0.5 TECU, with errors of order 0.1 TECU. This estimate is likely to be slightly large by a few tenths of TECU and is intended to compensate for the fact that there is a double bulge in FIG. 2 in which the plasmasphere is sometimes larger by 50% or more.

Applying this process, a daily estimate of the receiver bias, $$B_r$$, can be computed. To eliminate potential data errors and variabilities, the actual bias used is a 10-day running average of the daily estimates. It is also not unlikely to have entire days which do not meet the filtering criteria. For these missing days, the global bias average (for all days) is used in place of the daily estimate in the 10-day average.

FIG. 4 shows the 10-day average biases for three of the COSMIC satellites between Oct. 1, 2010 and Oct. 24, 2010. More specifically, FIG. 4 illustrates the daily variation of the bias estimates for antenna 0 of COSMIC satellite number 4 (04.0), antenna 1 of COSMIC 1 (01.1) and antenna 0 of COSMIC 6 (06.1). The right axis shows the number of data arcs available each day for the bias estimate. The histogram of FIG. 4 shows the number of arcs of data that satisfy the filtering criteria. The variabilities for satellite 4 and 6 appear to be of the order of 1 TECU but the estimated value seems to be stable. Satellite 1 shows a bimodal behavior. This is suspected of being due to a real discrete change in the hardware bias.

**Discussion**

The improved performance of the multipath weighted leveling can be seen in FIG. 5. Thus, FIG. 5 illustrates histograms of the difference between $$P_r$$ and $$L_r$$ using a new multipath weighted leveling scheme 502 and the old elevation angle weighted leveling scheme 504 for Dec. 21, 2006 in accordance with one or more compositions of the invention.

In other words, FIG. 5 shows the histograms of the elevation angle weighted leveling scheme 504 indicates the elevation weighted leveling used in GIM for ground-based GPS data. From the width of the histograms, the new weighting technique 502 levels the $$P_r$$ combination consistently closer to the $$P_r$$ combination than does the elevation angle weighted approach. This is as expected, as the new leveling weights are designed to minimize the variance of this distribution. Table 1 below tabulates the RMS difference for each panel of FIG. 5.

<table>
<thead>
<tr>
<th>COSMIC</th>
<th>MULTIPATH BASED</th>
<th>ELEVATION ANGLE BASED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.1 TECU</td>
<td>6.8 TECU</td>
</tr>
<tr>
<td>2</td>
<td>4.0 TECU</td>
<td>4.4 TECU</td>
</tr>
<tr>
<td>3</td>
<td>6.4 TECU</td>
<td>7.1 TECU</td>
</tr>
<tr>
<td>4</td>
<td>6.5 TECU</td>
<td>7.3 TECU</td>
</tr>
<tr>
<td>5</td>
<td>4.2 TECU</td>
<td>4.8 TECU</td>
</tr>
<tr>
<td>6</td>
<td>6.5 TECU</td>
<td>7.2 TECU</td>
</tr>
</tbody>
</table>

As shown, Table 1 illustrates a consistent improvement of about 0.5 TECU or more across all satellites.

The final result of the leveling/bias removal procedure is shown in FIG. 6. FIG. 6 shows the leveled and unbiased data from COSMIC 1 on Oct. 22, 2010. This figure contains all of the connected phase arcs for one day. The tight structure shows the leveling algorithm is consistent from arc to arc. The approach of the slant TECU measurement to zero as elevation angle increases shows the biases are also being appropriately computed.

One may consider the total error of these slant TECU measurement derived from COSMIC GPS signals. Hwang et al. [2010] have shown that the multipath error for COSMIC is of the order of a few cm. Using an upper limit of 4 cm, this is equivalent to 0.4 TECU. From experience with both ground
and space based data, the systematic error of the leveling algorithm may be approximated to be 2 TECU. Adding this error to the bias error of 0.5 TECU, the total error of these slant TECU measurements are estimated to be 2.1 TECU.

Hardware Environment

FIG. 7 illustrates a hardware system utilized in accordance with one or more embodiments of the invention. Satellite 702 represents the constellation of four or more satellites (or fewer satellites in certain situations) configured to transmit time and positioning information necessary to determine a location of a receiver. Space-borne receiver 704 and ground based receiver 706 are both configured to receive the information transmitted from satellite constellation 702 and use such information to determine a location. Ground based receiver 706 and/or processor 708 may also receive such information from space-borne receiver 704. Processor/computer 708 is configured to further process the signals from ground based receiver 706 and space-borne receiver 704 as described above. More specifically, processor 708 is configured to combine the GPS observations from receivers 704 and 706 and use the combination as a backbone for a modeling system that is used to estimate the global 3D electron density field.

Processor 708 may be a computer having general and/or special purpose hardware processors and a memory (e.g., random access memory [RAM]). Such a processor may be coupled to, and/or integrated with, other devices, including input/output (I/O) devices such as a keyboard, a cursor control device (e.g., a mouse, a pointing device, pen and tablet, touch screen, multi-touch device, etc.) and a printer.

