FORMOSAT-3/COSMIC Constellation Spacecraft System Performance: After One Year in Orbit

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***Abstract*—The FORMOSAT-3 mission, also known as Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), is the third major project of the Formosa Satellite (FORMOSAT) series implemented by the National Space Organization of Taiwan. FORMOSAT-3/COSMIC is a joint Taiwan/U.S. mission consisting of six identical low Earth orbit satellites. All six cluster satellites were successfully launched by a single Minotaur launch vehicle on April 15, 2006. The retrieved global positioning system (GPS) radio occultation (RO) data have been freely available online to the science community since shortly after the completion of satellite bus in-orbit checkout. Having completed the verification and validation, the worldwide science communities are highly satisfied with the RO data. Scientists have hailed the RO sensors as offering the most accurate, precise, and stable thermometers in space. After one year in orbit, all six FORMOSAT-3/COSMIC satellites were in good condition (except FM2, which had power shortage issues) and were on their way toward the final constellation of six separate orbit planes with 30° separation. Four out of six satellites had already reached their final mission orbit of 800 km by mid-May 2007. Together, the six satellites have generated a total of more than 2500 RO data per day. However, only 50%–70% of the RO data as received one year after launch could be retrieved into useful atmosphere profiles. The retrieved RO data, about 1800 per day on average, have been assimilated into numerical weather prediction models by many major weather forecast centers and research institutes. This paper provides an overview of the constellation mission, the spacecraft system performance after one year in orbit, the technical challenges we have encountered, and the performance enhancements we have accomplished.**

***Index Terms*—Constellation, Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), FORMOSAT-3, radio occultation (RO), remote sensing, satellite, system performance.**

I. INTRODUCTION

FORMOSAT-3/CONSTELLATION Observing System for Meteorology, Ionosphere, and Climate (COSMIC) is a joint mission of Taiwan and the U.S. The mission consists of six identical low Earth orbit satellites and is being carried out by Taiwan's National Space Organization (NSPO) and the U.S. University Corporation for Atmospheric Research (UCAR), Orbital Sciences Corporation (OSC), National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL), and Naval Research Laboratory (NRL). This is the third major project of the Formosa Satellite (FORMOSAT) series implemented by the NSPO. FORMOSAT-3/COSMIC's mission is to collect a large amount of atmospheric data for meteorological, climatic, ionospheric, and geodetic research, as well as for weather forecasting and space weather monitoring [1]–[5]. All six satellites were successfully launched by a single Minotaur launch vehicle from Vandenberg Air Force Base (VAFB) in California at 1:40 UTC (Coordinated Universal Time) on April 15, 2006 into the same orbit plane of a designated circular parking orbit, at an altitude of 516 km [6], [7].

The global positioning system (GPS) radio occultation (RO) science data have been freely available online to the science community since shortly after the completion of satellite in-orbit checkout [8], [9]. Preliminary results show that this new constellation GPS RO system can boost the accuracy of the prediction of hurricane behavior, significantly improve long-range weather forecasts, and monitor climate change with unprecedented accuracy and precision. The worldwide science community is highly satisfied with the science data results. Scientists have described the RO sensors as the most accurate, precise, and stable thermometer in space for measuring global and regional climate change [10], [11].

Preliminary assessments have also shown that the GPS RO data from FORMOSAT-3/COSMIC are of better quality than those from the previous missions [7], [12]–[15], e.g., the proof-of-concept GPS/Meteorology experiment, the Challenging Mini-Satellite Payload (CHAMP), and the Satelite de Aplicaciones Cientificas-C missions. The GPS RO soundings penetrate much farther down into the troposphere; from 70% to 90% of the soundings reach to within 1 km of the surface on a global basis [16]–[19]. As a result, the FORMOSAT-3/COSMIC

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TABLE I
FORMOSAT-3/COSMIC MISSION CHARACTERISTICS

Number	Six identical satellites
Weight	~ 61 kg (with payload and fuel)
Shape	Disc-shape of 116cm diameter, 18cm in height
Orbit	800km altitude, circular
Inclination Angle	72 degrees
Argument of latitude	52.5 degrees apart
Power	~ 81 W orbit average
Communication	S-band uplink (32 kbps) and downlink (2 Mbps)
Sounding	~2000 soundings per day
Data Latency	15 minutes to 3 hours
Design and Mission life	5 years
Launch date	15 April 2006

GPS RO data are making a positive impact on operational global weather forecast models. The European Centre for Medium-range Weather Forecasts (ECMWF) began to use the FORMOSAT-3/COSMIC data operationally from December 12, 2006 [20]. The National Centers for Environmental Prediction (NCEP) announced that the GPS RO data from the FORMOSAT-3/COSMIC mission would go into operational use with the implementation of the system of Gridpoint Statistical Interpolation/Global Forecast System at NCEP on May 1, 2007 [21]. Several other global operational centers, e.g., Taiwan's Central Weather Bureau (CWB), the Canadian Meteorological Centre, the United Kingdom Meteorological Office (UKMO), and Météo France, plan to use FORMOSAT-3/COSMIC data operationally later in 2007 [22], [23]. Hence, the FORMOSAT-3/COSMIC mission has become the world's first operational GPS RO constellation mission [22], [23]. This paper provides a constellation mission overview and reviews the spacecraft system performance after one year in orbit. It also assesses the technical challenges encountered and the performance enhancement achieved [24]–[26].

II. CONSTELLATION MISSION OVERVIEW

The FORMOSAT-3/COSMIC mission requirements were defined by NSPO and UCAR in order to meet the needs of the atmospheric science communities. NSPO served as the prime contractor for the development, deployment, and operations of the FORMOSAT-3/COSMIC spacecraft, while OSC provided the spacecraft, integrated and tested the first Flight Model (FM), and delivered the ready kits to NSPO for five additional spacecraft. NSPO integrated and tested FMs 2–6 in the Satellite Integration and Test facility in Hsinchu, Taiwan, and then coordinated the effort to integrate the six spacecraft in a stack configuration with the Minotaur launch vehicle provided by the U.S. Air Force at VAFB in California. UCAR provided the payload suite of scientific instruments and the science data processing of scientific instruments. Each spacecraft is equipped with a GPS Occultation Experimental Receiver (GOX) payload, developed by JPL and built by Broad Reach Engineering, a Tiny Ionospheric Photometer (TIP) built by NRL, and a Tri-Band Beacon (TBB), also provided by NRL. Table I shows the FORMOSAT-3/COSMIC mission characteristics, and Fig. 1 shows the spacecraft in deployed configuration, along with its major components [13]–[15].

After the successful launch of FORMOSAT-3/COSMIC satellites, NSPO conducted mission operations from the Satellite Operations Control Center (SOCC) with support from OSC, UCAR, and JPL for resolution of spacecraft anomalies, mission enhancement and scientific payload operations, and updating GOX payload firmware, respectively. The mission operation team in Taiwan is executing and managing all day-to-day activities of the system. Today, this team carefully conducts the deployment of the constellation and the constellation operations schedule in order to ensure that measurements are globally homogeneous and to minimize the latency of data fed into weather prediction models [13]–[15], [24], [25].

