JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 45, No. 6, November–December 2008

Mission Results from FORMOSAT-3/COSMIC Constellation System

Chen-Joe Fong,* Cheng-Yung Huang,† Vicky Chu,‡ and Nick Yen§
National Space Organization, Hsin-Chu 300, Taiwan, Republic of China
Ying-Hwa Kuo¶
University Corporation for Atmospheric Research, Boulder, Colorado 80307
Yuei-An Liou**
National Central University, Chung-Li 320, Taiwan, Republic of China
and
Sien Chi††
National Chiao-Tung University, Hsinchu 300, Taiwan, Republic of China

DOI: 10.2514/1.34427

The FORMOSAT-3/COSMIC spacecraft constellation consisting of six low-Earth-orbit satellites is the world's first operational Global Positioning System radio occultation mission. Its mission is jointly developed by Taiwan's National Space Organization and the United States's University Corporation for Atmospheric Research in collaboration with NASA's Jet Propulsion Laboratory and the Naval Research Laboratory for the three onboard payloads, which include the Global Positioning System occultation receiver, the triband beacon, and the tiny ionospheric photometer. The FORMOSAT-3/COSMIC mission was launched successfully from Vandenberg Air Force Base on 15 April 2006 into the same orbit plane of the designated 516 km circular parking orbit altitude. All six FORMOSAT-3/COSMIC satellites are maintained in a good state of health except spacecraft flight model 2, which has a power shortage, and flight model 3, currently staying at an orbit of 711 km due to a mechanism problem to be solved, and are on their way toward the final constellation of six separate orbit planes with 30 deg separations as planned. Five out of six satellites have reached their final mission orbit of 800 km as of November 2007. The FORMOSAT-3/COSMIC has processed over 1800 good atmospheric sounding profiles per day on average, which is larger than the number of worldwide radiosondes launched per day (∼900, mostly above the land). The atmospheric radio occultation sounding data are assimilated into the numerical weather prediction models for real-time weather prediction and typhoon/hurricane forecast. The global and some major nations' weather prediction centers have shown a significant positive impact and the forecast result will be also adapted to Taiwan's disaster warning and relief system once constellation deployment is completed by the end of 2007. With the invention of the open-loop technique by University Corporation for Atmospheric Research, the quality, accuracy, and lowest penetration altitude of the radio occultation sounding profiles are better than CHAMP data. This paper also describes the mission highlight, the constellation spacecraft system performance summary, the constellation mission operation result, and the mission science results.

Nomenclature

a	=	semimajor axis of the orbit altitude, km
N	=	refractivity
n_e	=	electron density, number of electrons per m^3
P	=	pressure, hPa
P_w	=	water vapor pressure, hPa
T	=	temperature, K
Δt	=	deployment time period, days
Ω	=	right ascension ascending node, deg

Presented as Paper 6086 at the AIAA SPACE 2007 Conference & Exposition, Long Beach, California, 18–20 September 2007; received 4 September 2007; accepted for publication 21 December 2007.

*Systems Engineering Manager, FORMOSAT-3 Program Office; also Ph.D. Candidate, Department of Photonics & Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan, Republic of China. Student Member AIAA.
†Associate Researcher, Science Development Office.
‡Operation Director, FORMOSAT-3 Mission Operation Team.
§Program Director, FORMOSAT-3 Program Office.
¶COSMIC Mission Director.
**Professor and Director, Center for Space and Remote Research.
††Professor, Department of Photonics & Institute of Electro-Optical Engineering, NCTU; also, professor of Department of Electrical Engineering, Yuan Ze University, Chungli 320, Taiwan, Republic of China.

I. Introduction

THE FORMOSA Satellite Series No. 3/Constellation Observing Systems for Meteorology, Ionosphere, and Climate mission, also known as the FORMOSAT-3/COSMIC mission, was launched successfully from Vandenberg Air Force Base in California on 15 April 2006 (16 April 2006 universal time coordinate) into the same orbit plane of the designated 516 km circular parking orbit altitude. The Global Positioning System (GPS) radio occultation (RO) technique, which makes use of radio signals transmitted by the GPS satellites, has emerged as a powerful approach for sounding the global atmosphere in all weather and over both land and ocean. As demonstrated by the proof-of-concept GPS/Meteorology (GPS/MET) experiment aboard NASA's Microlab-I satellite and later by the CHAMP, SAC-C, and GRACE missions, GPS RO data are shown to be of high precision, accuracy, and vertical resolution. And all these missions set the stage for the birth of the FORMOSAT-3/COSMIC mission. The FORMOSAT-3/COSMIC mission, consisting of six identical microsatellites, is the first operational GPS RO constellation in the world [1–5].

The FORMOSAT-3/COSMIC mission is jointly developed by Taiwan's National Space Organization (NSPO) and the United States's University Corporation for Atmospheric Research (UCAR) in collaboration with Orbital Sciences Corporation (Orbital) for the satellites and NASA's Jet Propulsion Laboratory (JPL) and Naval Research Laboratory (NRL) for the three onboard payloads including the GPS occultation receiver (GOX), the triband beacon (TBB), and the tiny ionospheric photometer (TIP). The FORMOSAT-3/COSMIC mission is to provide about 2500 soundings per day in near real time that give vertical profiles of temperature, pressure, refractivity, and water vapor in a neutral atmosphere and electron density in the ionosphere with global coverage at various attitudes. The GPS RO measurements generate extensive information to support operational global weather prediction, climate change monitoring, ionospheric phenomena, and space weather research [6–11].

II. Constellation Mission Overview

Table 1 shows the FORMOSAT-3/COSMIC mission characteristics. The FORMOSAT-3/COSMIC mission was defined together by NSPO and UCAR to meet the needs of the meteorology and science communities. NSPO, as the system integrator, was responsible for the design and development of the system requirements, system interfaces, system verification, system integration and test, launch site operation, launch and early orbit operation, constellation deployment, and mission operation, whereas Orbital provided the spacecraft bus, UCAR provided the payload suite and science data processing of scientific instruments, and the U.S. Air Force (USAF) provided the Minotaur launch vehicle. Each spacecraft is equipped with a GOX payload developed by JPL and built by Broad Reach Engineering (BRE), a TIP by NRL, and a TBB also by NRL [6–8].

Figure 1 illustrates the spacecraft in a deployed configuration and its major components. After the spacecraft to launch vehicle integration and test efforts between NSPO and the Minotaur launch team at Vandenberg Air Force base, the FORMOSAT-3/COSMIC satellites were successfully launched on 15 April 2006. NSPO conducted the constellation mission operations from Taiwan's Multi-Mission Center (MMC), also named the Satellite Operations Control Center (SOCC), with Orbital's support on spacecraft anomaly resolutions and UCAR's support on the mission enhancement and scientific payload operations [9].

Figure 2 shows the FORMOSAT-3/COSMIC constellation system architecture. The FORMOSAT-3/COSMIC constellation system consists of the six identical on-orbit microsatellites; spacecraft operations MMC in Taiwan; several telemetry, tracking, and command (TT&C) ground stations; two data receiving and processing centers; and the fiducial network. There are two TT&C local tracking stations (LTS) in Taiwan, one located in Chung-li and the other in Tainan. Both LTS have been upgraded and are capable of supporting the mission for Taiwan passes. There are also two remote terminal stations (RTS) to support the passes. One is located in Fairbanks, Alaska and the other one is located in Kiruna, Sweden. These two RTS are currently set as primary stations for the FORMOSAT-3/COSMIC mission to receive the on-orbit satellite science data in time [9].

