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FORMOSAT-3/COSMIC Spacecraft Constellation System, Mission Results, and Prospect for Follow-On Mission

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ABSTRACT

The FORMOSAT-3/COSMIC spacecraft constellation consisting of six LEO satellites is the world's first operational GPS Radio Occultation (RO) mission. The mission is jointly developed by Taiwan's National Space Organization (NSPO) and the United States' UCAR in collaboration with NSF, USAF, NOAA, NASA, NASA's Jet Propulsion Laboratory, and the US Naval Research Laboratory. The FORMOSAT-3/COSMIC satellites were successfully launched from Vandenberg US AFB in California at 0140 UTC 15 April 2006 into the same orbit plane of the designated 516 km altitude. The mission goal is to deploy the six satellites into six orbit planes at 800 km altitude with a 30-degree separation for evenly distributed global coverage. All six FORMOSAT-3/COSMIC satellites are currently maintaining a satisfactory good state-of-health. Five out of six satellites have reached their final mission orbit of 800 km as of November 2007. The data as received by FORMOSAT-3/COSMIC satellites constellation have been processed in near real time into 2500 good ionospheric profiles and 1800 good atmospheric profiles per day. These have outnumbered the worldwide radiosondes (~900 mostly over land) launched from the ground per day. The processed atmospheric RO data have been assimilated into the Numerical Weather Prediction (NWP) models for real-time weather prediction and typhoon/hurricane forecasting by many major weather centers in the world. This paper describes the FORMOSAT-3/COSMIC satellite constellation system performance and the mission results that span the period from April 2006 to October 2007; and reviews the prospect of a future follow-on mission.

Key words: FORMOSAT-3, COSMIC, GPS radio occultation, Remote sensing, Constellation deployment, Orbit raising, Satellite, Operation challenges

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1. INTRODUCTION

Radio Occultation (RO) techniques have been used in outer space to probe planetary ionospheres and atmospheres for over four decades. In the early 1960s, science teams at JPL/NASA and Stanford University developed one-way and two-way radio occultation techniques, respectively, to probe Mars. The combined techniques have since been used to probe the atmosphere of almost every planet and their moons in the solar system (Fjeldbo and Eshleman 1965; Kliore et al. 1965; Melbourne et al. 1994; Yunck et al. 2000).

The GPS/MET experiment (1995 - 1997) carried aboard the NASA-sponsored MICROLAB I satellite showed that the atmospheric limb-sounding technique using radio signals transmitted from GPS satellites offers certain advantages over the traditional passive microwave radiometry measurement. The GPS/MET experiment became the first

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"proof-of-concept" radio occultation mission to Earth (Kursinski et al. 1996; Ware et al. 1996; Rocken et al. 1997). The success of the GPS/MET mission engendered a series of other space missions between 1999 and 2002: Denmark's Oersted; South Africa's Sunsat; Argentina's SAC-C; Germany's CHAMP; and the joint US-German twin GRACE satellites. The GPS RO sounding data are shown to be of high accuracy and high vertical resolution (Yunck et al. 2000; Wickert et al. 2001; Liou et al. 2002; Pavelyev et al. 2002; Hajj et al. 2004).

These missions provide important milestones in the evolution of GPS RO techniques (Kursinski et al. 2000; Sokolovskiy et al. 2006), the development of the GPS ground tracking network and the data processing facilities. However, they are limited in terms of the spatial and temporal coverage and cannot produce sufficient data globally to meet near real-time forecast requirements. All these missions set the stage for a follow-on Constellation Observing Systems for Meteorology, Ionosphere, and Climate (COSMIC) mission, also known as the FORMOSAT-3/COSMIC mission. The joint Taiwan-US FORMOSAT-3/COSMIC mission provides a quantum leap in terms of the data volume and the data quality and becomes the first operational GPS RO constellation in the world (Anthes et al. 2000; Hajj et al. 2000; Rocken et al. 2000).

The primary goal of the FORMOSAT-3/COSMIC mission is to obtain in near real time vertical profiles of temperature, pressure, refractivity, and water vapor in the neutral atmosphere, and electron density in the ionosphere with global coverage at various altitudes (Liou et al. 2007). The RO measurements taken during the five-year mission produce about 2500 soundings per day, thus generating extensive information to support operational global weather prediction, climate change monitoring, ionospheric phenomena, space weather research, and estimations of connections of meteorological and ionospheric processes with regard to solar activity.

2. FORMOSAT-3/COSMIC MISSION OVERVIEW

Table 1 shows the FORMOSAT-3/COSMIC Mission Characteristics. The FORMOSAT-3/COSMIC mission involves the launch and the separation of six Low-Earth Orbit (LEO) satellites using an in-stack configuration housed in a USAF Minotaur Launch Vehicle to deploy in the same orbit plane of the designated 516 km circular orbit altitude (Yen et al. 2006; Fong et al. 2007a, b, 2008a, b, c).

Figure 1 shows the FORMOSAT-3/COSMIC constellation system architecture. The FORMOSAT-3/COSMIC constellation of six satellites was successfully launched on 15 April 2006. Following the completion of the six satellites' in-orbit checkout activities, the satellite began the constellation mission by operating the three onboard payloads at the parking orbit. The six satellites interact with the GPS satellites using the RO technique and communicate with the ground communication network (GCN). The downloaded GPS occulted sounding data of the planet Earth's atmosphere and ionosphere is further routed to the data processing centers in the US and Taiwan (Wu et al. 2006).

2.1 Space Segment

The FORMOSAT-3/COSMIC space segment comprises six satellites in a constellation-like formation. Each spacecraft is equipped with a GPS Occultation Experiment (GOX) payload developed by the Jet Propulsion Laboratory (JPL)

Table 1. FORMOSAT-3/COSMIC mission characteristics.

Number	Six small satellites
Weight	~ 61 kg (with payload and fuel) at launch
Shape/height	Disc-shape - 116 cm diameter
	Height - 18 cm
Orbit	Circular 800 km altitude at final constellation
Inclination Angle	72 degrees
Argument of latitude	6 orbit planes with 30 degrees (RAAN) and 52.5 degrees (AOL) apart between two adjacent orbit planes at final constellation
Power	~ 81 W orbit average
Communication	S-band uplink and downlink
Design life	> five years
Mission life	five years
Launch date	15 April 2006

and built by Broad Reach Engineering, a Tiny Ionospheric Photometer (TIP) by Naval Research Laboratory (NRL), and a Tri-Band Beacon transmitter (TBB) also by NRL. Figure 2 illustrates the spacecraft in a deployed configuration and its major components. Figure 3 shows a photo of the six satellites in a stowed configuration, stacked on the 4th stage of a MINOTAUR launch vehicle in an operation facility at the Vandenberg Air Force Base (VAFB). In the final constellation, each spacecraft will be maneuvered into one of the six orbit planes at the same altitude of ~ 800 km with a

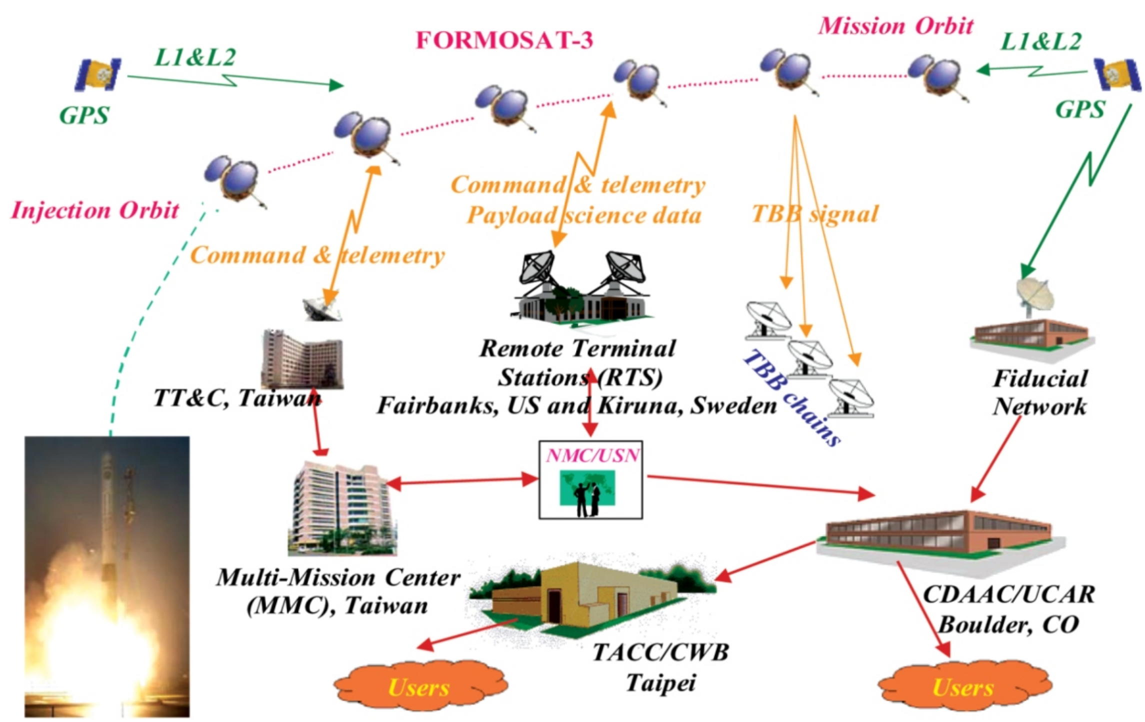

Fig. 1. FORMOSAT-3/COSMIC constellation system architecture.