All science data are processed by the UCAR COSMIC Data Analysis and Archive Center (CDAAC) located in Boulder, CO, and then transferred to the Taiwan Analysis Center for COSMIC at the CWB, as well as to other facilities for science and data archival [8], [9]. The processed results are then passed from the CDAAC to the U.S.'s National Environmental Satellite, Data, and Information Service at National Oceanic and Atmospheric Administration (NOAA). These data are further routed to weather centers all over the world, including the Joint Center for Satellite Data Assimilation, NCEP, ECMWF, CWB, UKMO, the Japan Meteorological Agency, the Air Force Weather Agency, and others. The data under the operations team's integral teamwork effort are currently provided to these weather centers within 90 min (data latency requirement is 180 min) of satellite on-orbit science data collection in order to be used by the operational weather forecast model [24], [25].

III. CONSTELLATION SPACECRAFT SYSTEM PERFORMANCE: AFTER ONE YEAR IN ORBIT

A. Constellation Spacecraft Performance Summary

The FORMOSAT-3/COSMIC constellation provides a unique opportunity to assess the performance of multiple spacecraft at the same time. During the early weeks of the deployment, the satellites were spaced very closely together and in cluster formation. This has offered scientists a unique opportunity to verify the high precision of GPS RO measurements. Table II shows the constellation spacecraft performance summary as of April 15, 2007. After one year in orbit, all six FORMOSAT-3/COSMIC spacecraft were in good condition (except for the FM2 satellite, which had power shortage issues since March 2007) and were on their way toward the final constellation of six separate orbit planes with 30° separation [6], [7], [13]–[15].

B. Spacecraft Subsystem On-Orbit Performance Summary

Table III shows the operational status of each subsystem in all six spacecraft. Table IV shows the spacecraft subsystem performance and its major functions. All the radio frequency (RF) uplink and downlink trend data show that the spacecraft meet the specified RF subsystem requirements. Suspected space weather disturbances, which are correlated to the spacecraft onboard computer reboot and spacecraft reset events, had no performance impact on the command and data handling subsystem and spacecraft system. The flight software subsystem (FSW) status of all six satellites is normal, and the spacecraft are recovered automatically as expected by design

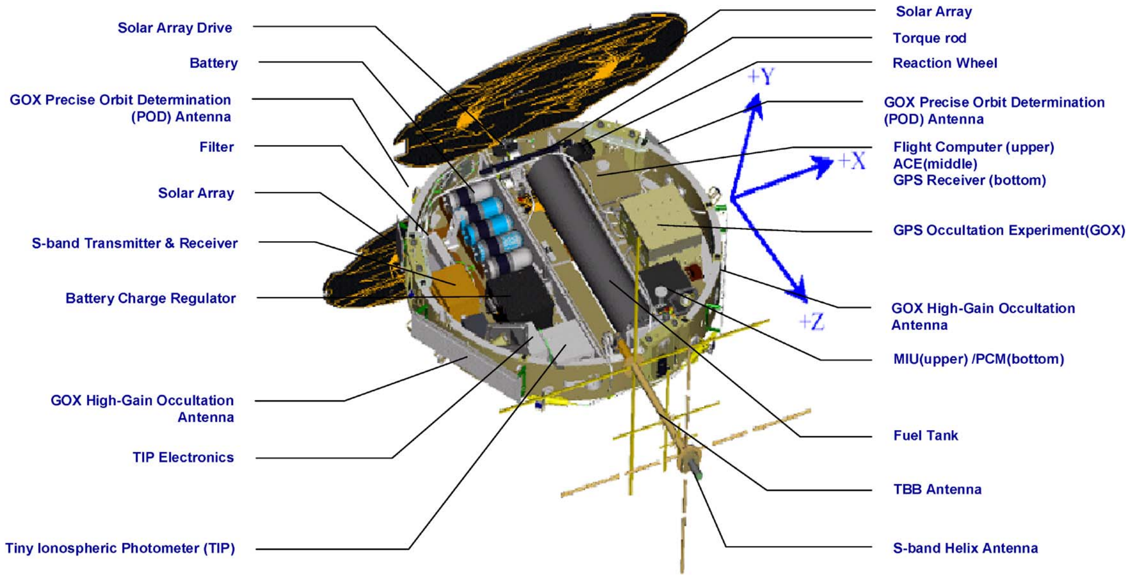


Fig. 1. FORMOSAT-3/COSMIC spacecraft in deployed configuration.

TABLE II
CONSTELLATION SPACECRAFT PERFORMANCE SUMMARY (APRIL 15, 2007)

SC ID	Summary
FM1	☐ Healthy ☐ Bus GPSR GPS Non-Fixed -> Operation Solution ☐ GOX Reboot Loop -> Auto Recovery
FM2	☐ Solar Array Power Shortage -> Reduced GOX Operation ☐ BCR dMdC Charge Algorithm Issue-> CSD Charge or FSW update ☐ Payload PCM DC Off -> TBB & TIP Off
FM3	☐ Healthy ☐ Bus GPSR GPS Non-Fixed -> Operation Solution ☐ OCC2 (ANT03) SNR Decreasing -> Recovery after High Beta Angle
FM4	☐ Healthy ☐ Bus GPSR GPS Non-Fixed -> Operation Solution
FM5	☐ Healthy
FM6	☐ Healthy ☐ Bus GPSR GPS Non-Fixed -> Operation Solution ☐ GOX Reboot Loop -> Under Investigation

TABLE III
SPACECRAFT OPERATION STATUS OF EACH SUBSYSTEM IN ALL SIX SPACECRAFT (APRIL 15, 2007)

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	Plan VI
FM2	Normal	Normal (Power Shortage)	Fixed-Yaw	Normal	High Rate	Reduced Operating	Off	Off
FM3	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating	Operating	Plan VI
FM4	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating	Operating	Plan VI
FM5	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating	Operating	Plan VI
FM6	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating	Operating	Plan VI

TABLE IV
SPACECRAFT SUBSYSTEM PERFORMANCE (APRIL 15, 2007)

Unit	Major Function	One-Year Performance
Payload (PL)	GPS radio occultation (RO) primary mission	☐ Trends on SNR data after FB4.3 uploaded did not show any sign of degradation at all from the available data. ☐ FM1 and FM6 had reboot loop issues and are still under investigation. ☐ TBB & TIP are functioning OK.
Radio Frequency Subsystem (RFS)	RF uplink and downlink	☐ No RF degradation observed from FM1 to FM6. ☐ All RF trending data meet specified criteria.
Command and Data Handling Subsystem (C&DH)	Command handling and telemetry gathering, health and maintenance, GPS receiver management	☐ The GPS Non-fixed on FM1, FM3, FM4 & FM6 Bus GPS receivers impacted onboard time maintenance, ACS performance and TIP payload time stamping. Operation Solution by upload State vector using GOX PVT data was performed to eliminate all impacts. ☐ The suspected space weather correlated onboard computer reboot and spacecraft reset events have no performance impact on C&DH and Spacecraft
Flight Software Subsystem (FSW)	FC/ACS/BCR Flight software, software upload, payload, launch vehicle interface	☐ FSW status on all satellites is normal; SC are automatically recovered from abnormal conditions. ☐ Under normal FSW condition, the error count increased rate is smaller than 10/day.
Attitude Control Subsystem (ACS)	Control of nadir pointing and sun pointing, GPS data processing	☐ Correct ACS mode transition was observed. ☐ All six spacecraft performed their ACS functions on orbit as expected.
Reaction Control Subsystem (RCS)	Orbital transfer and raising	☐ FM2, FM5, FM6 and FM4 have arrived at the mission orbits, and the remaining propellant masses for these three satellites are around 2.0 kg (~30% of full capacity) ☐ RCS functions are all healthy and ready for any planned orbit maneuvers in the future.
Thermal Control Subsystem (TCS)	Maintain avionics and battery at operating temperatures	☐ Thermal behavior of all six satellites is normal and in good shape.
Electrical Power Subsystem (EPS)	Solar array and battery charge control, power switching, deployment sequence	☐ No sensible degradation on all six satellite except FM2. ☐ Solar power reduced on FM2 and Reduced GOX operation plan was modified. ☐ Pressure difference on FM1~FM4 reduced to safe range (<650 psi) and stable now. ☐ Power margin is estimated at 40% on solar power except FM2.

