Space and Ground Segment Performance and Lessons Learned of the FORMOSAT-3/COSMIC Mission: Four Years in Orbit

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Abstract

The FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) M~~m~~ission consisting of six Low-Earth-Orbit (LEO) satellites is the world's first demonstration constellation using radio occultation signals from Global Positioning System (GPS) satellites. The atmospheric profiles derived by processing radio occultation signals are retrieved in near real-time for global weather/climate monitoring, numerical weather prediction, and space weather research. The mission has processed, on average, 1,400 to 1,800 high-quality atmospheric sounding profiles per day. The atmospheric radio occultation ~~soundings~~ data are assimilated into operational numerical weather prediction models for global weather prediction, including typhoon/hurricane/cyclone forecasts. The radio occultation data has shown a positive impact on weather predictions at many national weather forecast centers. A ~~proposed~~ follow-on mission was proposed that transitions the ~~program from the~~ current experimental research ~~system~~ mission into a significantly improved real-time operational ~~system~~mission, which will reliably provide 8,000 radio occultation soundings per day. The follow-on mission, as planned, will consist of 12 LEO satellites (compared to 6

satellites for the current mission) with ~~a~~ data latency requirement of 45 minutes (compared to 3 hours for the current mission), which will provide greatly enhanced opportunities for operational forecasts and scientific research. This paper will address the FORMOSAT-3/COSMIC system and m~~system and m~~ission overview, the spacecraft and ground system performance after four years in orbit, the lessons learned from the encountered technical challenges and observations, and the expected design improvements for the ~~new~~ spacecraft and ground system for FORMOSAT-7/COSMIC-2.

1 Introduction

The FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) (FS-3/C) M~~m~~ission is a joint Taiwan-U.S. demonstration satellite mission that was launched in April 2006. The objective of FS-3/C is to demonstrate the value of near-real-time GPS Radio Occultation (GPS-RO) observations in operational numerical weather prediction. FS-3/C is currently providing global GPS-RO data in near-real-time to over 1,400 users in more than 52 countries. The GPS-RO data has been demonstrated to be a valuable asset to the climate, meteorology, and space weather communities. The GPS/Meteorology (GPS/MET) experiment (1995-1997) showed that the GNSS-RO technique offers great advantages over the traditional passive microwave measurement of the atmosphere by satellites and became the first space-based "proof-of-concept" demonstration of GNSS-RO mission impacts ~~to Earth's observation~~ (Ware et al., 1996; Kursinski et al., 1996; Rius et al., 1998; Anthes et al., 2000; Hajj et al., 2000; Kuo et al., 2000). For a more complete history of GNSS-RO see Yunck et al. (2000) and Melbourne et al. (2005). The extraordinary success of the GPS/MET mission inspired a series of other RO missions, e.g., the Ørsted (in 1999), the SUNSAT (in 1999), the Satellite de Aplicaciones Cientificas-C (SAC-C) (in 2001), the Challenging Minisatellite Payload (CHAMP) (in 2001), and the twin Global GNSS Radio Occultation Mission for Meteorology, Ionosphere & Climate Gravity Recovery and Climate Experiment (GRACE) missions (in 2002), ~~the~~ Europe's meteorology operational satellite series A (MetOp-A) (in 2006) (Luntama et al., 2008), and the Oceansat-2 (in 2009) (Perona et al., 2007).~~.~~

The FS-3/C mission uses single differencing~~e processing~~ to extract excess atmospheric phases for each occultation event beacuse it is less susceptible to GPS ground station tracking errors (Schreiner et al. 2009). FS-3/C has proven to increase the accuracy of the predictions of hurricane/typhoon/cyclone behavior, significantly improve long-range weather forecasts, and monitor climate change with unprecedented accuracy (Anthes et al., 2000; Anthes et al., 2008; Kuo et al., 2000, Kuo et al., 2004, Kuo et al., 2008; Liou et~~.~~ al., 2007). The success of the FS-3/C mission has initiated a new era for near real-time operational exploitation of global navigation satellite system (GNSS) RO soundings (Yunck et al., 2000).

However, the FS-3/C ~~m~~Mission will reach the end of its five-year design life in 2011, and the critical real-time satellite observing capability will begin to degrade as satellites become no longer operational. As a result, the National Space Organization (NSPO) and National Oceanic and Atmospheric Administration (NOAA) intend to jointly develop the FORMOSAT-7/COSMIC-2 (FS-7/C-2) ~~m~~Mission. FS-7/C-2 will incorporate the next generation GNSS-RO receiver, a significantly improved spacecraft design~~significantly n improved and new developed spacecraft design~~, and ~~a greater~~more substantial ground communication network for data download ~~as a follow-on constellation mission to FS-3/C~~(Chu et al., 2008; Fong et al., 2008c; Fong et al., 2009a; Fong et al., 2009b).

FS-7/C-2 is intended to provide continuity of the GPS-RO data as well as provide the next generation of GNSS-RO data to the scientific community and the global weather centers~~users~~. The objective of the FS-7/C-2 M~~m~~ission is to collect a large amount of atmospheric and ionospheric data primarily for operational weather forecasting and space weather monitoring as well as meteorological, climate, ionospheric, and geodetic research. In addition, the system will allow scientists to collect data over unpopulated and remote regions (such as the polar and oceanic regions) in support of research in these areas. This paper will address the ~~system and~~FS-3/C ~~m~~system and mission overview, the spacecraft and ground system performance after four year in orbit, the lessons ~~we have~~ learned from the encountered technical challenges and observations, and the expected design improvements for the new FS-7/C-2 spacecraft and ground system.

2 FS-3/C System and Mission Overview

The FS-3/C space segment ~~is comprised of~~ includes six Low-Earth-Orbit (LEO) satellites in a constellation-like formation. The FS-3/C satellite constellation was successfully launched into the same orbital plane at 516 km altitude at 01:40 UTC on 15 April 2006. The FS-3/C satellites are equipped with three onboard payloads including a GPS Occultation Receiver (GOX), a Tri-Band Beacon (TBB), and a Tiny Ionospheric Photometer (TIP). The ~~intended~~ satellite constellation was ~~planned~~intended to ~~have~~ include six orbit planes at 800 km final mission altitude with 30 degree separation for evenly distributed global coverage.~~ One of the six satellites, designated as FM3, was not able to maneuver to the 800 km final orbit due to a solar array drive mechanism problem during the orbit raising phase that prohibited the continuous thrust firing of the FM3. Therefore, FM3 was maintained at an orbit altitude of 711 km. The other five FS-3/C satellites (all except FM3) reached their final mission orbit altitude of 800 km by the end of November 2007 (Fong et al., 2008b).~~

The FS-3/C system that is in operation today consists of ~~the~~ six satellites, a Satellite Operations Control Center (SOCC) in Taiwan, four remote tracking stations (RTSs), two local tracking stations (LTSs), two data processing centers, and a fiducial network. The SOCC uses the real-time telemetry and the back orbit telemetry to monitor, control, and manage the spacecraft state-of-health. There are two LTSs: one located in Chungli, Taiwan and the other in Tainan, Taiwan. There are four RTSs operated by NOAA to support the satellite passes: Fairbanks Command and Data Acquisition Station (FCDAS) in Fairbanks, Alaska and Kongsberg Satellite Services Ground Station (KSAT) in Tromsø, Norway, which are currently ~~set as~~ the two primary stations for the mission. T~~; and t~~he Wallops station in Virginia~~, USA~~ and the McMurdo station in McMurdo, Antarctica~~, which~~ provide backup support as needed for the mission (Fong et al., 2008c; Fong et al., 2009a; Fong et al., 2009b).

The science RO data is downlinked from the satellites to the RTS and then transmitted from the RTS via NOAA to the two data processing centers. The two data processing centers are the CDAAC (COSMIC Data Analysis and Archive Center) located in Boulder, Colorado~~, USA,~~ and the TACC (Taiwan Analysis Center for COSMIC) located at the Central Weather Bureau (CWB) in Taiwan. The fiducial GNSS data is combined with the occulted and referenced GNSS data from the GOX payload to remove the satellite clock errors.

The science data collected by the GOX and TIP payloads ~~science data~~ are processed by the CDAAC and TACC. The results processed by the CDAAC are then passed to the National Environmental Satellite, Data, and Information Service (NESDIS) at NOAA. These data are further routed to the international weather centers including the Joint Center for Satellite Data Assimilation (JSCDA), National Centers for Environment Prediction (NCEP), European Centre for Medium-range Weather Forecast (ECMWF), United Kingdom Meteorological Office (UKMO), Japan Meteorological Agency (JMA), Air Force Weather Agency (AFWA), Canadian Meteorological Centre (Canada Met), French National Meteorological Service (Météo France), and Taiwan's CWB~~, etc~~. The data are provided to the global weather centers within ~~the~~ 180 minutes to meet the data latency ~~requirement in order~~limit required to be assimilated into the numerical weather prediction (NWP) models.

