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FORMOST-3/COSMIC MISSION TO GLOBAL EARTH WEATHER MONITORING, OPERATION, AND TACC/CDAAC POST-PROCESSING

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1. INTRODUCTION

The GPS/MET experiment showed that the atmospheric limb sounding using GPS radio signals offers great advantages over the traditional passive microwave measurement of the atmosphere by satellite. The GPS/MET's extraordinary success has induced the Denmark's Ørsted, South Africa's Sunsat, Argentine's SAC-C, German's CHAMP, and US-German's twin GRACE missions, launched between 1999 and 2001 (Yunck et al., 2000).

Although these missions provide important milestones in the evolution of the GPS sounding techniques and develop the GPS ground tracking network and data processing facilities, they are limited in terms of their spatial and temporal coverage and cannot produce enough data globally to meet the atmospheric research and prediction requirements. All these missions set the stage for the follow-on Constellation Observing Systems for Meteorology, Ionosphere, and Climate (COSMIC) mission, also known as FORMOSAT-3/COSMIC mission (Liou 2005; Wu et al., 2005).

2. FORMOSAT-3/COSMIC Mission

The FORMOSAT-3/COSMIC mission – the first operational GPS occultation constellation – is jointly developed by Taiwan's National Space Organization (NSPO) and UCAR in collaboration with NASA's Jet Propulsion Laboratory (JPL) and Naval Research Laboratory (NRL), and with the participation of many government, academic and private organizations. The mission plans to deploy a constellation of six LEO satellites for weather forecast, climate monitoring, and atmospheric, ionospheric and geodesy researches. The FORMOSAT-3/COSMIC constellation allows six spacecraft to collect 2500 sounding data on the average per day world wide with a statistically uniform coverage spatially and temporally. Figure 1 shows the FORMOSAT-3/COSMIC constellation.

Each of the FORMOSAT-3/COSMIC spacecraft comprises a spacecraft bus and three payload instruments. The primary instrument on board is an advanced version of the JPL-developed GPS receiver (GOX), which will receive the radio signal from GPS satellites. When the radio signal passes obliquely through Earth's atmosphere, the measured occultation signal will be used to infer the density, temperature, and moisture of the atmosphere at various heights. In addition to the GPS receiver, each FORMOSAT-3/COSMIC spacecraft will carry two secondary instruments: a Tiny Ionosphere Photometer (TIP) and a Tri-Band Beacon (TBB) Transmitter. These payloads will provide two-dimensional measurements of electron density, an important aspect of the upper atmosphere. These readings will complement the GOX ionospheric occultation mission between 90 and 750 km altitudes.

The planned launch date of the FORMOSAT-3/COSMIC is set in the spring of 2006. The mission life is 2 years with a goal of 5 years. The final mission orbit has an altitude of 750–800 km. When stowed for launch, each FORMOSAT-3/COSMIC cylindrical spacecraft, roughly 1 m in diameter by 18 cm high, will weigh about 70 kg with payload and fuel. The spacecraft will be launched into a low Earth orbit with an altitude of approximately 500 km, and with an inclination of approximately 72°. At deployment, the satellite's two solar panels will extend outward. Orbit-raising maneuvers will be performed to place satellites into six prescribed 800km orbital planes, which are separated by approximately 24° in their longitudinal ascending nodes. Table 1 shows the major characteristics for FORMOSAT-3/COSMIC mission (Anthes et al., 2000).

The ground segment consists of S-band antenna ground stations for both uplink and downlink. Two Remote Tracking Stations (RTS), mainly for data collections and command back-up, will be located at Fairbanks, Alaska, USA, and Kiruna, Sweden. Two Local Tracking Stations (LTS) to control the six satellites are located in Chungli and Tainan of Taiwan, respectively. NSPO mission operations will be responsible for

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constellation operation via the Multi-Mission Center (MMC) located in NSPO.

There are two data centers for receiving and processing the science data: (1) the COSMIC Data Analysis and Archive Center (CDAAC) located at Boulder, Colorado, USA, and (2) the Taiwan Analysis Center for COSMIC (TACC) at Central Weather Bureau (CWB) in Taiwan. Satellite and payload commanding are handled by NSPO from the two LTSs. The data from the six satellites are transmitted to the high latitude ground stations in Fairbanks and Kiruna. From these receiving ground stations the downlinked data will be immediately forwarded to CDAAC via the Internet and are expected to arrive Taiwan within 10 minutes of the reception at the RTS.