from abnormal reboot/reset conditions. Under normal FSW conditions, the error count is less than ten per day. The thermal control subsystem is behaving nominally across the range of solar beta angles. There was an issue concerning excessive Earth horizon sensor (EHS) temperature increases at high beta angles, which has been resolved by an operations solution of turning off the secondary payloads during these periods [6], [24]–[26].

The principal contributors to the attitude control subsystem (ACS)'s pointing error are the orbital position, solar beta angle effect, hardware, and hardware configuration. The spacecraft's magnetically controlled ACS performed correct mode transition as designed, and all six spacecraft performed their on-orbit ACS functions as expected. However, ACS experienced excursions from the required ±5° pointing accuracy in roll, pitch, and yaw, which sometimes has an impact on GOX sciences data. Fig. 2 shows the FM5 spacecraft attitude on-orbit performance (roll/pitch/yaw pointing error) with respect to the raised spacecraft altitude and beta angle for one-year data since launch. FM5 started performing orbit transfer on May 7 (Day 127),

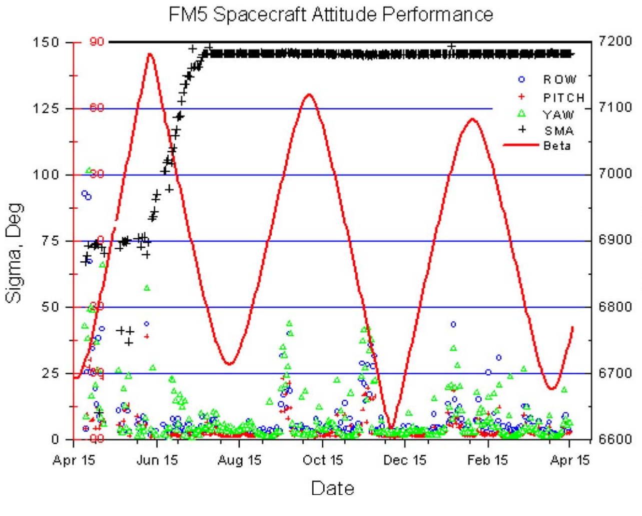
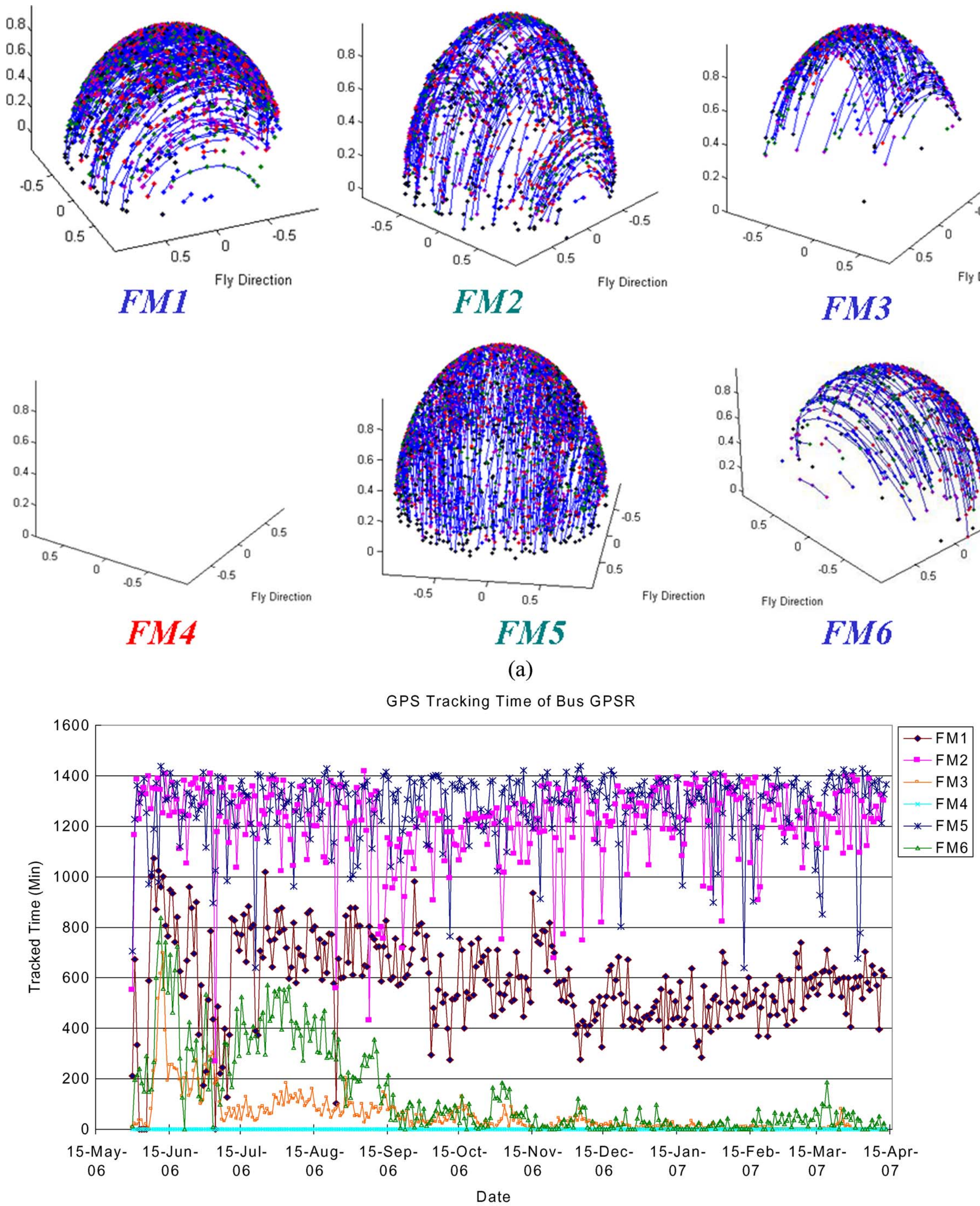


Fig. 2. FM5 spacecraft attitude on-orbit performance (roll/pitch/yaw pointing error) with respect to the raised spacecraft altitude and beta angle for one-year data since launch.



(a)

(b)

Fig. 3. (a) GPS 3-D tracking coverage of all six spacecraft Bus GPS Receivers. (b) Number of GPS satellite vehicle tracked statistics for all six spacecraft Bus GPSRs of one-year data after launch.