Table 1 FORMOSAT-3/COSMIC mission characteristics

Number	Six identical microsatellites
Weight	~61 kg (with payload and fuel)
Shape	Disc shape of 116 cm in diameter, 18 cm in height
Orbit	800 km altitude, circular
Inclination	Angle of 72 deg
Argument of latitude	52.5 deg apart
Power	~81 W orbit average
Communication	S-band uplink and downlink
Design and mission life	5 years
Launch date	15 April 2006

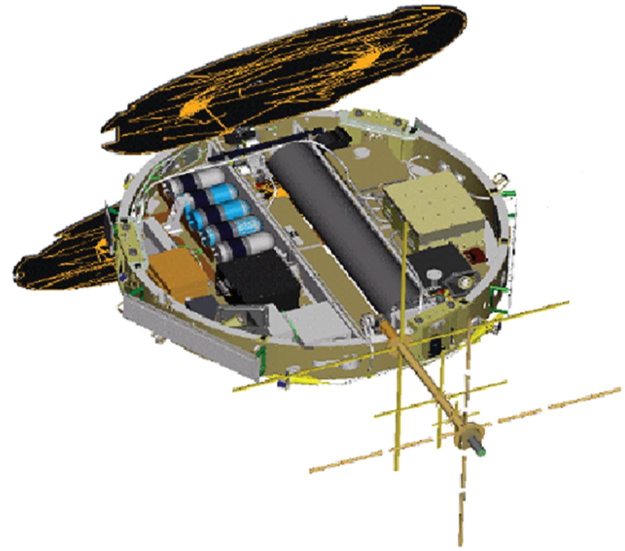

Fig. 1 FORMOSAT-3/COSMIC spacecraft in deployed configuration.

The MMC uses the real-time telemetry and the back orbit telemetry to monitor, control, and manage the spacecraft state of health (SOH). The downlinked science data is transmitted from the RTS via the Network Management Center (NMC)/Universal Space Network (USN) located in Horsham, Pennsylvania to the two data receiving and processing centers: the COSMIC Data Analysis and Archive Center (CDAAC) in Boulder, Colorado and the Taiwan Analysis Center for COSMIC (TACC) located at the Central Weather Bureau (CWB) in Taiwan. The fiducial GPS data are combined with the occulted and referencing GPS data from the GOX payload to remove the clock errors through double differencing. All collected science data are processed by CDAAC and then transferred to TACC and other facilities for science and data archival [6–10].

The processed results are then passed from the CDAAC to the United States's National Environmental Satellite, Data, and Information Service (NESDIS) branch of the National Oceanic and Atmospheric Administration (NOAA). These data are further routed to weather centers around the world [including the Joint Center for Satellite Data Assimilation (JSCDA), the National Centers for Environment Prediction (NCEP), the European Centre for Medium-Range Weather Forecast (ECMWF), CWB, the United Kingdom Meteorological Office (UKMO), the Japan Meteorological Agency (JMA), the Air Force Weather Agency (AFWA), the Canadian Meteorological Centre (Canada Met), etc.] and are ready for assimilation into weather prediction models. The data are currently provided to weather centers within 90 min (data latency requirement is 180 min) of satellite on-orbit science data collection to be ingested by the operational weather forecast model [5].

III. Mission Tradeoff and Highlights

The FORMOSAT-3/COSMIC mission was performed with reasonable trades that allowed the mission to reduce cost without taking away from the overall quantity and value of the data. Some of the key mission highlights that NSPO, UCAR, and Orbital implemented at the top-level mission and system-level tradeoff to produce science data with a great value from a small set of resources are described in the following subsections [12].

A. Fault Tolerant vs Rad-Hard Approach

The FORMOSAT-3/COSMIC spacecraft were designed to allow faults to happen and to recover from them instead of spending more money to make them radiation hardened enough to be impervious to most faults. The satellite uses the Orbcomm spacecraft bus heritage, a successful product line of the Orbital Science Corporation, which was modified as necessary for this mission. The FORMOSAT-3/COSMIC spacecraft had already demonstrated its ability to recover

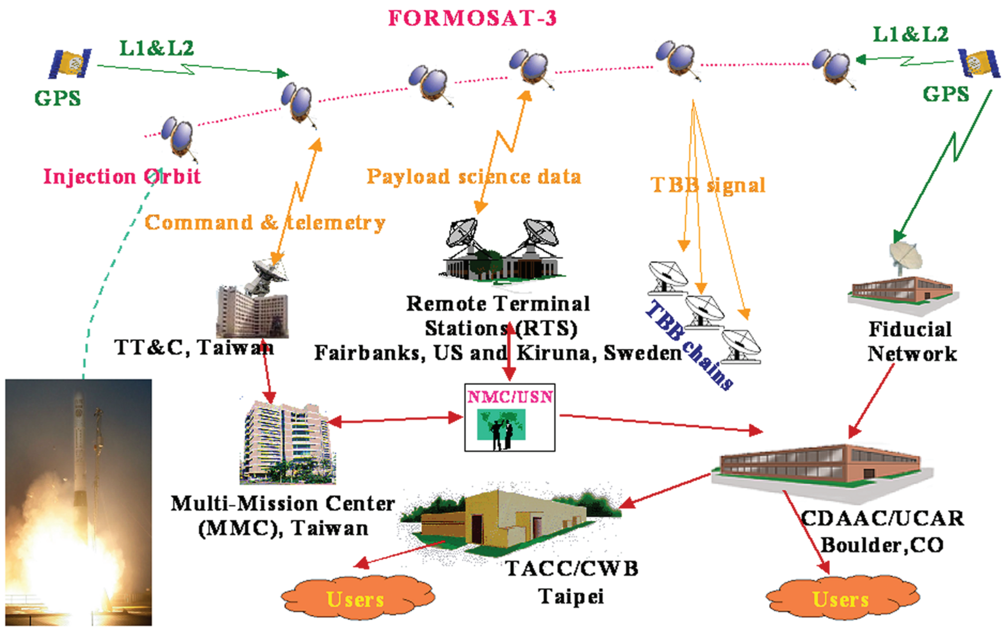

Fig. 2 FORMOSAT-3/COSMIC constellation system architecture.

autonomously in its in-orbit performance from most faults in comparison with other missions that required some ground intervention.

B. Single String vs Redundancy Design Approach

The spacecraft reliability was achieved by using a constellation system perspective to design the spacecraft. This makes the FORMOSAT-3 spacecraft a single-string spacecraft design that can tolerate a large fault on a spacecraft while the constellation system (redundancy in system) is still capable of delivering good science data. On other, bigger weather satellites and on most of the expensive ones that carry multiple instruments, a catastrophic fault to the spacecraft terminates the science from all the instruments. The design of FORMOSAT-3 could afford to lose one (or more) spacecraft and still deliver a significant amount of science data. Also, the spacecraft was designed so that multiple units could be stacked on a single launch vehicle.

C. On-Orbit Test-Bed Verification of GPS RO Payload

Without the follow-on SAC-C, CHAMP, and GRACE mission, the FORMOSAT-3/COSMIC could not be so successful in providing a quantum leap in the data volume and the lower troposphere data quality. These pre-FORMOSAT-3/COSMIC missions provided important milestones in the evolution of GPS sounding techniques and the development of the GPS ground tracking network and the data processing facilities. The SAC-C satellite in particular was provided as an on-orbit test bed for the development of the open-loop tracking scheme. The goal of this mission is to track 90% of all rising and setting occultation soundings into the lowest 1 km of the atmosphere. And so, all rising occultation on FORMOSAT-3/COSMIC will start with the open-loop tracking data before the receiver can lock its loop several kilometers above the ground. Also, the lessons learned from these missions passed over to the FORMOSAT-3/COSMIC constellation mission, so that the mission risk on FORMOSAT-3/COSMIC was reduced to a lower level.

