Combining LEO Satellites (COSMIC) Navigation Data with Ground-Based (CMONOC) GPS Observations to Image Ionospheric Electron Density over China

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Abstract: The main limitation to spatial resolution in ionospheric tomography is the limited geometrical coverage provided by ground-based GPS observations. This problem can be alleviated by data obtained from the LEO satellites. In this paper, LEO satellite based navigation data for precise orbit determination are assimilated together with ground-based GPS observations to simultaneously image ionospheric electron density over China. High precise dual frequency GPS data from the Crustal Movement Observation Network of China (CMONOC) and the Constellation Observation System for Meteorology Ionosphere and Climate (COSMIC) on 7th November 2006 are used to invert a time series of the ionospheric electron density (IED) profiles over China. Experimental results demonstrate the imaging effectiveness due to COSMIC data used in the inversion, and the peak density in F2 (NmF2) is verified by ionosonde data. The potential benefits using COSMIC data in such system are also discussed.

Keywords: global positioning system (GPS); computerized ionoshperic tomography (CIT); ionoshperic electron density (IED); radio occultation; COSMIC, IART

1 Introduction

Since Hajj et al. (1994) first proposed the application of radio occultation data in ionospheric imaging, the advantages gained using this data source have been examined (Rius et al., 1997; Wickert, J., C. Reigber, et al., 2001; Gao and Liu, 2002; Stolle, 2004; Yuan and Wen, 2005; Yin and Mitchell, 2005 etc.). GPS occultation data comes from rising or setting process provides the horizontal ray information that is not available from angle-limited ground-based GPS CIT, while dual-frequency navigation receivers onboard LEO satellites provide upward looking TEC data that allow for improved 3-D imaging of the topside ionosphere and plasmasphere. The combined inversion of both ground-based and LEO satellites based GPS measurements improves the geometry in comparison to that found when using either data set independently (CN Mithell, 2001; P Ying and CN Mitchell, 2005). Global and regional ground-based GPS networks (e.g. IGS and CMONOC) and space-based GPS (e.g. CHAMP and COSMIC etc.) observations also provide unprecedented opportunity for further improving the CIT technique.

Placing a constellation of continuous GPS receivers in low-earth orbit, such as COSMIC, provides an extremely powerful system of continuously and extensively measuring ionosphere, the most important part of atmosphere. COSMIC, by using of GPS occultation, will make it possible to obtain continuous and global 3-D images of ionospheric electron density. The COSMIC consists of a constellation of six micro-satellites, and each one is in an almost circular orbit with altitude 750 ~ 800km and 72° inclination angle. All of six satellites provide global coverage of science data, on a daily basis. In theory, COSMIC can provide nearly 5600 globally distributed occultations and more navigation data per day suitable for ionospheric sensing.

In China, the CMONOC provides high precision dual frequency GPS data for studying the activities of the ionosphere over China (Yuan and Ou, 2002). Based on GPS dada from CMONOC, inverting IED has been implemented using the CIT technique and some related improvements/algorithms have also been made/ developed (Yuan et al., 2005; Wen et al, 2007a-c; Wen 2007; Wen et al, 2008). Preliminarily, a set of CHAMP-based GPS dada has been combined with CMONOC-based GPS observations to image ionospheric electron density over China (Yuan et al., 2005).

In this work, the combined inversion of space-based (navigation data but not occultation data) and ground -based GPS measurements has been tried using a single tomographic algorithm (IART). A time series of IED profiles over China are reconstructed on November 7, 2006 with an improved algebraic reconstruction technique (IART) tomographic algorithm using ground-based GPS measurements from CMONOC and space-based GPS measurements from COSMIC. This work is aimed to know how to improve the determination of IED density in the images combining LEO satellites navigation data with ground-based GPS observation. The potential benefits using LEO satellites based data to study the structure of ionosphere and plamasphere are also discussed.

2 Basic Method of Tomographic Inversion

2.1 Tomographic Formulation

The CIT technique applies Ionospheric slant TEC (STEC) to invert IED. Ionospheric STEC is defined as the line integral of IED along the ray path from satellite to receiver, it can be expressed as:

$$STEC = \int_l Ne(\vec{r}, t) ds \tag{1}$$

where *Ne* is the IED at a point in the ray path *l* from satellite to receiver, and $\vec{r}$ is the position vector of the point.