2006 and arrived at mission orbit on July 19 (Day 200), 2006. From the spacecraft trend data, we observed no major pointing performance improvement when FM5 arrived at its mission orbit. This seems to be the same for the other satellites (FM2, FM4, and FM6). As for pointing knowledge performance, all six spacecraft meet the requirements of both roll and pitch axes. Each spacecraft is equipped with two EHSs to provide roll and pitch attitude information. The EHS is relatively precise compared to coarse sun sensor (CSS) and Magnetometer and can provide attitude information to meet the pointing knowledge requirement. While the attitude information for the yaw axis relies on the coarse attitude sensors (CSS and Magnetometer), it is difficult to meet the pointing knowledge requirement when attitude excursion occurs [6], [14], [25].

The spacecraft Bus GPS Receiver (GPSR) is designed to be the main source of ACS navigation information. However, for six spacecraft, some of the GPSRs rarely work well. For the spacecraft with poorly performed GPSR, the navigation

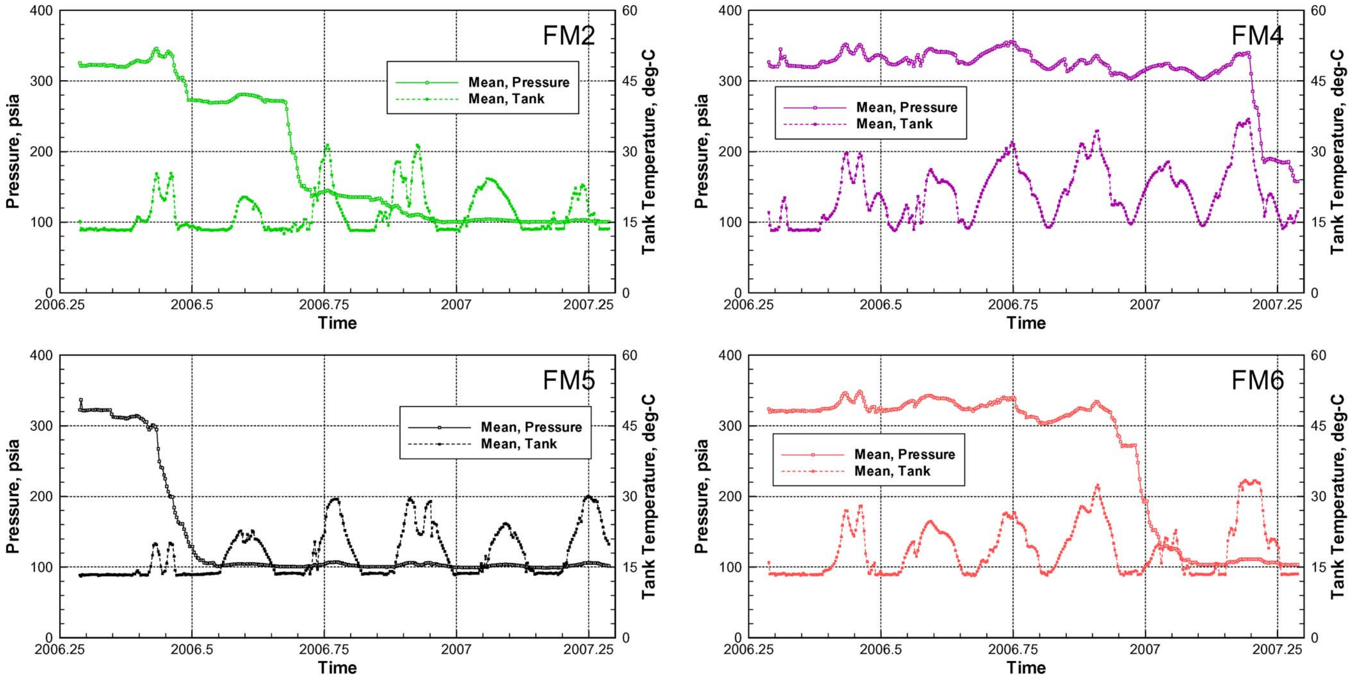


Fig. 4. Trending plots of the tank pressures and temperatures for FM2, FM4, FM5, and FM6 (from April 15, 2006 to April 15, 2007).

information is externally fed by daily uploaded position/velocity/time (PVT) information from the ground, such that the ACS FSW could propagate the correct PVT and perform the navigation function. As shown in Fig. 3(a), the GPS 3-D on-orbit tracking coverage of all six spacecraft Bus GPSRs was reconstructed on the ground around October and November 2006, for two to three days of tracking data depending on the number of GPS satellite vehicle tracked status. Fig. 3(b) shows the duration of the tracked GPS satellite statistics for all six spacecraft Bus GPSRs for one year. It is shown in Fig. 3 that FM2 and FM5 are fully functional, and any degradation is not shown, unlike FM1, FM3, and FM6, which are only partially functional and have suffered performance degradation since launch. FM4's GPSR has tracked almost no GPS signals from the beginning [6], [14], [25].

The reaction control subsystem is designed for providing the required thrust to transfer the satellites from their parking orbits to the higher altitude mission orbits. The plots in Fig. 4 illustrate the trend of tank pressure and tank temperature for FM2, FM4, FM5, and FM6. When the satellite orbit is in high beta angle situations, direct solar heating will cause a higher temperature level in the satellite. Direct solar heating also influences the tank temperatures and pressures. During the delta-V burns periods, the tank pressure decreases from 320 psi to around 100 psi. Fig. 4 also shows that the orbit-raising maneuvers were completed for FM5, FM2, and FM6, and the orbit transfer was still in processes for FM4 one year after launch [25].

There is a 40% power margin on average for each spacecraft observed, based on the one-year trend data. There is also no sensible degradation in the power system on any of the satellites except FM2, which is suffering from an additional 20% power shortage when the 40% original margin is taken into account. It is observed that the FM2 maximum power capacity of the solar arrays had been reduced by about 50% starting on March 1, 2007 [6], [13], [14]. In Fig. 5, we show the one-year trend of solar power and battery state of charge (SOC), ACS mode, and payload on–off status for FM2.

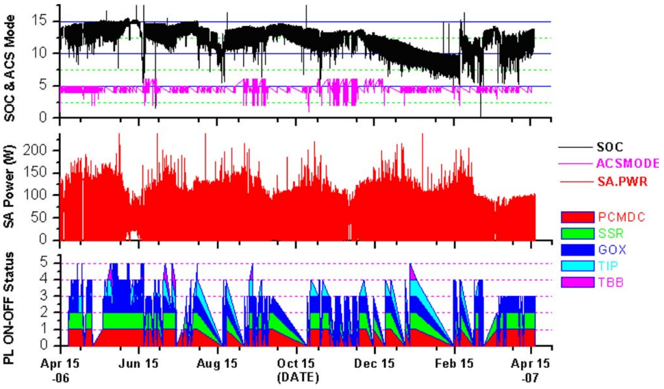


Fig. 5. One-year trend of solar power and battery SOC, ACS mode, and payload on–off status on spacecraft FM2.

C. Constellation Deployment Mission Results

FM2, FM4, FM5, and FM6 have reached their respective mission orbits, and the remaining propellant masses for these four satellites are around 2.0 kg, which is equivalent to 30% of the full tank capacity. For detailed constellation deployment mission results and associated problems encountered, please refer to another paper submitted to this special issue [25].