3. FORMOSAT-3/COSMIC Mission Prospect

The FORMOSAT-3/COSMIC constellation will span the globe and retrieve ~2,500 vertical profiles of the atmosphere each day, covering the oceans as densely as land mass. The mission will demonstrate the real-time operation capability by providing global snapshots of the atmosphere and ionosphere sounding data. Figure 2 shows the schematic diagram of the GPS radio occultation technique. The GPS signal path is bended as the signal passes through the Earth's limb due to atmospheric refraction known as radio occultation. The principle is used to inverse the density, temperature, and other parameters of the atmosphere and ionosphere. The result will be meteorological data at heights up to 60 km and ionospheric data up to 800 km.

Figure 3 shows the constellation of six FORMOSAT-3/COSMIC satellites and it monitors as many as 2,500 profiles of the atmosphere each day. Each green dot represents a location of radio occultation event measured by FORMOSAT-3. In comparison, terrestrial sounding stations provide only 900 profiles of measurements (red dots). For the first time, the FORMOSAT-3/COSMIC system will demonstrate the usefulness of GPS radio occultation in obtaining global atmospheric "snapshots" in near-real time. The system has the potential to furnish valuable data for weather prediction, global climate-change analysis and research, and ionospheric research and prediction.

Figure 4 shows the FORMOSAT-3/COSMIC system architecture. The space segment consists of the six LEO satellites and the GPS constellation. Each satellite will be put in one of six orbit planes at the same altitude of ~800 km and 72° inclination. The spacecraft orbits are phased 24° apart in ascending node and 52.5° apart in argument of latitude. The final constellation will allow the six spacecraft to collect 2500 sounding data on the average per day world wide with a statistically uniform coverage spatially and temporally.

The mission operation of this program is divided into three major phases: (1) Launch and early orbit (L&EO) checkout, (2) Orbit transfer and constellation deployment, and (3) Real-time operational demonstration. Each phase offers an opportunity to address specific challenges in metrology and climate, space weather, and geodesic science.

4. Science Research

4.1. Weather and Space Weather Forecasts

The lack of traditional data over the oceans and polar region leads to the uncertainties in the initial state of weather predictions. The occultation data with high vertical resolution can effectively contribute the weather forecasting (Kursinski et al., 2000; Sokolovskiy, 2000; Lee et al., 2000). The electron density and TEC from ionospheric occultation data and the TIP and TBB data will also contribute to the space weather forecast via the ionospheric numerical models, e.g., GAIM (Hajj, 2004).

4.2. Climate and Atmospheric Researches

The averaged 2500 occultation data per day will provide an accurate global monitoring with unprecedented long-term climate research. It supports the obtainment of accurate geopotential heights, enables the detection of gravity waves, reveals the height and shape of the tropopause globally, and improves the understanding of tropopause-stratosphere exchange processes (Liou et al. 2005a, b). Typhoons are the most serious and threatening weather events among all natural disasters in Taiwan. Figure 5 shows the assimilated route of Mindulle typhoon in June 2004 by adding the CHAMP data. It shows that additional occultation data makes better agreement with the optimized route before Mindulle landing. Figure 6 shows the comparison of dry temperature profiles retrieved by UCAR(solid) and NCU(dot) and ECMWF(+) models. The temperature difference above 25 km is due to the different background climatological models used.

Various inversion methods and codes were developed in Taiwan and applied to study the gravity waves in the stratosphere and the wave structures in the ionosphere (Liou et al., 2002, 2003, 2004, 2005c; Pavelyev et al., 2002; Pavelyev et al. 2003). The observations by ground-based GPS network were used to sense precipitable water vapor and its dynamics during the passage of typhoon (Liou and Hwang, 2000). In addition, the GPS ray-tracing observational operators have been implemented into the Taiwan CWB's global assimilation system.

4.3. Ionospheric research

The ionospheric occultation data and the TIP and TBB data are used for the calculation of electron density and TEC to study the ionospheric structure, the scintillation and irregularities, the tomography, and the auroral maps (Hajj, 2000). In Taiwan, four transmitter/receiver pairs of 30 MHz bistatic coherent radars are being set up to measure the E region electron density profiles (Chu and Wang, 2002; Chu and Wang, 2003). They will be used to validate the Es irregularities obtained from FORMOSAT-3 data and to aid the TBB special mission operation. An Ionospheric Data Center for the FORMOSAT-3/COSMIC mission is set up for the collection of ground TBB data and the ionospheric data products associated with GOX and TIP.