D. Geodesy Constellation Deployment Approach

The FORMOSAT-3/COSMIC constellation deployment approach was the world's first mission to launch the entire constellation on a single launch vehicle. All six satellites were delivered to the same injection orbit and they were in a cluster formation flying in configuration after launch separation. Then, the six satellites were deployed into six different orbit planes. Orbit transfer maneuvers by each spacecraft were required to achieve the final constellation at the designated mission orbit.

This approach requires a lot of time for orbit deployment; however, this approach reduces the size of the propulsion subsystem and the complexity of the attitude control subsystem (ACS) on each spacecraft. The approach uses the natural physics of the Earth's oblateness (and time) to allow the spacecraft to drift instead of employing complex propulsion systems or even having to use individual launch vehicles to insert the spacecraft directly into their orbit planes. The FORMOSAT-3/COSMIC mission takes the advantage of the nodal precession to conduct the orbit raising maneuvers at the appropriate times, so that the effect of different altitudes makes orbital planes drift. The nodal precession is a well-known gravity phenomenon due to the Earth's oblateness.

E. Using Existing Ground Infrastructure and Taking Advantage of Automated Ground Operations

The FORMOSAT-3/COSMIC mission takes advantage of NSPO's existing established Multi-Mission Control Center with minimal modifications and also by using the USN ground system and a simple S-band downlink scheme. All the ground interfaces adopted the standard Consultative Committee for Space Data Systems (CCSDS) downlink protocol. Also, this mission takes advantage of existing data transfer technologies to simplifying the ground communication network infrastructure.

The spacecraft have a sufficient fault detection correction (FDC) design with autonomous recovery onboard, allowing the entire constellation to be operated by a couple of people during each shift on the ground. However, with the 3 h data latency of this mission (90 min was achieved), fully automated ground operations to further minimize resources were required to execute orbit-to-orbit, shift-to-shift, and day-to-day mission activities. Also, the science processing and data transfer were highly automated.

IV. Constellation Spacecraft System Performance

Table 2 shows the current spacecraft operation status of each subsystem in all six spacecraft. Overall, the health of the six FORMOSAT-3/COSMIC spacecraft was good enough to carry out the mission except for flight models_2 and 3 [13,14]. The spacecraft's magnetically controlled attitude control system does experience excursions from the required ±5 deg pointing accuracy in roll, pitch, and yaw, which sometimes impacts science data.

Table 2 Spacecraft state of health

Spacecraft	Operational mode	Spacecraft state	ACS mode	Electrical power subsystem mode	Command and data handling mode	GOX	TIP	TBB
FM1	Normal	Normal	Fixed yaw	Normal	High rate	Operating	Operating	Operating
FM2	Normal	Normal (power shortage)	Fixed yaw	Normal	High rate	Operating by beta angles	Off	Off
FM3	Normal	Normal	Fixed yaw	Normal	High rate	Operating by beta angles	Off	Off
FM4	Normal	Normal	Fixed yaw	Normal	High rate	Operating	Operating	Operating
FM5	Normal	Normal	Fixed yaw	Normal	High rate	Operating	Operating	Operating
FM6	Normal	Normal	Fixed yaw	Normal	High rate	Operating	Operating	Operating

A 40% power margin on average for each spacecraft is observed based on the 1-year trend data. There is also no sensible degradation for the power system on all six satellites except for flight model_2 (FM2), which is suffering a 20% power shortage when the 40% original margin is taken into account. The thermal control subsystem is behaving nominally across the range of solar beta angles. FM3 is currently staying at an orbit of 711 km due to a mechanism problem to be solved.

There was an issue concerning Earth sensor temperature rising too high at high beta angles, but it was resolved by an operations solution to turn off the secondary payloads during these periods. FM2, FM5, FM6, FM4, and FM1 have reached their respective mission orbits, and the remaining propellant masses for these five satellites is approximately 2.0 kg, which is the equivalent of 30% of full-tank capacity. Five major anomalies encountered during the launch and early orbit (L&EO) and constellation deployment phases are described in the following subsections.

A. Bus GPS Receiver Nonfixed Issue

The spacecraft bus GPS receiver (GPSR) of FM1, FM3, FM4, and FM6 could not reliably acquire and lock on the signals from the GPS constellation. And the bus GPSR sometimes provided erroneous data causing problems in the attitude processing and the timing system; those data glitches resulted in the strange attitude behaviors of the spacecraft. The issue was resolved by commanding four known state vectors daily to each corresponding spacecraft from SOCC. The state vector is obtained from the GOX payload. NSPO picked FM5 and FM2 as the first two spacecraft to be raised from their parking orbit because their GPS receivers were behaving nominally. This allowed the team to perform orbit determination using the data from the spacecraft bus GPS receiver. As for FM4 and FM6, NSPO has modified the thrusting procedure to include GOX operations as part of the burn activities [9].

B. High Beta Angle Effect

There were thermal anomalies related to orbital high beta angles. At high beta angles, the spacecraft is under constant sunlight (no eclipse). It causes the Earth sensor temperature to rise higher than expected. Additionally, the battery pressures were rising higher and closer to the specified limit during this time period. To solve the issue, the operations team turns TIP and TBB off when the beta angle is higher than 60 deg. To resolve the battery pressure issue, the power engineers fine-tuned the charge rate to maintain the battery within the normal pressure limit through frequent monitoring and commanding until the modified flight software was delivered by Orbital, which included a new battery overpressure protection function. This new software was successfully uploaded early this year and is now maintaining the battery pressures autonomously [9].

C. FM2 Power Shortage

In Fig. 3, we show the 1-year FM2 solar power, battery state of charge (SOC) profile, ACS mode, and payload on/off status. Generally, the average solar power falls between 140 and 150 W with a 200 W solar array power capacity in design. The real flight experience shows that the battery capacity is greater than its nameplate in typical operation. The maximum battery capacity or SOC can be as high as 15 Ah after being charged. The peak power tracking scheme can maintain the solar array operations at its maximum power output but is restricted by maximum battery charge current as well. On 1 March 2007, the operations team observed that the maximum power capacity of the solar arrays had been reduced by about 50%. FM2 had experienced a sudden solar array power shortage. A recovery plan to operate the GOX at a reduced duty cycle was analyzed and executed. Currently, FM2 is supporting the operation of the GOX at a ~70% duty cycle with the secondary payloads turned off at all times [12–14].

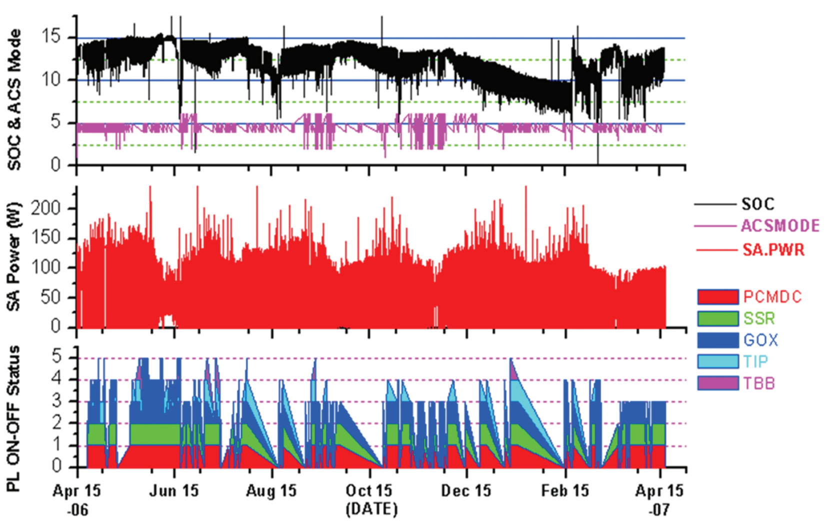

Fig. 3 The 1-year trend of solar power, battery SOC, ACS mode, and payload on–off status on spacecraft 2 (FM2). The operations team observed that the maximum power capacity of the solar arrays had been reduced by about 50% starting on 1 March 2007.