To simplify IED inversion, the imaged region of the ionosphere is discretized into some small pixels in a selected reference frame. Within each pixel, the electron density can be assumed to be constant in a certain period. Then the STEC along the ray path can be represented as a finite sum of integrals along segments of the ray path length. The formulation can be written as follows:

$$STEC_i = \sum_{j=1}^{n} A_{ij} x_j + e_i \quad i = 1, 2, \cdots, m \tag{2}$$

and its matrix notation:

$$y_{m\times 1} = A_{m\times n} x_{n\times 1} + e_{m\times 1} \tag{3}$$

where *n* is the number of pixels in the image, *m* is the number of STEC measurements, *y* is a column vector of the *m* known STEC measurements, *A* is an $m\times n$ matrix with A_{ij} being the length of ray *i* traversing through pixel *j*, *x* is a column vector consisting of all the unknown electron density parameters in all pixels, and *e* is a column vector associated with the discretization errors and measurement noises.

2.2 Inversion Algorithm

To solve Equation (3), a tomographic algorithm is required to determine the unknown electron density distribution. Various inversion algorithms have been developed since Austen et al (1986) first proposed the CIT technique. Here an improved algebraic recon -struction technique (IART) first proposed and examined by Wen et al. (2007) is selected in this paper. Its inversion procedure can be simply described as:

$$x^{k+1} = x^k + \lambda_k (y_i - a_i x^k) \tag{4}$$

$$\lambda_k = g^k / (a_i \cdot g^k) \tag{5}$$

where $g^k = \left[g_1^k, g_2^k, \cdots, g_n^k \right]$, and $g_i^k = a_{ij} x_j^k$.To ensure a high-quality image and physical sense of the reconstruction, it is necessary to estimate the error vector. In this work, the error vector is estimated using the following equations (Wen et al., 2007a):

$$e^{k+1} = \sqrt{\sum_{i=1}^{m} (y_i - y_i^{(k+1)})^2 / \sum_{i=1}^{m} y_i^2} \tag{5}$$

$$y_i^{k+1} = \sum_{j=1}^{n} A_{ij} x_j^{k+1} \tag{6}$$

where y_i is the ith row of the column vector *y*, x_j^{k+1} is the *j*th member of the vector of pixels x^{k+1}, and *k* is the *k*th iteration to *x*. When *e* less than a given value before, the iteration procedure terminated, and then final value of *x* was determined.

3 Data and Experiment

3.1 Data Sources

The observational inputs to the ionoshperic tomography include ground-based GPS measurements from the CMONOC and space-based GPS measurements from navigation receivers onboard COSMIC, supplied by the the COSMIC Data Analysis and Archival Center (CDAAC, UCAR).

Ground-based dual frequency GPS observations are recorded at a 30-second time interval, and the elevation angle of 15 degree is adopted. The space-based COSMIC data are listed in details as follows:

- RINEX files for the topside ionosphere and plasmasphere; decoded COSMIC data with sample rate of 1 second, which is represented as NAV (navigation data) in this paper.

- COSMIC orbit files: precision orbit in SP3 format.

- RINEX files for occultation ray path; decoded medium rate COSMIC data with 1 Hz sample rate, which is expressed as OCC (occultation data) in this paper.

COSMIC satellites are equipped with two types of receivers: ones are for precise orbit determination (POD) and the others for occultation data collection. Here, the space-based measurements NAV are combined with ground-based GPS observations to image the IED over China since NAV can apply abundant information of upward looking TEC for ionosphere inversion, while the use of LEO based measurements just limited to OCC before.

3.2 Outline of Experiment

Inverting ionospheric electron density is performed using L4 (L1-L2) phase observations. A ten-minutes observation session is adopted, which means an inverted result is individually calculated using 10 minutes continuous observations. Data for 7th November 2006 is processed. The inverted space ranges from 70° to 140° in longitude, 10° to 55° in latitude, and from 100km to 1000km in altitude. The size of the cells are 5°(longitude), 2.5°(latitude) and 50 km (altitude) respectively and the number of pixel is 6783 in total.

At the beginning of assimilation process, the international reference ionosphere (IRI) 2007 model was used to initialize the described pixel structure. Using the IART algorithm, a series of iterative process is then carried out to modify the IED value within the pixels crossed by both the COSMIC-GPS and ground-based GPS radio links.

4 Results and Discussion

Table 1 explains the notation used for the different data that we describe in sections. GRO, COM and IRI represent the inversion results from ground-based GPS alone, combination of ground-based GPS and COSMIC navigation data, and IRI2007 model, respectively.

To discuss contributions to data coverage, a comparison is made between the inversion results from ground-based GPS data (GRO) and both ground-based and COSMIC data (COM) with IRI2007 model studies, as shown in Figure 1 at 19:00BT (Beijing Time).