3 Spacecraft Performance after Four Years in Orbit

3.1 Spacecraft Constellation Performance

The FS-3/C in-orbit system performance over the last four years is considered to be more than satisfactory in meeting its mission goals. The experimental constellation was ~~intended~~ defined to have ~~be~~ a two-year ~~experimental~~ spacecraft mission life, and ~~the~~a ~~with a five-year~~ spacecraft design life ~~is~~of five-years. The spacecraft hardware failure and/or degradation are proceeding as anticipated. Although the expectation of the entire 6-satellite constellation continuing operations into the fifth year and beyond is not realistic, a partial constellation with degraded performance is likely to continue for a few more years. It is~~In addition, the authors~~ believed that the lessons learned from the in-orbit operations will provide a solid foundation to migrate the experimental system into a ~~realistically~~ stable and reliable operational system for follow-on missions.

The operation status of the key subsystems for all six satellites after four years in orbit is shown in Table 1. The battery power issue is a common and continuous major degradation problem for all spacecraft. For clarity, the satellites will be referred to as “FMx” where x is 1:6. FM4 and FM6 are experiencing significant battery degradations that are causing the payloads to be powered off unexpectedly, even at high battery state-of-charge. In addition, FM2 experienced a sudden significant solar panel power shortage in mid-November 2007. Since then, the output power of FM2 was reduced to one-half of the maximum solar array power capability, from 200 W to 100 W. The root cause of the FM2 power shortage is still undetermined. FM3 encountered ~~the~~ a solar array drive mechanism failure at 711 km orbit that prohibited the continuous ~~led to the inhibited propellant~~ thrust firing of the FM3. The other five FS-3/C satellites reached their final mission orbit altitude of 800 km by the end of November 2007 (Fong et al., 2008b). FM3 ~~for the continuous orbit raising and~~ track~~ing~~ed the solar power at reduced duty cycle depending on the power status of the spacecraft. The secondary payloads, TIP and TBB, on FM2 and FM3, as shown in Table 1, have been powered off due to the power shortage issues. Furthermore, FM3 has been in a severe abnormal condition (much more frequent loss of communication and low power status) since July 2010 (Fong et al., 2010).

Figure 1 shows the spacecraft system performance observed over the past four years (since launch) for the GOX mission payload with the ~~GOX payload~~ duty cycle on, and spacecraft ADCS (Attitude Determination and Control Subsystem) attitude performance vs. spacecraft sun beta angle. The sun beta angle is defined as the angle between the spacecraft orbital plane and the vector from the sun. It ~~that~~ determines the percentage of time the spacecraft in low Earth orbit spends in direct sunlight, absorbing solar energy. The GOX payload should be on during the normal operation period except during the constellation deployment phase.

In Figure 1, it is observed that all spacecraft continue to operate with the GOX payload duty cycle on at high percentage rates even as the spacecraft bus and payload start to show degradation. FM1 has provided good payload performance, however it shows worse attitude performance than the other spacecraft. FM2 started to show reduced GOX payload duty-cycle ~~GOX~~ on operations due to a battery charging efficiency-decreased phenomena that was experienced after the satellite was recovered from lost communication in June 2009. FM3 encountered malfunctions of the solar array drive mechanism ~~malfunctions~~ starting in August 2007 when it reached a 711 km orbit. FM3 has been kept at that altitude and the GOX payload has been operating at low duty cycle since then. FM4 performed very well during the four year operational period, but recently its battery has shown significant degradation. FM5 has provided good spacecraft performance, however its GOX payload shows low SNR problems~~,~~ ~~causing~~ resulting in difficulties generating ~~good~~ useful data ~~to be hard to generate~~ even when the GOX payload is on. FM6 has a similar GOX payload low SNR problem. In September 2007, FM6 experienced loss of communications ~~in September 2007~~ for 67 days. The satellite resumed contact and recovered on its own after a computer master reset event occurred over the South Atlantic Anomaly (SAA) region. In summary, d~~D~~ue to ~~a~~ the batteries~~y~~ aging ~~issue~~, four out of the six spacecraft have begun to encounter a battery degradation problem. FM4 and FM6 are worse than the other four spacecraft. The major on-orbit performance highlights for all spacecraft are summarized in Table 2.

3.2 GOX Mission Payload Performance

Figure 2 shows the four-year statistics for the number of daily occultation events for (a) atmosphere profiles ~~for the four years since launch~~ and (b) ionosphere profiles of electron density ~~for the four years since launch~~. The ~~contributed~~ atmosphere and ionosphere occultation profiles contributed by ~~from~~ each spacecraft are shown in Table 3.

The GOX payload performance summaries are shown in Table 4. As the primary mission payload, four GOX ~~payload~~instruments are being operated at a duty cycle of 100% and two other GOX ~~payloads~~instruments (onboard FM2 and FM3) are being operated based on the state of the power charge at various sun beta angles (due to the power shortages). ~~The beta angle is defined as the angle between the spacecraft orbit plane and the vector from the sun that determines the percentage of time the spacecraft in low Earth orbit spends in direct sunlight, absorbing solar energy.~~ There are many factors that affect the quality of the occultation data received from the GPS signals. Among them, the low SNR on the occult~~at~~ing precision orbit determination (POD) antenna seems to affect the data quality the most. Four spacecraft (FM1, FM3, FM5, and FM6) have exihibited a low SNR anomaly on the POD1 antenna for the GOX payload. FM2 exhibited a low SNR anomaly on POD2.

In February 2009, the FM6 GOX payload SNR decreased, however,~~ to where~~ the GOX payload operating temperature was not over ~~its~~ the red high limit (the limit that will shut down the GOX payload power ~~by the~~ autonomously)~~ control system~~. The RO profiles decreased to less than 100 per day and FM6 could only generate good RO data while the operating temperature was less than 25 °C. After two months of low RO data generation, the spacecraft was flip-flopped and the FM6 GOX payload recovered on its own and began to operate ~~in~~ at full duty cycle.

~~The RO data generation is dependant on the duty cycles of the power-on condition. More details regarding the GOX payload on and off performance will be discussed in the next sub-section. In order to assess the GOX payload instrument performance, all of the other payloads were powered off for the GOX software revision upload, and there are only few events on some spacecraft when the GOX payload instruments were powered off for trouble shooting. The GOX payload instrument itself on all six spacecraft has performed reliably over the past four years.~~

3.3 Spacecraft Payload On/Off Performance

The causes of the GOX payload being powered off are categorized as follows: nadir mode due to attitude excursion; stabilized mode after thrust burns; processor reboot/resets; entrance to stabilized/safehold mode; power shortage; derivative of battery molecular to charge (dMdC) anomaly; nadir mode after thrust burns such that spacecraft enters into power contingency; and Power Control Module (PCM) Direct Current (DC) Off anomaly. From the GOX payload duty cycle on values shown in Figure 1, it is possible to compile the GOX payload duty cycle on statistics for one to four years, which are shown in Figure 3. It is observed that the FM2 & FM3 power shortages are the main cause of the degraded average GOX duty cycles ~~annually~~on those spacecraft. After the completion of the orbit transfer, FM4 and FM5 ~~are~~ demonstrate~~ing~~ the best GOX payload performance. The drop in FM6 GOX payload duty cycles in the second year is due to the complete loss of communications for 67 days. Additionally, the low SNR issue makes FM6 the 4th best performing satellite among the 6 satellites, following FM4, FM1, and FM5 for GOX payload performance.

3.4 Spacecraft Ni-H2 Battery Performance

There is another payload off phenomenon that did not belong to any category listed in the previous sub-section that is relevant to the battery performance degradation issue. Beginning in April 2009, the operations team has observed the GOX payload unexpectedly turn off while the spacecraft ha~~wa~~s ~~in~~ good power and attitude conditions,~~, -~~ where the battery state-of-charge (SOC) indicated is higher than the design value of 5.5 ampere-hours, and the spacecraft is operating nominally at the Nadir-Yaw mode. This phenomenon is beginning to be a frequently recurring event on all six spacecraft. According to the spacecraft design, the payload will be turned off only when any of the following design conditions are met: (1) the external payload off ground command is sent; (2) the low power spacecraft battery SOC falls below 5.5 ampere-hours; (3) three flight computers (Attitude Control Electronics (ACE), Battery Control Regulator (BCR), or Flight Computer (FC)) have been rebooted or reset; or (4) the spacecraft attitude has entered into stabilize / safehold / thrust mode.

The battery performance degradation issue has become one of the major triggers of the unexpected payload off phenomenon. The un~~p~~expected payload off is categorized as a de~~i~~v~~e~~iation from the normal payload off that ~~are~~is initiated by either (1) ~~by~~ the ground command or (2) autonomous internal command due to insufficient solar power charge to the battery. The S-band transmitter is turned on and needs to draw a substantial amount of power and current with a higher demand priority from the bus during a ground Telemetry Tracking and Control (TT&C) pass~~es~~. This lowers the bus voltage further if the battery cannot provide sufficient power in time. Consequently, the battery degradation effect may cause the payload to be turned off sometimes during a ground TT&C pass. The battery degradation, as observed, has shown to cause the bus voltage to be lower than 11 V~~v~~olts (compared to the nominal 14 V~~v~~olts), but slightly higher than 10 V~~v~~olts. Since the input voltage requirement for the tank pressure transducer is above 11 V~~v~~olts, the pressure transducer reading will decrease dramatically and become unreliable to reflect the low bus voltage status when the actual bus voltage falls below 11 V~~v~~olts. In addition, when the value of bus voltage is below the Power Control Module (PCM) design value of 10 V~~v~~olts, the payload will be turned off by the PCM internal command due to the internal under voltage protection circuit design (Fong et al., 2010).