D. GOX Payload On-Orbit Performance Summary

Table V shows the GOX firmware build (FB) change history since launch. Fig. 6 shows the one-year RF signal-to-noise ratio (SNR) performances of four GOX antennas (POD1, POD2, OCC1, and OCC2) on each GOX payload instrument in FM3

TABLE V
GOX FB CHANGE HISTORY SINCE LAUNCH

Version	Upload date	Objective
FB4.1	5/18/2006	An improved atmospheric model for open loop tracking.
FB4.2	5/30/2006	1. Double precision P2 Phase. 2. To facilitate ionospheric occultation. 3. Bookkeeping.
FB4.2.1	6/29/200	1. To avoid logging unnecessary data and to get more occultation events. 2. To make sure that occulting satellites do not get used in the Navigation solution.
FB4.3	12/27/2006	1. Fix bugs such as: azimuth window, rising occultation to end earlier than at the commanded height, integer cycle slips during transition from open to closed loop tracking of rising occultation, halt acquisition and tracking of a particular PRN 2. Insertion of S4 scintillation parameter for ionosphere study.

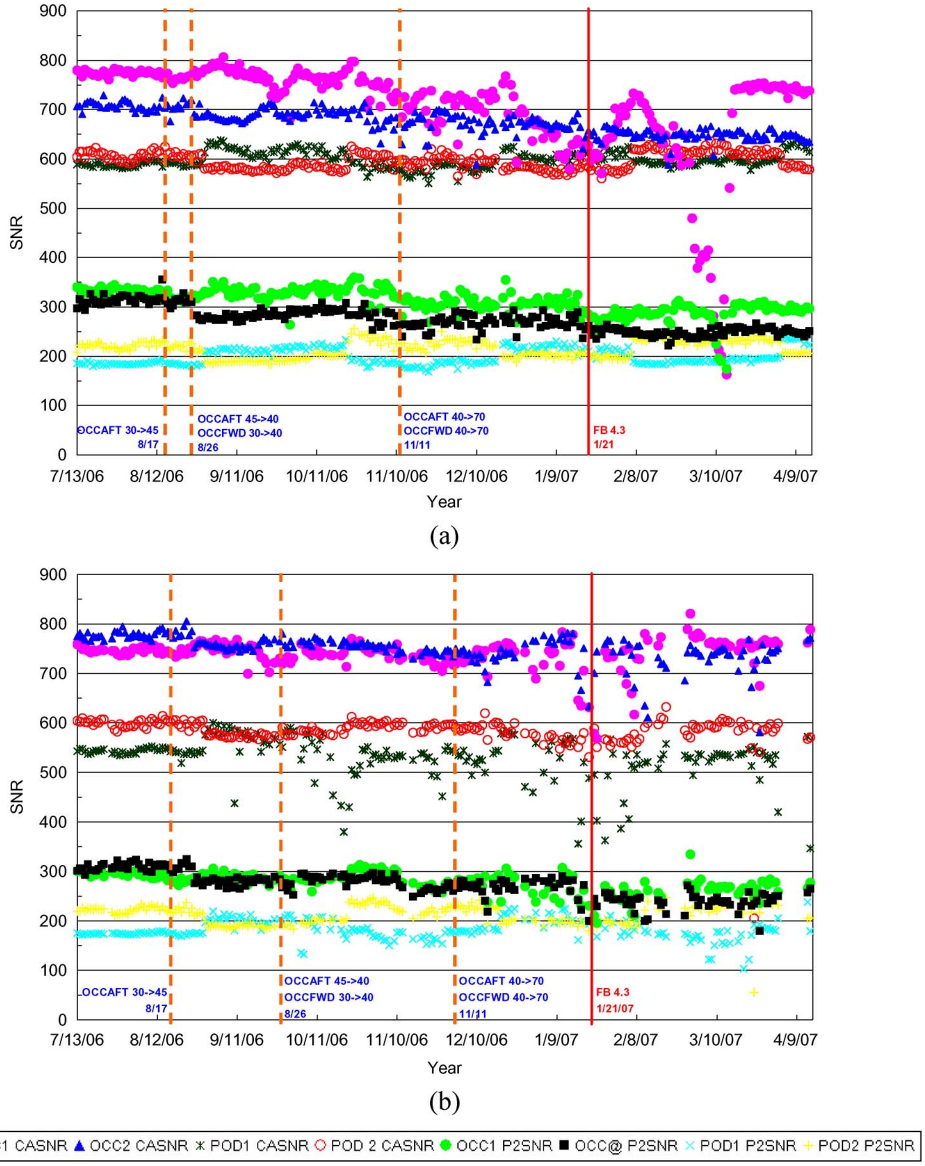
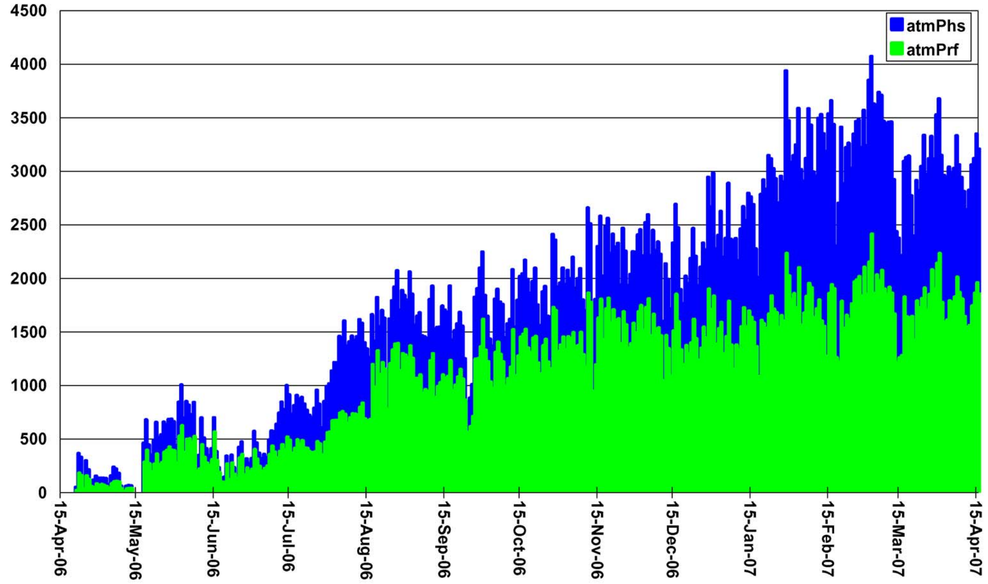
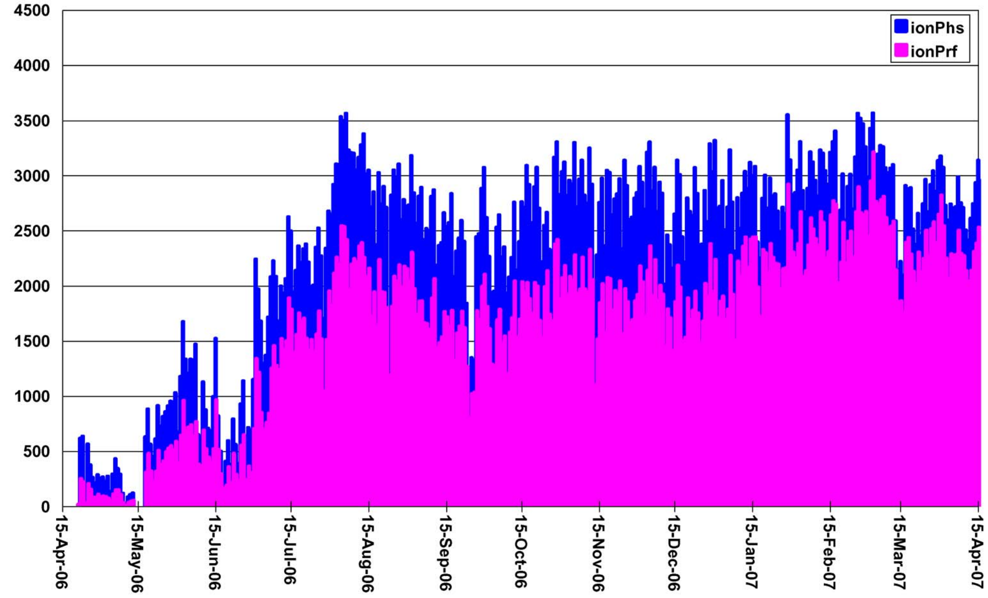


