Preparing for COSMIC: Inversion and Analysis of Ionospheric Data Products

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Abstract. The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) is scheduled for launch in 2006. COSMIC will consist of six low earth orbiting satellites in planes separated by 24° to provide global atmospheric and ionospheric observations. One of the goals is to demonstrate near real-time processing of data products for numerical weather prediction and space weather applications. Each COSMIC satellite will carry three payloads: (1) a Global Positioning System (GPS) occultation receiver with two high-gain limb viewing antennas and two antennas for precision orbit determination, (2) a Tiny Ionospheric Photometer (TIP) for monitoring the electron density via nadir radiance measurements along the sub-satellite track, and (3) a Tri-Band Beacon (TBB) transmitter for ionospheric tomography and scintillation studies. The data from all these payloads will be processed at the COSMIC Data Analysis and Archival Center (CDAAC). Here we give an overview of the ionospheric data products from COSMIC and focus on the plans and preliminary simulation studies for analyzing the ionospheric occultation data and combining them with ground-based GPS, TIP, and TBB observations.

1 Introduction

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) is a joint Taiwan–U.S. mission with the goal to launch six low earth orbiting (LEO) micro-satellites in early 2006. All six satellites will be launched together on a Minotaur rocket. After the launch vehicle reaches the injection orbit, the satellites will be released one by one. During the following thirteen months, the satellites will slowly be distributed to their final configuration in six different orbital planes at 750 km to 800 km altitude (all orbits will be circular), with 72° inclination and 24° separation. During this deployment phase the satellites will be fully operational. The expected life-time of the mission is about five years.

Each COSMIC satellite will carry three payloads to study the Earth's neutral atmosphere and ionosphere: A Global Positioning System (GPS) receiver, connected to four antennas (two limb viewing antennas for neutral atmospheric radio occultation sounding and two antennas for precise orbit determination and ionospheric monitoring), will provide data for atmospheric and ionospheric research, weather prediction, and climate change studies. A Tiny Ionospheric Photometer (TIP) will measure the ultraviolet emission due to recombination of oxygen ions and electrons in the ionosphere along the sub-satellite track on the Earth's night-side. Finally, a Tri-Band Beacon (TBB) will transmit radio signals on three frequencies (150 MHz, 400 MHz, and 1067 MHz) which will be received by chains of receivers on the ground with the main goal to determine the line-of-sight total electron content (TEC) and ionospheric scintillation levels. A collection of papers with a detailed description of COSMIC and its potential science applications can be found in [12].

One key objective of COSMIC is to demonstrate the value of the radio occultation (RO) data for weather forecasting and inclusion in space weather models. Thus, COSMIC "real-time" data products will be available to researchers and leading numerical weather prediction centers worldwide within less than 150 minutes of data collection. In this paper we focus on the plans and ongoing preparations at the COSMIC Data Analysis and Archival Center (CDAAC) in Boulder, Colorado, for analyzing the ionospheric data anticipated from COSMIC.

2 Ionospheric Data Products

At the time of writing, CDAAC considers to provide the following baseline ionospheric data products from COSMIC:

<u>GPS receiver:</u>

- High-resolution (1 Hz) absolute TEC to all GPS satellites in view at all times (useful for global ionospheric tomography and assimilation into space weather models).
- Occultation TEC and derived electron density profiles.
- Scintillation parameters for the GPS transmitter–LEO receiver links.

<u>Tiny Ionospheric Photometer:</u>

- Nadir intensity on the night-side (along the sub-satellite track) from radiative recombination emission at 1356 Å(135.6 nm).
- Derived F-layer peak density and critical frequency (foF2).
- Location and intensity of ionospheric anomalous structures such as the Auroral oval.

<u>Tri-Band Beacon:</u>

- Phase and amplitude of radio signals at 150, 400, and 1067 MHz transmitted from the COSMIC satellites and received by chains of ground receivers.

- TEC between the COSMIC satellites and the ground receivers.
- Scintillation parameters for the LEO transmitter–ground receiver links.

