1.11 COSMIC – A SATELLITE CONSTELLATION FOR ATMOSPHERIC SOUNDINGS FROM 800 KM TO EARTH'S SURFACE

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1. INTRODUCTION

The Taiwan/US satellite mission COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) is in preparation for launch in late 2005. COSMIC will consist of six satellites in six orbital planes. The orbits will be circular at about 800 km altitude, with a 72 degree inclination, and 24 degree separation in ascending node. Each satellite will carry three atmospheric science payloads: (1) a GPS (Global Positioning System) radio occultation receiver for ionospheric and neutral atmospheric profiling and 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.

Atmospheric and ionospheric profiles can be derived by the radio occultation (RO) technique. As a signal travels through the atmosphere from a transmitting GPS satellite to a GPS receiver in Low Earth Orbit (LEO) it is retarded and bent. This results in an added phase and Doppler shift which can be detected very precisely by the GPS receiver aboard the LEO satellite. Signals from occulting GPS satellites are received on the COSMIC satellites to profile the ionospheric electron density from orbital altitude (800 km) through the F2 layer and the E layer with about 1.5 km vertical resolution. As the GPS satellite sets further, the occulting signals are used to profile atmospheric refractivity from ~40 km to the surface with vertical resolution of a few hundred meters. Since relative transmitter and receiver velocities can be determined with an accuracy of about 0.1 mm/sec and clock errors can be differenced out, it is possible to isolate the Doppler shift due to the atmosphere, the so-called excess Doppler. Signal bending, α as a function of impact parameter, a, (see Figure 1) can be computed with high accuracy from the excess Doppler shift observed at the LEO satellite. In the presence of atmospheric multipath propagation, the bending angle is computed by radio holographic techniques utilizing the excess phase and amplitude of the received signal (Gorbunov 2002, Jensen et al. 2003). From the bending angle versus impact parameter data, vertical profiles of refractivity as a function of radius, r, can be derived under the assumption of local spherical symmetry of the refractive index field. Further analysis converts refractivity to electron density in the ionosphere (Schreiner et al. 1999). In the neutral atmosphere (stratosphere and troposphere), the derived refractivity profiles are primarily a function of temperature, pressure, and water vapor (Rocken et al. 1997). Effects due to hydrometeors and other particulates can generally be ignored (Solheim et al. 1999). Thus, COSMIC will deliver about 2500 atmospheric occultation profiles per day from near the surface to 800 km altitude. These data will be used for numerical weather prediction, climate monitoring, and for space weather research and model developments.

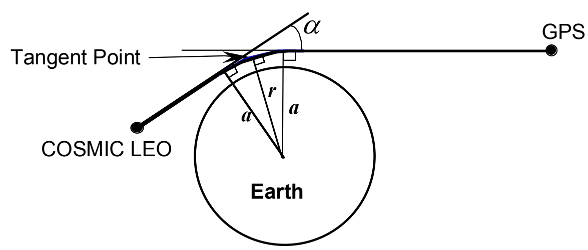

Figure 1. Schematic of radio occultation observation. Retrieved profiles are attributed to the location of the tangent point. During setting occultations the tangent point approaches Earth surface from above, during rising occultations the tangent point rises above Earth. A GPS occultation observed from about 800 km LEO takes about one minute to decent from 100 km to the surface and the bending angle reaches approximately 1 degree near the surface.

The GPS RO sounding technique, making use of highly coherent radio signals from the GPS has many unique characteristics, including: (i) high accuracy, (ii) high vertical resolution, (iii) all weather sounding capability, (iv) independent of radiosonde or other calibration, (v) no instrument drift and (vi) no satellite-to-satellite bias (Rocken et al. 1997; Kursinski et al. 1997; Kuo et al. 2004).

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Anthes et al. (2000) provides many examples on the possible applications of COSMIC GPS RO data to meteorology and climate. For space weather research, the COSMIC GPS observations will provide top and bottom side ionospheric profiles with high vertical resolution, total electron content (TEC) in the ionosphere and the plasmasphere, and measurements of scintillations. The TIP and the TBB payloads will provide data specifically for ionospheric science and space weather monitoring. The TIP will measure the ultraviolet emission due to the recombination of oxygen ions and electrons on the night-side ionosphere. The intensity of this emission can be related to the TEC in the near-nadir pointing direction. The TBB will transmit on three frequencies (at 150, 400 and 1067 MHz) that can be received on the ground or by other satellites to determine the TEC and ionospheric scintillation levels. In this paper we provide an overview of the COSMIC mission and present example space weather results from past and present radio occultation missions.

