The Use of GPS/MET Data for Ionospheric Studies

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LONG-TERM GOAL

The long-term goal of this research is to specify global high-resolution 4-D ionospheric electron density fields and scintillation maps close to real-time. These data products will assist in the development of better physics based models and may lead to improvements in short-term “Space Weather” prediction.

SCIENTIFIC OBJECTIVES

The primary scientific objective of this research is to develop GPS radio occultation inversion techniques that compute accurate ionospheric electron density profiles (even in the presence of horizontal inhomogeneities), and thus provide a key parameter of the local ionospheric state. Another important objective is to estimate the profiling accuracy of each developed technique. A final objective is to investigate the feasibility of locating regions of scintillation in the ionosphere with space-based GPS data. It is clear that developing fast and efficient algorithms is an underlying objective here and will be necessary for performing accurate space weather prediction in the future.

APPROACH

We use comparisons of GPS/MET derived profiles with correlative data to validate different GPS radio occultation inversion techniques. The tested inversion techniques use dual frequency GPS/MET carrier phase (L1 and L2) data received in LEO at ~735 km altitude to compute ionospheric electron density profiles (EDPs). The inversion techniques are also formulated to use calibrated dual frequency TEC (not bending angle) data computed from the difference in L1 and L2 phase measurements. The TEC data is calibrated by using data from both the ascending and descending parts of the LEO orbit with respect to the largest impact distance (see discussion below in Work Completed section). The standard inversion technique uses the assumption of local spherical symmetry in refractivity (electron density) in the vicinity of the GPS to LEO ray tangent point. This technique is using the Abel transform and is shown to work well under calm ionospheric conditions. In regions with strong electron density gradients, however, this technique can result in large EDP errors. To minimize these errors we also examine a three dimensional (3D) inversion technique that is constrained with the horizontal structure

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of an a priori 3D electron density field. Three sources of a priori electron density fields are used as input for testing the constrained inversion technique. Comparisons with correlative ionosonde foF2 data and GPS ground-based vertical TEC data are used to validate both the Abel and the 3D constrained inversion techniques.

WORK COMPLETED

This section summarizes the most significant work completed in this study. A great deal of effort went into improving the accuracy of three previously developed inversion algorithms: 1) the Abel inversion; 2) the 3D constrained inversion, constrained by horizontal structure of 1st guess electron density field; and 3) 3D variational assimilation. Development of the 3D variational assimilation technique was suspended due to apparent numerical instabilities that arose from a lack of observational data. However, modifications to the Abel and 3D constrained inversion procedures were developed, coded and tested under this study in an effort to improve and speed up processing. These modifications involve formulating the inversion problem to use dual frequency TEC data that are calibrated with data from the opposite side of the occultation (with respect to the largest impact distance) [Schreiner et al., 1998]. Numerical simulations were performed to substantiate the use of dual frequency TEC data (as opposed to single frequency bending angle data) for estimating large scale features of the inverted profiles [Schreiner et al., 1998]. The use of dual frequency TEC data (instead of single frequency) allows for the efficient removal of clock and orbit errors and is thus well suited for computing EDPs on-orbit and in near real-time. The use of calibrated TEC data eliminates the effect of the ionosphere above the LEO altitude, but is truly only valid when the GPS satellite is in the LEO orbital plane. Initial statistical comparisons show that the non-calibrated inversions possess a statistically significant bias with respect to ionosonde foF2 data, whereas the calibrated inversions do not possess a bias.

Once we were confident in the above modifications, ionosonde foF2 and GPS vertical TEC correlative data were acquired and used to perform statistical comparisons with hundreds of GPS/MET derived ionospheric soundings that were computed with the Abel and 3D constrained techniques.

In addition, we began searching our database for evidence of scintillation in 50 Hz data. Algorithms to locate regions of scintillation given GPS phase and amplitude data have been identified, but software development and data processing have not been started. The Abel inversion and the 3D constrained inversion with 1st guess fields are summarized briefly below.

Abel inversion

This approach is using the assumption of local spherical symmetry of refractivity (which is proportional to electron density) in the vicinity of tangent points of the rays. We have formulated our Abel inversion software to use calibrated dual frequency TEC data.