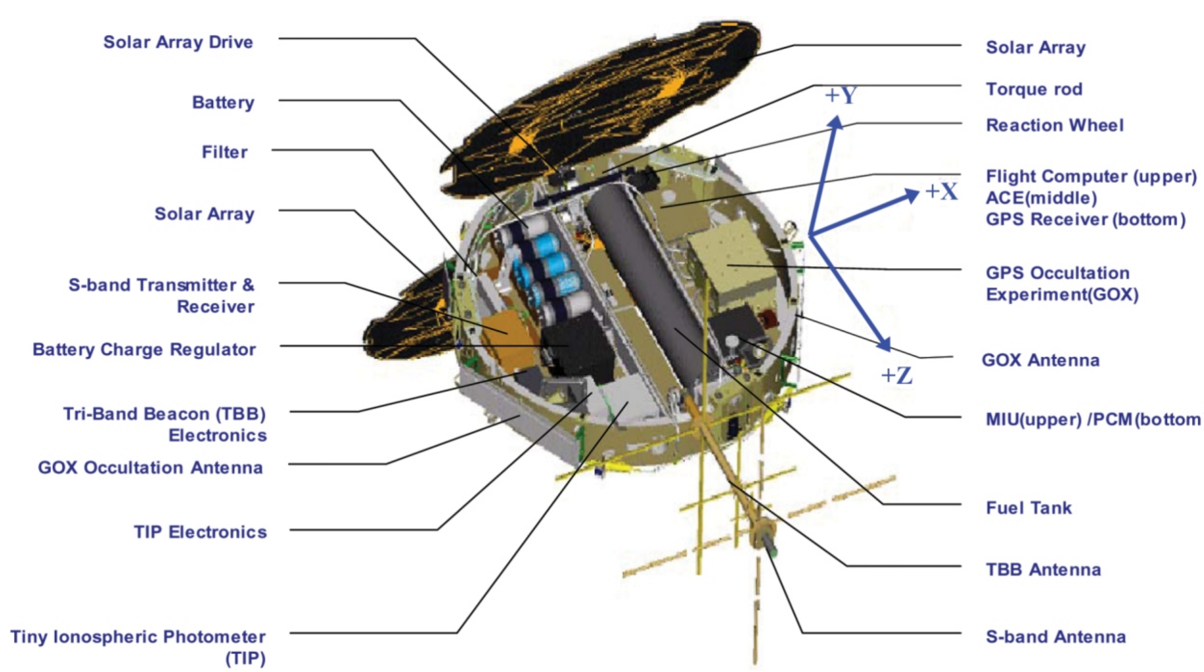

Fig. 2. FORMOSAT-3/COSMIC spacecraft in deployed configuration.

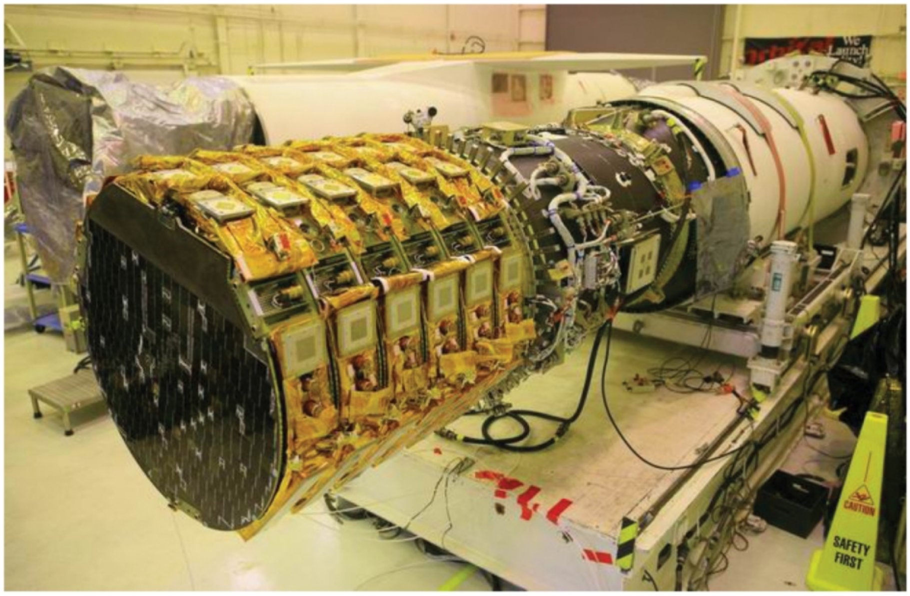

Fig. 3. Six FORMOSAT-3/COSMIC satellites stacked on the minotaur launch vehicle.

constant 72-degree inclination. The spacecraft orbits are phased ~30 degrees apart in ascending node and 52.5 degrees apart in Argument of Latitude (AOL).

2.2 Ground Segment

The FORMOSAT-3/COSMIC ground segment consists of the Spacecraft Operations Multi-Mission Center (MMC) in Taiwan, four TT&C (Telemetry, Tracking and Command) Ground Stations, two Data Receiving and Processing Centers, and the Fiducial Network. There are two TT&C Local Tracking Stations (LTS), one located in Chungli and the other in Tainan, Taiwan, respectively; both LTSs have been upgraded and are capable of supporting the mission for Taiwan passes. There are two Remote Terminal Stations (RTS) at high latitude. One is located at Fairbanks at Alaska, and the other one is located at Kiruna, Sweden. These two RTS TT&C Stations are the primary stations to effectively support the passes of the FORMOSAT-3/COSMIC satellites at 72-degree inclination. In addition, Hawaii and Australia RTSs and Taiwan LTSs may be used as backup stations to the primary TT&C stations for additional data dumps and/or spacecraft emergencies.

The Command, Telemetry and Science data flow of the mission are shown in Fig. 4. NSPO's MMC uses the real-time telemetry and the back orbit telemetry to monitor, control, and manage the spacecraft's state-of-health (SOH). The downlinked science data is transmitted from the RTS via the NMC/USN (Network Management Center/Universal Space Network) to the two Data Receiving and Processing Centers: (1) CDAAC (COSMIC Data Analysis and Archive Center) which is located at Boulder, Colorado, USA; and (2) TACC (Taiwan Analysis Center for COSMIC) located at the Central Weather Bureau (CWB) in Taiwan. The Fiducial GPS data is combined with the occulted and referencing GPS data from the GOX payload to remove clock errors. All collected science data are processed and archived by CDAAC/TACC and then transferred to the users for various data applications. Some of the processed results are then passed to the National Environmental Satellite, Data, and Information Service (NESDIS) at NOAA and further routed to the weather centers throughout the world including the Joint Center for Satellite Data Assimilation (JSCDA), National Centers for Environment Prediction (NCEP), European Centre for Medium-range Weather Forecast (ECMWF), CWB, UK Meteorological Office (UKMO), Japan Meteorological Agency (JMA), Air Force Weather Agency (AFWA), Canadian Meteorological Centre (Canada Met), Meteo France, etc. And they are made ready for assimilation into weather prediction models (Kuo et al. 2000, 2004). The data is provided to weather centers within 180 minutes of on-orbit collection in order to be assimilated into the operational weather forecast model (Wu et al. 2006; Yen et al. 2006).

3. CONSTELLATION MISSION OPERATIONS

The constellation mission operations are divided into four phases. Phase I is the Launch and Early Orbit (L&EO) phase, Phase II is the constellation deployment phase, Phase III is the final constellation phase, and Phase IV is the extended mission phase. Phase I includes launch, separation, ground initial acquisition, spacecraft checkout, and payload checkout. During the Phase II time period, the spacecraft is

- **Command:**
  - *Normal: MMC → NMC → RTS → SC*
  - *Backup: MMC → TT&C → SC*
- **Telemetry:**
  - *Real-time:*
    - SC → TT&C → MMC
    - SC → RTS → NMC → MMC
  - *Back Orbit*
    - Normal: SC → TT&C → MMC
    - Backup/L&EO: SC→ RTS → NMC → MMC
- **Payload science data (GOX & TIP)**
  - *Normal: SC → RTS → NMC → CDAAC*
  - *Backup: SC→ TT&C → MMC → NMC → CDAAC*
- **Payload science data (TBB)**
  - *Normal: SC/TBB → TBB ground receivers*
- **Other science raw data (GPS FID)**
  - *FIDNET → CDAAC*
- **Science data Re-transmission**
  - *CDAAC → TACC*

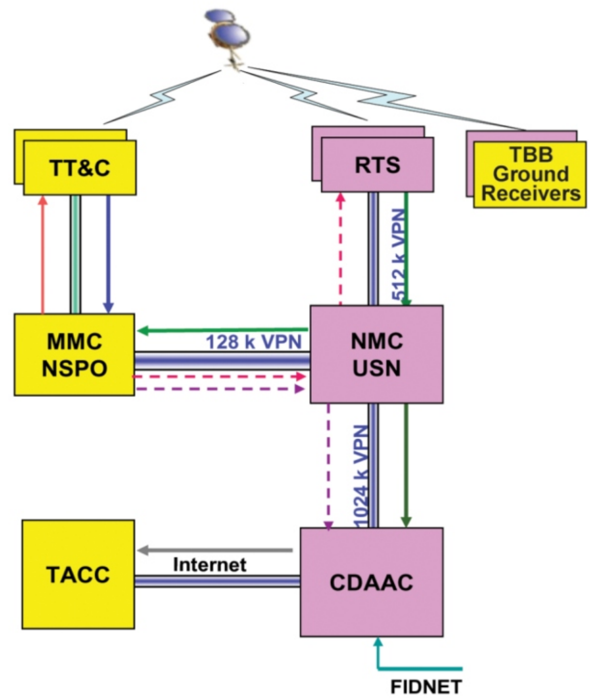

Fig. 4. FORMOSAT-3/COSMIC command, telemetry and science data flow.

raised by its onboard propellant to the final mission altitude at different times to the designated orbit planes by means of nodal precession. The science mission is conducted when there is no thrusting burn. All spacecraft should reach their final orbits with each designed RAAN (Right Ascension of Ascending Node) and AOL (Argument of Latitude) at Phase III. All science experiments will be conducted continuously. The duration of Phase IV would be from the third year to the fifth year after launch. These phases' statuses are summarized in Chu (2006).

3.1 Launch and Ground Initial Acquisition

As a consequence of spacecraft separation after launch, the cluster of six satellites passed over the ground stations at nearly the same time during the initial spacecraft acquisitions. Spacecraft beacon mode was sequentially turned on to radiate RF beacon signals such that the ground station could acquire signals correctly according to the arriving spacecraft. No signals were received for the initial spacecraft acquisitions at Fairbanks RTS during the first pass, due to an inaccurate estimate of spacecraft state vectors upon the spacecraft's separation from the launch vehicle. The FORMOSAT-3/COSMIC spacecraft were later acquired manually by the backup 13-meter-diameter antenna at Fairbanks. The electrical power for all six satellites was normal from the telemetry display. Four out of the six satellites had stopped tumbling soon after the separation from the fourth stage of the launch vehicle and the other two satellites were in tumbling mode for nearly two orbits after the separation. In addition to the spacecraft' initial acquisition issue, the Spacecraft Flight Model No. 5 (FM5) telemetry indicated that the solar array might not be deployed completely. After a second deployment command was sent at the second orbit, the FM5 solar arrays were confirmed as successfully deployed.