Output/results from processor 708 may be presented on a display (that may be integrated into/with processor/computer 708) or provided to another device for presentation or further processing or action. In one embodiment, such a display comprises a liquid crystal display (LCD) having a plurality of separately addressable liquid crystals. Alternatively, the display may comprise a light emitting diode (LED) display having clusters of red, green and blue diodes driven together to form full-color pixels. Each liquid crystal or pixel of the display changes to an opaque or translucent state to form a part of the image on the display in response to the data or information generated by the processor from the application of the instructions of a computer program and/or operating system to the input and commands.

The processor/computer 708 may also optionally comprise an external communication device such as a modem, satellite link, Ethernet card, or other device for accepting input from, and providing output to, other processors/computers 708. Processor 708 may be configured to execute a computer program/instructions stored in memory or permanent storage that cause the processor 708 to perform the steps necessary to implement and/or use the present invention or to load the program of instructions into a memory, thus creating a specialized component for/representing the ionosphere and plasmasphere which contribute (e.g., to determine a daily bias for the receiver). The actual bias for the receiver may consist of a 10-day running average of the daily biases.

CONCLUSION

This concludes the description of the preferred embodiment of the invention. The following describes some alternative embodiments for accomplishing the present invention. For example, any type of computer, such as a mainframe, minicomputer, or personal computer, or computer configuration, such as a timesharing mainframe, local area network, or standalone personal computer, could be used with the present invention.

In summary, embodiments of the invention provide a new processing system for COSMIC data. This new system uses the information in the multipath combination to provide a TEC level based on variance reduction of the combination. This level is more accurate than an alternate weighting scheme, i.e., the elevation based weighting scheme used by GIM. Using the correctly leveled phase connected arcs from COSMIC, a relative receiver differential bias can be estimated. The process of leveling and bias estimation has an error of order 2.1 TECU.

With a processing system in place, it is now possible to systematically assimilate COSMIC GPS measurements into a model such as JPL/USC GAIM. Such tool can be utilized to systematically include COSMIC measurements on a daily basis. It has been shown that such inclusion leads to improved profile structures and better global data coverage.

The foregoing description of the preferred embodiment of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above
teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

REFERENCES


The method of claim 5, wherein the estimating the bias comprises utilizing an unbiased level of a pseudo-range correction.

The method of claim 1, wherein the utilizing comprises:

obtaining ground-based GPS observations.

The method of claim 3, wherein the phase leveling comprises utilizing an unbiased level of a pseudorange code ionospheric observable to set a level of a carrier phase ionospheric observable.

The method of claim 1, wherein the utilizing comprises estimating a bias of the space-borne satellite receiver and a second receiver.

The method of claim 5, wherein the bias is estimated by utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.

The method of claim 1, wherein the utilizing comprises:

obtaining space-borne global positioning system (GPS) data of ionospheric delay from a space-borne satellite receiver;

obtaining ground-based GPS observations;

combining the space-borne GPS data with the ground-based GPS observations; and

utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.

The method of claim 1, wherein the utilizing comprises:

obtaining space-borne global positioning system (GPS) data of ionospheric delay from a space-borne satellite receiver;

obtaining ground-based GPS observations;

combining the space-borne GPS data with the ground-based GPS observations; and

utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.

The method of claim 1, wherein the utilizing comprises:

obtaining space-borne global positioning system (GPS) data of ionospheric delay from a space-borne satellite receiver;

obtaining ground-based GPS observations;

combining the space-borne GPS data with the ground-based GPS observations; and

utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.

The method of claim 1, wherein the utilizing comprises:

obtaining space-borne global positioning system (GPS) data of ionospheric delay from a space-borne satellite receiver;

obtaining ground-based GPS observations;

combining the space-borne GPS data with the ground-based GPS observations; and

utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.

The method of claim 1, wherein the utilizing comprises:

obtaining space-borne global positioning system (GPS) data of ionospheric delay from a space-borne satellite receiver;

obtaining ground-based GPS observations;

combining the space-borne GPS data with the ground-based GPS observations; and

utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.

The method of claim 1, wherein the utilizing comprises:

obtaining space-borne global positioning system (GPS) data of ionospheric delay from a space-borne satellite receiver;

obtaining ground-based GPS observations;

combining the space-borne GPS data with the ground-based GPS observations; and

utilizing the combination in a model to estimate a global three-dimensional (3D) electron density field.
10. The system of claim 9, wherein the space-borne GPS data is obtained via the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC).

11. The system of claim 9, wherein the utilizing comprises phase leveling the space-borne GPS data.

12. The system of claim 11, wherein the phase leveling comprises utilizing an unbiased level of a pseudorange code ionospheric observable to set a level of a carrier phase ionospheric observable.

13. The system of claim 9, wherein the utilizing comprises estimating a bias of the space-borne satellite receiver and a second receiver.

14. The system of claim 13, wherein the bias is estimated by taking cross correlations between multiple different ground based GPS measurements.

15. The system of claim 13, wherein the estimating the bias for the second receiver comprises:
   tabulating a smallest measurement of an arc that passes through a filtered region of the ionosphere;
   averaging the smallest measurements over a course of a day;
   subtracting, from the average, a component for the ionosphere and plasmasphere contributions, to determine a daily bias for the second receiver.

16. The system of claim 15, wherein the bias for the second receiver comprises a 10-day running average of the daily biases.

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