3D constrained inversion: constrained by horizontal structure of 1st guess electron density field

This inversion does not use the Abel technique at all. GPS observations are used to adjust the magnitude in each layer of the guess field, while preserving the relative horizontal variations. The technique was implemented very similar to the method described in our 1997 proposal, but has also been formulated to use calibrated dual frequency TEC data. Three sources of a priori electron density fields are used as input for the constrained inversions: a) the Parameterized Real-Time Ionospheric Specification Model (PRISM) [Daniell, 1995] when adjusted with global foF2 (critical frequency) data based on ionosondes; b) the PRISM model when adjusted with global ionospheric map (vertical TEC) data; and c) 3D tomographic reconstructions of the ionosphere using GPS ground-based and GPS/MET space-based total electron content (TEC) data [Rius et al., 1997]. The inversion source code was modified to ingest these a priori fields. The PRISM code was modified to output electron density on a grid specified by the observations. Significant effort also went into the development of a subroutine that could interpolate the tomographic fields with coarse spatial resolution to observation points of interest. This subroutine allows us to constrain the solution with horizontal information from a variety of sources, as long as the source can represent electron density on a grid of latitude, longitude, and height.

RESULTS

First we present inversion results of two occultations to illustrate some potential EDP differences between each inversion technique that are due to differences in the assumed horizontal structure of electron density. Then we present statistical comparisons for the Abel and 3D constrained inversions. We finish with an update of scintillation results.

Individual Occultations

Figure 1 compares the three different constrained inversion solutions with Abel solutions and correlative ionosonde foF2 data for two different occultations. The left panel shows an example occultation where the Abel inversion performs better than all of the constrained inversion approaches. The right panel shows a comparison where the Abel solution does not perform as well as the constrained solutions that use PRISM with foF2 and TEC data. Both occultations in ***Figure 1*** occur near the post sunset ionosphere where horizontal gradients can be expected. The differences in NmF2 shown in ***Figure 1*** correspond to approximately 0.7 MHz in foF2.

Abel inversion comparisons

The Abel inversion provides a vertical electron density profile (N vs. altitude) assuming spherical symmetry. In practice we assign this profile to the latitude and longitude of the tangent point of the ray at the altitude of the reconstructed F2 peak. We compare GPS/MET derived foF2 data to the closest ionosonde foF2 data within 1,200 km of the reconstructed GPS/MET profile. To compare the Abel inversions to Global Ionospheric Map (GIM) vertical TEC data, the electron density profile is integrated from orbit altitude to the ground to obtain an equivalent measurement of sub-satellite vertical TEC. We compare the GPS/MET vertical TEC to GIM data that is interpolated to the assigned position and time of the reconstructed profiles.

For our comparisons we have processed GPS/MET occultations from 4 days (February 20th-23rd) in 1997 when A/S was off. The ionosonde foF2 data are from a network of 45 ionosonde stations, and the vertical TEC data are derived from the global network of GPS ground receivers. The mean and rms deviations of GPS/MET Abel inversions compared to ionosonde foF2 and GIM TEC data are summarized in the first line of Table 1. For each case we also calculated a constrained linear regression that originates from zero, assuming that a bias in the observations should be statistically proportional to electron density. The Abel inversion approach agrees globally with the foF2 correlative data at the 0.5 MHz rms level (~ 10% level) with a negligible mean difference. The agreement over CONUS and Europe is near the 0.4 MHz rms level. The precision of the ionosonde critical frequency (foF2) data is approximately 0.1 MHz [Kroehl, personal communication, 1998], considerably less than 0.5 MHz. Possible sources of difference that may be contributing significantly to the 0.5 MHz rms include: the inherent spatial variability of the ionosphere along with the fact that a correlative matching criterion of 1,200 km (the average match distance is 680 km) is used in this study, the temporal variability not captured by the hourly ionosonde data, the horizontal smearing of occultations that are off to the side of the LEO orbit (~ 3,000 km of smear for 45 degree azimuth angle), or a breakdown of the spherical symmetry assumption near high gradient regions.