Table 5 shows the average variation rate per year of the battery for each spacecraft. FM4 and FM6 have shown the worst battery degradation. The spacecraft battery degradation ~~certainly~~ ~~has~~ significantly impacts ~~on~~ the spacecraft operational life and the total number of GOX payload occultation profiles.

4 Ground System Performance

4.1 NSPO Ground Systems

NSPO was in charge of the mission operations of FS-3/C after launch including the early orbit checkout and initialization, constellation orbit deployment, and normal and contingent satellite operations. The facility used for the mission operations is the ~~Satellite Operation Control Center (~~SOCC~~)~~ located in Hsin-Chu, Taiwan. The SOCC includes four subsystems: (1) Mission Operation subsystem for the real-time satellite operations during ~~a~~ station contact; (2) Flight Dynamics ~~Facility~~ Facility for the orbit determination, prediction and maneuver planning; (3) Science Control subsystem for the science data preprocessing; and (4) Mission Control subsystem for the operation planning and command scheduling. NSPO also provides two ~~Telemetry Tracking and Control (~~TT&C~~)~~ stations, ~~(or~~ typically called ~~G~~ground ~~S~~stations)~~,~~ in Taiwan to support the contingent operations of FS-3/C.

In the early orbit checkout phase, the SOCC successfully sent commands to FS-3/C for spacecraft State of Health (SOH) inspection and hardware/software initialization. The measured performance of the in-orbit spacecraft compared to the expected results from the relevent ground tests ~~will~~ show the SOH of a specarft in orbit. Some components, such as the GPS receiver and the battery charging parameters, were reconfigured for improved performance. In the constellation orbit deployment phase, the six FS-3/C satellites were maneuvered into the mission orbit altitude one by one in a planned time sequence. Each satellite took 4-6 weeks to maneuver into its mission orbit. The satellite constellation was fully deployed in 19 months. After the deployment, five of the six satellites had successfully reached the predefined mission orbits (except the FM3 whose onboard propulsion function was degraded which prohibited it from reaching its final mission orbit altitude). ~~As mentioned previously, FM3 stayed in a lower orbit altitude of 711 km, which is 89 km lower than the other five satellite orbits of 800 km.~~

In the normal operations phase, the SOCC routinely uplinked the time-tagged command loads to the satellites so that for each scheduled station contact, the satellites would sequentially turn on their transmitter, downlink payload data, downlink SOH data and then turn off their transmitter. On average, there are approximately 80 station contacts per day to dump the onboard payload data for near real-time meteorological research and operational applications. During normal operations some satellite anomalies also occurred, such as FC computer resets, BCR computer resets, ACE computer resets, Master resets and Phoenix resets. Phoenix is an off state of the satellite when satellite is out of battery power and is used to support satellite recovery when power condition is back to stable. Each type of reset was recovered by sending a series of configuration commands so that both the satellite and payload could resume normal operation as soon as possible.

All six satellites have experienced some anomalies in the electric power subsystem and/or payload instrument performance causing onboard electronic power shortages and payload duty-cycle reduction. The SOCC and the operation team used operational methods to reduce the impacts of the anomalies and increase the payload data output. It has proven difficult to maintain the FS-3/C constellation in the current SOH status after four years in operation.

4.2 NOAA Ground Systems

When FS-3/C was launched, ground station support was contracted with the Universal Space Network (USN) through their stations at Poker Flats, Alaska and Kiruna, Sweden. USN performed very well for 2 years, but in an effort to reduce operational costs NOAA made a decision to employ indigenous resources. NOAA assets were established for FS-3/C at Fairbanks Command & Data Acquisition Station (FCDAS) as well as Wallops Command & Data Acquisition Station (WCDAS), and services were contracted with Kongsberg Satellite Services (KSAT) at their Tromsø Satellite Station through NOAA agreements with the Norwegian Space Centre. Since April 2008, NOAA stations have been providing both uplink and downlink services and Tromsø has been providing downlink services only. Ground station support availability for FS-3/C was required to perform at 90% or better. Over the course of FS-3/C operations, ground stations services have performed at 95% or better with only minor interruptions due to occasional equipment issues (hung servers or processors, for example).

FS-3/C command uplink and telemetry downlink activities are coordinated by the NSPO SOCC with the Remote Tracking Stations (RTS). Once upcoming FS-3/C passes have been deconflicted with other ground station activities, SOCC generates spacecraft ephemeris, spacecraft command uploads and ground schedules and distributes the files to the ground stations. All contacts with the spacecraft are established and conducted autonomously via schedules executed at the SOCC and the RTS, with the exception of any real-time commanding conducted by Mission Control personnel at SOCC. During the pass, the spacecraft and ground system are autonomously monitored by SOCC as the data stored on the spacecraft is downlinked to the ground station. After the spacecraft contact has ended, all connections are autonomously terminated and the RTS ~~D~~data server forwards the Contact Report to the SOCC as well as the Payload Data Files to the Data Processing Centers for processing.

FS-3/C mission data is distributed from data servers at the ground stations across the ~~open internet~~ world wide web via Secure File Transfer Protocol (SFTP) to the SOCC and CDAAC. Figure 4 shows the flow of data between the RTS, SOCC and CDAAC. One week prior to real-time, the spacecraft ephemerides (2 line element sets) and RTS pass schedules are made available to the mission team for operations. Timeliness can vary but SFTP has been found to be a very reliable and inexpensive means for distributing the data globally. A typical post contact scenario consists of transferring real-time and non-real-time spacecraft data to SOCC, followed by the transfer of mission files to CDAAC and then to SOCC. Statistics show that mission data arrives at CDAAC for processing within 15 minutes after spacecraft loss of signal (LOS), which is the end of the scheduled spacecraft contact with the ground station,~~)~~ 97% of the time.

4.3 Science Data Processing

The COSMIC Data Analysis and Archival Center (CDAAC) at UCAR currently processes COSMIC data in near real~~-~~-time for operational weather centers and the research community. The CDAAC also reprocesses RO data in a more accurate post-processed mode (within 6 weeks of observation) for COSMIC and other missions such as~~:~~ GPS/MET, CHAMP, SAC-C, GRACE, TerraSAR-X, (and METOP/GRAS in the near future). The data processing at the CDAAC includes: GPS site coordinate and zenith tropospheric delay (ZTD) estimation for a global ground-based reference network, high-rate (30 second) GPS satellite clock estimation, LEO precision orbit determination, computation of L1 and L2 atmospheric excess phases (Schreiner et al., 2009), retrieval of neutral atmospheric bending angles and refractivity for each LEO occultation event (Kuo et al. 2004), estimation of absolute total electron content (TEC), and retrieval of electron density profiles (Schreiner et al., 1999). The CDAAC also provides COSMIC TIP calibrated radiance products. All COSMIC products are made available freely to the community at www.cosmic.ucar.edu.

Since the launch of the FS-3/C constellation in April 2006, COSMIC has provided a large amount of valuable ~~payload~~ science data to the operational and research communities. As of Sept 1, 2010, COSMIC and CDAAC have produced over 2.5 million high quality neutral atmospheric and ionospheric sounding profiles, over 2.6 million absolute TEC data arcs, S4 scintillation observations, over 16,000 hours of quality controlled TIP radiances, and a significant (but not centrally archived) amount of ground-based ~~CERTO/~~TBB observations. On average, COSMIC currently produces around 1,000 GPS-RO soundings per day. Approximately ninety percent of these are processed and delivered ~~(~~via the Global Telecommunications System (~~–~~GTS) to operational centers within three hours. T~~; t~~he remaining ten percent have higher latency due to the satellites' inability to downlink every orbit (~100 minutes). The COSMIC RTSs are down-linking and forwarding the payload data to the CDAAC in less than 15 minutes on average. The CDAAC processes a single dump of payload data into profiles and forwards them to the GTS via NOAA in less than 10 minutes. The average latency of COSMIC data is currently approximately ~~75~~ 90 minutes for single orbit dumps. The reliability of the RTS stations and the CDAAC near real-time processing system have been measured at greater than 95% and 99.5%, respectively.

5 Lessons Learned from Encountered Technical Challenges

This section contains highlights of some major challenges encountered and enhancements accomplished after twenty-four satellite-years (4 years x 6 satellites) of operation in orbit of the FS-3/C mission. There are many lessons learned from the four years of operations, which can be used to improve similar future missions (Fong et al., 2008a; Fong et al, 2008b; Fong et al., 2008c; Fong et al., 2009a; Fong et al., 2009b).

5.1 Mission Lessons Learned

Table 6 highlights three major mission lessons learned. They are: (1) the determination of the spacecraft communication frequency, (2) the prevention of the Radio Frequency Interference

(RFI) among the three different payloads in each spacecraft, and (3) the quantity definition of the radio occultation profiles.

5.2 Payload Lessons Learned

The GOX payloads are performing well and reliabily at the instrument level based on the assessment of the available data as discussed in Section 3.2. However, there are some lessons learned from the observed GOX performance at the payload subsystem level. The major lessons learned from the data assessment at the GOX payload subsystem level, as summarized in Table 7, are: (1) GOX POD ~~Low~~ low SNR problem, (2) GOX OCC ~~Low~~ low SNR problem, and (3) GOX SNR ~~Decrease~~ decrease at h~~H~~igh t~~T~~emperature.