Table 3 The 1-year statistics results of payload powered-off phenomenon on all six spacecraft

	FM1	FM2	FM3	FM4	FM5	FM6	Total	Percentage, %
Nadir	21	1	10	13	6	6	57	35.6
Burn to stabilized	——	23	1	1	4	11	40	25.0
Processor reboot	3	11	——	1	7	6	28	17.5
Stabilized/safehold	4	3	3	1	——	1	12	7.5
Power shortage	——	9	——	——	——	——	9	5.6
dMdC	——	3	1	——	1	1	6	3.8
Burn to Nadir	——	——	——	1	1	2	4	2.5
PCM dc off	——	4	——	——	——	——	4	2.5

D. Payload Powered Off

The payload powered-off statistics shown in Table 3 were analyzed from day 2006-175 to 2007-105. Before day 2006-175, the 8-deg-off angle in the Earth sensors have not been fixed and the GOX has not been on for a continuous 24 h. We also excluded the action events done by the operations team, such as flight software and common spacecraft database upload, and some processors reset by the team, etc. The events for payload off reduce the science data volume. The goal of the statistics is to realize the causes of payload off. During the 1-year operation, the causes of payload off are categorized as follows: 1) processor reboot, 2) entrance to stabilized/safehold mode, 3) stabilized mode after thrust burns, 4) nadir mode after thrust burns so that spacecraft enters into power contingency, 5) power contingency due to staying in nadir mode too long, 6) derivative of battery molecular to charge (dMdC) anomaly, 7) FM2 power shortage, and 8) power control module (PCM) dc off anomaly [12–14].

E. GOX Payload Reboot Loop

Two kinds of reboot loop anomaly events were observed; one is that the GOX instrument will automatically reboot itself when there is no navigation solution for 15 min. This happened on FM1 and FM6 in the past. The other kind of reboot anomaly is that consecutive reboots occurred every 15 min. When GOX has this kind of anomaly, the GOX instrument can still be automatically recovered by power cycle command. FM6 had the latter kind of reboot anomaly in February and April of 2007. Recently, however, FM6 did not recover by itself. A low signal-to-noise ratio (SNR) of the navigation antenna was deemed to be the root cause when the spacecraft entered into the beta angle between 0 and −30 deg. A new firmware was loaded in June to enable the selection of the other healthy antenna as the navigation antenna. The reboot loop stopped since then [12].

V. Constellation Mission Operations Results

To make the data applicable to weather prediction, the mission objectives are to have the data distributed as homogeneously as possible around the globe and to have the data fed into weather prediction models as soon as possible. Two key constellation parameters were derived during the mission planning stages:

1) All six satellites will be deployed into six orbital planes with a 24 deg separation angle (later changed to 30 deg for even distribution) in right ascension of the ascending node between adjacent orbits.

2) The orbit phasing is 52.5 deg in the argument of latitude between adjacent orbits so that ground stations can receive the measurement every revolution for every satellite. This is an important factor to ensure the shortest possible data latency to feed the operational weather forecasting centers.

With the inclination angle of 72 deg and the eccentricity of 0, the constellation deployment ($\Delta\Omega$ in degrees) can be expressed by

$$\Delta\Omega \cong -6.3804 \times 10^{13} \Delta(a^{-7/2}) \cdot \Delta t \tag{1}$$

where a is the semimajor axis of the orbit in kilometers and Δt is the deployment time period in days.

The current constellation status is shown in Fig. 4. The dashed line is the planned schedule and the dots record the execution results of the thrusting. It was observed that there is a pause period in FM2's thrusting because the team changed the orbital separation from 24 to

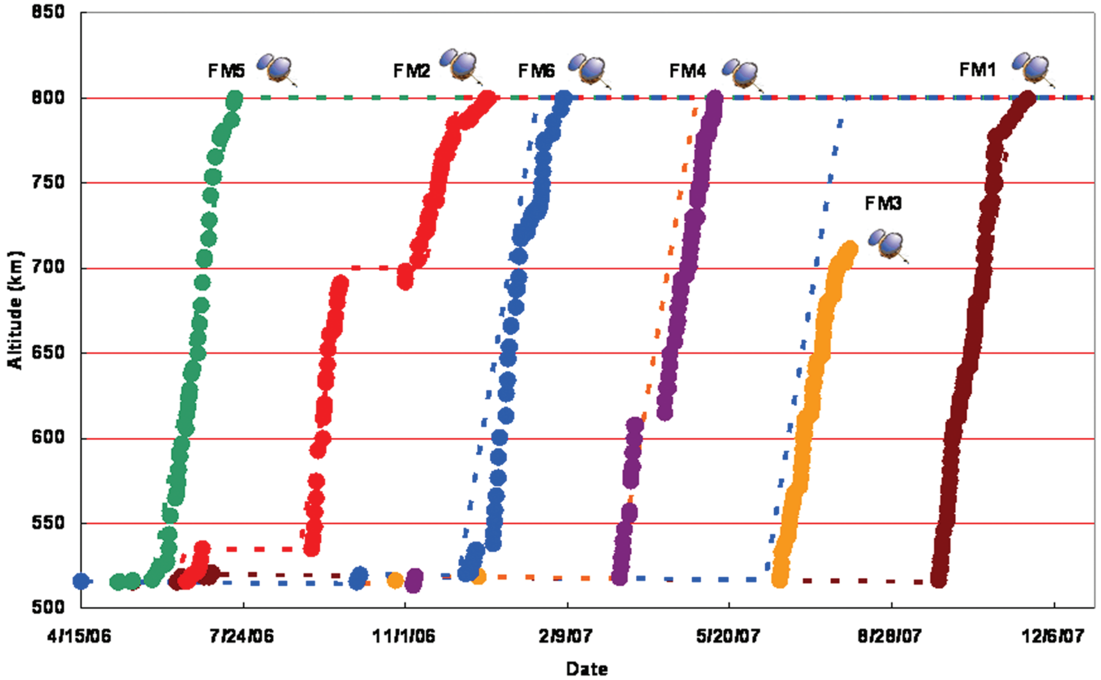

Fig. 4 FORMOSAT-3/COSMIC as-is burn history and deployment timeline.

30 deg. The modification will extend the constellation deployment period. However, the change is strongly requested by the worldwide science community because it is found the spacecraft at parking orbit can collect data with a better quality than expected, and the scientists' desire is to have a more evenly distributed constellation [8,9,15,16].

VI. Mission Science Results

The radio occultation method for obtaining atmospheric soundings is summarized by Kursinski et al. [3]. By measuring the phase delay of radio waves from GPS satellites as they are occulted by the Earth's atmosphere as shown in Fig. 5, accurate and precise vertical profiles of the bending angles of radio wave trajectories are obtained in the ionosphere, stratosphere, and troposphere. From the bending angles, profiles of atmospheric refractivity are obtained. The procedures used to obtain stratospheric and tropospheric bending angles and refractivity profiles from the raw phase and amplitude data for the COSMIC mission are described by Kuo et al. [5].

The refractivity, N, is a function of temperature (T in K), pressure (P in hPa), water vapor pressure (P_w in hPa), and electron density (n_e in number of electrons per m^3):

$$N = 77.6(P/T) + 3.73 \times 10^5(P_w/T^2) - 40.3 \times 10^6(n_e/f^2) \quad (2)$$

where f is the frequency of the GPS carrier signal in Hz. The refractivity profiles can be used to derive profiles of electron density in the ionosphere, temperature in the stratosphere, and temperature and water vapor in the troposphere.