A 4D-VAR data assimilation system using ionospheric occultation data and NCAR TIE-GCM model was developed to investigate global ionospheric dynamics and the space weather forecast (Chen et al., 2003). Figure 7 shows the comparison of inversed global ionospheric electron density structures whose data are coming from the photometer onboard the TIMED satellite and ground-based GPS receivers. In the investigation of global ionospheric dynamics and space weather prediction, the development and validation of the ionospheric occultation retrieval were studied (Tsai et al., 2001).

4.4. Geodesy research

The POD data can be used to recover temporal gravity variations caused by oceanic mass redistribution, atmosphere and ocean mass pressure were analyzed (Hwang, 2001; Hwang and Hwang, 2002). A CTODS package was developed for precise orbit and gravity determination from space-borne GPS data. The 3D inversion of the Earth's mantle discontinuity (Bott, 1982) was studied by comparing the EGM96 gravity model with the perturbation of satellite orbit (Yu et al., 2003). In the tandem configuration during the FORMOSAT-3 deployment period, further comparisons based on the continuous orbit variation with respect to time and altitude will be conducted to investigate the discontinuity at depth of 670 km and within the mantle.

5. CDAAC/TACC Processing

5.1. CDAAC Operation

CDAAC at UCAR is the data processing, archival and distribution center for FORMOSAT-3/COSMIC mission. The processed data includes the GOX, TIP, and ground-based GPS fiducial data. The CDAAC data processing will be performed in two ways: (1) continuous rapid real-time processing and (2) post-processing. The atmospheric occultation product will be ready for assimilation into weather prediction model, on average, within 3 hours from the time of data collection in orbit (Kuo et al., 2000).

In contrast to the real-time processing, which is performed automatically, the post-processing will be performed in batches, typically it will take one month. The post-processing differs from real-time processing in several respects by providing more fiducial data (one second IGS data); better orbits with IGS final orbit and pole files; and better gridded or higher resolution weather data. The FORMOSAT-3/COSMIC data products will be made available to the international science and operation communities from CDAAC and TACC.

5.2. TAAC Operation

TACC is served as a mirror site of CDAAC. TACC will perform its own analysis of the data and distribute its products and CDAAC products to the user community in Taiwan. It is capable of processing the collected science data if necessary, and will post-process special cases requested by research groups.

CWB collaborates with National Space Organization for the plan and the establishment of TACC for FORMOSAT-3/COSMIC mission. TACC has made progress to the final stage. After operating software update and performing the final task of integration and test, TACC will operate regularly after the satellites launch.

6. Conclusion

The FORMOSAT-3/COSMIC mission opens a new novel way of approaching global Earth weather monitoring. With the demonstration of real-time operations, FORMOSAT-3/COSMIC data will complement other earth observing systems and improve global weather analyses and Numerical Weather Prediction (NWP) forecasts. The success of FORMOSAT-3/COSMIC mission will inaugurate an age of operational GPS sounding for weather forecasting, climate prediction, ionospheric monitoring, and a suite of related earth science pursuits.

Acknowledgments

The authors would like to thank to the contribution of the FORMOSAT-3/COSMIC program team, the Taiwan science teams, and the corporation with NSC, CWB, NSF, UCAR, JPL, NRL, and Orbital.

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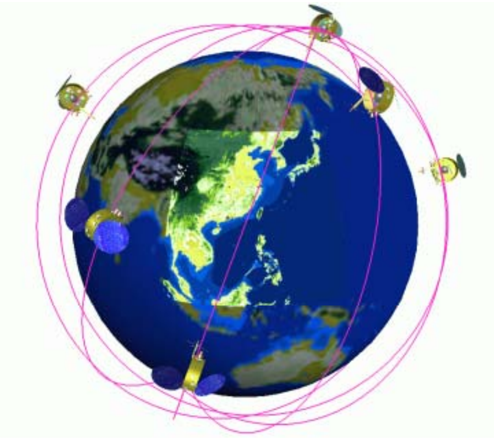

Figure 1. The FORMOSAT3/COSMIC constellation.

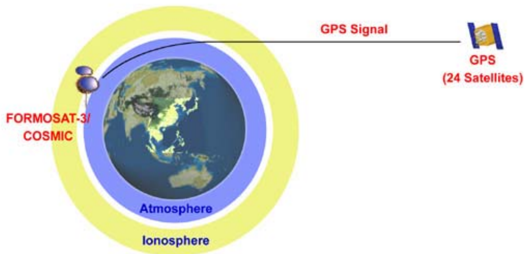

Figure 2. The FORMOSAT-3/COSMIC GPS radio occultation technique.