In addition to providing these baseline ionospheric products, CDAAC will also work to combine different data types to provide improved products for ionospheric research. For example, it is well known that the accuracy of RO-derived electron density profiles is limited by horizontal ionospheric gradients. The TIP on each satellite, as well as the signals received on ground from the TBB transmitters, will provide valuable information about the ionospheric horizontal gradients in the vicinity of the occultations. Thus, the ionospheric occultation data are complementary to the data from the TIP and TBB instruments and it is anticipated that the different observations can be combined to improve derived electron density profiles and to estimate two-dimensional (2D) electron density structure in the plane of occultation.

3 Ionospheric Profiles from Occultations

During the first months after launch, the COSMIC satellites will gradually be lifted into their final orbits. Thus, at the beginning of the mission, most ionospheric occultations will start at a relatively low altitude (450 km to 500 km), similar to the altitude of the German CHAMP satellite at the beginning of its mission. As practice, CDAAC has therefore begun the processing of a subset of the CHAMP ionospheric RO data. Figure 1 shows a few examples of derived electron density profiles from CHAMP differential (L1−L2) phase observations, using the not always valid assumption of local spherical symmetry (presumably giving rise to large errors below the F-layer).

The electron density at the orbit altitude was obtained from the observed TEC near the orbit altitude using a novel approach that will be described in more detail in a forthcoming paper. Disregarding horizontal gradients, it can be shown that the TEC for tangent radius, r, just below the orbit altitude is related to the electron density, N_e, at the orbit altitude, as

$$\mathrm{TEC}(r) - \mathrm{TEC}(r_\mathrm{orb}) \approx \sqrt{2r_\mathrm{orb}} N_\mathrm{e}(r_\mathrm{orb}) \sqrt{r_\mathrm{orb} - r} \,, \tag{1}$$

where r_orb is the radius at the orbit altitude. Essentially, the electron density at orbit altitude at the beginning of an occultation was derived from the occultation data by fitting a square root function to the uppermost few kilometers (about 10 km) of TEC observations. Equation (1) was derived under the assumption of a circular satellite orbit and constant electron density along the orbit track. The latter assumption may cause a significant error in the estimate of the electron density using (1). In Fig. 1 the asterisks indicate the in situ electron density provided by the Planar Langmuir Probe on board CHAMP. The comparisons to the uppermost points of the electron density profiles indicate errors (almost 20 % in one case) in the derived electron density at the top of the profiles. This is presumably due to horizontal gradients along the

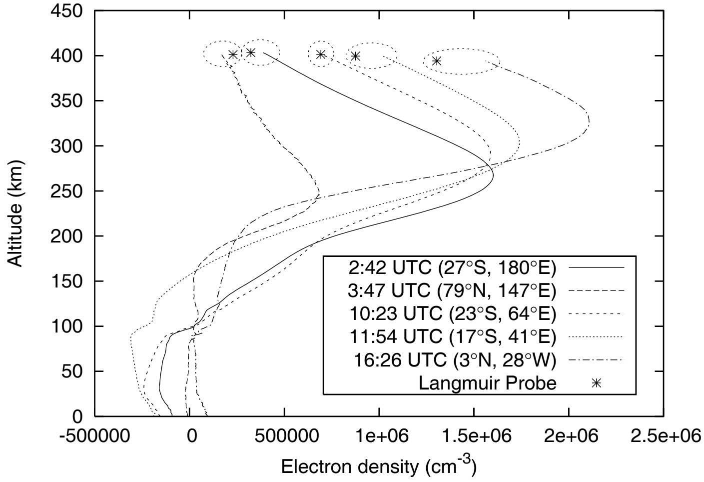

Fig. 1. Examples of retrieved electron density profiles from CHAMP occultations on October 12, 2003. Corresponding electron density measured by the CHAMP Langmuir Probe is indicated by an asterisk at the top of each profile.

orbit track, not accounted for in (1). An alternative approach [11], uses an adaptive electron density model of the topside ionosphere and plasmasphere in the inversion of CHAMP ionospheric occultation observations.

The profiles in Fig. 1 have been processed from so-called calibrated TEC [14], an approach to estimate the occultation TEC below the orbit. For the processing of CHAMP data, the calibration method was modified using the estimated electron density at the satellite orbit and assuming exponential decay of the electron density above the orbit (CHAMP does not collect positive elevation angle data necessary to apply the calibration as described in [14]).