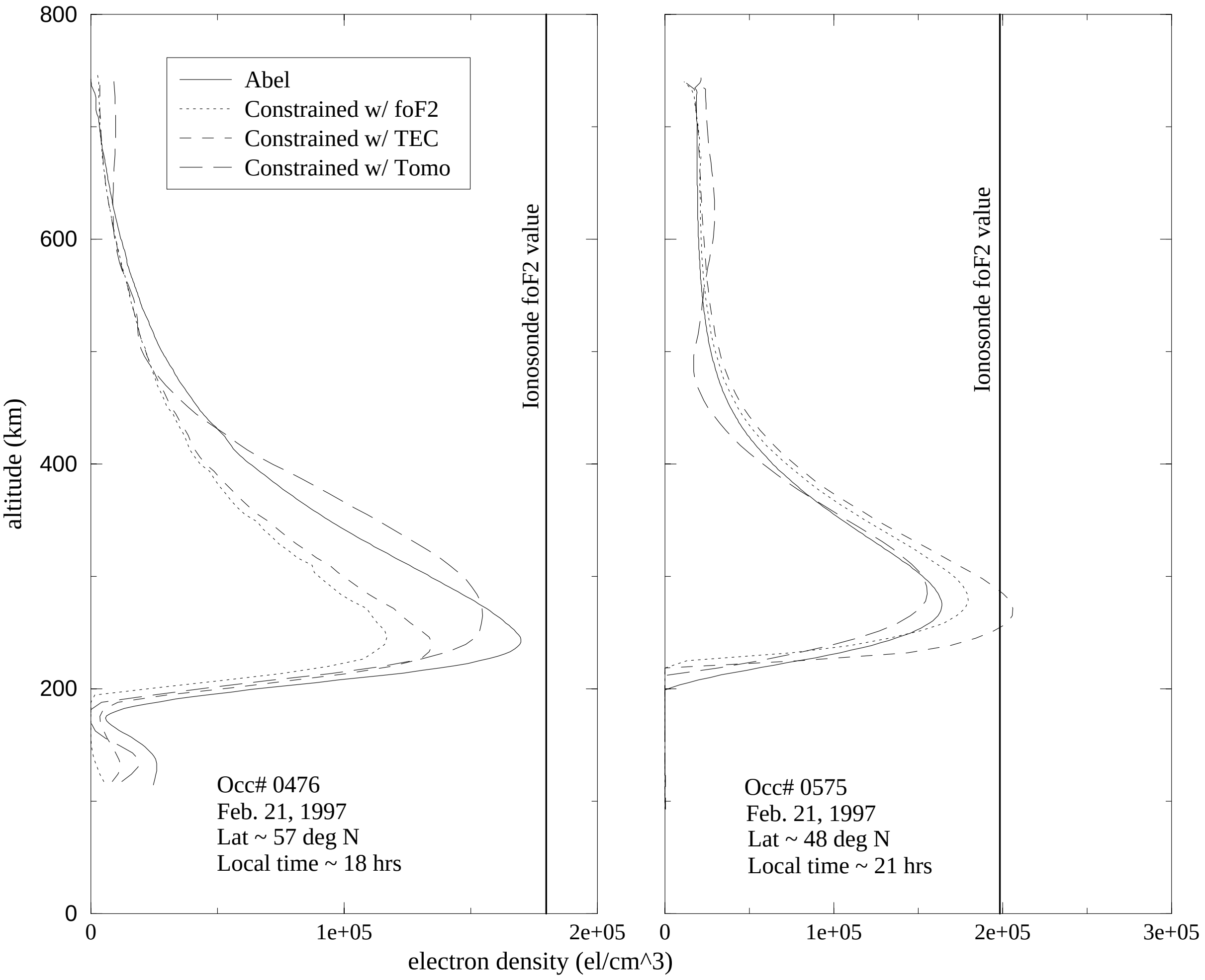

Figure 1: Comparisons of Abel and constrained inversions for two occultations in the post sunset ionosphere. The Abel inversion compares with the ionosonde foF2 data (truth) better than the constrained inversions for the occultation in the left panel.
The right panel shows an occultation where the inversion constrained with PRISM (when adjusted with GPS vertical TEC) performs the best. The differences in NmF2 shown here correspond to ~0.7 MHz in foF2.