Table 1. Inversion results representation in terms of their inputs

Results	Ground-based GPS	COSMIC observations	IRI2007 model
GRO	√		
COM	√	√	
IRI			√

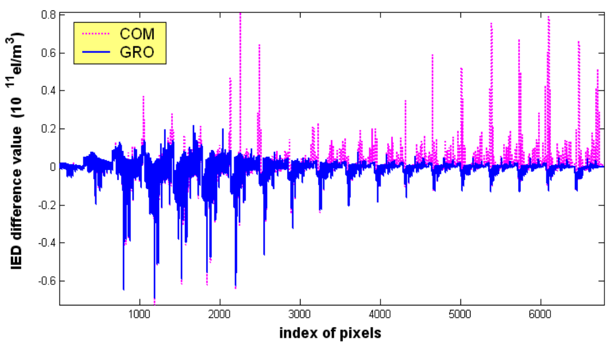

Figure 1. IED differences between inversion and IRI model results. The blue solid lines represent the results from GRO, and magenta dash lines represent the results from COM

From the characters of the IART tomographic algorithm, it is known that the pixels in the reconstructed region are initialized with IED values from the IRI2007 model, and they will be modified when the ray path intersected with corresponding pixels. In other words, the initialed IED value of one pixel keeps invariable if there is not any ray path pass through it. In Figure 1, after about the 3000th pixel the IED values within more pixels are changed by the information from COM. The pixels after the 3000th are corresponding to above 450km in altitude from the surface of earth in this experiment. It is just in middle or upper ionosphere region. Meanwhile the intersections of the GPS signal from the transmitters to COSMIC onboard receivers with ionosphere just in the middle or upper ionosphere region. All of these indicate that the LEO satellites navigation data provide us more information of the upper ionosphere region.

Table 2 shows the locations of the ionosondes used in this experiment. Data from these stations are reserved for image verification, which are compared to the F-layer peak density values in the images produced by the IART algorithm. Table 3 shows the absolute mean errors in terms of the peak electron density (NmF2) compared with

Table 2. The location of ionosonde satations

Ionosonde Station	Latitude (geographic)	Longitude (geographic)
Kokubunji	35.7°	139.5°
Yamagawa	31.2°	130.6°
Okinawa	26.3°	127.8°

Table 3. NmF2 errors at 19:00BT

Results	NmF2	
	Absolute Mean Error(10^{10}el/m^3)	Mean error (%)
GRO	6.06	31.54
COM	2.93	15.26
IRI	6.06	31.54

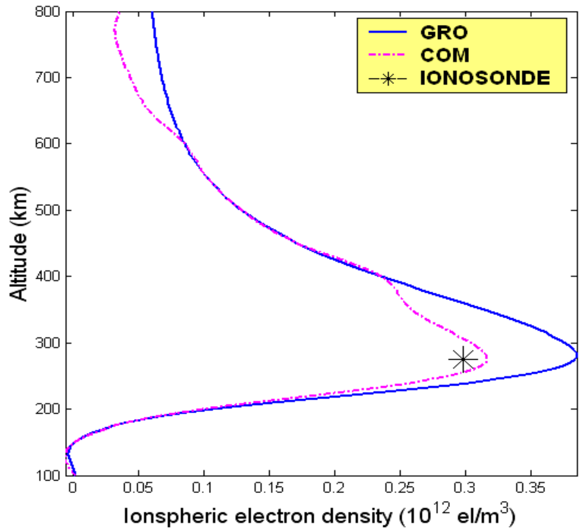

Figure 2. A comparison of the reconstructed IED profiles with the peak density from ionosonde data recorded at the Okinawa station. The blue solid lines represent the results from GRO and magenta dash lines mean from COM. The asterisk symbol represents ionosonde data.

these ionosondes data over China.

It can be seen that the best result is obtained by combining ground and space-based GPS data. The value from ground-based GPS data is equal to that from IRI model. This may be because there is not information enough to modify the peak density in the profile over the three ionosonde stations, thus the IED value equal to the initial value. Figure 2 shows a comparison of the reconstructed IED profiles with the peak density from ionosonde data recorded at the Okinawa station. In this figure, the vertical profiles have been plotted at point 26.5° E and 127.8° N. It shows that the peak density inverted by COM data closer to that from ionosonde than by ground-based GPS alone. It indicates that the results are clearly improved by addition of the LEO satellites data to the ground-based data.