3.2 Beacon Mode Exit

Each of the satellites flew in a cluster after launch and all beacon modes of the satellites worked well for the first and second orbit. However, problems were encountered when not receiving telemetry from spacecraft at the third and the fourth orbit. The exit-beacon-mode-flag uplink command was sent to all six satellites and verified the downlink signals of all satellites at the fifth orbit. It was later determined that the reason for the erroneous telemetry reception on orbits three and four was that the onboard bus GPS receiver (GPSRs) aboard FM3, FM4, and FM6 were unable to lock onto the GPS signals for proper time synchronization for the beacon mode.

3.3 Spacecraft and Payload Checkout

The spacecraft checkout starts when the satellite exits the beacon mode after the initial spacecraft acquisition. The flight software configurations were checked and confirmed as normal on all six satellites, initially; later the navigation anomalies that were attributed to the erroneous GPSR behaviours appeared at Launch plus three (L + 3) days. It was not possible to isolate the root cause of these erroneous GPS behaviours. However, an alternative resolution of feeding the known state vector to each spacecraft via uplink commands regularly was able to stop the GPS-related navigation anomalies. All six satellites were ready to power on the payload at L + 6 days. The GOX payload of each spacecraft was powered on first at L + 6 days, the TIP payload on at L + 8 days, and TBB payload on at L + 13 days respectively, according to the operation in-orbit checkout plan.

3.4 Constellation Deployment

During the Constellation Deployment phase the satellites were separated sequentially from the same injection orbit. The satellites needed to perform orbit transfers using their onboard propellants at different times in order to achieve the designated separate orbital planes through the nodal precession. The nodal precession is a well-known gravity phenomenon where the orbital plane drifts (i.e., RAAN precession) due to the Earth's oblateness.

With the inclination angle of 72 degrees and the eccentricity of 0, the constellation deployment (in degree) can be expressed by:

$$6.3804 \quad 10^{13} \quad (a^{7/2}) \quad t \tag{1}$$

where "a" is the semi-major axis of the orbit altitude in km and " t" is the deployment time period in days. In other words, the spacecraft with different altitudes will have different orbital plane drift rates. For example, two orbit planes will drift apart 0.3 degrees per day when the two satellites have a 300 kilometers difference in altitude.

3.5 Argument of Latitude (AOL) Final Phasing

Each ground station can support one pass from an elevation angle of +10 to -10 degrees. If there are two satellites flying over the same ground station at the same time, the ground station can only support one satellite unless there are special arrangements made. Therefore, in addition to the RAAN deployment, a 52.5-degree phasing on Argument of Latitude (AOL) must be implemented to assure that one-orbit worth of occultation science data can be sent to the receiving stations. There is no need to have separation burns to do the phasing on the AOL. The strategy is to perform the AOL phasing adjustment for each spacecraft in conjunction with the orbit manoeuvring of that spacecraft when it approaches the final mission altitude. For example, the AOL phasing adjustment for FM 2 and FM 6 with respect to FM5 (the first spacecraft reached 800 km altitude) began when FM2 and FM6 were raised to 780 and 720 km, respectively. The separation angles in both RAAN and AOL phasing of each spacecraft are achieved at the same time by detailed thrusting activities planned during the final approach (Fong et al. 2006, 2007a, b, 2008a; Yen et al. 2006).

3.6 Final Constellation and Extended Mission Phase

The final constellation of FORMOSAT-3/COSMIC will have six orbit planes. Each orbit is at an altitude of 800 km and inclination angle of 72 degrees. The separation angle among orbit planes is 30 degrees and the AOL separation between satellites in adjacent orbit planes is 52.5 degrees. The final constellation set up allows the six satellites to collect 2500+ atmospheric sounding data on an average per day, worldwide.

The constellation configuration as of December 2007 is shown in Fig. 5, where five satellites (FM5, FM2, FM6, FM4, and FM1) successfully reach the 800-km mission orbits. The dash lines are the planned schedule and the dots recorded the execution results of the thrusting. The FM3 encountered the solar array drive mechanism anomaly and this blocks the FM3 thrust burn activity to be deployed at the 800 km mission orbit after reaching the 711 km orbit (Fong et al. 2008a).

4. CONSTELLATION OPERATIONS CHALLENGES AND SOLUTIONS

Several operations challenges encountered since launch are addressed and can be referred to (Yen et al. 2006; Fong et al. 2007a, b, 2008a, b, c; Chu 2006). The following summarizes some of the major operations challenges encountered during the mission.

4.1 GPSR Non-Fixed

The GPSR Non-Fixed issue can be described as an overall problem when the bus GPS Receiver is not able to lock on to sufficient GPS signals for the spacecraft navigation control while in orbit. The bus GPSR non-fixed anomaly has caused a series of other problems during the L&EO phase. These problems include the satellites' bad flight attitudes, power contingency time jumping, erroneous position indications, the SMA = 0 (Semi-Major Axis) anomaly, and the TIP payload time stamping issue. The GPSR non-fixed issue causes the GPSR to provide no or incorrect information to the onboard Flight Computer (FC). In this case, both the onboard spacecraft FC time and the Attitude Control Subsystem (ACS) propagator were contaminated by the erroneous GPSR's position, velocity and time (PVT) information. The GPSR non-fixed issue is attributed to the onboard avionic grade bus GPS Receiver that has only five receiving channels.

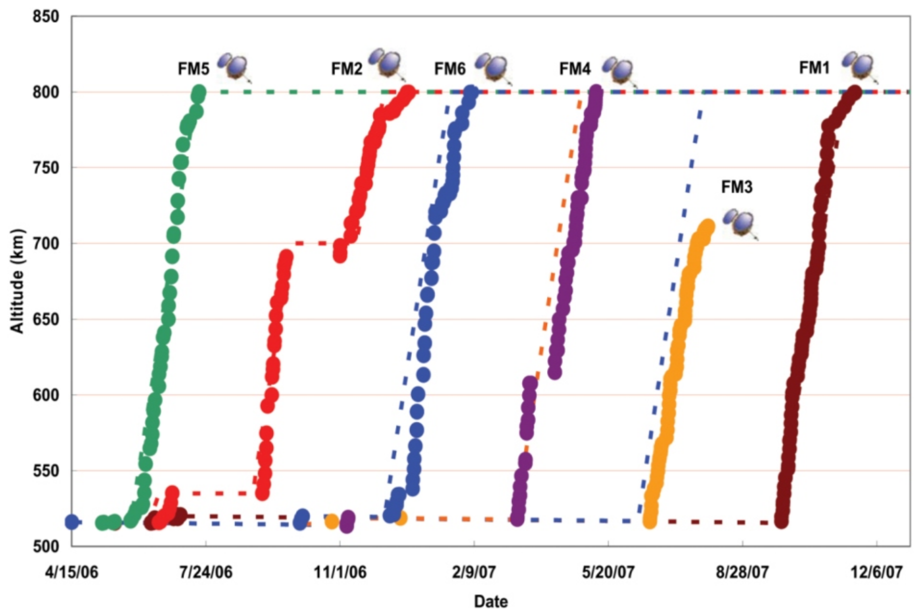

Fig. 5. FORMOSAT-3/COSMIC as-is burn history and deployment timeline.

GPS antenna three-dimensional (3D) tracking coverage of each spacecraft GPSR can be reconstructed as shown in Fig. 6. Figure 6 is the three-dimensional topography of the GPS - received signals from each spacecraft bus GPS receiver. The good GPS-receiving coverage as shown in FM2 and FM5 case in Fig. 6 is almost hemisphere where FM2 and FM5 belong to this case. In contrast, the FM3 only can acquire the signal from the GPS, which is close to the zenith. It was observed that there are some receiving gaps in the low elevation angle in certain azimuth directions of FM1, FM3, and FM6 bus GPSR. The FM4 GPS receiver has tracked no signal since the beginning of the L&EO operation (Fong et al. 2007a, b, 2008a, b, c). The operations solution is to routinely uplink both the correct spacecraft state vector and time commands to each spacecraft, respectively, as obtained from the accurate precision orbit determination (POD) data of the GOX payload of each corresponding spacecraft. This is to assure proper spacecraft attitude control and navigation.

4.2 Spacecraft Attitude Challenge at Parking Orbit

In the first month of the L&EO phase, most of the spacecraft attitudes stay at Nadir-Yaw mode (attitude for scientific experiments) for only 66% of the time on average. Although the design analysis of the spacecraft attitude showed that lower Nadir-Yaw mode at the parking altitude should be anticipated due to a larger spacecraft attitude excursion than at the final mission orbit of 800 km. The low Nadir-Yaw mode could not meet the science data acquisition requirement and must be improved.

At L + 27 days, or Coordinated Universal Time (UTC) Day 132, it was found to have an 8-degree offset in the parameter of Earth horizon sensor (EHS) pointing. The spacecraft utilizes two Goodrich-Barnes 13 - 500 static Earth horizon sensors for roll and pitch attitude determination. Each EHS consists of detectors with a 22-degree high field of view that detects and reports on the angle between the sensor's bore-sight and the Earth's horizon. A systematic input error in the Direction Cosine Matrixes (DCMs) was made to transform the sensor angle into the spacecraft body frame coordinate system. After the corrected parameters were uploaded to each spacecraft, the attitude of all spacecraft significantly improved while in the Nadir-Yaw mode (or over 90% of the time). Since then, spacecraft attitude trending data shows that each spacecraft meets the attitude requirement from the parking orbit to the final mission orbit except during thrust burns (Fong et al. 2007a, b, 2008a, b, c).