As seen from **Table 1**, reconstructed foF2 values have a very small bias with respect to the ionosondes, while the reconstructed TEC data are significantly biased with respect to the GIM TEC. This is explained by that portion of the ionosphere above the LEO altitude, which is not reconstructed from the radio occultation data. Therefore, the mean difference between the reconstructed TEC and the GIM TEC gives an estimate of TEC above the LEO altitude.

3D Constrained Inversion Comparisons

Constrained inversions formally provide us with a 3D electron density field. Thus, for comparisons to ionosondes we calculate the vertical electron density profile (and the corresponding foF2) at the site of the ionosonde. To compare the constrained inversions to GIM vertical TEC data, the electron density profile is integrated as is done for the Abel statistics. When applying these electron density fields as constraints for our inversions, we process only those occultations that take place over Europe or the continental USA. We do this because these are the only two regions with enough observational data to significantly adjust the horizontal structure of the a priori electron density fields.

The results of the foF2 and TEC comparisons of the PRISM and tomographic constrained inversions are summarized in **Table 1**. The precision of the GIM vertical TEC data (as compared to TOPEX altimeter vertical TEC data) varies from 2 TECU under quiet to 4 TECU under disturbed ionospheric conditions [Pi, personal communication, 1998].The constrained inversions do not show statistically significant improvement over the Abel inversions. The reconstructed foF2 from the constrained inversions are negatively biased as compared to Abel inversions. This may be explained by the use of insufficiently accurate a priori electron density fields and the non-linearity of the constrained solutions with respect to the a priori electron density fields. The adjustment of PRISM with TEC results in slightly better agreement as compared to the PRISM constrained inversions using ionosonde data. The reason may be that the TEC observational network is denser than the ionosonde network, which results in better reproduction of the horizontal structure of the global electron density fields. 3D inversions constrained with the tomographic fields generally have a smaller rms difference than the PRISM constrained solutions, which may indicate that the tomographic a priori fields are more accurate than the adjusted PRISM fields. Since the number of constrained inversion comparisons is not too high, our conclusions must be considered preliminary. More samples should be computed to allow adequate culling of data and to provide more statistically significant validation results.

Table 1: Summary of statistical comparisons for 97.051-054 (Feb 20th-23rd, 1997).

	Comparisons to the ionosonde foF2				**Comparisons to the GIM TEC**			
	# of matches	**Mean [MHz]**	**RMS [MHz]**	**RMS (linear regress.) [MHz]**	**# of matches**	**Mean [TECU]**	**RMS [TECU]**	**RMS (linear regress.) [TECU]**
Abel inversion (world)	163	-0.002	0.53	0.53	783	-2.82	3.41	1.55
Abel inversion (CONUS & EUROPE)	34	-0.05	0.37	0.37	40	-2.38	2.97	1.14

PRISM constrained inversion by ionosondes	33	-0.31	0.55	0.47	40	-2.85	3.50	1.50
PRISM constrained inversion by TEC	34	-0.19	0.50	0.45	40	-2.72	3.22	1.10
Tomography constrained inversions	17	-0.18	0.48	0.46	18	-2.19	2.86	1.25

Scintillation Studies

When observing scintillation, it is desirable to sample the phase and amplitude at as high a rate as possible to limit aliasing of the high frequency components of the signal. During the GPS/MET mission, a handful of experiments were conducted to track 50 Hz ionospheric occultation data from orbit altitude to the ground. These data have not been processed beyond the level 0 data format. However, an abundance of neutral atmospheric occultation data from GPS/MET (acquired at a 50 Hz rate) can still be searched for evidence of ionospheric scintillation when the link is sufficiently above the neutral atmosphere . These 50 Hz data do not sample entire occultations from orbit altitude to the ground, but they do provide approximately a 20-30 second snapshot of scintillation activity along the occulted ray. Initial efforts have found evidence of scintillation activity in the GPS/MET satellite data. ***Figure 2*** shows the L1 C/A signal-to-noise ratios (SNR) for two occultations that occurred on February 16th, 1997. The occulting rays stay above the stratosphere for the first 30 seconds of each occultation The SNR data for occultation #0070 is shown in the left panel and does not show evidence of scintillation.