4 Combining TIP and Occultation Data

The TIP will provide nadir observations of radiative recombination emission at 1356 Å, with a temporal resolution of several seconds. These observations will give information about the horizontal ionospheric gradients along the sub-satellite track, and can be used in conjunction with the GPS occultation data to estimate the 2D electron density structure in the occultation plane (assuming that the occultation plane is near coincident with the orbit plane). Figure 2 shows the setup for a simulation experiment, using the IRI-90 ionosphere, where the occultation takes place in a region of large horizontal gradients. Synthetic data were obtained as integrated electron density (occultation data) and integrated squared electron density (radiation data). These data were then inverted using weighted least squares according to assumed error

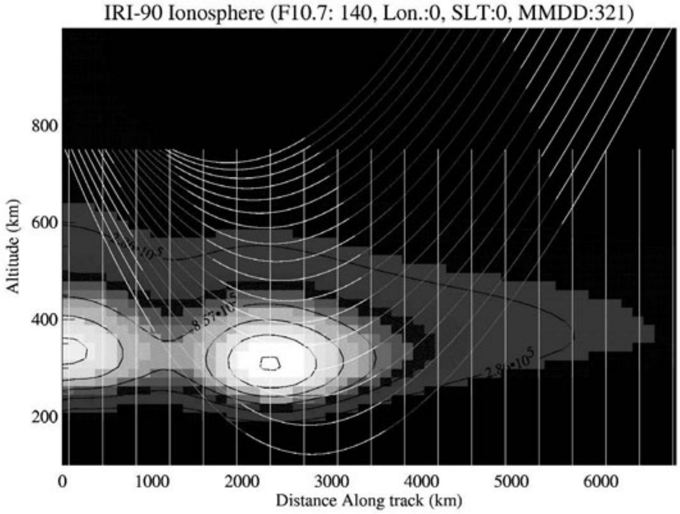

Fig. 2. Simulations of GPS occultation measurements (curved lines across the image) and TIP measurements (vertical lines) through the IRI-90 ionosphere.

covariances (see [4] for more details). The reconstruction algorithm was based on a parameterization of the vertical structure assumed to be a generalized Chapman profile, with the parameters being the height and density at the F-layer peak, as well as three parameters describing an altitude dependent scale height. Fifty-six parameters were used to parameterize the horizontal variation via the F-layer peak density.

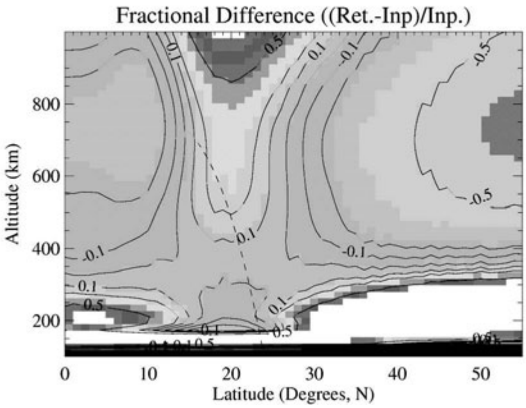

Fig. 3. Fractional error of 2D retrieval as compared to the IRI-90 ionosphere. Dashed line rising from approximately 24°N represents the tangent point trajectory.

Figure 3 shows the fractional reconstruction error as compared to the "truth" (the IRI-90 ionosphere) in the simulation experiment. Although large fractional errors occur far from the occultation tangent points, the result near the tangent points indicates the value of the TIP measurements in conjunction with the occultation data. Results from simulation experiments combining space-based UV radiance measurements with ionospheric occultation data have also been reported in [3, 8, 16].

5 Ionospheric Scintillations

One of the objectives of the TBB is global monitoring of ionospheric scintillations [1]. Ionospheric scintillations on satellite to ground links are often associated with plasma bubbles or sharp electron density gradients. Measurements of phase and amplitude scintillations at 150 MHz, 400 MHz, and 1067 MHz, will provide valuable data for scintillation studies and for generation of global scintillation maps.