2. OVERVIEW OF THE COSMIC MISSION

COSMIC is a joint mission between Taiwan and the U.S., with the goal to launch six LEO satellites in late 2005. The 1 m diameter, 70 kg, micro satellites are presently integrated and tested at the National Space Program Office (NSPO) in Taiwan. Figure 2 shows one of the first satellites (left panel). All six satellites will be stacked on top of each other and launched together on a Minotaur rocket (Figure 2, right panel).

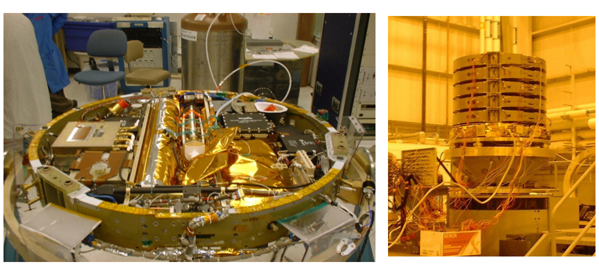

Figure 2. Assembled COSMIC satellite (left panel) and 6-satellite stack similar to the way it will be launched (right panel).

After the launch vehicle reaches the injection orbit the satellites will be released one by one. The satellites all have propulsion which will then be used to distribute them to their final constellation in six orbit planes at 750-800 km altitude, with 72 degree inclination and 24 degree separation. Using propulsion and differential precession it will take approximately 13 months for all the satellites to reach their final destination to complete the constellation. However all satellites will be operational, collecting science data during this deployment phase. In fact, the deployment phase provides opportunities for special studies for ionospheric, neutral atmospheric, and solid Earth geodesy science. The satellites will initially be clustered more densely and their data can be used to study the effect of densely spaced radio occultation profiles on weather models. While the satellites orbits are in close proximity, small differences in their relative orbit trajectories will be used by geodesists for studies of Earth's gravitational field.

With the ability of performing both rising and setting occultations, COSMIC is expected to produce approximately 2500 GPS RO soundings uniformly distributed around the globe within a 24 hour period (Figure 3).

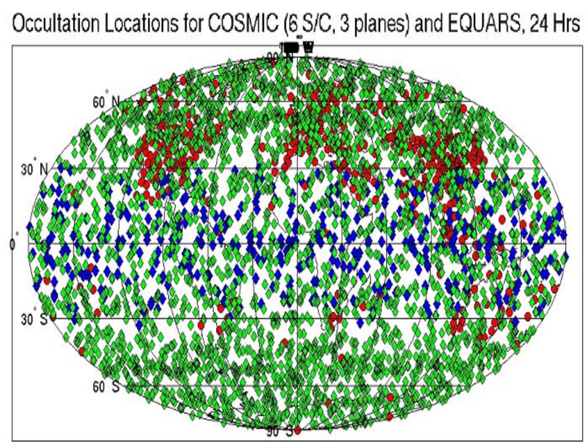

Figure 3. Typical GPS RO sounding locations from COSMIC (in green) and radiosonde sites in red. The figure also shows, in blue, the expected sounding locations from the Brazilian EQUARS mission. EQUARS is expected to overlap at least with part of the COSMIC mission and would nicely complement COSMIC in the tropics.

2.1. *COSMIC Data Analysis*

One key objective of the COSMIC mission is to demonstrate the value of the RO data for weather forecasting. For this demonstration, and for the inclusion in space weather data assimilation models, COSMIC data products will be delivered to the leading numerical weather prediction centers worldwide within less than 180 minutes of data collection on orbit. To achieve this low-latency goal each satellite will dump its data after each orbit to one of two high latitude dedicated COSMIC Earth stations in Kiruna, Sweden and Fairbanks, Alaska. These ground stations have recently been installed and they will receive the ~9

Mbyte science data dump from each satellite pass. There will be 14-15 passes per day per satellite. The data from each of these dumps is expected to contain about 30 RO soundings, plus all the other GPS observations, spacecraft data needed for the science data inversion (such as attitude information), and data from the TIP science instrument.

Since the COSMIC orbit period is about 100 minutes, the data will be at most 100 minutes old when received on the ground. The data will be forwarded within about five minutes to the COSMIC Data Analysis and Archival Center (CDAAC), in Boulder Colorado, and then to the Taiwan Analysis Center for COSMIC (TACC) in Taiwan. The CDAAC will also collect data from a worldwide network of ground-based GPS receivers operated by various organizations under the umbrella of the International GPS Service (IGS, http://igscb.jpl.nasa.gov/). The ground-based data are needed for the determination of the precise orbits of the COSMIC LEO satellites and for solving for the GPS receiver and transmitter oscillator/clock offsets and drifts. The global GPS data have to be dual frequency observations at a 1 Hz sampling rate from high quality GPS receivers. They should be available at CDAAC with no more than a 15 minute delay.