NSPO had made a lot of effort to fine-tune the spacecraft and ground operations to improve the spacecraft performance and the operational agility. UCAR has also made significant progress in fine-tuning the GOX performance and the postprocessing in the data processing center to generate more and better-quality data. The data distribution is becoming more global as the constellation deployment continues.

Figure 6 shows the number of daily atmospheric and ionospheric occultation events since launch. The "atmPhs" means the atmospheric RO events that can be observed by FORMOSAT satellites and "ionPhs" represents the ionospheric events. In Fig. 6, $\sim$37% of the total events cannot be retrieved for vertical atmospheric profiles and $\sim$25% for ionospheric profiles. Figure 6 shows that the FORMOSAT-3/COSMIC mission has processed 1800+ good atmospheric sounding profiles per day, which is more than the number of worldwide radiosondes launched ($\sim$900 mostly above the land) per day and 2500+ good ionospheric sounding profiles per day. The occultation events collected by the current FORMOSAT-3/COSMIC constellation have achieved $\sim$70% of the mission goal of 2500 events per day.

Thanks to the continuous improvements of UCAR's research group, the phase lock loop (PLL) technique employed in the previous RO missions such as CHAMP and SAC-C was retired, and UCAR is employing an open-loop (OL) technique for the first time on FORMOSAT-3/COSMIC mission. Most of the occultation measurements can now penetrate to altitudes as low as 1 km above the Earth's surface [17]. It was estimated that about 70% of the COSMIC soundings penetrate below 1 km over the sea surface in the tropics, with about 90% reaching this depth in high latitudes. This is not a fundamental limit of the RO technique, and it is expected to be improved in the future. The new open-loop firmware version 4.3 was uploaded to the GOX payload in July 2006 and this caused a large jump in August 2006 of the daily RO event numbers.

During the first few months after launch, several of the satellites orbited within a few tens of kilometers of each other. This afforded an unprecedented opportunity to compare RO soundings from different platforms and instruments. These comparisons have verified the expected high precision of RO soundings; the precision of individual profiles in the upper troposphere/lower stratosphere is equivalent to about 0.05°C [18,19].

Figures 7 and 8 show the global distribution statistics of the lowest height of the retrieved profiles for the FORMOSAT-3/COSMIC (135,312 profiles) and CHAMP (9512 profiles) satellites for the period from 1 January to 10 May 2007, respectively. Because the Earth's ground level height varies with mountains or an ocean, the lowest height of the tangent point of the retrieved GPS signals also varies. Thus, we separate the RO retrieved radial profiles into groups: one group is over the ocean and one group is over the land. Figures 7a and 8a show the lowest height distributions of the RO retrieval profiles of the land group for FORMOSAT-3/COSMIC and CHAMP, respectively. We note that they are mostly below 0.5 km in the southern polar region. In most other land regions, the lowest heights are all below 1 km. Those with the lowest height above 1 km are mostly located in mountainous areas such as the Himalayas, the Tibetan highland, and the Andes in the South America, because high mountains prevent GPS RO signals with a lower tangent point height from being detected. Figures 7b and 8b show the lowest height (based on the ellipsoidal surface) distributions of the RO retrieval profiles of the ocean group for FORMOSAT-3/COSMIC and CHAMP, respectively. We can see that the lowest retrieval height in the southern polar region is lower and in the equatorial region is higher in comparison with the other ocean areas for both FORMOSAT-3/COSMIC and CHAMP data [20].

Figure 9 shows a comparison between the lowest altitude penetration of an RO event and the latitude for FORMOSAT-3/COSMIC and CHAMP. The data used was from 1 January to 10 May 2007. The bold solid line in Fig. 9 is the median value of the lowest altitude penetration for FORMOSAT-3/COSMIC. The solid lines above and under the median value are, respectively, the 75 and 25% statistical average value of the distributed data for FORMOSAT-3. The bold dashed line is the median value of the lowest altitude penetration for CHAMP. The dashed lines above and under the median value are the 75 and 25% statistical average value of the distributed data for FORMOSAT-3. The gray area plot is the water vapor specific humidity distribution in altitude and latitude. The specific humidity data are obtained from the NCEP model from the month of March from 1968 to 1996 [20].

The ECMWF and the NCEP of the United States assimilated the data into the real-time operational forecast systems. The preliminary results have shown that the FORMOSAT-3/COSMIC data improve the predictions of typhoon/hurricane tracks, including when and where they will hit the land [21,22]. The analysis result by ECMWF

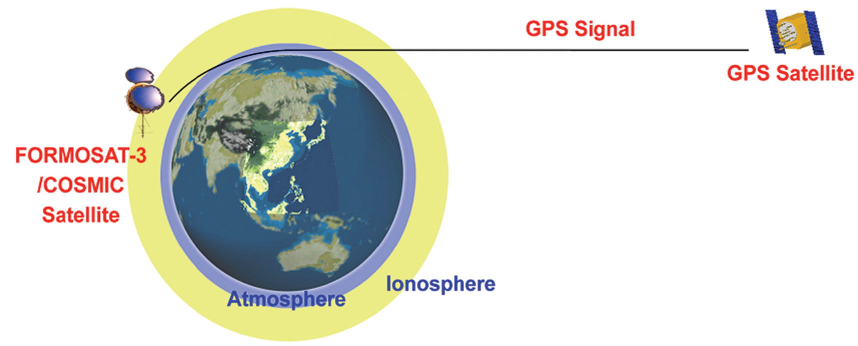

Fig. 5 Schematic diagram illustrating radio occultation of GPS signals.