4.3 Thrust Burn Challenges

Numerous thrust burn failures were experienced during the orbit raising of FM5. The spacecraft back-orbit data were analyzed and it was determined that the incorrect mass properties, and its consequently derived Center of Gravity (CG)/Moment of Inertia (MOI), primarily attributed to the thrust burn failure. This is verified by using the animation display of the dynamic EDU (Engineering Development Model) simulator with real telemetry data to locate the origin of the error in the ground test records. The thrust gain factor in the spacecraft model is designed to be adjustable by ground command. The thrust Proportional-Integral-Derivative (PID) gain "factor" was adjusted for roll and yaw to optimise for the thrust torque (i.e., Radius Force). The thrust burn activity was performing well after implementing the

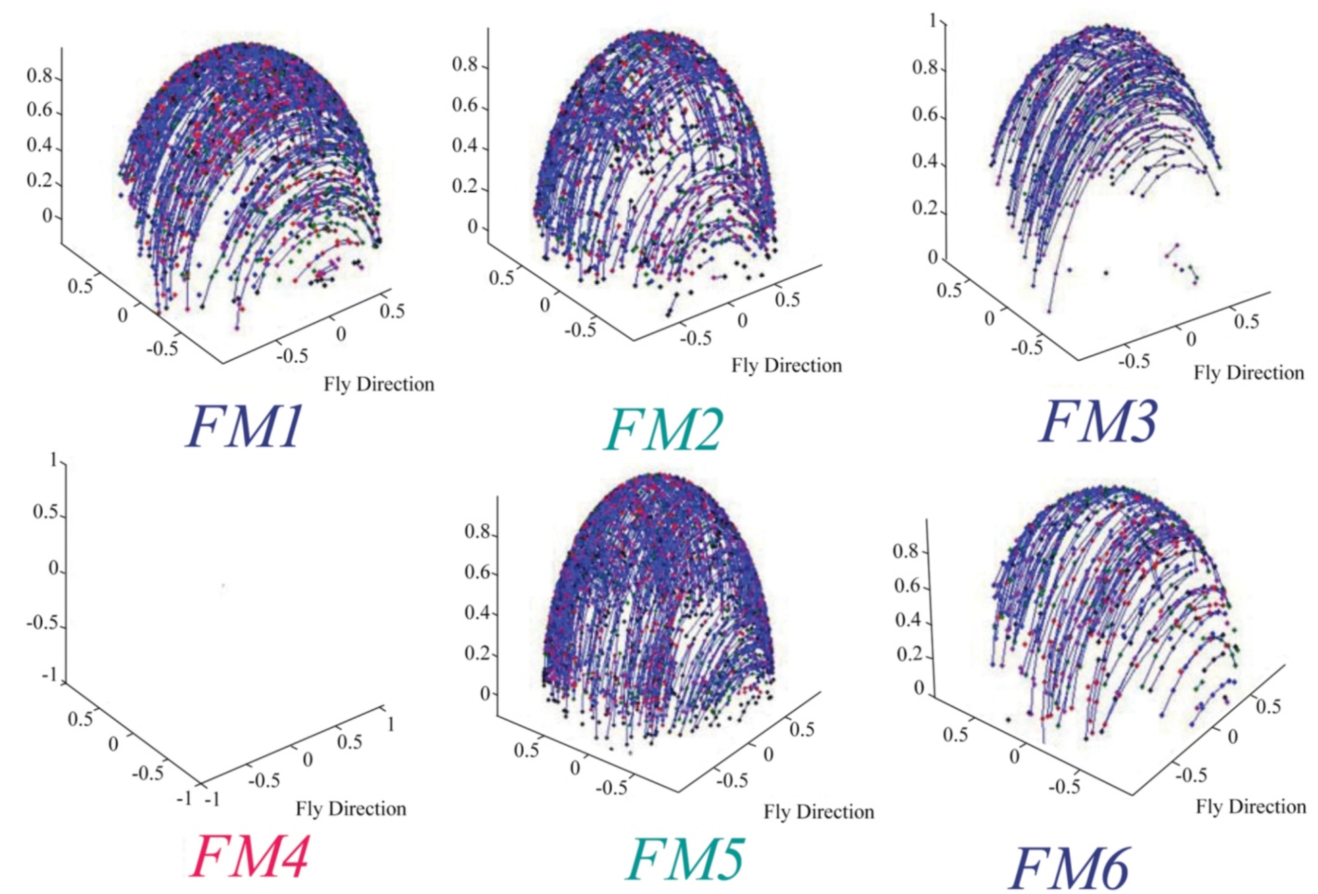

Fig. 6. Spacecraft bus GPSR 3D tracking coverage of GPS satellites.

fine tuning of the PID. The impact of the thrust burn failure indicated that the full burn initiated by routine process as planned could not be performed. This has caused the orbit transfer activities of the first spacecraft, FM5, at a more prolonged schedule than planned.

During the follow-on FM2 and FM6 thrust burns, poorer success rates (~ 50%) were encountered when the thrusting occurred during the spacecraft's sun lit periods, but near 100% success rates were achieved when the thrusting occurred when the spacecraft was in eclipse. Two different algorithms were used in the spacecraft ACS design depending upon numbers of Cosine Sun Sensors (CSSs) to generate a sun vector for the spacecraft Attitude Reference System (ARS) to perform attitude control. However, one of the algorithms generates an unreliable sun vector when measurement discontinuity during the transition to sunless flight and causes the ARS to generate a large pseudo attitude transient incident. The lesson learned from this observation is to perform the thrust burn at spacecraft local eclipse period when possible to eliminate erroneous CSS input to the ACS thrusting control system.

4.4 Constellation Plan Evolution

The mission operation plan changes as time passes. The constellation plan, the GOX operation plan, the TIP operation plan, and the TBB operation plan have been changed to better fit the science goals. Originally, there were two pairs of tandem flight for FM2 and FM3, and FM4 and FM5, respectively, during the initial constellation deployment phase. The purpose of the tandem flight is to undertake additional geodetic research. However, as the spacecraft FM3 and FM4 have been very close together since the separation from the launch vehicle, the data as generated from April to October could be used for geodesy research at the parking orbit of 516 km without executing the tandem flights as scheduled (Hwang et al. 2006). Instead, the constellation plan was changed to increase science data dumps for the tropical storms (typhoons and hurricanes, etc.) prediction forecast studies during the Intensive Operating Phase (IOP) campaign between July and November 2006.

The original constellation plan at an 800 km orbit with 24-degree separation planes was for a shorter deployment time consideration (13 months after launch), but this is not favourable for ionospheric monitoring and climate seasonal variability studying due to non-uniform coverage globally. A shorter duration to complete the constellation deployment was planned originally because the payload instrument was designed to "focus" at 800 km mission orbit. On one hand, the data quality of the early phase (mostly at a lower orbit) was determined to be surprisingly better than anticipated, and the satellite constellation deployment time became a lesser concern. On the other hand, scientists from Taiwan and the US coherently favored the 30-degree separation with a ~6 month longer satellite constellation deployment duration over 24-degree separation for globally uniform coverage in local solar time (LST). This constellation deployment plan change reflects that an integral teamwork among the operations team and data users leads to a greater mission success.

The constellation deployment plan change from a 24-degree separation to 30-degree separation was made after the completion of the FM5 orbit transfer and during the FM2 orbit raising. The decision was made to put the FM2 orbit transfer on hold in October 2006 to allow FM2 to further separate from FM5. The completion of the final constellation consequently shifted from May to December 2007 (Yen et al. 2006; Liou et al. 2007).

4.5 Computers Resets/Reboots

A total of thirty-seven (37) computer resets had been observed up to May 2007 since the launch. 32 out of 37 computer resets were deemed to be related to the highly energetic particle activities as shown in Fig. 7, which illustrates the projected geographic locations on Earth during these reset/reboot events over the one-year period since launch. In Fig. 7, NOAA's POES satellites 1-Year > 300 kEV energetic particle chart (courtesy of NOAA) is shown for comparison. Further investigation shows that most time of those anomalies occurred and the spacecraft ground tracking locations are highly correlated to the space radiation environment based on NOAA's space weather alert and warning timeline. Single Event Effects (SEEs) in the South Atlantic Anomaly (SAA) region and the northern polar region were later identified to be the most probable root cause. According to the FDC (Failure Detection and Correction) design of FORMOSAT-3/COSMIC spacecraft, most of those anomalies were sensed and recovered automatically by onboard FDC functions. No spacecraft performance has been degraded yet by these anomalies.

4.6 Maximizing Science Data Downloads

A total of 84 data dumps per day can be realized when all six spacecraft reach the final mission constellation. In the early phase of the mission, only a total of 12 data dumps (2 per each spacecraft) in a day could be executed, primarily due to the cluster formation during the constellation deploy-