2.2. *Ionospheric Data Products*

Currently, CDAAC plans to provide the following baseline ionospheric data products from COSMIC.

GPS receiver:

- High-resolution (1 Hz) absolute total electron content (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 (1 Hz below the satellite altitude and 50 Hz below ~140 km)

- Scintillation parameters for the GPS transmitter–LEO receiver links

Tiny Ionospheric Photometer:

- Nadir intensity on the night-side (along the sub-satellite track) from radiative recombination emission at 1356 Å

- Derived F-layer peak density and critical frequency (f0F2)

- Location and intensity of ionospheric anomalous structures such as the Auroral oval

Tri-Band Beacon:

- 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

Additionally to providing these baseline ionospheric products, CDAAC will also work to combine the different data types to provide improved products for space weather research. For example, it is well known that the accuracy of RO-derived electron density profiles is limited by horizontal ionospheric gradients. The TIP, measuring the nadir intensity with a temporal resolution of several seconds, will provide valuable information about the ionospheric horizontal gradients along the sub-satellite track. Thus, the two data types are complementary and can be combined to improve derived profiles and to estimate the 2D electron density structure in the occultation plane in cases where the occultation plane is near coincident with the LEO orbit plane (Dymond et al. 2000).

3. EXAMPLE SPACE WEATHER RESULTS

In this section we present a few examples of results from past and present radio occultation missions and discuss plans and prospects for COSMIC to provide data for space weather research.

3.1. *Ionospheric profiles from GPS occultations*

The proof-of-concept GPS/MET experiment was the first satellite mission to exploit the GPS radio occultation technique. Several thousand ionospheric electron density profiles were retrieved from the GPS/MET occultations over a period of about two years (Schreiner et al. 1999). Figure 4 shows the statistical comparison between GPS/MET-derived ionospheric profile characteristics and nearby ionosonde data. The top panel in

Figure 4 shows scatter plot of the F-layer peak density, whereas the bottom panel shows scatter plot of the height of the F-layer peak.

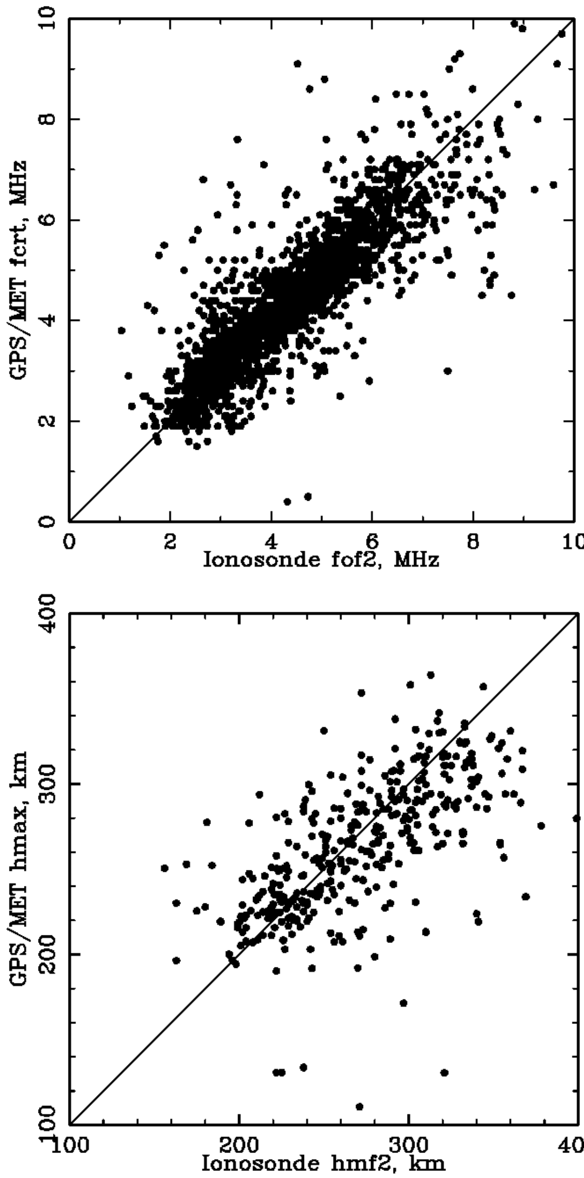

Figure 4. Scatter plots showing statistical comparison between GPS/MET-derived f0F2 and ionosonde f0F2 (top), as well as GPS/MET-derived hmF2 and ionosonde hmF2 (bottom).