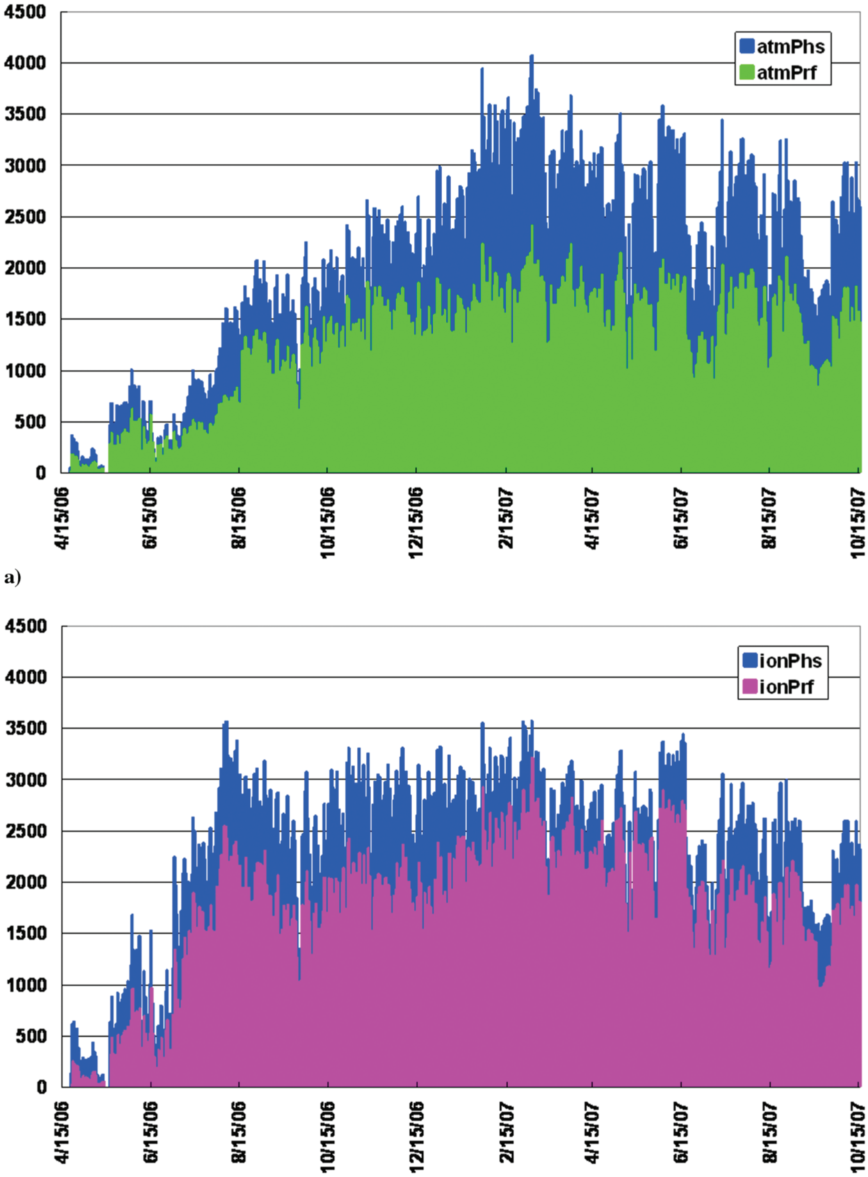

Fig. 6 Statistics of the number of daily occultation events 1.5 years since launch: a) atmosphere profiles, and b) ionosphere profiles of electron density.

shows that the FORMOSAT-3/COSMIC measurements improve the accuracy of their forecast by about 11% in the southern hemisphere at 100 mb. More than 70% of the data have a latency of less than 3 h, as reported by the ECMWF [18,23]. NCEP's studies have shown that their forecasts have significantly improved the accuracy of the forecast when the FORMOSAT-3/COSMIC data are assimilated into the system [18]. Taiwan's CWB has reported that the contribution of FORMOSAT-3/COSMIC has advanced their prediction capabilities by 2 years [22].

The ability to take ample measurements over the polar region is providing new insights into the research occurring in that area. It is found that the region forecast model over Antarctica was colder than previous predictions based on insufficient data quantity and that the scientists have begun to make the temperature correction based on the addition of data from the FORMOSAT-3/COSMIC occultation measurements [24]. The data collected from June to September 2006 have been used to construct the temperature profile of Antarctica in the stratosphere. Scientists have found the vertex effect of ozone depletion [25].

The launch of this innovative satellite constellation has brought in a new era of studying the effects of ionospheric space weather. The GPS RO data also generate a large amount of ionospheric RO data that are inverted into vertical electron density profiles and total electron content (TEC) along GPS-FORMOSAT-3/COSMIC radio links. These data, together with the complementary secondary payload (TIP and TBB) data, are valuable for the generation of ionospheric tomography, scintillation region imaging, evaluation of ionospheric models, and use in space weather data assimilation systems [18,26–29]. Taking advantage of dense and global three-dimensional observation coverage, a new ionospheric structure and some important atmosphere–ionosphere coupling theories have been observed and proven based on observations made. The newly discovered ionospheric structure, namely the low-latitude ionospheric plasma cave, shows a depleted plasma region underneath the region of strongest plasma concentration [25]. Observing this new ionospheric structure will improve the fundamental understanding of the ionospheric dynamics and will be beneficial for evaluating the ionospheric effects on the space environment, such as communications, orbit determination accuracy of the space vehicle and object, etc. The data provided by FORMOSAT-3/COSMIC have also uncovered a unique ionospheric structure, which could possibly be associated with tropical rainstorms and is proposed to be formed by an atmosphere–ionosphere coupling process. FORMOSAT-3/COSMIC's capability to observe vertical plasma distribution across

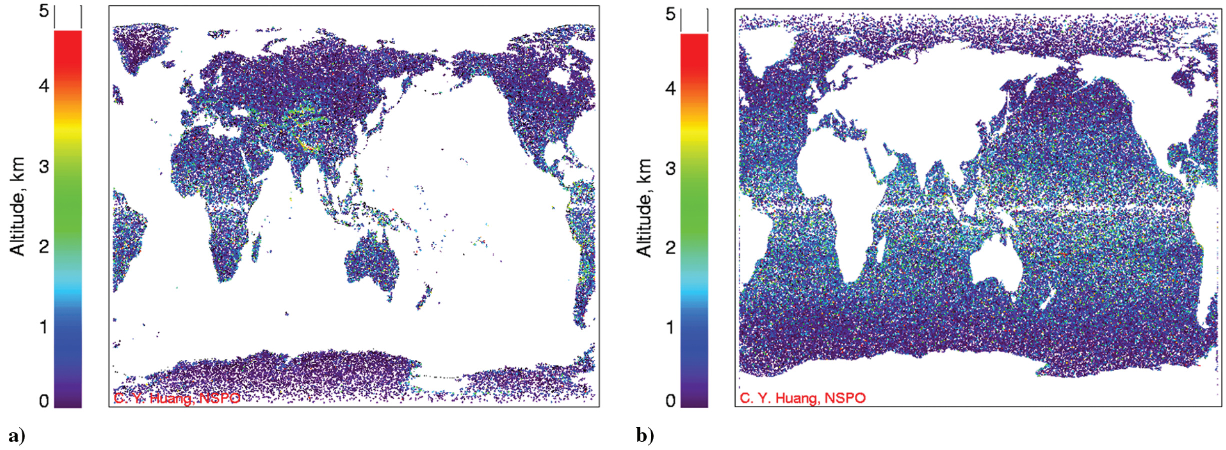

Fig. 7 Global distribution statistics of the lowest height for FORMOSAT-3/COSMIC satellites (135,312 retrieved profiles) for the period of 1 January–10 May 2007: a) land area, and b) ocean area.

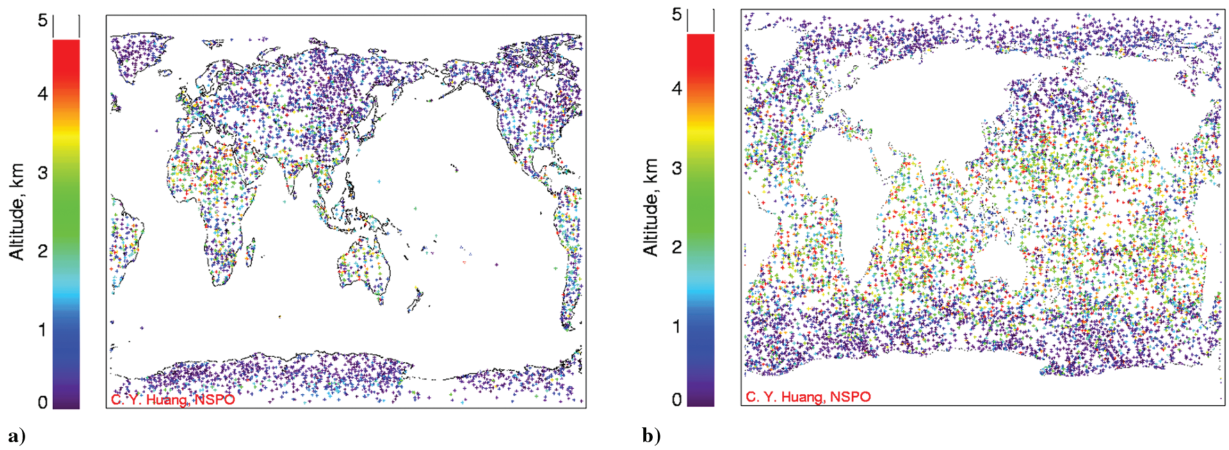

Fig. 8 Global distribution statistics of the lowest height for CHAMP satellites (9512 retrieved profiles) for the period of 1 January–10 May 2007: a) land area, and b) ocean area.