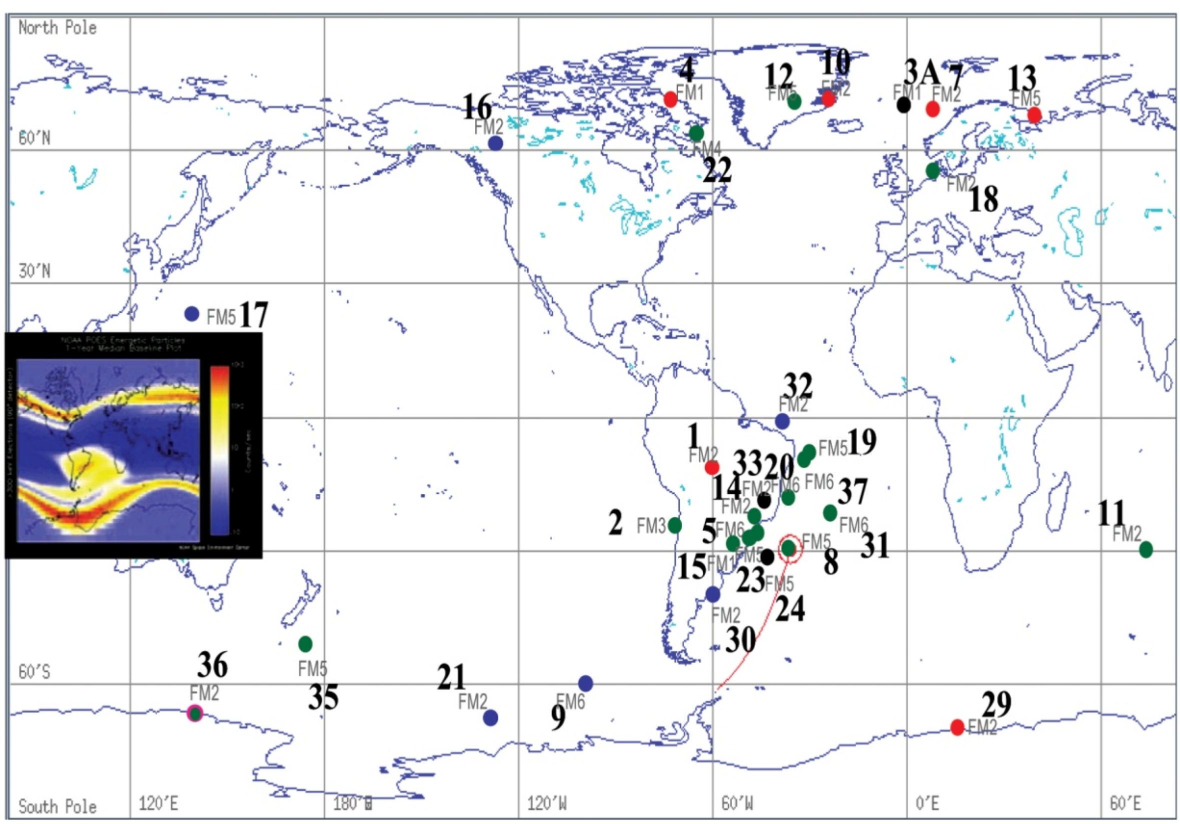

Fig. 7. The geographic location of the spacecraft resets/reboots events one year since launch and comparison with the NOAA POES satellite's 1-year > 300 kEV energetic particle chart (Courtesy From NOAA).

ment phase. The GOX firmware was upgraded to improve the quality and the quantity of the science data as the satellite constellation configuration (such as altitudes, field of views, etc.) changed. In parallel, optimization efforts were implemented to the spacecraft operations processes, the ground software, the ground control auto scripts, and the spacecraft flying formation, etc. to maximize the number of science data dumps per day. Currently there are around 66 dumps on average per day, a dramatic increase from the 12 dumps a day as originally planned (Fong et al. 2007a, b, 2008a, b, c).

4.7 Data Overflow Issue

The spacecraft science data are temporarily stored in a 128 Mbyte Solid State Recorder (SSR). The GOX payload is configured as GOX-A for primary and GOX-B for redundancy. GOX-A and GOX-B is separately allocated a 32 Mbytes memory space (or about a three orbit capacity) each in the SSR. GOX data would have an over-wrapping issue when the data is not dumped within every third contact with the scheduled RTS. The 32-Mbyte GOX storage memory shouldn't be an issue for an evenly spaced satellite constellation at the final mission orbit. However, in the L&EO phase, narrowing the GOX antenna field of view to control the data volume is one way to avoid data loss due to the over-wrapping in the SSR when the scheduled RTS is limited to receive the data dumps. Intentionally dumping the science data into space is another way to prevent the over-wrapping issue from occurring during the L&EO phase. There is still a small percentage of science data dumped into space during the spacecraft thrusting activities that demand allocated RTS supports (Fong et al. 2006, 2007a, b, 2008a, b, c).

4.8 GOX Data Gapping Issue

It was observed and identified that 29% of data dropouts from the retrieved science RO data was belong to the GOX data gapping issues. After investigating those questionable raw data, we found out the same data dropouts pattern was also observed during the ground End-To-End (ETE) tests but the on-orbit results are much worse now. It is also summarized that there would be data gapping issue in the GOX science data when dumping the spacecraft telemetry data and science data simultaneously. As a result of several on-orbit experiments, the GOX data gaps issue will be disappeared if the spacecraft telemetry data dumping is performed separately from the GOX data dumping. This new scheme has rescued 70% of those science data with data gapping issue. We also found out that if the science data is downloaded alone, even a typical routine dump with a ~0.04% data dropouts will causes an 8% RO data gapping. The operations team decides to make the same science data dump twice routinely. Practically, these two dumps will not drop the same data packets so it can make up for any data dropouts. Even through this double dumps scheme will increase local data storage memories and double the data transfer time from ground station to the data analysis centers, it is still worthy to saved the 8% science data eventually (Fong et al. 2007a, b, 2008a, b, c).

5. SPACECRAFT CONSTELLATION SYSTEM ON-ORBIT PERFORMANCE

The spacecraft subsystems and the state of spacecraft health as of 15 April 2007 are summarized below, after a year in orbit. Unlike a single spacecraft mission, the FORMOSAT-3/COSMIC satellite constellation provides a unique opportunity to assess the performance of multiple spacecraft at the same time (Patel et al. 1999; Fong et al. 2006, 2007a, b, 2008a, b, c).

5.1 Spacecraft Bus Performance

The overall system performance results of all six satellites can be referenced to Fong et al. (2007a, b, 2008b). Table 2 shows the current spacecraft operation status of each subsystem in all six satellites. Table 3 highlights the major on-orbit status for all satellites. Spacecraft No. 2 (FM2) experienced many resets and reboots events compared to the other satellites.

Table 2. Spacecraft state-of-health.

Spacecraft	Operational Mode	SC State	ACS Mode	EPS Mode	C & DH Mode	GOX	TIP	TBB
FM1	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating	Operating	Operating
FM2	Normal	Normal	Fixed-Yaw	Power Shortage	High Rate	Operating	Off	Off
FM3	Normal	Normal	Fixed-Yaw	Power Shortage	High Rate	Operating	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

Table 3. Major on-orbit status for all satellites.

Spacecraft ID	Summary
FM1	GOX Reboot Loop (Sep. 2007)
FM2	PCM DC Converter Abnormally Off (Aug. 2006)
	Solar Panel Power Shortage (Mar. 2007)
	Battery Pressure Difference Anomaly (Dec. 2006)
	Charge Anomaly (Feb. 2007)
	GOX Reboot Loop (Aug. 2007)
FM3	Solar Array Driver Lockout (Aug. 2007)
FM4	Bus GPSR Received No GPS signal at all (since launch)
FM5	GOX RF1 Lower SNR (May 2007)
	GOX Reboot Loop (July 2007)
FM6	GOX Reboot Loop (Feb. and Apr. 2007)
	FM6 Lost of Contact (Sept. ~ Nov. 2007)

Notably, there are FM2 and FM3 power shortage anomaly issues. On 1 March 2007, the FM2 maximum solar array output power was reduced from 200 to 100 W. The effect was deemed to be mechanical and resulted in a permanent power failure from one solar array. A reduced GOX payload operation plan was implemented to take into account the power shortage condition of FM2. Currently FM2 is able to operate the GOX at a ~70% duty cycle with the secondary payloads (TIP and TBB) turned off at all times. On 3 August 2007 FM3 encountered the solar array drive mechanism malfunction when it reached a 711 km orbit. The stuck solar array effects were two-folded, one was to block the thrusting to continue to 800 km mission orbit, and the other one was the lost sun tracking capability of solar array for the spacecraft. Currently FM3 is able to operate the GOX at a ~50% duty cycle with TBB and TIP payloads turned off at all times. The reasons for this anomaly are still under investigation.

FM6 lost its ground communication link on 8 September 2007. There was no telemetry which indicated a spacecraft problem prior to the FM6 lost event. Many emergency recovery attempts were tried but failed. A routine recovery plan was implemented as an investigation of the root cause continued. After a duration of 2 months (from UTC Day 252 - 317 of 2007) FM6 recovered on its own. The FM6 transmitter RF spectrum as received from the Taiwan Station near the time of recovery looked normal with no sign of degradation and the spacecraft was checked to be in good health and started to provide data again on UTC Day 318 of 2007. The root cause analysis and ground simulation test for this lost communication event is still under investigation. Science data from FM6 are looking good and are provided to users from CDAAC/TACC.

5.2 Spacecraft Attitude Performance

Spacecraft System State of Health (SOH): All six spacecraft are operating normally. Although there are alternative ways to solve the various GPSR anomalies to recover the spacecraft altitude controls, the investigation of the root cause of the GPSR anomaly issue continues. In orbit with a low beta angle, the spacecraft achieve a maximum eclipse time, yet the measurements of the Cosine Sun Sensors (CSS) on the spacecraft may experience interference from the Albedo effect. On the other hand, with a high beta angle effect, the spacecraft in eclipse time is substantially decreased when the beta angle is above 60 degrees. The spacecraft is in the sunlit region all the time when the beta angles are larger than 68 degrees. The Earth horizon sensor is exposed to solar radiation continuously when the beta angle is above 68 degrees. The FORMOSAT-3/COSMIC spacecraft thermal control and electric power design required all six spacecraft to perform flip-flop (i.e., the spacecraft rotate 180 degrees in nadir direction) when the spacecraft crossovers the zero degree beta angle. Consequently the GOX POD direction needs to be switched and commanded by the GOX receiver when the spacecraft flip-flop occurs.

Figure 8 shows one of the spacecraft's (FM6) daily on-orbit system performance with downloaded spacecraft attitude profile (roll, pitch, and yaw in one sigma), orbit raising attitude (or SMA) and beta angle for reference.