Generally, the comparisons in Figure 4 show reasonable agreement between the two data sets, although there are some discrepancies. Most of the discrepancies can be explained partly by the limitation of the occultation data to provide accurate vertical profiles in the presence of horizontal gradients, and partly by the difference in location and time between the occultation observations and the nearby ionosonde measurements.

During the first months after launch, the COSMIC satellites will gradually be lifted into their final orbits. Thus, at the beginning of the mission, the ionospheric occultations will start at a relatively low altitude, similar to the altitude of the German CHAMP satellite (Wickert et al. 2004) at the beginning of its mission. As practice, CDAAC has therefore begun the processing of a subset of the CHAMP ionospheric radio occultation data. Figure 5 shows a few examples of derived electron density profiles from CHAMP differential (L1-L2) phase observations. The obviously large errors below the F-layer in some cases can be attributed to the horizontal gradients not taken into account in the data inversion. Thus, the inversion should be viewed merely as a mapping of the 3D electron density distribution into a 1D profile, containing entangled information of both vertical and horizontal gradients. Separate, and more accurate, information about the vertical and horizontal electron density structure can be obtained when combining the occultation data with other data sources, e.g., via data assimilation. The crosses near the top of the profiles 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 a systematic discrepancy between the Langmuir Probe data and the occultation data. The cause of this discrepancy is currently being investigated at CDAAC.

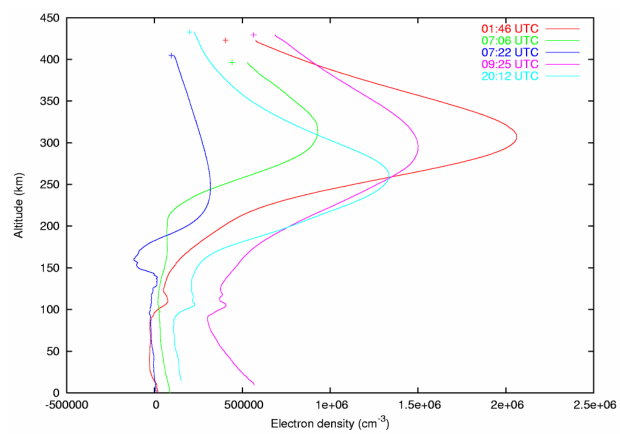

Figure 5. Examples of retrieved electron density profiles from CHAMP occultations on August 31st, 2002. Crosses indicate CHAMP Langmuir Probe data at the beginning of the occultations.

3.2. *Ionospheric Scintillations*

One of the objectives of the TBB is global monitoring of ionospheric scintillations (Bernhardt et al. 2000). 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, 400, and 1067 MHz, will provide valuable data for scintillation studies and for generation of global scintillation maps.

Another kind of scintillations will be measured with the GPS occultation receiver around 100 km altitude. It is hypothesized that this kind of scintillations arises as a result of sporadic E-layers (Gorbunov et al. 2002). Figure 6 shows an example from the GPS/MET experiment where the phases and amplitudes at the beginning of a setting occultation (50 Hz, neutral atmosphere) exhibit large oscillations, characteristic of multipath propagation, presumably caused by a sporadic E-layer. Thus, it might be possible to detect sporadic E-layers globally using the occultation data. Additionally, it will be possible to localize ionospheric irregularities along the occultation path (Sokolovskiy et al. 2002) and investigate the vertical structure associated with sporadic E-layers by inversion based on thin screen model wave propagation.

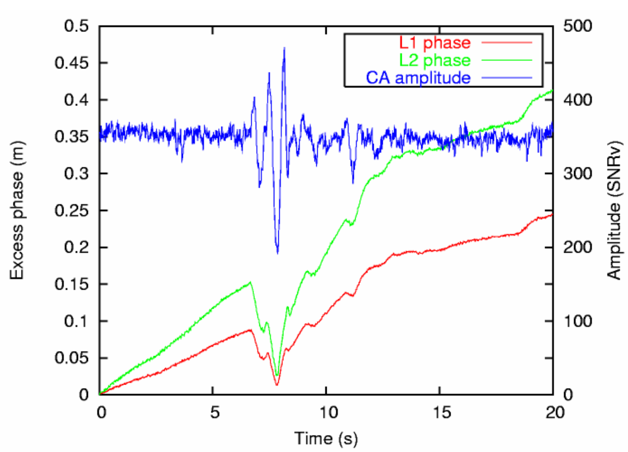

Figure 6. Excess phase and amplitude over the first 20 s of a GPS/MET occultation (50 Hz) which occurred near 30 N, 105 W, at 8:09 UTC on February 4th, 1997.