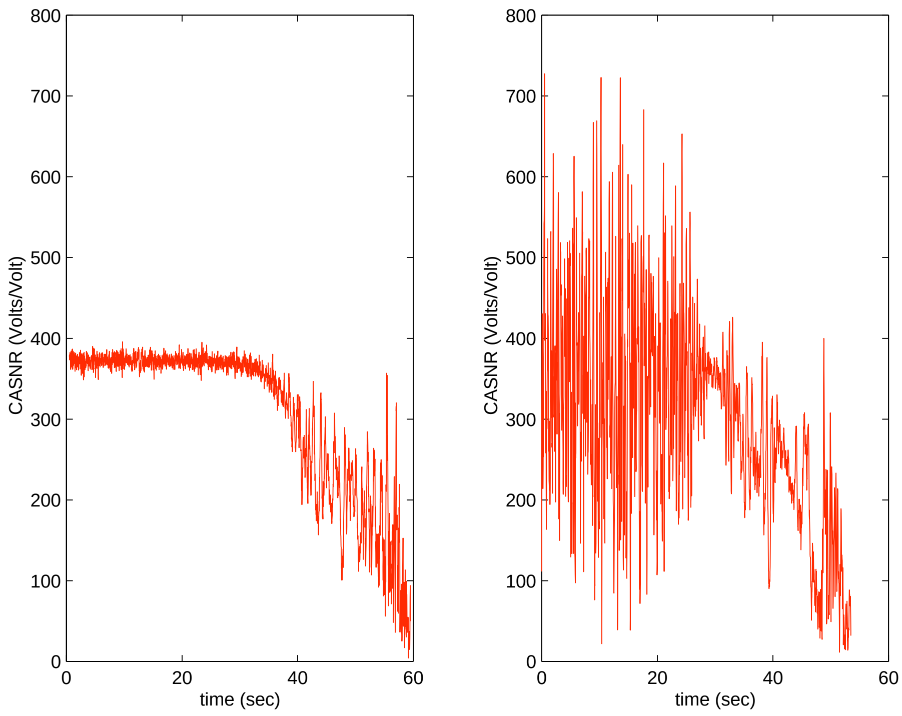

Figure 2: 50 Hz CA SNR data for neutral atmospheric profiles with and without evidence of scintillation. The left panel shows the SNR data for occultation #0070 which had a latitude of ~36 degrees North and a local time of approximately 22.5 hours. The computed S4 index over the first 20 seconds of data is 0.005. The right panel shows evidence of scintillation for occultation # 0077 which occurred at latitude 10 degrees South at a local time of near 23.5 hours. The computed S4 index for occultation # 0077 over the first 20 seconds of data is 0.113.

The computed S4 index (defined as the standard deviation of received power divided by the mean power) over the first 20 seconds of data is 0.005. Occultation #0070 occurred at a latitude of ~36 degrees North and a local time of approximately 22.5 hours. The right panel shows evidence of scintillation for occultation # 0077 that occurred at latitude 10 degrees South and at a local time of near 23.5 hours. The computed S4 index for occultation # 0077 over the first 20 seconds of data is 0.113, which is considered minor scintillation activity. Although we can sense scintillation from this occultation data, we do not know where along the line of site the scintillating region exists. Development of algorithms to locate the regions that cause the scintillation are the subject of future work.

Figure 3 shows the L1 C/A signal-to-noise ratio (SNR) and EDPs (after Abel inversion) for two occultations from February 1997. This figure was presented in the previous proposal, and is only included here to address the lower frequency SNR fluctuations for occultation number 0262 on day 97.054 between 400 and 800 km altitude. These flucturations occur in about 5 % of the GPS/MET occultations. After some investigation, these lower frequency fluctuations have been correlated with the unwinding of the MicroLab-1 solar panel (which occurs every orbit) and thus are attributed to local spacecraft multipath.