5.3 Spacecraft Electrical Power Performance

The spacecraft electrical power performance consists of the battery usage and solar array output capability. The nominal value of the battery capacity is 10 Ah. The real

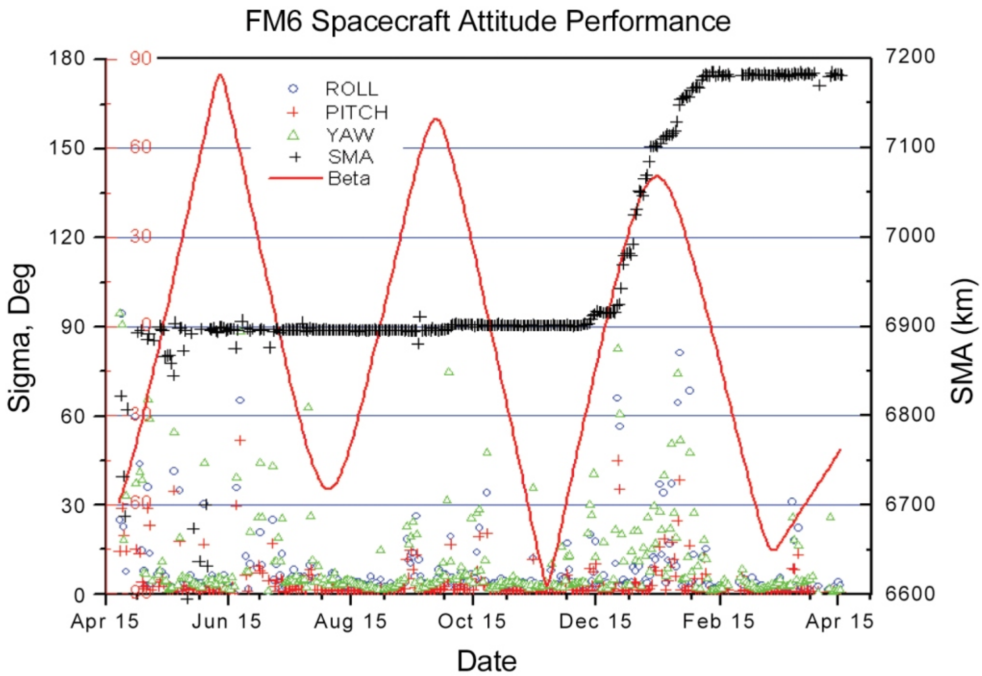

Fig. 8. FORMOSAT-3/COSMIC spacecraft (FM6) system on-orbit performance.

flight experience shows the capacity is greater than as designated in typical normal operation. The maximum battery capacity or State of Charge (SOC) can be as high as 15 Ah after being charged. If the spacecraft attitude excursion occurs for a prolonged duration over several sunlit periods, the EPS Contingency will then be triggered when the battery SOC falls below the set limit of 5.5. In this case, the payloads will be powered off and the spacecraft power will soon be recovered. The minimum battery voltage is around 12 volts in any operation scenario since launch.

5.4 Payload Powered off Statistics

The top table of payload powered off statistics (unit is number of event) shown in Fig. 9 was analysed from UTC Day 175 of 2006 to Day 105 of 2007. Before Day 175 of 2006, the 8-degree bias angle in the Earth horizon sensor hadn't been fixed and the GOX was not able to be powered on for 24 continuous hours. Figure 9 also excludes the action events undertaken by the operations team, such as FSW (Flight Software) and CSD (Common Spacecraft Database) upload, some processors being reset by the ground command, etc. The goal of the statistics is to analyse the causes of payload powered off and implement the preventive actions to reduce the payload power-off events. To ensure the quality of the FORMOSAT-3/COSMIC science data, the payload instrument is set to be operative only when spacecraft attitude is stable in the Nadir/Yaw or Nadir mode. The criterion is mainly defined by the spacecraft nadir pointing error and should be within 15 degrees. During the one-year operation, the causes of payload off are categorized as: (1) processor reboot; (2) entrance to stabilized/safe-hold mode; (3) stabilized mode after thrust burns; (4) Nadir mode after thrust burns so that the spacecraft enters into power contingency; (5) power contingency due to staying in Nadir mode too long; (6) dMdC (Battery cell Hydrogen's mole change over Coulomb's change) anomaly; (7) power shortage; and (8) PCM (Power Control Module) DC off anomaly. Most payloads off events were caused by the Nadir mode effect before May 2007. After that, the Kalman filter was programmed to be reset automatically when spacecraft entered into Nadir mode. The Kalman filter reset operations were implemented in June 2007. Since then, the Nadir mode effects on the payload off have almost disappeared.

6. PAYLOAD ON-ORBIT PERFORMANCE

6.1 GOX Payload Performance

The GOX flight software Firmware-Build versions 4.0 (FB4.0) and 4.1 (FB4.1) were stored on board the GOX-A and GOX-B payload instruments before launch, respectively. After payload checkout the CDAAC and TACC reported that good POD and OCC data have been received when spacecraft attitudes are stabilized and that they are able to perform good orbit determination. CDAAC was able to process the POD and OCC data into useful profiles; however, the profiles were truncated at about six km altitude above the sea level. The truncation of the profiles is due to known issues with the FM firmware for open loop (OL) tracking (Sokolovskiy et al. 2006; Chiu et al. 2008). FB4.2

	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%

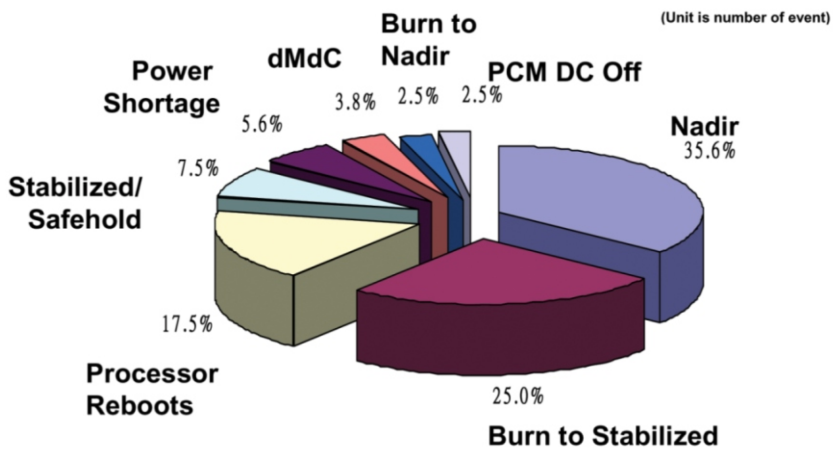

Fig. 9. One-year statistics results of payload off phenomenon on all six satellites.

and soon FB4.2.1 were later generated and were uploaded to the spacecraft in early June and July 2006, respectively. FB4.2 was built to avoid POD logging unnecessary data and to exclude occulting satellites to be used for navigation solution. FB4.2.1 was built to fix some bugs found in FB4.2 and adjust some parameters in the firmware. Those include the improvement to the P2(L2) phase's resolution and modification on the forward POD scheduling function to help rising ionospheric occultations to start earlier at lower altitudes and some fixes correct on offset and the drift error in the open loop model for rising occultation function. The FB 4.2.1 was further modified to limit the azimuth angle in the firmware to 50 degrees for proper GOX operations.

The latest GOX firmware version on all six GOX payload instruments is Flight Build version 4.3. This version was uploaded to the GOX payload instruments in February 2007. The main changes in FB 4.3 include (1) maximizing azimuth windows of occultation antennas from 45 to 75 degrees; (2) terminating rising occultations later at the designated height; (3) fixing the Az/El reporting log message; and (4) improving the message format consistency. The GOX firmware Flight Build version 4.4 was uploaded only to the GOX that had a reboot loop anomaly issue. The main purpose of FB4.4 was to let GOX choose the forward POD antenna as the default POD antenna.

Figure 10 shows the one-year RF Signal-to-Noise (SNR) performances on four GOX antennas (POD1, POD2, OCC1, and OCC2) of each GOX payload instruments in all six satellites. The definition of the daily SNR value shown in these figures (Figs. 10a to f) is the bottom limit of the top 90% SNR value of all the tracked GPS satellites' signal SNR values received by that particular antenna on that day. In these figures only data received after 13 July (Day 194 of 2006) using FB4.2.1 was uploaded for evaluation.

By looking at the P2 SNR value first, it can be seen that the value shifts up for a certain period time (around three months), and then shifts down again and keeps to another value for another time period. The main reason for that is the spacecraft is required to perform a "flip-flop" when the spacecraft crossovers the zero degree beta angle as described in Section 5.2 of this paper. From the figures, it seems that CA and P2 SNR on both of the OCC1 and OCC2 antennas all show a trend of degradation in SNR values before FB4.3 was uploaded. However, after a detailed analysis it is seen that the decrease in SNR value is mainly due to the configuration changes of parameter on both of the OCC aft-ward and forward antennas. The occultation windows on all six GOX payload instruments were adjusted from 30 (originally) to 70 degrees, and the dates of change and changes in the window value are indicated in the figures. The trend in SNR for the date after FB4.3 was uploaded did not show any sign of degradation at all from the available data.