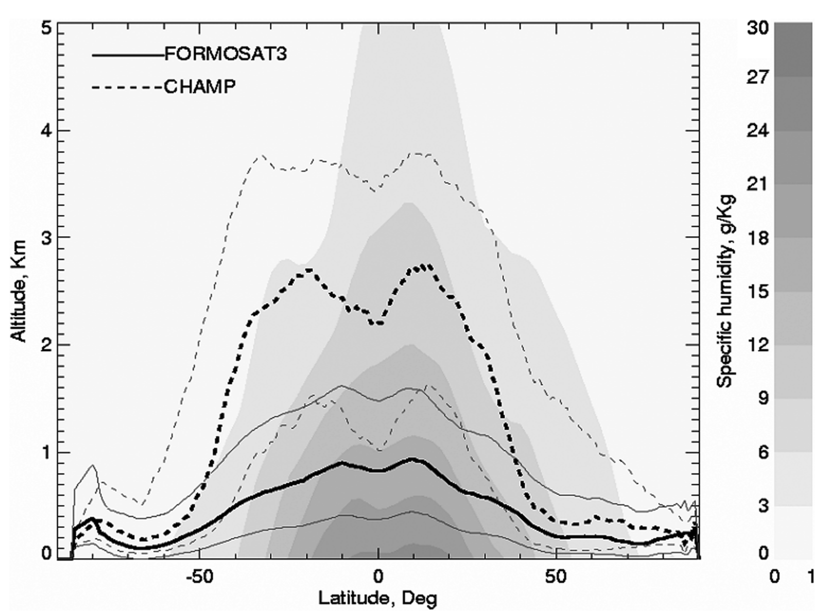

Fig. 9 Comparison of the lowest altitude penetration of RO event vs latitude for FORMOSAT-3/COSMIC and CHAMP. The data used is from the period of 1 January–10 May 2007. The bold solid line and bold dashed line are the median value of the lowest altitude penetration for FORMOSAT-3 and CHAMP, respectively. The solid line and the dashed line under the median value are the 75 and 25% statistical average values of the distributed data for FORMOSAT-3 and CHAMP, respectively. The gray area plot is the water vapor specific humidity distribution in altitude and latitude. The specific humidity data are obtained from the NCEP model from the month of March from 1968 to 1996.

a 24 hr local time period led to the verification of a plausible physical mechanism of this unique ionospheric structure [30,31]. The influences of the tropical rainstorms and atmospheric weather have been included as considerations for space weather.

VII. Conclusions

The joint Taiwan–U.S. FORMOSAT-3/COSMIC mission is providing a powerful demonstration of radio occultation in particular and of the remote sensing applications of microsatellite constellations in general. With the development of the open-loop technique by UCAR, the quality, accuracy, and lowest penetration altitude of the RO sounding profiles are better than the CHAMP data. Currently, about 1800 high-quality soundings are being retrieved daily on a global basis. These data are being provided to global weather prediction centers in near real time and have demonstrated their impact on weather forecasts. The data are available to researchers free of charge, and over 600 scientists representing more than 40 countries from all over the world have registered to use the data.

Through steady maintenance of the good health of the spacecraft and the continuous enhancements made to FORMOSAT-3/COSMIC, the provision of atmospheric profiles in terms of data volume and data latency have been proven to have great benefits for weather forecast and atmospheric/ionospheric research. NSPO has gained a lot of unique practical experience and learned many lessons by going through the mission definition, system design, system integration and test, launch integration and operations, and mission operations while cooperating with international agencies. A follow-on program is promoted to continue the meaningful mission, which will bring the evolutional change to realize and predict the weather and climate of Earth.

Acknowledgments

The authors wish to thank the contributions of the FORMOSAT-3/COSMIC program team, the mission operation team, the flight operation team, the ground operation team, the constellation deployment team, the anomaly resolution team, the Taiwan science teams, and the cooperation of the National Science Council (NSC), CWB, the National Science Foundation (NSF), UCAR, NCAR, JPL/NASA, NRL, USAF, NOAA and Orbital. The authors would also like to express special thanks to Albert Hsiao, Eddy Yang, and Shao-Shing Chen for their excellent mission support. Special thanks are given to Dean Hawes of Orbital Sciences Corporation for summarizing the mission tradeoff and highlights section, and C. H. Lin of the National Cheng Kung University (NCKU) for summarizing the ionosphere research.

References

[1] Anthes, R. A., Rocken, C., and Kuo, Y. H., "Application of COSMIC to Meteorology and Climate," *Terrestrial, Atmospheric, and Oceanic Sciences*, Vol. 11, No. 1, 2000, pp. 115–156.

[2] Yunck, T. P., Liu, C. H., and Ware, R., "A History of GPS Sounding," *Terrestrial, Atmospheric, and Oceanic Sciences*, Vol. 11, No. 1, 2000, pp. 1–20.

[3] Kursinski, E. R., Hajj, G. A., Leroy, S. S., and Herman, B., "The GPS Occultation Technique," *Terrestrial, Atmospheric, and Oceanic Sciences*, Vol. 11, No. 1, 2000, pp. 53–114.

[4] Hajj, G. A., Lee, L. C., Pi, X., Romans, L. J., Schreiner, W. S., Straus, P. R., and Wang, C., "COSMIC GPS Ionospheric Sensing and Space Weather," *Terrestrial, Atmospheric, and Oceanic Sciences*, Vol. 11, No. 1, 2000, pp. 235–272.

[5] Kuo, Y.-H., Wee, T.-K., Sokolovskiy, S., Rocken, C., Schreiner, W., Hunt, D., and Anthes, R. A., 2004, "Inversion and Error Estimation of GPS Radio Occultation Data," *Journal of the Meteorological Society of Japan*, Vol. 82, No. 1B, 2004, pp. 507–531. doi:10.2151/jmsj.2004.507

[6] Fong, C.-J., Wu, B. H., Yen, N., and Chen, P., "Application of FORMOSAT-3/COSMIC Mission to Global Earth Monitoring," AIAA Paper 2005-6774, Aug. 2005.

[7] Wu, B. H., Fong, C.-J., Huang, C. Y., Liou, Y. A., Yen, N., and Chen, P., "FORMOSAT-3/COSMIC Mission to Global Earth Weather Monitoring, Operation, and TACC/CDAAC Post-Processing," *86th AMS Annual Meeting, 14th Conference on Satellite Meteorology and Oceanography*, American Meteorological Society, Boston, Jan. 2006, pp. 1–6.

[8] Yen, N., Fong, C.-J., Chu, V., Hsiao, A., Tsai, T., and Huang, C. Y., "FORMOSAT-3/COSMIC Mission to Global Earth Weather Monitoring: Early Orbit, Orbit Transfer and Mission Operation Overview," *FORMOSAT-3/COSMIC Data Users Workshop*, University Corporation for Atmospheric Research, Boulder, CO, Oct. 2006.