5.3 Spacecraft System Lessons Learned

The spacecraft state of health ~~is directly~~ correlates directly~~d~~ to the payload performance. The FS-3/C spacecraft is a modified version of a heritage design of the successful ORBCOMM spacecraft. However, the FS-3/C spacecraft, a micro-grade spacecraft (<100kg), is not equipped with full comprehensive redundancy for avoiding single critical failure in design and/or high reliability components in critical instruments for durability. Five major spacecraft system lessons learned, as described in Table 8, are: (1) SSR (Solid State Recorder)/MIU (Mission Interface Unit) GOX d~~D~~ata d~~D~~ropouts, (2) s~~S~~pacecraft d~~D~~esign ~~P~~philosophy, (3) s~~S~~pacecraft ~~D~~downtime, (4) c~~C~~omputer~~s~~ ~~R~~resets/~~R~~reboots, and (5) ADCS (Attitude Determination and Control Subsystem) p~~P~~erformance.

6 Design Improvements for the Follow-on System

6.1 Mission Trades and Improvements

In order to apply the lessons learned from the FS-3/C program to create an operational constellation, several mission trades have been studied. The results of the FS-7/C-2 mission trade studies are summarized in Figure 5 (Fong et al., 2010; Yen et al., 2009; Yen et al., 2010).

The FS-7/C-2 satellites will be equipped with the next-generation GNSS-RO receiver (TriG) to collect more soundings per receiver. The TriG will have the ability to track GPS, Galileo and GLONASS GNSS systems, which includes 29 operational GPS satellites, 18 planned GLONASS, and 30 planned GALILEO satellites. The TriG mission payload receiver will have the capability to receive the GPS L1/L2/L5 signals, the GALILEO E1/E5/E6 signals, and the GLONASS L1/L2/L5 signals. This payload instrument will significantly improve the amount of data collected, which will lead to improved mission applications.

Figure 6 depicts the proposed FS-7/C-2 mission architecture. The FS-7/C-2 program is planned to have 12 satellites, which will result in collecting 8,000 profiles per day. The mission baseline includes 6 satellites at low-inclination-angle orbit and 6 satellites at high-inclination-angle orbit so that the mission will collect more data from the low latitudes over what is currently being collected. Participants on the joint program will work together on the data processing and data utilization to improve the data processing aspect of the system.

6.2 Spacecraft Trades and Improvements

The FS-7/C-2 spacecraft will have improved payload performance, better attitude performance, simplified operation, simplified orbit transfer, increased data storage, and modular design for additional compatible science payloads. The spacecraft bus design intended for the follow-on system vs. the current FS-3/C bus design is shown in Table 9.

NSPO is responsible for the acquisition and management of the spacecraft for the FS-7/C-2 ~~p~~Program. The acquisition goal is to acquire the twelve (12) spacecraft along with the spacecraft design, information on the development, manufacture, assembly, integration, testing, and operations from a spacecraft contractor through a procurement contract. NSPO will integrate the mission payloads onto the contractor-provided spacecraft and perform the required integral system testing at NSPO. Additionally, it is planned that the spacecraft contractor will provide the necessary support to the integral integration and test (I&T) at NSPO, and the launch site operations. The satellite (including spacecraft and payload) major milestones will be developed to incorporate the spacecraft development along with the subsequent production schedule of the spacecraft contractor and the integral satellite I&T at NSPO to meet the intended launch periods as illustrated in the NSPO-NOAA Joint Program Integrated Master Schedule.

NSPO also plans to develop an additional NSPO self-reliant spacecraft along with the RO mission payload to be launched during the second launch of the joint mission. NSPO will be responsible for the system/subsystem design that will meet the satellite System Performance Requirements and perform the integral satellite I&T and the launch site preparation activities.

6.3 Ground Trades and Improvements

The biggest and probably most challenging improvement for the next generation ground system will be meeting the objective latency requirement of 15 minutes. FS-7/C-2 threshold latency of 45 minutes is expected to be easily achievable with twice per orbit data dumps in each orbit plane and will be a great improvement over FS-3/C latency. Meeting the objective latency of 15 minutes is more difficult to achieve. Data recovery trades are currently being evaluated as part of the FS-7/C-2 mission definition to determine feasibility versus affordability.

A ground system solution for FS-7/C-2 that will meet threshold latency requirements will likely employ 10 to 12 ground stations, 2 at each of the poles and 6 to 8 around the equator, to capture data from satellites in both orbit planes. The high-inclination orbit plane will be supported by the existing polar sites at Fairbanks, Wallops, Tromsø, and McMurdo, and will require an additional station inside the Antarctic Circle to compl~~i~~ement McMurdo. For the low-inclination orbit plane, a host of new equatorial ground stations will be required. Conceptually there would be 3-4 ground stations in the Americas and an additional set of 3-4 in Asia-Indonesia. Figure 7 shows an optimized set of potential ground station locations to meet the low-inclination orbit plane threshold latency, as well as providing coverage for some of the high-inclination orbit plane passes. The yellow circles are the 10 degree elevation coverage circle of the potential ground stations, when LEO satellite passes within this yellow circle, then satellite could be acquired by the ground station located in the circle center. In the figure, the upper red line is 24 degree northern latitude, and the lower red line is the 24 degree southern latitude. These two lines are the upper and lower bound of the low-inclination satellite trajectories of the launch #1. Trades are currently being performed to look at existing ground station options versus deploying FS-7/C-2 unique sites that are optimized to meet mission needs.

To meet the objective latency, two options are currently being studied – a more extensive network of ground stations ~~versus~~ and crosslink via the National Aeronautic and Space Administration’s (NASA) Tracking and Data Relay Satellite System (TDRSS). Both are currently being considered as part of this trade and implementation will depend largely on the total cost to deploy and operate the option. A ground station solution will be difficult to deploy but if stations could be leveraged from existing sites and/or future programs it may be more feasible and very cost effective to operate. On the other hand, TDRSS would be relatively easy to deploy but be potentially expensive for long term service.

Another item in the ground system trade is alternate data transfer options from the ground stations to the data processing centers to better meet latency needs of multiple users. SFTP via ~~open internet~~the world wide web to multiple users, including potential secondary payload data centers, may not provide adequate latency. Dedicated communication lines may be required to meet the more stringent latency requirements.

6.4 Data Processing Trades and Improvements

Data processing architecture for FS-7/C-2 will remain relatively the same as FS-3/C but will require~~:~~ reliable and low latency input data from FS-7/C-2 GNSS-RO payloads and GNSS ground network, updates to data processing software including GNSS (GPS, Galileo, and Glonass) capability, and more computational power to support the improved and additional number of RO instruments. To make data processing more robust for an operational environment, a data processing system (DPS) will be installed at the Environmental Satellite Processing Center (ESPC) in NOAA’s Satellite Operations Facility (NSOF) in Suitland, Maryland. ESPC will be the prime data processing center in the United States for FS-7/C-2, providing GNSS-RO data products to the operational weather community. NOAA will provide long-term archive of FS-7/C-2 data in their Comprehensive Large Array-Data Stewardship System (CLASS).

7 Conclusion

The FS-3/C satellites have performed successfully for over 4 years~~ now~~. It is not a perfect constellation for an operational system, but it has achieved more than satisfactory results for an experimental system operating in a semi-operational manner. The FS-3/C satellites are degrading as anticipated; however, NSPO assesses these satellite will continue to operate in a reduced capacity ~~into~~ for the next few years. The success of the FS-3/C mission has initiated a new era for near real-time operational use of GNSS-RO soundings. NSPO is committed to continuing the FS-3/C satellite constellation operation to collect RO data to minimize the data gap duration between the end of FS-3/C and the beginning of FS-7/C-2. NSPO and NOAA ~~will proceed with~~have already begun the FS-7/C-2 joint mission implementation.

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References

Anthes, R. A., Rocken, C. & Kuo, Y. H.: Application of COSMIC to Meteorology and Climate, Terrestrial, Atmospheric and Oceanic Sciences, Vol. 11, No.1, pp. 115-156, 2000.

Anthes, R. A., Bernhardt, P. A., Chen, Y., Cucurull, L., Dymond, K. F., Ector, D., Healy, S. B., Ho, S.-P., Hunt, D. C., Kuo, Y.-H., Liu, H., Manning, K., McCormick, C., Meehan, T. K., Randel, W. J., Rocken, C., Schreiner, W. S., Sokolovskiy, S. V., Syndergaard, S., Thompson, D. C., Trenberth, K. E., Wee, T. K., Yen, N. L., and Zeng, Z.: The COSMIC / FORMOSAT-3 Mission: Early Results, Bulletin of the American Meteorological Society, Vol. 89, No.3, pp. 313-333, doi:10.1175/BAMS-89-3-313, 2008.

Chu, C.-H., Yen, N., Hsiao, C.-C., Fong, C.-J., Yang, S.-K., Liu, T.-Y., Lin, Y.-C., and Miau, J.-J.: Earth observations with orbiting thermometers – prospective FORMOSAT-3 / COSMIC follow-on mission, Proceedings of Small Satellite Conference 2008, Logan, Utah., USU, Logan, 2008.