The SNR value for OCC1 on spacecraft No. 3 (FM3), as

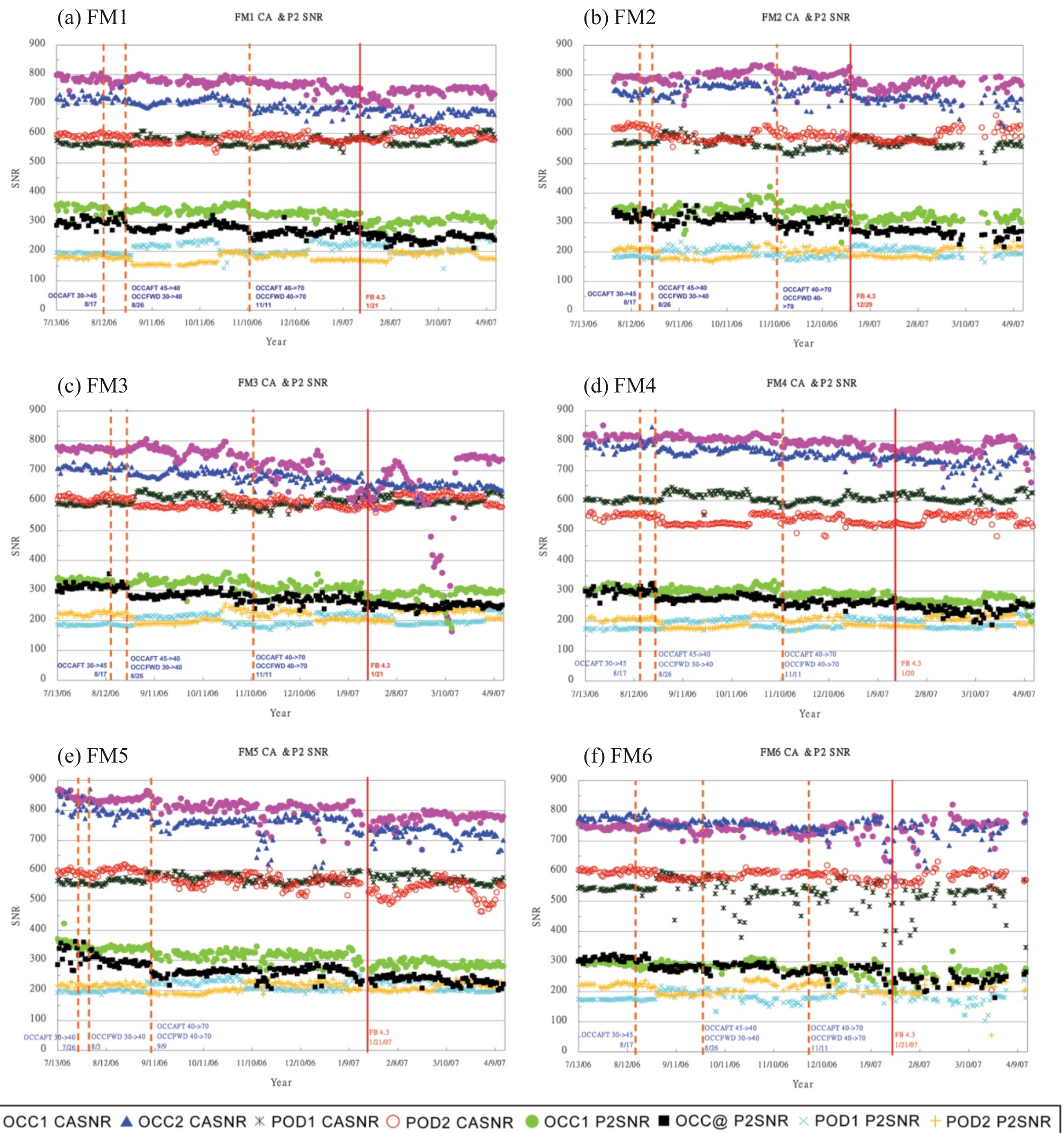

Fig. 10. FORMOSAT-3/COSMIC payload POD & OCC CA and P2 SNR for: (a) spacecraft No. 1 (FM1), (b) spacecraft No. 2 (FM2), (c) spacecraft No. 3 (FM3), (d) spacecraft No. 4 (FM4), (e) spacecraft No. 5 (FM5), and (f) spacecraft No. 6 (FM6).

seen in Fig. 10c, does show a decrease, as the value drops rapidly when the spacecraft is at a much higher beta angle. However, it is observed that the SNR value returns to a normal value when the GOX temperature is lower than 40 degrees C, when spacecraft FM3 is leaving the high beta a ngle. A recovery plan to counteract this issue is still under investigation. The GOX payload on spacecraft No. 6 (FM6) in Fig. 10f shows an anomaly of the GOX unusual consecutive reboots. In general, GOX will reboot itself if there is no navigation solution within 15 minutes. The reboot loop of the GOX instrument should automatically recover itself as evidenced by spacecraft No. 1 (FM1), 2 (FM2), 5 (FM5), and 6 (FM6). However, FM6 also experienced two consecutive reboot anomalies every 15 minutes for several continuous hours without automatic recovery in February and in April of 2007. The root cause was preliminarily identified as the low signal-to-noise ratio of the navigation antenna when the spacecraft entered into a beta angle between 0 and -30 degrees. A new firmware build version 4.4 (FB 4.4) was loaded in June 2007 and the reboot loop has since ceased (Fong et al. 2007b).

6.2 TIP Payload Performance

The TIP payload is an ionospheric photometer for observing the Earth's naturally occurring far-ultraviolet airglow to characterize the ionosphere and neutral atmosphere. The TIP counts ultraviolet photons emitted from the F2 layer of the atmosphere directly below the spacecraft. The TIP mission is planned to occur during the orbit eclipse period. Like the GOX, TIP data is also stored in the SSR/PC. The collected data are periodically dumped to the ground station via an S-Band RF downlink.

All TIPs are operating normally except the disabled FM2 and FM3 TIP operation because of the power shortage issue. The TIP payload anomalies include a TIP instrument initialization issue, a time stamp issue due to bus GPSR non-fixed issue; a TIP night-time operation starting too early issue; and a time labelling issue (Anthes et al. 2008).

7. PRELIMINARY SATELLITE CONSTELLATION MISSION RESULTS

In the early phase of the FORMOSAT-3/COSMIC mission, the satellites were in close formation and provided an opportunity to test the precision of the GPS RO measurements. Taiwan's science teams conducted an Intense Observation Period (IOP) campaign between May and November of 2006 to cross-validate RO data with other observations (ground-based radiosondes, other weather satellites, airplane dropsondes, balloons, radars, ionosondes, digisonde, etc.). Scientists from other nations, such as the US, Japan, and Korea also conducted similar IOP campaigns. The presentation package of early results and IOP campaigns during this period could be found on the NSPO website (NSPO 2006).

7.1 The First RO Soundings

The first electron density profiles were obtained on the sixth day after launch (L + 6 days), and the first atmospheric occultation event and profile were received and processed at L + 8 days by FM1 and FM4. These two satellites were roughly a few hundred kilometers apart which correspond to a distance separation for the RO soundings of about 1.5 km. The close agreement of the two FORMOSAT-3/COSMIC RO soundings demonstrates the precision of the GPS radio occultation technique (Anthes et al. 2008).

The close proximity of the FORMOSAT-3/COSMIC satellites flying in cluster configuration after separation provided a unique opportunity to estimate the precision of the GPS radio occultation remote sensing technique based upon closely collocated occultations (< 10 km separation of tangent points). From the UCAR's preliminary estimates the RMS difference of refractivity between 10 and 20 km altitude was less than 0.2% due to smaller separation of the occultation pairs and due to parallel occultation planes. In the lower troposphere, the maximal RMS was ~0.8% at 2 km altitude and decreased abruptly to ~0.2% between six and eight km altitude. The RMS difference of electron density in the ionosphere between 150 and 500 km altitude for collocated occultations is about 103 cm^{-3}. For details refer to Schreiner et al. (2007).

7.2 GPS RO Events

Figures 11 and 12 show the number of daily atmospheric and ionospheric occultation events since launch respectively. There are more than 1103936 (669441 received)

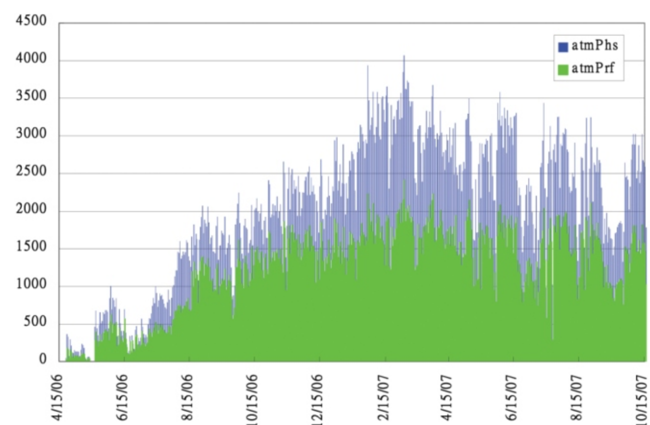

Fig. 11. One-and-half year statistics of the number of daily occultation events for atmosphere profiles since launch.

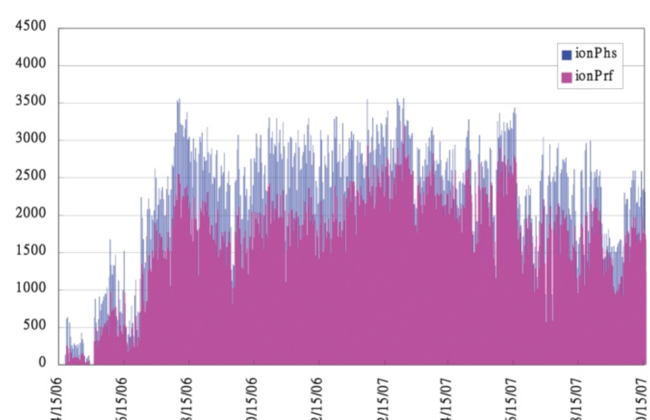

Fig. 12. One-and-half year statistics of the number of daily occultation events for ionosphere profiles of electron density since launch.

atmospheric profiles and 1252629 (933616 received) ionospheric profiles generated by TACC/CDAAC for outside distribution through 15 October 2007. The "atmphs" in Fig. 11 means the number of excess phase files that were generated and also represent the atmospheric RO events can be observed by FORMOSAT-3/COSMIC satellites; "ionphs" indicates ionospheric RO events as shown in Fig. 12. As seen in Fig. 11, ~37% vertical atmospheric profiles of the total events can not be retrieved, and compared to ~25% for ionospheric profiles in Fig. 12. Figures 11 and 12 show that the data as received by FORMOSAT-3/COSMIC satellites at current constellation have been post processed in near real time into 2500 good ionospheric profiles and 1800 good atmospheric profiles per day, respectively. These have outnumbered the worldwide radiosondes (~900 mostly over land) launched from the ground per day. The occultation events collected by the current FORMOSAT-3/COSMIC constellation have achieved ~80% of the mission goal of 2500 events per day.

The mission-planned goal of 2500 or more daily profiles may be difficult to accomplish. The main reasons for the anticipated lower number are: (1) FM2 and FM3 is scheduled at reduced GOX operation duty cycle due to the power shortage issue as described in Section 5.1; (2) to avoid SSR receiver memory overflow, some of the GOX science data are scheduled and dumped into space (not to a ground station), and forever lost; (3) during orbit elevation, precise orbit determination is impossible and RO data cannot be processed; (4) science data gaps in high-rate data packet and need further manual processing; and (5) poor data quality, short Fiducial data, or imperfectly retrieval methods. NSPO is currently working with UCAR and the science teams to resolve these issues and try to provide the best quality and maximum RO numbers for the science user community. The mission team is still striving to meet the 2500 soundings per day goal when these satellites get to their final satellite constellation configuration and remaining data quality issues resolved.

7.3 Science Data Dissemination

Through a joint effort by the NSPO and UCAR, raw data and data products have been disseminated to the international community in near real time (under three hours) via TACC/CDAAC since August 2006. Several global weather operational centers (e.g., ECMWF, NCEP, UKMO Meteo France, and CWB) have started integrating FORMOSAT-3/COSMIC data for operational use, and have reported encouraging results. Research groups have also been performing experiments to assess the impact of FORMOSAT-3/COSMIC data on global/regional weather analysis and prediction, including tropical cyclone predictions. From TACC and CDAAC website data, the number of registered data users between August 2006 and August 2007 exceeded 537 in 42 countries (CDAAC website; TACC website).