[9] Fong, C.-J., Yen, N., Chu, V., Chen, S.-S., and Chi, S., "Operations Challenges from the FORMOSAT-3/COSMIC Constellation for Global Earth Weather Monitoring," *IEEE Aerospace Conference 2007*, Institute of Electrical and Electronics Engineers, New York, March 2007, pp. 1–14. doi:10.1109/AERO.2007.352986

[10] Fong, C.-J., Yen, N., Yang, S. K., Chen, S. S., and Chi, S., "GPS Radio Occultation and Mission Results from FORMOSAT-3/COSMIC Spacecraft Constellation," *3rd International Conference on Recent Advances in Spacecraft Technologies*, Institute of Electrical and Electronics Engineers, New York, 2007, pp. 748–753. doi:10.1109/RAST.2007.4284093

[11] Cheng, C.-Z. F., Kuo, Y.-H., Anthes, R. A., and Wu, L., "Satellite Constellation Monitors Global and Space Weather," *Transactions of the American Geophysical Union*, Vol. 87, No. 17, 2006, p. 166.

[12] Chu, C.-H. Vicky, Yang, S.-K., Fong, C.-J., , Yen, N., Liu, T.-Y., Chen, W.-J., Hawes, D., Liou, Y.-A., and Kuo, Y.-H., "The Most Accurate and Stable Space-Borne Thermometers—FORMOSAT-3/COSMIC Constellation," *21st Annual AIAA/USU Conference on Small Satellites*, SSC07-VII-1, AIAA, Reston, VA, 2007.

[13] Yen, N., Fong, C.-J., Chu, V., Huang, C.-Y., Chi, S., Chen, S.-S., Wu, L., and, Kuo, Y. H., "FORMOSAT-3/COSMIC Spacecraft Constellation System, Mission Results and Prospect for Follow-On Mission," *Terrestrial, Atmospheric, and Oceanic Sciences* (submitted for publication).

[14] Fong, C.-J., Yang, S.-K., Chu, C.-H., Huang, C.-Y., Yeh, J.-J., Lin, C.-T., Kuo, T.-C., Liu, T.-Y., Yen, N. L., Chen, S.-S., Kuo, Y.-H., Liou, Y.-A., and Chi, S., "FORMOSAT-3/COSMIC Constellation Spacecraft System Performance: After One Year in Orbit," *IEEE Transactions on Geoscience and Remote Sensing* (submitted for publication).

[15] Liou, Y.-A., Pavelyev, A. G., Liu, S.-F., Yen, N., Huang, C.-Y., and Fong, C.-J., "FORMOSAT-3 GPS Radio Occultation Mission: Preliminary Results," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 45, No. 11, Nov. 2007, pp. 3813–3826. doi:10.1109/TGRS.2007.903365

[16] Fong, C.-J., Shiau, W.-T., Chu, C.-H., Yang, S.-K., Lin, C.-T., Kuo, T.-C., Huang, C.-Y., Yen, N., and Chen, S. S., Kuo, Y.-H., Liou, Y.-A., and Chi, S., "Constellation Deployment for FORMOSAT-3/COSMIC Mission," *IEEE Transactions on Geoscience and Remote Sensing* (submitted for publication).

[17] Sokolovskiy, S., et al., "GPS Profiling of the Lower Troposphere from Space: Inversion and Demodulation of the Open-Loop Radio Occultation Signals," *Geophysical Research Letters*, Vol. 33, July 2006, p. L14816. doi:10.1029/2006GL026112

[18] Anthes, R. A., Bernhardt, P. A., Chen, Y., Cucurull, L., Dymond, K. F., Ector, D., Healy, S. B., Ho, S.-P., Hunt, D. C., Kuo, Y.-H., Liu, H., Manning, K., McCormick, C., Mehan, T. K., Randel, W. J., Rocken, C., Schreuber, W. S., Sokolovskiy, S. V., Sundergaard, S., Thompson, D. C., Trenberth, K. E., Wee, T. K., Yen, N. L., and Zeng, Z., "The COSMIC/FORMOSAT-3 Mission: Early Results," *Bulletin of the American Meteorological Society*, (to be published).

[19] Schreiner, W., Rocken, C., Sokolovskiy, S., Syndergaard, S., and Hunt, D., "Estimates of the Precision of GPS Radio Occultations from the COSMIC/FORMOSAT-3 Mission," *Geophysical Research Letters*, Vol. 34, No. 4, 2007, p. L04808. doi:10.1029/2006GL027557

[20] Huang, C.-Y., Cheng, C. Z., Lin, R. H., Fong, C.-J., Wicker, J., and Hsiao, C. C., "Radio Occultation Retrieval of Atmospheric Profiles in the FORMOSAT-3/COSMIC Mission: Current Status," *Terrestrial, Atmospheric, and Oceanic Sciences* (submitted for publication).

[21] Kuo, K.-H., Guo, Y.-R., Liu, H., Terng, C. T., and Lin, Y.-T., Impact of GPS Radio Occultation Data on Typhoon Prediction, *Second FORMOSAT-3/COSMIC Data Users Workshop*, University Corporation for Atmospheric Research, Boulder, CO, Oct. 2007.

[22] Huang, C.-Y., Wang, C.-J., and Chen, S.-Y., A Study for the Impact of GPS RO Data Assimilation on Regional Weather Prediction, *Second FORMOSAT-3/COSMIC Data Users Workshop*, University Corporation for Atmospheric Research, Boulder, CO, Oct. 2007.

[23] Healy, S., "Assimilation of GPS Radio Occultation Measurements at ECMWF," *European Centre for Medium-Range Weather Forecasts Newsletter*, No. 111, European Centre for Medium-Range Weather Forecasts, Reading, England, UK, Spring 2007.

[24] Manning, K. W., and Kuo, Y. H., "Using COSMIC Refractivity Profiles in an Evaluation of Antarctic Forecast Models," *Weather and Forecasting* (submitted for publication).

[25] Wang, K.-Y., and Lin, S.-C., "First Continuous GPS Soundings of Temperature Structure over Antarctic Winter from FORMOSAT-3/COSMIC Constellation," *Geophysical Research Letters* (to be published).

[26] Syndergaard, S., Schreiner, W. S., Rocken, C., Hunt, D. C., and Dymond, K. F., "Preparing for COSMIC: Inversion and Analysis of Ionospheric Data Products," *Atmosphere and Climate: Studies by Occultation Methods*, edited by U. Foelsche, G. Kirchengast, and A. K. Steiner, Springer–Verlag, New York, 2006, pp. 137–146

[27] Lei, J., and Coauthors, "Comparison of COSMIC Ionospheric Measurements with Ground-Based Observations and Model Predictions: Preliminary Results," *Journal of Geophysical Research*, Vol. 112, No. A7, 2007, p. A07308. doi:10.1029/2006JA012240

[28] Dymond, K. F., McDonald, S. E., Coker, C., Bernhardt, P. A., and Selcher, C. A., "Simultaneous Inversion of Total Electron Content and UV Radiance Data to Produce F Region Electron Densities," *Radio Science*, Vol. 41, No. 6, 2006, p. RS6S19. doi:10.1029/2005RS003363

[29] Bernhardt, P. A., and Siefring, C. L., "New Satellite Based Systems for Ionospheric Tomography and Scintillation Region Imaging," *Radio Science*, Vol. 41, No. 5, 2006, p. RS5S23. doi:10.1029/2005RS003360

[30] Lin, C. H., Wang, W. B., Hagan, M. E., Hsiao, C. C., Immel, T. J., Hsu, M. L., Liu, J. Y., Paxton, L. J., Fang, T. W., and Liu, C. H., "Plausible Effect of Atmospheric Tides on the Equatorial Ionosphere Observed by the FORMOSAT-3/COSMIC: Three-Dimensional Electron Density Structures," *Geophysical Research Letters* (to be published).

[31] Lin, C. H., Hsiao, C. C., Liu, J. Y., and Liu, C. H., "Longitudinal Structure of the Equatorial Ionosphere: Time Evolutions of the Four-Peaked EIA Structures," *Geophysical Research Letters* (submitted for publication).

I. Boyd
Associate Editor