Fig. 6. FORMOSAT-3/COSMIC Payload POD & OCC CA and P2 SNR for (a) FM3 and (b) FM6. "POD" means Precision Orbit Determination Antenna, and "OCC" means Occultation Antenna.



(a) Atmospheric occultation events



(b) Ionospheric occultation events

Fig. 7. One-year statistics showing the number of daily occultation events for (a) atmosphere profiles one year since launch. (b) Ionosphere profiles of electron density one year since launch. The term "atmprf" means the number of daily atmospheric profiles (atmprf) retrieved since launch. The term "atmphs" means the number of excess phase files generated and also represents the atmospheric RO profiles that can be observed by FORMOSAT-3 satellites in the neutral atmosphere (stratosphere and troposphere); "ionprf and ionphs" indicates ionosphere.

and FM6 spacecraft. In these figures, only data received after July 13 (Day 194), 2006, where FB4.2.1 was uploaded, are shown. The definition of the daily SNR value shown in Fig. 6(a) and (b) is the bottom limit of the top 90% SNR value of all the tracked GPS satellites' signal SNR values received by that particular antenna either in coarse/acquisition or precision (P2) signal code. Following the uploading of FB version 4.3 (FB4.3) of the GOX payload to all the six spacecraft, from December 2006 onward, the trends of the GOX payload's (SNR) data did not show any sign of degradation at all from the available GPS RO science data. The SNR value of OCC1 on spacecraft FM3 shown in Fig. 6(a) did show a decreasing tendency; the value drops very rapidly when the spacecraft is at a high beta angle. We observe that the SNR value returns to its normal value when GOX temperature is below 40 °C and spacecraft FM3 leaves the high beta angle. The decreasing of GOX SNR on FM6, as shown in Fig. 6(b), is related to the reboot-loop issue and will be addressed later [6].

E. GPS RO Profile Statistics After One Year

Fig. 7 shows the number of daily atmospheric profiles (atmprf) and ionospheric profiles (ionprf) retrieved since launch. The term "atmphs" in Fig. 7 indicates the number of excess phase files that are generated and also represent the atmospheric RO profiles that can be observed by FORMOSAT-3 satellites in the neutral atmosphere (stratosphere and troposphere). The "ionphs" in Fig. 7 indicates ionosphere. The new

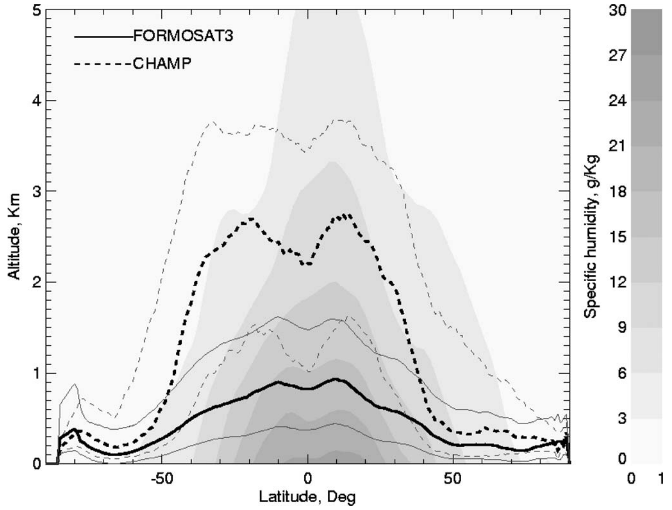


Fig. 8. Comparison of the lowest altitude penetration of RO events versus latitude for FORMOSAT-3/COSMIC and CHAMP. The data used was taken from January 1 to May 10, 2007. The bold solid line is the median value of the lowest altitude penetration for FORMOSAT-3. The solid line above and under the median value are respectively the 75% and 25% statistical average value of the distributed data for FORMOSAT-3. Same for CHAMP for bold dashed and dashed lines. The gray area plot is the water vapor specific humidity distribution in altitude and latitude. The specific humidity data are obtained from an NCEP model of March 1968 to 1996.

open-loop FB version 4.2.1 (FB4.2.1) was uploaded to the GOX payload in July 2006, which caused a large jump in the daily RO profile numbers for August 2006. From Fig. 7, it is clear that ∼37% of the total events cannot be retrieved to neutral vertical atmosphere profiles. This is true for ∼25% of ionospheric profiles. Fig. 7 also shows that the FORMOSAT-3/COSMIC mission has processed 1800 high-quality neutral atmospheric sounding profiles per day, which is more than the total number of worldwide radiosondes launched (∼900 mostly over land) per day and 2500 good ionospheric sounding profiles per day. The occultation events collected by the current FORMOSAT-3/COSMIC constellation have realized ∼70% of the mission goal of 2500 events per day so far [13]–[15], [24].

F. Penetration of RO Profiles in FORMOSAT-3/COSMIC Into the Lower Troposphere

UCAR's research group contributes continuous improvements to the RO technique. The phase-locked loop technique employed in earlier RO missions was replaced by a novel open-loop technique for the FORMOSAT-3/COSMIC mission. Most of the occultation measurements can now penetrate to altitudes as low as 1 km above the Earth's surface. 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 at high latitudes [12]–[14], [16]–[18]. Fig. 8 compares the lowest altitude penetration of RO profiles versus latitude for FORMOSAT-3/COSMIC and CHAMP. The data were taken from January 1 to May 10, 2007. The bold solid line in Fig. 8 is the median value of the lowest altitude penetration for FORMOSAT-3/COSMIC. The solid lines above and below the median value are, respectively, the 75% and 25% statistical average values 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 below the median value are the 75% and 25% statistical average values of the distributed data for FORMOSAT-3. The gray area plot is the water vapor specific humidity distribution with respect to altitude and latitude. The specific humidity data are obtained from an NCEP analysis averaged from March 1968 to 1996 [18], [24].

IV. OPERATIONAL CHALLENGES AND PERFORMANCE ENHANCEMENTS

Below are highlights of some major operations challenges encountered and enhancements accomplished during the launch and early orbit and constellation deployment phases [6], [24], [25].