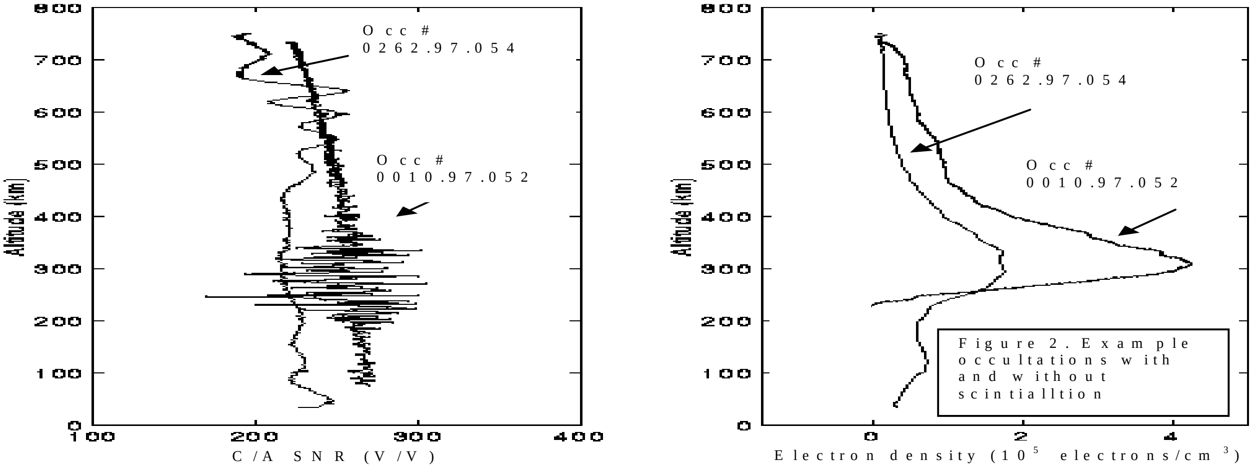

Figure 3: Example of scintillation and local spacecraft multipath in GPS/MET observations. The local spacecraft multipath is evident in the C/A SNR plot for occultation 0262 on 97.054 between 400 and 800 km altitude.

IMPACT/APPLICATION

The majority of the effort over the last year has been directed towards improving and validating different radio occultation inversion techniques through statistical comparisons with correlative data. We have found that occultation electron density profiling with the Abel technique is difficult to improve upon with the 3-dimensional (3D) constrained inversion technique that uses a priori (1st guess) horizontal gradient information as a constraint. We believe this to be due to the insufficient accuracy of the a priori fields that are available today. Due to a small number of statistical samples these results should be treated as preliminary. Many more samples should be computed to allow adequate culling of data and to provide more statistically significant validation results. Until adequate 1st guess fields become available, it makes sense to suspend development of constrained inversion techniques and concentrate on the assimilation of GPS/MET data into tomographic algorithms that have been previously developed by other groups.

We have demonstrated the use of 50 Hz occultation data to detect regions that cause ionospheric scintillation. If those regions causing scintillations are not too extensive, then they may be located by comparing multidirectional observational data. With a lack of such data, irregularities may be located along the line of sight. We are planning to develop techniques that use combined phase and amplitude data to locate inhomogeneities that cause scintillation along the GPS-LEO ray. This may lead to improved definition of regions that cause radio communication problems.

RELATED PROJECTS

Below we list several projects that work on using GPS occultation data. We are providing all of these groups with data and work closely with most of them.

1. Ionospheric Studies with GPS/MET data are conducted at Phillips Lab, Hanscom under direction of D. Anderson, and at the Jet propulsion Laboratory by G. Hajj (Hajj *et al*., 1994).

2. Dr. Ken Dymond at NRL is working on algorithms to combine data from the Tiny Ionsopheric Photometer (TIP) and GPS occultation soundings for improved 2-D retrieval of electron density fields.

3. The Danish Meteorological Institute and Saab Ericsson of Sweden are working on the development of software for ionospheric data retrieval in response to a NASA/NOAA/USAF Integrated Program Office (IPO) contract.

4. Rius *et al*. (1997) in Spain developed tomographic techniques that use GPS/MET occultation data and ground based GPS data to determine 4-D electron density fields.

5. Groups at UCAR, JPL, U. of Arizona, and Stanford U. are working on retrieval of occultation data in the neutral atmosphere.

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