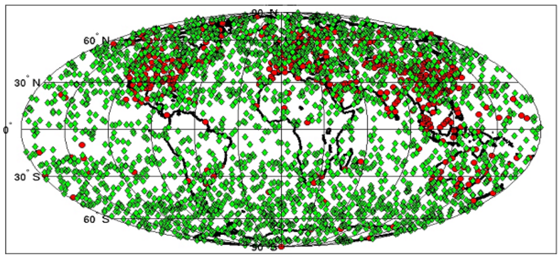

Figure 3. The FORMOSAT-3/COSMIC constellation monitors as many as 2,500 profiles of the atmosphere each day. In comparison, terrestrial sounding stations provide only 900 profiles of measurements (red dots).

Table 1. The FORMOSAT-3/COSMIC mission major characteristics

Main Parameter	Description
Number	Six satellites
Weight	~ 70 kg (with payload and fuel for each satellite)
Shape	Disc-shape of 1m diameter and 18cm in height
Orbit	700-800km altitude, Circular
Inclination Angle	72 degree
Power	~ 81 W orbit average
Communication	S-band uplink and downlink
Orbit Period	~ 100 minutes
Mission Life	2 Years With 5 years Design Life
Launch date	Scheduled at the spring of 2006 by USAF's Minotaur Launch Vehicle.

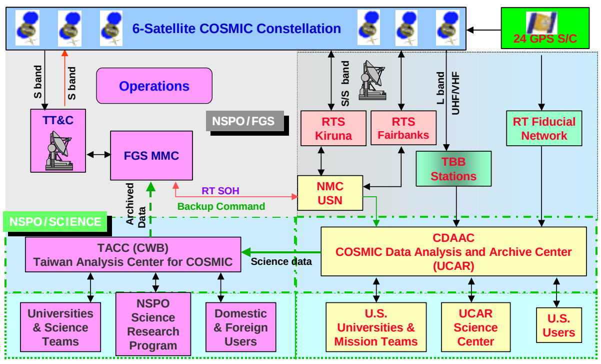

Figure 4. The FORMOSAT-3/COSMIC system architecture.

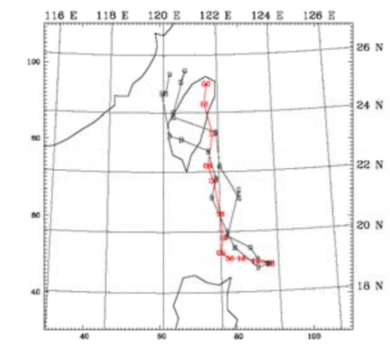

Figure. 5 Assimilated typhoon route by adding CHAMP occultation data. Red denotes the CWB's optimized route; Right and left blacks denote the assimilated routes by using traditional measurements and by traditional plus CHAMP data.

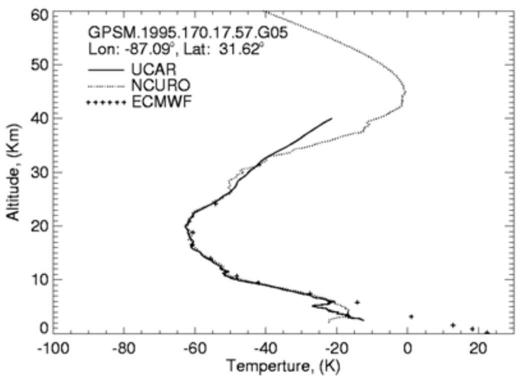

Figure 6. The comparison of dry temperature profiles which were retrieved by UCAR(solid) and NCU(dot) and ECMWF(+) model. The temperature difference above 25 km is due to the different background climatological models be used.

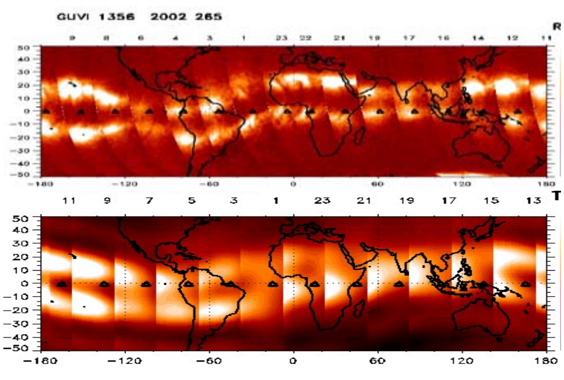

Figure 7. Observing nighttime (23LT) electron density structure using the photometer and ground-based GPS receivers. (Top: 135.6 nm emission collected on TIMED satellite; Bottom: GPS TEC)