A. Spacecraft Bus GPS Receiver Issue

The spacecraft Bus GPSR of FM1, FM3, FM4, and FM6 could not reliably acquire and lock onto the signals from the GPS constellation, as shown in Fig. 3. The Bus GPSR sometimes provides erroneous data, causing problems in the TIP payload time stamping, ACS navigation processing, and the onboard timing system. These data problems cause the navigation to output erroneous data and result in erratic attitude excursion behaviors on the spacecraft. The issue has been resolved by inhibiting any state vector solution from the Bus GPSR and then 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, since 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 the other four spacecraft (FM1, FM3, FM4, and FM6), NSPO has modified the thrusting procedure to include GOX operations as part of burn activities [24]–[26].

B. High Beta Angle Effect

There were thermal anomalies related to orbital high beta angles. At high beta angles, the spacecraft were in constant sunlight. This causes the EHS temperature to become higher than expected. In addition, the battery pressures rose higher and closer to the specified limit during this time period. To solve this issue, TIP and TBB were turned off when the beta angle was higher than 60°. To resolve the battery pressure issue, the charge rate was fine-tuned to maintain the battery within the normal pressure limit through frequent monitoring and commanding. The power control flight software was subsequently modified to include a new battery overpressure protection function, and this was successfully uploaded early in 2007. Currently, the battery pressure is being maintained at nominal condition autonomously [6], [13]–[15].

C. Spacecraft FM2 Power Shortage

As shown in Fig. 5, generally, the average solar power falls into 140–150 W with a 200-W solar array power capacity in design. Actual flight experience shows that battery capacity is

(days)

S/C ID	GOX	TBB (all on)	TIP
FM1	272	220 (27)	244
FM2	248	14 (4)	173
FM3	287	232 (14)	246
FM4	301	224 (1)	244
FM5	301	217 (12)	246
FM6	276	123 (7)	192

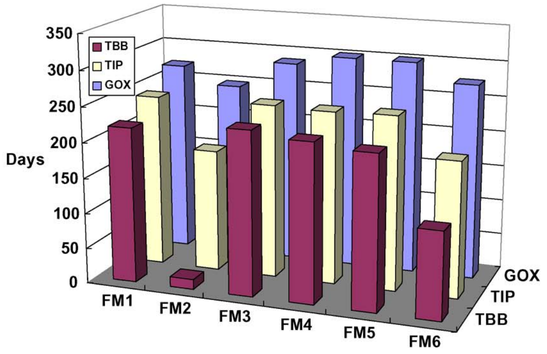


Fig. 9. One-year payload (GOX/TBB/TIP) power-on statistics.

	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 %

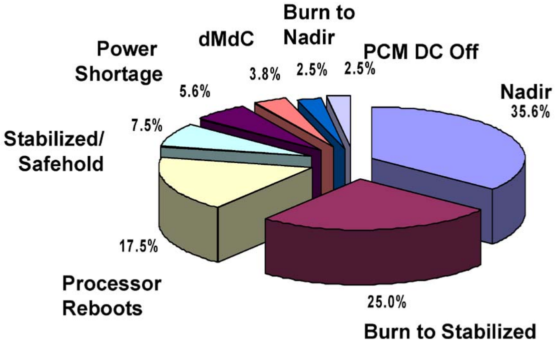


Fig. 10. One-year statistical results of payload power-off phenomenon on all six spacecraft. During the one year operation, the causes of payload off are categorized to: (1) Nadir mode due to attitude excursion; (2) Stabilized mode after thrust burns; (3) Processor reboot/resets; (4) Entrance to stabilized/safehold mode; (5) FM2 power shortage; (6) Derivative of Battery Molecular to Charge (dMdC) anomaly; (7) Nadir mode after thrust burns so that spacecraft enter into power contingency; and (8) Power Control Module (PCM) Direct Current (DC) Off anomaly.

greater than a specified value in typical normal 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 at its maximum power output, but it is restricted by maximum battery charge current as well. On March 1, 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. An investigation of this power shortage anomaly resulted in a recovery plan to operate the GOX at a reduced duty cycle. Currently, FM2 is supporting the GOX at ~70% duty cycles with the secondary payloads remaining off at all times [13]–[15].

D. Payload Power-On/Off Statistics

The one-year payload (GOX/TBB/TIP) power-on data statistics are shown in Fig. 9. We can see that the spacecraft FM4 and FM5 have the GOX payload on most days. FM2 has the least GOX power due to the power shortage already mentioned. FM6 has the second-worst GOX payload power-on due to the GOX reboot-loop issue addressed below. TIP and TBB power on also show the same trend. The one-year statistical results of payload power-off phenomenon on all six spacecraft are shown in Fig. 10, and the data are analyzed from Day 175 of 2006 to Day 105 of 2007. Before Day 175 of 2006, the 8° off angle in EHS has not been fixed, and the GOX has not been on for continuous 24 h. We also exclude the action events undertaken by the operations team, such as FSW and common spacecraft database upload, resetting of some processors, etc. The events for payload off will eventually reduce the GOX RO science data volume. The purpose of gathering these statistics is to determine the causes of payload off. During the one-year operation, the causes of payload off are categorized in the following: 1) nadir mode due to attitude excursion (35.6%); 2) stabilized mode after thrust burns (25%); 3) processor reboot/resets (17.5%); 4) entrance to stabilized/safehold mode (7.5%); 5) FM2 power shortage (5.6%); 6) derivative of battery molecular to charge anomaly (3.8%); 7) nadir mode after thrust burns, so that spacecraft enter into power contingency; and 8) power control module direct current off anomaly. Fig. 5

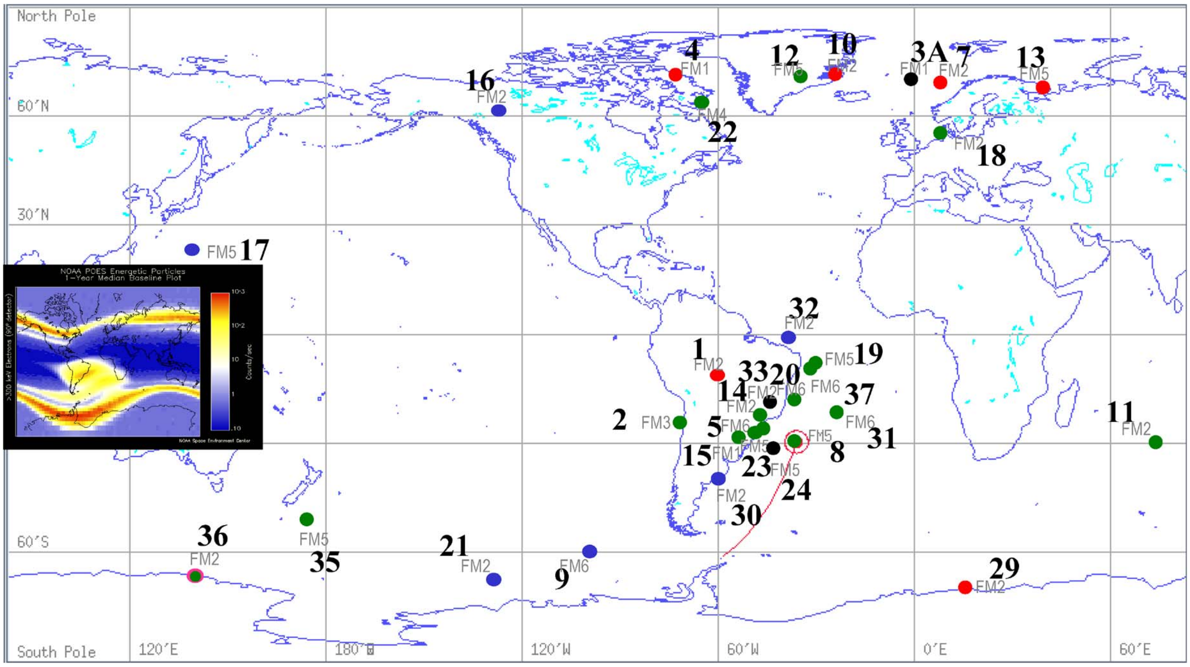


Fig. 11. Geographic location of the spacecraft reset/reboot events one year after launch, and comparison with the NOAA POES satellite's one-year > 300-keV energetic particle chart (courtesy of NOAA).