Another kind of scintillation will be measured with the GPS occultation receiver at tangent altitudes around 100 km. It is hypothesized that this kind of scintillation arises as a result of sporadic E-layers [6, 7]. Figure 4 shows an example from the proof-of-concept GPS/MET radio occultation experiment (launched in April 1995) where the phases and amplitudes at the beginning of a setting occultation (50 Hz sampling rate starting at about 120 km) exhibit large oscillations, characteristic of multipath propagation, presumably caused by a sporadic E-layer. Simulations of radio occultation data affected by

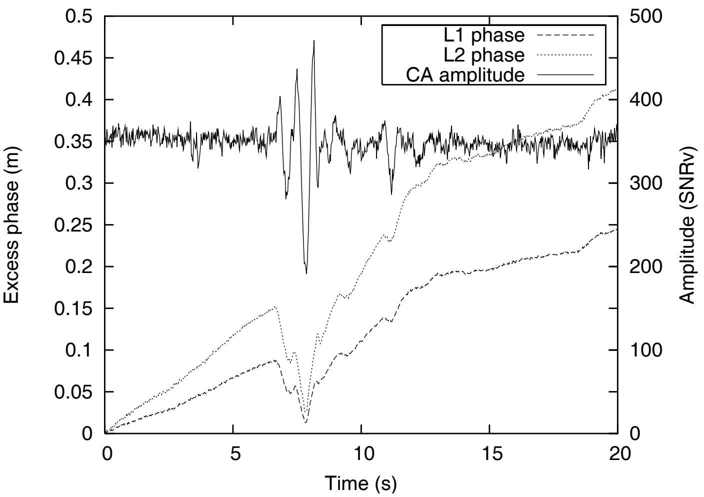

Fig. 4. Excess phase and amplitude over the first 20 s of a GPS/MET occultation (50 Hz) which occurred near 30°N, 105°W at 8:09 UTC on February 4, 1997.

multipath propagation in the lower troposphere [2, 5] show similar characteristic excess phase depletions as the ones seen around 8 s (at tangent altitudes around 100 km) in Fig. 4. Thus, it might be possible to detect sporadic E-layers globally using the occultation data. Additionally, it may be possible to localize ionospheric irregularities along the occultation path [15] and investigate the vertical structure associated with sporadic E-layers by inversion based on thin screen model wave propagation.

6 Ionospheric Tomography and Assimilation

The ionospheric RO data from COSMIC will contain valuable high-resolution information about the vertical electron density gradients, but also entangled information about the horizontal structure in the occultation plane. One way of separating the vertical and horizontal information is to combine the RO data with a priori information from an ionospheric model [8]. This can be done within the framework of ionospheric tomography using the RO TEC data. Figure 5 shows the result of combining the data from a GPS/MET occultation with the NeUoG climatological ionospheric model [13]. In the tomographic reconstruction algorithm, the ionosphere was divided into 1000 layers and 45 horizontal bins over a 60° span. The inversion took into account very large a priori uncertainties and error correlations in the NeUoG model, such that the occultation data were heavily weighted, while the NeUoG model mostly contributed with important information about large-scale horizontal gradients (see [9] for more details).

An alternative approach which will be considered for the COSMIC data is 2D variational analysis (or assimilation) of the retrieved electron density profiles using a refractive index mapping operator [17]. Within this framework, it

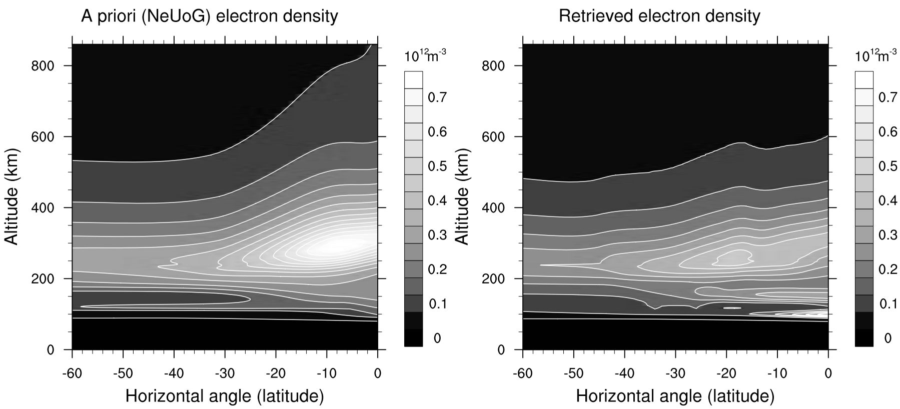

Fig. 5. A priori (left) and tomographically reconstructed (right) electron density in the occultation plane for an ionospheric GPS/MET occultation which occurred near 28°S at ~9:30 LT on February 20, 1997.