Fong, C.-J., Shiau, A., Lin, T., Kuo, T.-C., Chu, C.-H., Yang, S.-K., Yen, N., Chen, S. S., Huang, C.-Y., Kuo, Y.-H., Liou, Y.-A., and Chi, S.: Constellation deployment for FORMOSAT-3/COSMIC mission, IEEE Transactions on Geoscience and Remote Sensing, Vol. 46, No.11, pp. 3367-3379, doi:10.1109/TGRS.2008.2005202, 2008a.

Fong, C.-J., Yang, S.-K., Chu, C.-H., Huang, C.-Y., Yeh, J.-J., Lin, C.-T., Kuo, T.-C., Liu, T.-Y., Yen, N., Chen, S. S., Kuo, Y.-H., Liou, Y.-A., and Chi, S.: FORMOSAT-3 / COSMIC constellation spacecraft system performance: After One Year in Orbit, IEEE Transactions on Geoscience and Remote Sensing, Vol. 46, No.11, pp. 3380-3394, doi:10.1109/TGRS.2008.2005203, 2008b.

Fong, C.-J., Huang, C.-Y., Chu, V., Yen, N., Kuo, Y.-H., Liou, Y.-A., and Chi, S.: Mission results from FORMOSAT-3/COSMIC constellation system, AIAA Journal of Spacecraft and Rockets, Vol. 45, No. 6, pp. 1293-1302, doi:10.2514/1.34427, 2008c.

Fong, C.-J., Yen, N. L., Chu, C.-H., Yang, S.-K., Shiau, W.-T., Huang, C.-Y., Chi, S., Chen, S.-S., Liou, Y.-A., and Kuo, Y.-H.: FORMOSAT-3/COSMIC spacecraft constellation system, mission results, and prospect for follow-on mission, Terrestrial, Atmospheric and Oceanic Sciences, Vol. 20, doi:10.3319/TAO.2008.01.03.01(F3C), 2009a.

Fong, C.-J., Yen, N. L., Chu, C.-H., Hsiao, C.-C., Liou, Y.-A., and Chi, S.: Space-based Global Weather Monitoring System – FORMOSAT-3/COSMIC Constellation and its Follow-On Mission, AIAA Journal of Spacecraft and Rockets, Vol. 46, No. 4, pp 883-891, doi: 10.2514/1.41203, 2009b.

Fong, C.-J., Whiteley, D., Yang E., Cook, K., Chu, V., Schreiner, B., Ector, D., Wilczynski, P., and Yen, N.Y.: Space & Ground Segment Performance of the FORMOSAT-3 / COSMIC Mission: Four Years in Orbit, Joint OPAC-4 & GRAS-SAF Climate & IROW-1 Workshop, Graz, Austria, 2010.

Hajj, G. A., Lee, L. C., Pi, X., Romans, L. J., Schreiner, W. S., Straus, P. R., and Wang, C.: COSMIC GPS ionospheric sensing and space weather, Terr. Atmos. and Ocean. Sci., 11(1), 235-272, 2000.

Kursinski, E. R. ,Hajj, G. A., Bertiger, W. I., Leroy, S. S., Meehan, T. K., Romans, L. J., Schofield, J. T., McCleese, D. J., Melbourne, W. G., Thornton, C. L., Yunck, T. P., Eyre, J. R. and Nagatani, R. N.: Initial results of radio occultation observations of Earth's atmosphere using the Global Positioning System, Science, 271(5252), 1107-1110, 1996.

Kuo, Y.-H., Sokolovskiy, S., Anthes, R., and Vandenberghe, V.: Assimilation of GPS radio occultation data for numerical weather prediction, Terrestrial, Atmospheric and Oceanic Sciences, Vol. 11, No. 1, pp. 157–186, 2000.

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

Kuo, Y.-H., Liu, H., Ma, Z. and Guo, Y.-R.: The Impact of FORMOSAT-3/COSMIC GPS Radio Occultation, Proceedings of 4th Asian Space Conference and 2008 FORMOSAT-3 / COSMIC International Workshop, Taipei, Taiwan, NSPO, Hsinchu, Taiwan, 2008.

Liou, Y.-A., Pavelyev, A. G., Liu, S. F., Pavelyev, A. A., Yen, N., Huang, C. Y., and Fong, C.-J.: FORMOSAT-3 GPS radio occultation mission: preliminary results," IEEE Transactions on Geoscience and Remote Sensing, Vol. 45, No. 10, pp. 3813-3824, doi:10.1109/TGRS.2007.903365, 2007.

Luntama, J.-P., Kirchengast, G., Borsche, M., Foelsche, U., Steiner, A., Healy, S., von Engeln, A., O'Clerigh, E., Marquardt, C.: Prospects of the EPS GRAS Mission For

Operational Atmospheric Applications, Bull. Am. Meteorol. Soc., 89(12), 1863-1875, doi: 10.1175/2008BAMS2399.1, 2008.

Melbourne, W. G.: Radio Occultation Using Earth Satellites: A Wave Theory Treatment, John Wiley & Sons, Inc., ISBN 0-471-71222-1, 2005.

Perona, G., Notarpietro, R., Gabella, M.: GPS radio occultation on-board the OCEANSAT-2 mission: An Indian (ISRO) – Italian (ASI) collaboration, Indian Journal of Radio Space Physics, 36(5), 386-393, 2007.

Rius, A., Ruffini, G., and Romeo, A.: Analysis of ionospheric electron-density distribution from GPS/MET occultations, IEEE Trans. Geosci. Remote Sens., 36(2), 383-394, 1998.

Schreiner, W.S., Sokolovskiy, S. V., Rocken, C., and Hunt, D.C.: Analysis and Validation of GPS/MET Radio Occultation Data in the Ionosphere, Radio Sci., 34(4), 949-966, doi:10.1029/1999RS900034, 1999.

Schreiner, W.S., Rocken, C., Sokolovskiy, S., and Hunt, D.C.: Quality assessment of COSMIC/FORMOSAT-3 GPS radio occultation data derived from single- and double-difference atmospheric excess phase processing. GPS Solutions, 14(1), 13-22, doi:10.1007/s10291-009-0132-5, 2009.

Ware, R., Rocken, C., Solheim, F., Exner, M., Schreiner, W., Anthes, R., Feng, D., Herman, B., Gorbunov, M., Sokolovskiy, S., Hardy, K., Kuo, Y., Zou, X., Trenberth, K., Meehan, T., Melbourne, W,. and Businger, S.: GPS sounding of the atmosphere from low earth orbit: Preliminary results, Bull. Am. Meteorol. Soc., 77(1), 19-40, 1996.

Yen, N. L. and Fong, C.-J.: FORMOSAT-3 Evaluation Report and Follow-on Mission Plan, NSPO-RPT-0047_0000, National Space Organization (NSPO), Hsinchu, Taiwan, 2009.

Yen, N. L.: FORMOSAT-3/COSMIC Follow-On Mission Plan and Current Progress, Joint OPAC-4 & GRAS-SAF Climate & IROW-1 Workshop, Graz, Austria, 2010.

Yunck, T. P., Liu, C. H. and Ware, R.: A History of GPS Sounding, Terrestrial, Atmospheric and Oceanic Sciences, Vol. 11, No.1, pp. 1-20, 2000.

Appendix: Acronyms and Abbreviations

ACE Attitude Control Electronics

1	ADCS	Attitude Determination and Control Subsystem
2	AFWA	Air Force Weather Agency
3	Ant#	Antenna No. #
4	ATT	Attitude
5	BCR	Battery Charge Regulator
6	C&DH	Command and Data Handling
7	CDAAC	COSMIC Data Analysis and Archive Center
8	CHAMP	Challenging Minisatellite Payload
9	COSMIC	Constellation Observing Systems for Meteorology, Ionosphere, and Climate
10	Canada Met	Canadian Meteorological Centre
11	CLASS	Comprehensive Large Array-Data Stewardship System
12	CSSA	Coarse Sun Sensor Assembly
13	CSSA#	Coarse Sun Sensor Assembly no. #
14	CWB	Central Weather Bureau
15	DC	Direct Current
16	dMdC	Derivative of Battery Molecular to Charge
17	DPC	Data Processing Center
18	DPS	Data Processing System
19	ECMWF	European Centre for Medium-range Weather Forecast
20	EPS	Electrical Power Subsystem
21	ESPC	Environmental Satellite Processing Center
22	FB	Firmware Build
23	FC	Flight Computer
24	FCDAS	Fairbanks Command and Data Acquisition Station
25	FDC	Failure Detection Correction
26	FM	Flight Model

FM#	Flight Model no. #
FPGA	Field Programmable Gate Array
FS-3	FORMOSAT-3
FS-7/C-2	FORMOSA SATellite mission no.7/ Constellation Observing Systems for Meteorology, Ionosphere, and Climate mission no. 2
FSW	Flight Software
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPS/MET	GPS/Meteorology
GOX	GPS Occultation Receiver
GPSR	GPS Receiver
GRACE	Gravity Recovery and Climate Experiment
GTS	Global Telecommunications System
I&T	Integration and Test
IV&V	Independent Verification and Validation
JMA	Japan Meteorological Agency
JPL	Jet Propulsion Laboratory
JSCDA	Joint Center for Satellite Data Assimilation
KSAT	Kongsberg Satellite Services Ground Station
LEO	Low-Earth-Orbit
LOS	Loss of Signal
LTS	Local Tracking Station
MAG	Magnetometer
Météo-France	French National Meteorological Service
MIU	Mission Interface Unit