shows that the top three causes are attitude excursions, stabilized mode after thrust burn, and processor reboot/reset and that they have occupied around three quarters of all payload power-off events [13]–[15].

E. Computers Reset/Reboot

A total of 32 out of 37 spacecraft resets and reboots, including flight computer (FC), battery charge regulator (BCR), and attitude control electronics (ACE), have been observed through May 11, 2007 since launch. Fig. 11 shows the projected geographic locations of these reset/reboot events on the Earth after one year in orbit. The black dot in Fig. 11 represents the location of the spacecraft where master reset occurs; the red dots represent where the reboot occurs on FC of the spacecraft; the blue dots are for BCR; and the green dots are for ACE. Fig. 11 also includes NOAA's Polar Operational Environmental Satellite (POES)'s one-year > 300-keV energetic particle chart for comparison (courtesy of NOAA). Further investigation shows that most of the time and geolocations the spacecraft anomalies occurred are closely correlated to the space radiation environment. Single event effects in the South Atlantic anomaly region and the polar region are identified as the most probable root cause. No spacecraft performance has been degraded by these anomalies [13]–[15], [24].

F. GOX Payload Reboot Loop

Two kinds of GOX payload reboot-loop anomaly event were observed. The first kind is that the GOX instrument will automatically reboot and recover itself when there is no navigation solution for 15 min. This has happened on FM1 and FM6. For the second kind, consecutive reboots have occurred every 15 min and cannot be recovered automatically or by a power cycle command. FM6 had the latter kind of reboot anomaly in February, April, and July of 2007. The cause was preliminarily identified as the low SNR of the navigation antenna when the spacecraft entered into beta angle between 0° and $-30°$. A new FB version 4.4 (FB 4.4) was loaded in June 2007, enabling GOX to select the other healthy antenna as the navigation antenna, which is in the forward fly direction. The reboot loop has since ceased [6], [13]–[15], [24].

G. SSR Data Overflow

The solid state recorder (SSR) data storage only allocated 32 MB for GOX-B out of 128-MB total memory. During the constellation deployment phase, it was always possible to accumulate GOX data more than 32 MB before dumping the data to the ground. When the data overflow took place, it always came along with the data wrapping (disorder) because the 32 MB was not an integer numbers of the science data packet size, and the write pointer of the SSR would pass over the read pointer when data overflow occurred. To resolve this issue, the operations team narrowed the GOX's field of view to control the data volume. When the spacecraft orbit planes separated and the availability of ground pass became better, the team opened up the GOX's field of view and scheduled the dump to prevent the occurrence of SSR data overflow. The autoscheduling tool was generated to optimize the ground station utilization so as to minimize data dumped. After all spacecraft reach the final constellation with the orbit phasing under control, the loss of data due to SSR overflow no longer occurred [6].

H. GOX Data Gapping Issue

The GOX data gapping problem is that 29% of RO science data have gapping issues. After investigating questionable raw data, we found that a similar data dropout pattern has been observed in the ground End-To-End (ETE) tests. However, the on-orbit gapping issue is much worse than that found in the ETE tests. Through several analyses and tests, it was concluded that when dumping the stored spacecraft data and science data simultaneously, the data dropouts are the worst. The operations team made these two data dumps separately to recover the data dropout issue, and rescued 70% of the lost data. Even when the science data are downloaded alone, the data dropouts still cause 8% of data gapping. A typical dump has a very small amount of data dropouts (∼0.04%), but it actually causes 8% of RO data gapping. The remedy for reducing data gapping is to dump the same science data twice. Eventually, these two dumps will not drop the same data packets, so we can make up any dropout. The saved data from double dumps are only about 0.04% of the whole data volume, but the RO data will increase 8%. Hence, even though double dumps increase local data storage and double the data transfer time from ground station to the data analysis center, they are still worthwhile. [6], [13], [14], [24].

I. Assimilation in Numerical Weather Prediction Models

The ECMWF and the NCEP are assimilating the RO data into their real-time operational forecast systems. Preliminary results have shown that the FORMOSAT-3/COSMIC data improve the prediction of typhoon/hurricane tracks, including when and where they will hit land. ECMWF shows that the FORMOSAT-3/COSMIC measurements improve the accuracy of their forecasts 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 ECMWF [12], [20]. NCEP's studies have shown that their forecasts have significantly improved in accuracy when the FORMOSAT-3/COSMIC data are assimilated into the system [12], [21]. Taiwan's CWB has reported that the contribution of FORMOSAT-3/COSMIC has advanced their prediction capabilities by two years [27].

J. Impact on Ionospheric Space Weather Structure

The launch of the innovative FORMOSAT-3/COSMIC satellite constellation has ushered in a new era of studying the effects of ionospheric space weather [28], [29]. Taking advantage of dense global 3-D observation coverage, a new ionospheric structure and some important atmosphere–ionosphere coupling theories have been proposed and verified based on observations made [28]. A newly discovered ionospheric structure, namely, the low-latitude ionospheric plasma cave, shows a depleted plasma region underneath the region of strongest plasma concentration [28]. Meticulous observation of this new ionospheric structure will certainly improve our fundamental understanding of ionospheric dynamics and will be beneficial in evaluating ionospheric effects on the space environment and on communications through space. 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 [29]. FORMOSAT-3/COSMIC's capability to observe vertical plasma distribution across a 24-h period led to the verification of a plausible physical mechanism of this unique ionospheric structure. The influences of the tropical rainstorms and atmospheric weather have been included as considerations for space weather [28], [29].

V. CONCLUSION

We have summarized the satellite constellation system performance after one year in orbit. All six spacecraft are in good condition after six satellite years of operation and were on their way toward the final constellation. With the development and application of the open-loop tracking technique by JPL and UCAR, the quality, accuracy, and lowest penetration altitude of the RO sounding profiles have been improved in comparison to previous RO missions. As of April 15, 2007, about 1800 high-quality soundings were being retrieved daily on a global basis. The constellation spacecraft system on-orbit performance will be constantly monitored, tracked, evaluated, and enhanced by NSPO's operations team in the future. It is anticipated that an increasing number of global operational centers will use FORMOSAT-3/COSMIC data operationally for the years to come.

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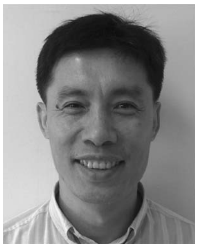

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