3.3. *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. This can be done within the framework of ionospheric tomography using the RO TEC data. Figure 7 shows the result of combining the data from a GPS/MET occultation with the NeUoG climatological ionospheric model (Leitinger et al. 1996). In the tomographic reconstruction algorithm, the ionosphere was divided into 1000 layers and 45 horizontal bins over a 60 degree 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.

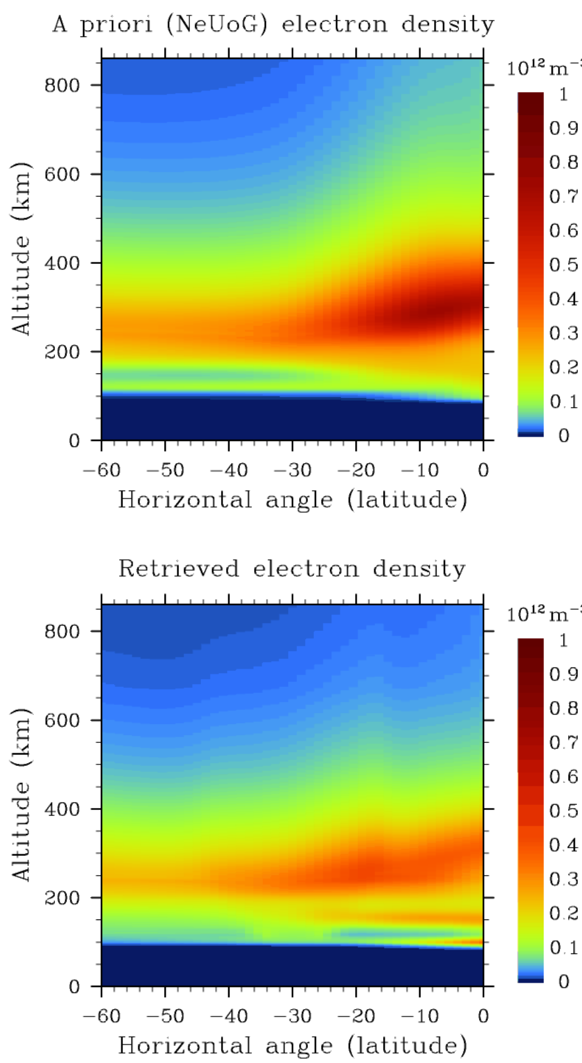

Figure 7. A priori (top) and tomographically reconstructed (bottom) electron density in the occultation plane for an ionospheric GPS/MET occultation which occurred near 28 S, at 9:30 LT on February 20th, 1997.

An alternative approach which will be considered for the COSMIC data is three-dimensional variational analysis (or assimilation) of the retrieved electron density profiles using a refractive index mapping operator (Syndergaard et al. 2004). With such an approach it will be possible to include correction for multipath propagation generated by sporadic E-layers (cf. Figure 6), something which tomographic reconstruction does not allow for.

It will also be considered to include data from Global Ionospheric Maps (GIMs) (Figure 8), 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. The GIMs available from the Jet Propulsion Laboratory (JPL) has a temporal resolution of one hour and a spatial resolution of 2 by 2 degrees.

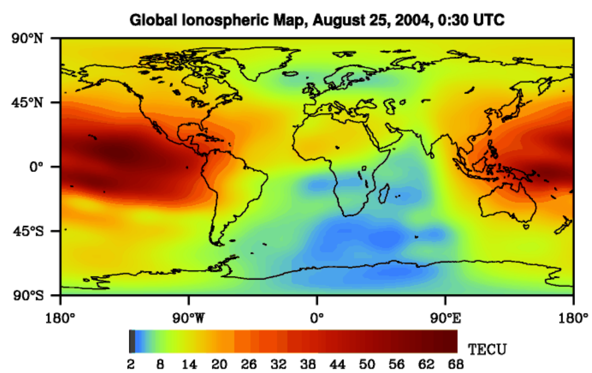

Figure 8. Example of Global Ionospheric Map. Data by courtesy of JPL.

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 electron density distribution in the plane of occultation.

4. SUMMARY

The six satellite COSMIC mission, scheduled for launch by the end of 2005, is expected to provide a very 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 space weather research.

Three instruments onboard each COSMIC satellite will provide ionospheric data. The GPS receiver payloads will probe the ionosphere up to about 800 km using the radio occultation 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 subsatellite 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. In combination, it is expected 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 variation.

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