NARL	National Applied Research Laboratories
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NSC	National Science Council
NSF	National Science Foundation
NSOF	NOAA's Satellite Operations Facility
NSPO	National Space Organization
NWP	Numerical Weather Prediction
OCC#	Occultation No. #
OSC	Orbital Sciences Corporation
PCM	Power Control Module
PL	Payload
POD	Precision Orbit Determination
POD#	Precision Orbit Determination No. #
RF	Radio Frequency
RF#	Radio Frequency No. #
RFI	Radio Frequency Interference
RO	Radio Occultation
RTS	Remote Tracking Station
RWA	Reaction Wheel Assembly
SAA	South Atlantic Anomaly
SAC-C	Satellite de Aplicaciones Cientificas-C
SADA	Solar Array Drive Assembly

S/C	Spacecraft
SFTP	Secure File Transfer Protocol
SNR	Signal-to-Noise Ratio
SOC	State-of-Charge
SOCC	Satellite Operations Control Center
SOH	State-of-Health
SSR	Solid State Recorder
TACC	Taiwan Analysis Center for COSMIC
TBB	Tri-Band Beacon
TBR	To Be Reviewed
TDRSS	Tracking and Data Relay Satellite System
TEC	Total Electron Content
TIP	Tiny Ionospheric Photometer
UCAR	University Corporation for Atmospheric Research
UKMO	United Kingdom Meteorological Office
USA	United States of America
USAF	United States Air Force
USN	United Service Network
VC#	Virtual Channel No. #
VIDI	Velocity, Ion Density and Irregularities
WCDAS	Wallops Command and Data Acquisition Station
ZTD	Zenith Tropospheric Delay

Table 1. ~~Spacecraft~~ Mission Operation Status of Each Subsystem for All Six Spacecraft~~.~~

S/C No.	Operational Mode	Spacecraft State	ADCS Mode	EPS Mode	C&DH Mode	GOX	TIP	TBB
FM1	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating	Low Beta Operating	Low Beta Operating
FM2	Normal	Power Shortage (Note 5)	Fixed-Yaw	Normal	High Rate	Reduced Duty-Cycle Operating	Off (Note 1)	Off (Note 1)
FM3	Normal @711 km (Note 3)	SADA Stuck (Note 3)	Fixed-Yaw	Normal	High Rate	Off (Note 4)	Off (Note 1)	Off (Note 1)
FM4	Normal	Battery Degradation (Note 2)	Fixed-Yaw	Normal	High Rate	Operating	Low Beta Operating	Low Beta Operating
FM5	Normal	Normal	Fixed-Yaw	Normal	High Rate	Operating (Low SNR)	Low Beta Operating	Low Beta Operating
FM6	Normal	Battery Degradation (Note 2)	Fixed-Yaw	Normal	High Rate	Operating (Low SNR)	Low Beta Operating	Low Beta Operating

Note: 1. Secondary payloads are power off due to power shortage.

2: Significant FM4 & FM6 battery degradations cause payload power off at high battery state-of-charge.

3: FM3 was kept at 711 km orbit due to stuck solar array drive.

4: FM3 has been in an abnormal condition (lost of communication) since July.

5: FM2 experienced a sudden solar panel power shortage with only one solar panel working.

SADA = Solar Array Drive Assembly

ADCS = Attitude Determination and Control Subsystem

EPS = Electrical Power Subsystem

C&DH = Command and Data Handling

Low Beta = low sun beta angle

Table 2. Spacecraft Constellation Performance Summary.

S/C ID	Summary
FM1	Bus GPSR GPS Non-Fixed -> Operation Solution GOX RF1 (POD1/ANT0) Lower SNR -> GOX Reboot Loop -> GOX FB 4.4 Update Payload Unexpected Off -> Battery Degradation Bad Attitude
FM2	BCR dMdC Charge Algorithm Issue -> FSW Update Solar Array Power Shortage -> Reduced GOX Operation GOX Reboot Loop -> GOX FB 4.4 Update Battery Pressure Difference Anomaly -> FSW Update PCM DC Converter Abnormally Off -> TBB & TIP Off Loss of Communication -> Auto Recovery
FM3	Loss of Communication -> Auto Recovery Solar Array Driver Lockout -> Reduced GOX Operation Bus GPSR GPS Non-Fixed -> Operation Solution GOX RF1 (POD1/ANT0) Lower SNR -> GOX Reboot Loop -> GOX FB 4.4 Update Payload Unexpected Off -> Battery Degradation
FM4	Bus GPSR GPS Non-Fixed (since Launch)-> Operation Solution GOX RF1 (POD1/ANT0) Lower SNR -> GOX Reboot Loop -> GOX FB 4.4 Update Payload Unexpected Off -> Battery Degradation -> On-Orbit Battery Refreshment
FM5	GOX RF1 (POD1/ANT0) Lower SNR -> GOX Reboot Loop -> GOX FB 4.4 Update GOX RF4 (OCC1/ANT3) SNR Decreasing-> Operation Solution Bus GPSR degraded -> Operation Solution Payload Unexpected Off -> Battery Degradation -> On-Orbit Battery Refreshment
FM6	Loss of Communication -> -> Auto Recovery Bus GPSR GPS Non-Fixed -> Operation Solution GOX RF1 (POD1/ANT0) Lower SNR -> GOX Reboot Loop -> GOX FB 4.4 Update GOX SNR decreasing at High Temp. -> Auto Recovery Payload Unexpected Off -> Battery Degradation -> On-Orbit Battery Refreshment Orbit Raise-Up -> Under Investigation

Note: GPSR = GPS Receiver, RF1 = Radio Frequency No. 1, Ant0 = Antenna No. 0, POD = Precision Orbit Determination, FB = Firmware Build, BCR = Battery Charge Regulator, dMdC= Derivative of Battery Molecular to Charge, FSW = Flight Software, RF4 = Radio Frequency No. 4, Ant3 = Antenna No. 3, OCC1 = Occultation No. 1.

Table 3. Number of Occultation Profiles for Each GOX Instrument after Four Years in Orbit~~.~~

Atmosphere	FM1	FM2	FM3	FM4	FM5	FM6	Total
Operation Duration	1,397	1,282	1,173	1,424	1,401	1,302	7,979~~1,442~~
Atmosphere Profiles Per Day	285.07	229.48	242.94	333.37	248.73	242.96	1,~~468.06~~582.55
Total Atmosphere Profiles	398,245	294,198	284,970	474,713	348,475	316,335	2,116,936
Ionosphere	FM1	FM2	FM3	FM4	FM5	FM6	Total
Operation Duration	1,293	1,284	1,173	1,423	1,286	1,300	7,759~~1,442~~
Ionosphere Profiles Per Day	284.65	275.74	292.71	394.54	241.03	253.17	1,741.84~~571.4~~
Total Ionosphere Profiles	368,049	354,054	343,353	561,426	309,966	329,116	2,265,964

Table 4. GOX Payload Performance Summaries.

S/C No.	GOX Duty Cycle	POD1 RF1 ANT0	POD2 RF2 ANT1	OCC2 RF3 ANT2	OCC1 RF4 ANT3	60 day Average Data Profile (Mean/Peak)
FM1	100 %	Low SNR	Normal	Normal	Normal	290/350
FM2	80% -> 60%	Normal	Normal	Normal	Normal	200/320
FM3	60% -> 36%	Low SNR	Normal	Normal	Normal	150/300
FM4	100 %	Normal	Normal	Normal	Normal	300/420
FM5	100 %	Low SNR	Low SNR	Normal	Low SNR	160/310
FM6	100 %	Low SNR	Normal	Normal	Low SNR	130/300

Note: POD1 = Precision Orbit Determination No. 1, POD2 = Precision Orbit Determination No. 2, OCC1 = Occultation No. 1, OCC2 = Occultation No. 2; RF1 = Radio Frequency No. 1, RF2 = Radio Frequency No. 2, RF3 = Radio Frequency No. 3, RF4 = Radio Frequency No. 4; and Ant0 = Antenna No. 0, Ant1 = Antenna No. 1, Ant2 = Antenna No. 2, Ant3 = Antenna No. 3.

Table 5. Average Variation Rate per Year of Each Spacecraft Battery.