Using data from CMONOC and COSMIC, a time series of the inverted ionospheric electron densities over China are obtained. This includes 12 images of IED snapshots, as shown in Figure 3. Each snapshot is plotted with respect to latitude and height at the meridian plane of 120° E. The IED is expressed in unit of 10^{12}el/m^3. Since GPS data at universal time（UT） from 1:00 to 24:00 was used for inversion for that day in this experiment, the corresponding time in Beijing time (BT) is from 9:00 to 7:00 in the next day. In Figure 3 , an enhancement of the IED appears after sunrise in the snapshot at 9:00BT, an equatorial anomaly crest also appears at that time, and the feature exist until the peak density is arrive to 1.9×10^{12}el/m^3 at 13:00BT. There is also a hint of the tilt of ionization crest during the increasing process. Meanwhile the IED peak height is ascending from 300km to about 350km during the period from 9:00 to 13:00BT. IED begins to fall at 15:00BT, and the equatorial anomaly and the tilt feature of ionosphere crest begin to disappear. IED arrives at the minimum at 5:00BT in the next morning. In the last snapshot, it can be seen that the IED begins to increase again. From Figure 3, it can be found that the variation of inverted IED is consistent with the normal change laws in daytime and night time over China.

5 Summary and Future Work

The above results indicate that dual-frequency navigation receivers onboard COSMIC provide upward looking TEC data and allow for improved 3-D imaging of the topside ionosphere. The combination of COSMIC GPS data with ground-based GPS data improves the accuracy of peak density used CIT algorithm, and then provides a powerful tool to study the structure of ionosphere over China.

Future research for improving the CIT technique should be done from the following aspects: first, incorporate more other types of ionospheric measure -ments such as COSMIC occultation observations and ionosonde

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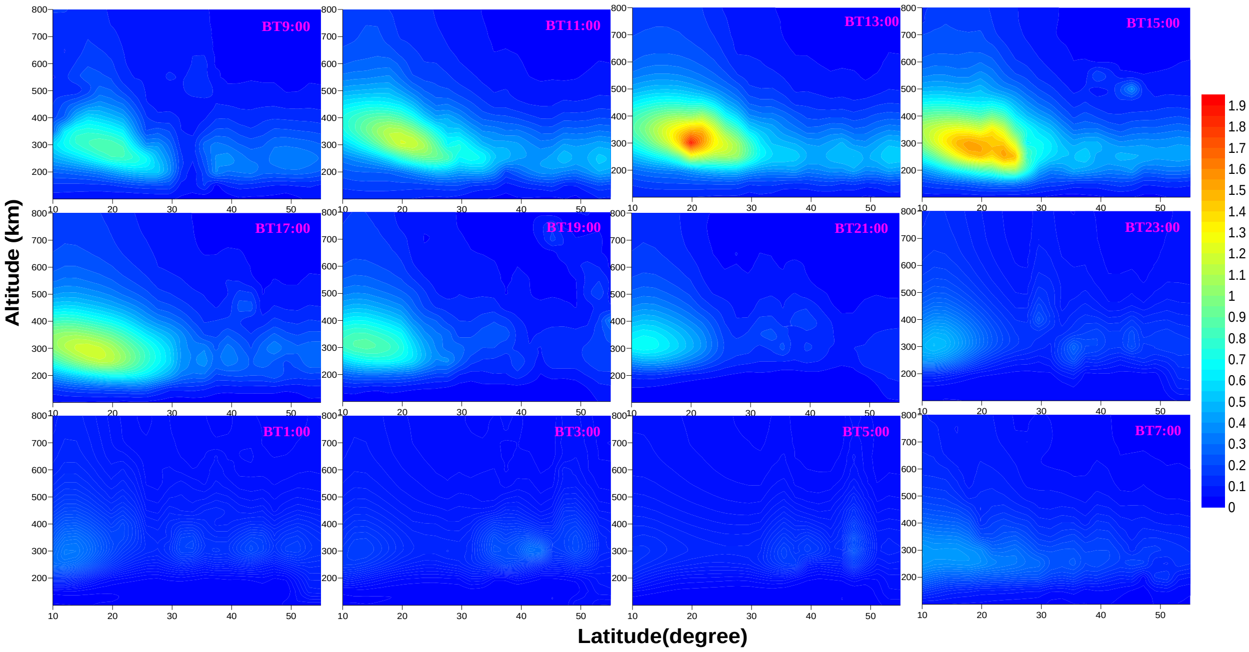

Figure 3. A time series of the ionospheric electron density snapshots at 120° E on the 7th November 2006. The time for each panel is given on the top right corner. The colorbar is in unit of 10^{12}el/m^3

data used to improve the vertical structure solution in the ionospheric tomography; second, further study can be taken to explore the structure of the ionospheric topside and plamasphere using of the LEO navigation data; finally, a more efficient CIT model should be established for combining multi data sources and refining its inversion method.

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