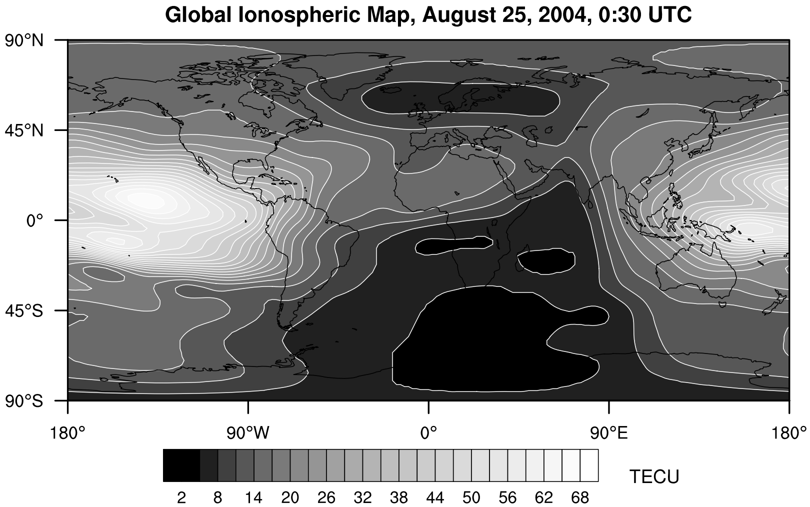

Fig. 6. Example of Global Ionospheric Map; data by courtesy of JPL.

will also be considered to include the 50 Hz data collected by the limb antennas at tangent altitudes below $\sim$ 120 km to produce electron density profiles in the lower part of the ionosphere with very high vertical resolution. Using the mapping operator, it should be possible to include correction for multipath propagation generated by sharp E-layer gradients (cf. Fig. 4), something which tomographic reconstruction does not allow for.

It will also be considered to combine the RO data with data from Global Ionospheric Maps (GIMs) (Fig. 6), as well as – when applicable – the data of similar nature from the TIP and the TBB transmitter. GIMs of vertical TEC are generated on a regular basis from a global network of ground-based GPS receivers. For general near real-time processing, CDAAC will most likely implement a simple approach [10] using the vertical TEC from GIMs to mitigate the effect of horizontal gradients in the retrieval of electron density profiles. At the same time, this approach gives a rough estimate of the three-dimensional electron density distribution in the vicinity of the occultation tangent points. The GIMs currently available from the Jet Propulsion Laboratory (JPL) has a temporal resolution of one hour and a spatial resolution of 2° by 2°.

7 Summary

The six satellite COSMIC mission, scheduled for launch in early 2006, is expected to provide a large amount of data useful for atmospheric sciences, numerical weather prediction, climate research, and space weather studies. In this paper we have given an overview of the COSMIC mission with a focus on the ionospheric data products that will be used for ionospheric monitoring and space weather research. Three instruments on board each COSMIC satellite will provide ionospheric data. The GPS receiver payloads will probe the ionosphere up to about 800 km using the RO technique, and beyond that they will measure the TEC to all GPS satellites in view. The Tiny Ionospheric Photometers will measure the nadir intensity from radiative recombination emission along the sub-satellite tracks, providing valuable information about horizontal gradients on the night-side ionosphere. Finally, the Tri-Band Beacons will provide TEC and measure scintillations on satellite-to-ground links. It is expected that the information on horizontal electron density gradients from ionospheric models, GIMs, TIP, and/or TBB observations, in combination with the occultation data, will improve electron density profiling for COSMIC, and perhaps even allow high-resolution estimates of the two- and three-dimensional electron density distributions in the vicinity of the occultations. In combination, it is anticipated that the ionospheric data from the COSMIC constellation will provide researchers with unprecedented high-resolution, global coverage information about the ionosphere and its spatial and temporal variations.

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