S/C ID	Batt V Mean [V]	Batt V Min [V]	Batt SOC Max [Ah]	Batt SOC Min [Ah]	PL Off SOC	Remarks
FM1	-0.034	-0.104	1.169	-0.657	~1.95	Battery degradation since 2008/4 Battery over pressure
FM2	-0.031	-0.159	-0.236	-0.036	~1	Battery degradation since 2008/10 Battery charging efficiency decreased
FM3	-0.094	-0.080	0.769	0.127	~0.45	Battery degradation since 2008/10
FM4	-0.060	-0.319	0.453	0.628	~2.5	Battery degradation since 2007/12 Battery over pressure
FM5	-0.026	-0.122	0.617	0.596	~1.95	Battery degradation since 2008/1
FM6	-0.042	-0.249	1.213	1.184	~2.5	Battery degradation since 2007/12 Battery over pressure

Note: PL = Payload

Table 6. Mission Lessons Learned~~.~~

Items	Implementation	Observation / Major Finding	Lessons Learned
Spacecraft Communication Frequency	- L-band downlink was chosen originally to simplify frequency coordination process - The downlink frequency was switched to S-band to avoid interference with on-board payload operating frequency	- T~~t~~he S-band downlink frequency is operated under constraints due to the RFI with other NASA and ESA satellites~~.~~	- Frequency selection shall be coordinated in the feasibility study phase and reviewed by all parties (mission, science, payload provider, bus provider)~~.~~
RFI A~~a~~mong Payloads	- RFI was not tested at the spacecraft system level to identify the interference severity on the ground~~.~~	- RFI was tested until on-orbit - GOX L2 signals ~~were~~ interfered ~~by~~ with VHF&L bands on TBB ALL-ON mode~~.~~ - Consequently, TBB reduced its operations at 2-band mode only~~.~~	- Frequency selection shall be coordinated in the feasibility study phase and reviewed by all parties (mission, science, payload provider, bus provider)~~.~~
Radio Occultation Profiles	- Mission requirement is set at 2,500 occultation profiles per day on average based on the estimate from a "near-perfect" constellation situation (~ 3,000 profiles per day)~~.~~	- Two major factors seem to be under-estimated: (1) PL down time (2) data filtered out by data quality control (for example: low SNR, etc.)~~.~~	- The flow-down of mission requirements shall be carefully implemented in the success criteria and shall consider the downtime for each segment~~.~~ - Improved S/C performance - Improved PL performance - Improve ground processing software

Note: PL = Payload

Table 7. Payload Lessons Learned~~.~~

Items	Implementation	Observation / Major Finding	Lessons Learned
GOX POD Low SNR P~~p~~roblem	- After GOX payload instrument, POD antenna cable link, and the POD antenna are assembled into the spacecraft, there is no ~~without~~ sufficient system level ground testing during system level I&T~~.~~	- RF1 low SNR anomaly in lower beta angle. First happened to FM6 (2007-041), then FM1 (2007-261), FM5 (2007-302), and FM3 (2008-245). Only FM2 & FM4 RF1 has no SNR problem - FM4 RF2 had low SNR problem since 2010-071, so FM4 now use RF1 only - FM5 RF2 started to show low SNR problem since 2010-160 in lower beta angle (< 15 degree).~~;~~ If RF2 decays like RF1 did, FM5 GOX will generate no OCC data~~.~~	- Should conduct reversed engineering to find the true cause of the problem - Should conduct adequate SNR test/measurement ~~in~~ at the system level during the ground testing in ~~the~~ future similar programs
GOX OCC Low SNR P~~p~~roblem	- GOX instrument, OCC cable link, and the OCC antenna may not be adequately modeled for thermal analysis for SNR sensitivity variations over the intended temperature range and the anticipated orbital conditions~~.~~	- FM5 RF4 low SNR in high beta angle while GOX temp>40 deg C - Started from 2008-~~Day~~ 082 whenever in higher beta angle period (|Beta| > 40 degree) ~~period~~ - Higher minus beta angle has negative impact to the RO observed occultations number while RF4 is the setting antenna - FM6 RF4 unstable and SNR drops periodically (2009-032~2009-105, 2009-151~2009-192, 2010-141~now)	- Ground commands to temporarily operate the spacecraft at the fixed SADA configuration ~~is~~ are able to cool down the GOX temperature below 35 degree C when beta < -50 degree - The ~~lesson learned is that the P~~payload thermal requirement and the related thermal analysis / testing should be properly implemented
GOX SNR Decrease at High Temperature	- Since 2009-035, FM6 SNR dropped; the RO profiles decreased to less than 100, FM6 only can generate good RO while GOX temp < 25~~.~~ - FM6 GOX ~~S/N ratio~~SNR decreases even when the temperature is not over its red high limit~~.~~	- Turn on GOX at definite time for one orbit at low beta angle, GOX On 4 hrs Off 4 hrs cycle to maintain GOX RO in a stable lower level around 120 profiles - After two months of minus beta angle (2009-086), S/C flipped back while RF3 is setting OCC antenna, GOX operates in full duty cycle, GOX RO increased to around 300 profiles~~.~~	- GOX performance is decreasing even though the temperature is still within the limits~~.~~ - GOX component detail thermal analysis, thermal verification, and thermal model correlation about thermal verification should be performed to make sure its component thermal design is OK~~.~~

Note: SADA = Solar Array Drive Assembly

1Table 8. Spacecraft System Lessons Learned~~.~~

Items	Implementation	Observation / Major Finding	Lessons Learned
SSR/MIU GOX Data Dropouts	- GOX data dropout ~~s~~ avoidance design was not implemented in the design requirements and the data dropout~~s~~ scenario was not detected at the subsystem or system level~~.~~ -	- GOX data dropouts occurred in almost every dump at the payload checkout in the early orbit phase - Separate VC1 and VC2 data dumps and perform double dumps to mitigate the data dropouts	- Reliable design of interface and protocol for data transfer should be specified in the hardware/software design requirements - No data dropouts must be proven and/or tested before flight
Spacecraft Design Philosophy	- FS-3/C is a proof-of-~~constellation-operation-~~ concept experimental mission. High reliability and robust design was not implemented in this program~~.~~ - FS-3/C uses single string design strategy	- System Level FDC (Fault Detection & Correction) strategy is applied to allow faults to happen and the S/C to recover from them - Temporary loss of the payload performance is much more ~~much~~ significant for 1 out of 6 ~~spacecrafts~~ S/C in the FS-3/C constellation than 1 out of ~~more than~~ 30+ spacecraft in a fleet like in ORBCOMM ~~fleet~~ when using multiple spacecraft as the constellation design redundancy philosophy	- Apply robust design and high reliability design philosophy for the operational mission - Continue to apply system-level FDC and implement the necessary redundancy ~~implementation~~ design in the spacecraft as well as in the constellation for the sufficient operational service availability in the follow-on mission
Spacecraft Downtime	- Due to the single string design, the spacecraft may often encounter anomalies ~~and~~ that cause ~~the~~ spacecraft downtime for various durations depending on the types of the anomalies~~.~~ - S/C downtime events will force payload power off and will reduce the GOX RO science data volume~~.~~	- Top three causes of the spacecraft anomalies are attitude excursions, stabilized mode after thrust burn, and processor reboot/reset. These causes ~~and that they have occupied around~~ have contrinbuted to appx. three quarters of all payload power off events~~.~~ - Some anomalies can be resolved by the ground operation solution to maximize GOX RO science data volume~~.~~	- Re-design ADCS thrust mode to be able to perform orbit maneuver correctly and improve ADCS performance - Use high reliable Processor / FPGA - Form a separate ADCS IV&V team to evaluate ADCS design, simulation, and test results to prevent errors that cause S/C downtime~~.~~
Computers Resets / Reboots~~Computers Resets / Reboots~~	- FS-3/C uses single string design strategy where none of the computers have a redundant design - The occurrence frequency of the Single Event Upset (SEU) is not defined clearly in the requirements documents - The SEU anomalies made the spacecraft lose valuable telemetry and payload data~~FS-3/C~~	- 262 out of 304 events are computer resets/reboots as-of-4-1-2010 - Most of the time and geo-locations the spacecraft anomalies that occurred are correlated to the space radiation environment - Root cause is due to the occurrence of Single event upset (SEU) event in the South Atlantic Anomaly (SAA) and the polar	- Spacecraft design with nonvolatile memory is recommended to secure lost critical spacecraft telemetry and payload data - Higher level red-tolerant or radiation-hardening design should be considered in the future - Similar FDC function should be also implemented ~~S/C The SEE anomalies made SC lost~~

Items	Implementation	Observation / Major Finding	Lessons Learned
	~~adapted the discrete computers architecture: Attitude Control Electronics (ACE), Battery Control Regulator (BCR), and Flight Computer (FC)~~ ~~FS-3/C uses single string design strategy that none of the discrete computers has any built-in redundancy design.~~ ~~The occurrence frequency of the Single Event Upset (SEU) is not defined clearly in the requirement document.~~ ~~The SEU anomalies made the spacecraft lost valuable telemetry and payload data.or external back-up unit for contingency~~	regions - The spacecraft will be recovered automatically following system level Failure Detection and Correction (FDC) strategies~~Totally 262 out of 304 events are computer resets/reboots as-of-4-1-2010~~ - ~~Most of the time and geo-locations the spacecraft S/C anomalies occurred are closely correlated to the space radiation environment.~~ - ~~Root cause is due to the occurrence of Single event effects (SEEs) in the South Atlantic anomaly region and the polar region~~ - ~~are identified as the most probable root cause.The spacecraft~~ - ~~will be SC recovered automatically following system level Failure Detection and Correction (FDC) strategies.~~ - ~~Use High reliable Processor/FPGA~~ - ~~Use system FDC strategies.~~	~~valuable telemetry and payload data. A design with nonvolatile memory is recommended to secure lost of critical S/CS/C housekeeping and payload data for the future missions.~~ - ~~A Hhigher level red-tolerant or radiation-hardening design should be considered in the future~~ - ~~The Similar FDC design makes the C&DH (and SC) can recover from anomalies automatically. A similar function should be also implemented in the future mission.~~
ADCS Performance	- The ADCS was equipped with only a coarse attitude sensor and without a rate sensor~~.~~ - The sun sensor processing algorithm generated incorrect sun vector data ~~from time-to-time~~periodically~~.~~	- The attitude performance is not stable ~~and~~ resulting in impacts to the GOX payload operation~~.~~ - Singularity occurred at each orbit to the FS-3 magnetic -based controller/estimator~~.~~ - The parameters of the attitude reference system have been tuned to gain better attitude performance~~.~~	- Better performance of attitude sensor, for example star tracker, may be used to improve the ADCS dramatically~~.~~ - Rate sensor, even the coarse rate sensor, will improve the Thrust Mode performance and therefore decrease the duration of the constellation deployment~~.~~ - The three-wheel (or four -wheel) zero-momentum-bias linear control system ~~to~~ should be considered in ~~the~~ future missions

Note: SSR/MIU = Solid State Recorder/Mission Interface Unit, VC1 = Virtual Channel No. 1, VC2 = Virtual Channel No. 2, FDC = Failure Detection Correction, FPGA = Field Programmable gate Array , IV&V = Independent Verification and Validation, C&DH = Command and Data Handling , FS-3 = FORMOSAT-3.