8. PROSPECTS FOR FOLLOW-ON (FO) MISSION

The FORMOSAT-3/COSMIC satellite constellation measures the phase delay of a GPS signal from the six small satellites to obtain the atmospheric parameters. It is anticipated that there will be 2500+ soundings per day, globally distributed, when the final constellation configuration is reached. As an augmenting follow-on mission, three improvements would further strengthen the current mission. The first aspect is to enhance the capability of the GPS receivers to accommodate signals from GLONASS and Galileo in addition to the GPS satellites. Second, with addition of more satellites a more densely populated global satellite constellation would better serve a variety of follow-on needs. Finally, optimizing the satellite constellation formation would balance regional coverage at different latitudes.

Currently, there are about 30 operational USAF GPS. When the GOX receivers can receive the data from both GPS and GLONASS, the occultation number can be increased by a factor of 1.8. When Galileo is also considered, the occultation number can be increased by a factor of 2.9. It is an effective way to increase the total RO soundings without increasing the number of satellites. The constellation formation can be optimized depending on the number of satellites that are considered in the follow-on mission to optimize the regional needs of the global coverage. The satellite constellation optimization may include the orbit plane inclinations, the separation angles, and the number of satellites on each orbit plane. The altitude of the constellation is not a system driver for occultation since the occultation antenna can be tuned based on the chosen altitude. As a matter of fact, cost is another dominant factor in the number of satellites and the satellite constellation formation, this issue will not be discussed in this paper.

The inclination angle and the orbit plane should have an impact on the occultation distribution in terms of latitude coverage. For easy illustration, the parameters of FORMOSAT-3/COSMIC are used as the baseline, except for the inclination angle. The total occultation number per satellite per day is about 420. The inclination angles of 0, 24, 48, 72, and 98.6 degrees in an 800-km altitude orbit are calculated and the results are shown in Fig. 13a. There are 75 soundings at a latitude of five degrees and 8 soundings at a latitude of twenty-five degrees as shown in Fig 13a, respectively. The occultation number distribution is almost symmetrical for the Northern Hemisphere and the Southern Hemisphere in spite of the inclination angles. A low inclination orbit can collect more RO data at a low latitude, and high inclination orbit at a high latitude. Therefore, the regional needs can be met by tailoring the inclination of the satellite cluster constellation. In fact, the represented area of the RO events at a low latitude is larger than that of a high latitude per degree latitude. In Fig. 13b, the number is the total area divided by the total occultation number from the Northern and Southern Hemispheres. For example, there will be one occultation per 1085   1085 km^2 per day per satellite at a latitude of five degrees, and one occultation per 3340   3340 km^2 at a latitude of twenty-five degrees. In other words, the smaller the number is, the more densely the occultations are distributed. FORMOSAT-3/COSMIC's inclination angle is 72 degrees; the occultation is sparser at low latitudes. For analysis, a constellation of combining inclination angles of 24 and 72 degrees will be considered for the Follow-On (FO) mission. In such conditions, more homogeneous distribution of occultation can be expected.

Figure 14a shows the occultation distribution of the FORMOSAT-3/COSMIC mission and the proposed FO mission. For easy comparison, the FO mission still has six LEO satellites in all, but with three satellites at a 24-degree inclination angle orbit and the other three satellites at a 72-degree inclination angle orbit. The result of the occultation distribution is more homogeneous in the FO plan. Figure 14a also shows the occultation distribution when FO is equipped with a GNSS receiver. GNSS represents GPS, GLONASS, and Galileo. A blue dashed line in Fig. 14a illustrates the condition with 20 satellites carrying GNSS receivers as a cartoon.

Another parameter to be discussed is the orbit planes. In addition to the time consumed in thrust parameter adjustment, FORMOSAT-3/COSMIC takes about 18 months to complete the satellite constellation deployment. During the period of thrust burns, the total number of retrieved RO data per day is reduced because no data is being collected from thrusting spacecraft, and also more ground passes are scheduled to support the thrusting activities. Therefore, the proposal for a FO is to put three satellites in the same orbit plane so that we can adjust only the argument of latitude. The deployment period can be shortened to within two months and the thrust period can be reduced by a factor of 0.2. One may question why FORMOSAT-3/COSMIC needs such a long time for orbit plane separation. The answer is that the spread of orbit planes can collect globally distributed soundings sooner. Figure 13b shows the coverage for FORMOSAT-3/COSMIC vs. FO. For one revolution, the FORMOSAT-3/COSMIC mission can cover ~25% of Earth surface area, and for 14 revolutions (about one day)

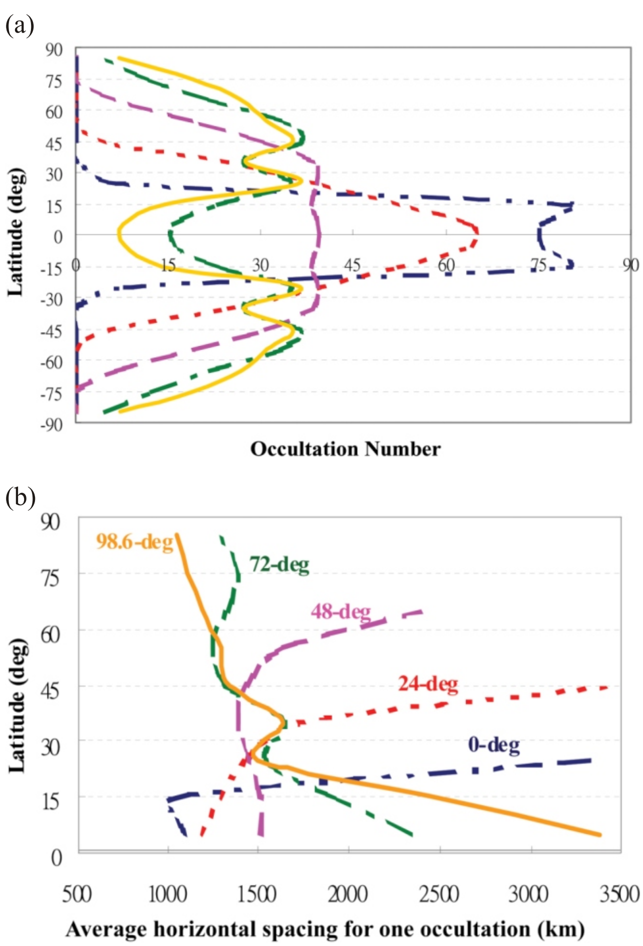

Fig. 13. (a) Occultation number/satellite/day for different inclination angles and (b) the average horizontal spacing by one occultation (km) for one satellite at different inclination angle in one day.

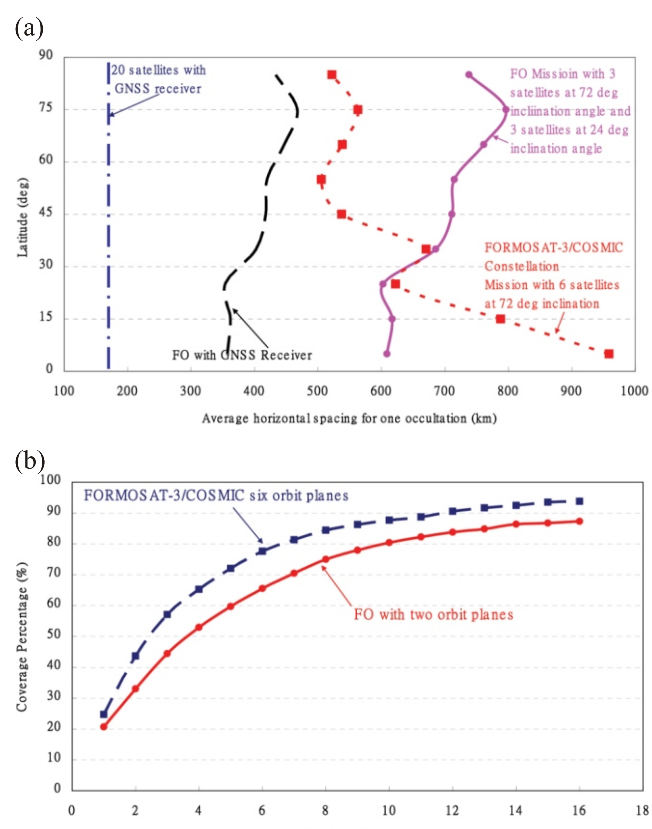

Fig. 14. (a) The average horizontal spacing by one occultation (km) for FORMOSAT-3/COSMIC and follow-on constellations with GPS receiver and GNSS receiver and (b) the percentage of global coverage versus the revolution number of satellites.

FORMOSAT-3/COSMIC can cover ~92% of Earth surface area. The definition of the coverage is the percentage of the grid. One grid is 10 degrees latitude by 10 degrees longitude. If the occultation occurs at the same grid, it is regarded as one grid. Concerning the coverage, six orbit planes are always better than two orbit planes. The FORMOSAT-3/COSMIC mission is contemporarily unique and the benefits of the RO technique have been proved in many applications, as has the positive impact to weather forecast systems. Many organizations in several countries are contemplating or proposing RO space projects to continue the similar FORMOSAT-3/COSMIC mission. As the FO proceeds, the United States, Europe, India, and Korea are also developing the next generation RO missions.

9. CONCLUSION

In addition to the operation of the six satellites, the on-orbit spacecraft system performances is monitored, tracked, and evaluated constantly by NSPO's operation team. The related operations process, firmware, ground software, and auto script modification or upgrades are required to improve the quality of the mission operations. The initial mission results, including the IOP campaign using innovative RO technology by researchers worldwide, and the global weather prediction centers, have shown significant positive impact. With the world's first demonstration of near real time satellite constellation operations, the success of the FORMOSAT-3/COSMIC mission initiates a new age for operational GPS RO soundings for monitoring and forecasting of terrestrial weather, space weather, and a suite of related Earth science pursuits. The FORMOSAT-3/COSMIC mission demonstrates an innovative approach of climate change monitoring.

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