Table 9. Spacecraft Bus Design for Follow-on System vs. FS-3/C~~.~~

Function	FS-7/C-2 Design Improvement	FS-3/C Design	Benefit
Weight	~150 kg (TBR)	61 kg (w/ Propellant)	Stacked or Single Launch Piggy-Back Launch
Attitude Control Performance	3-axis linear control Roll/Yaw:+/-1 deg. (3σ) Pitch: +/- 1 deg. (3σ) 3-Axis Gyro, 3-axis MAG, CSSAs, RWA x 3, Torque x 3, Star Tracker x 1	3-axis nonlinear control Roll/Yaw: +/-5 deg. (1σ) Pitch: +/- 2 deg. (1σ) Earth Sensor x 2, CSSA x 8, RWA x 1, Torque x 3, GPS Bus Receiver PL x 1	Improved PL Performance Better Attitude Performance Simplified Operation Simplified Orbit Transfer
Science Data Storage	250 MBytes	128 MByte (32M for GOX)	Simplified Operations
Avionics Architecture	Centralized Architecture Radiation - Hardness	Distributed Architecture (Multiple Avionics Boxes)	Simplified Integration Harnessing & Reduced Mass ~~Reduced~~
Electrical Power	Lithium Ion Battery Voltage Based Algorithm	Ni-H2 Battery dM/dC Charging Algorithm	Reduced Mass & Volume Simplified Operations
Structure	Aluminum (Al)	Metal Matrix	Reduced Cost ~~Reduced~~
Payload Interface	- ~~Main~~ Mission PL: TriG Rcvr - Science PL VIDI & Radio Frequency (RF) Beacon on low inclination satellites - Science PL on high inclination satellites TBD	- Primary PL: GOX - Secondary PL: TIP, TBB	Modular Design Reduced Cost ~~Reduced~~

Note: TBR = To Be Reviewed, TBD = To Be Determined, MAG = Magnetometer, CSSAs = Coarse Sun Sensor Assemblies, RWA = Reaction Wheel Assembly, VIDI = Velocity, Ion Density and Irregularities

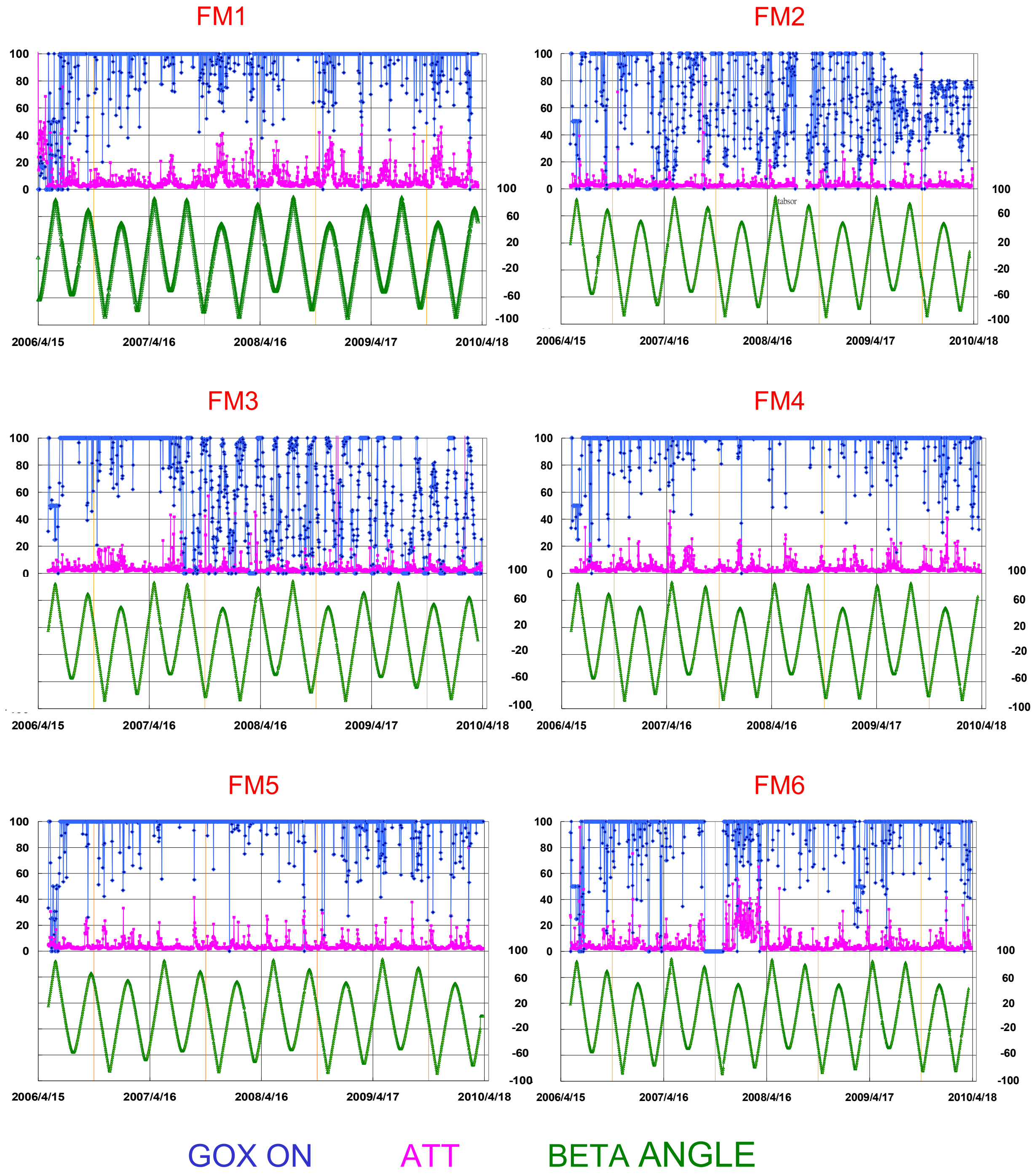
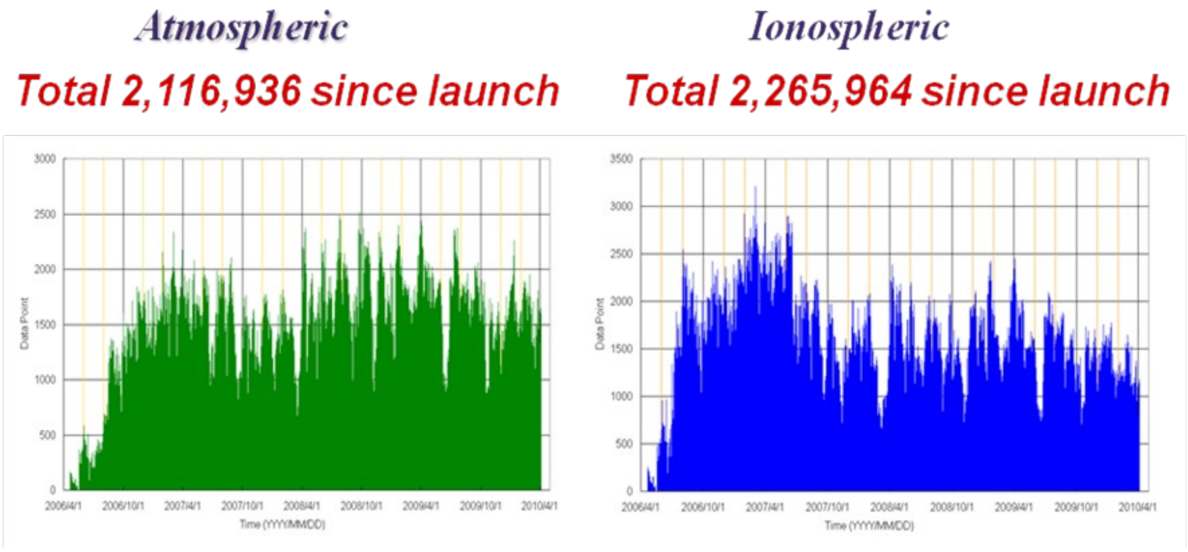


Figure 1. Spacecraft System Performance after Four Years in Orbit



(a) (b)

Figure 2. Four-Year Statistics Showing the Number of Daily Occultation Events (as-of-4/5/2010) for (a) Atmosphere Profiles, and (b) Ionosphere Profiles of Electron Density~~.~~

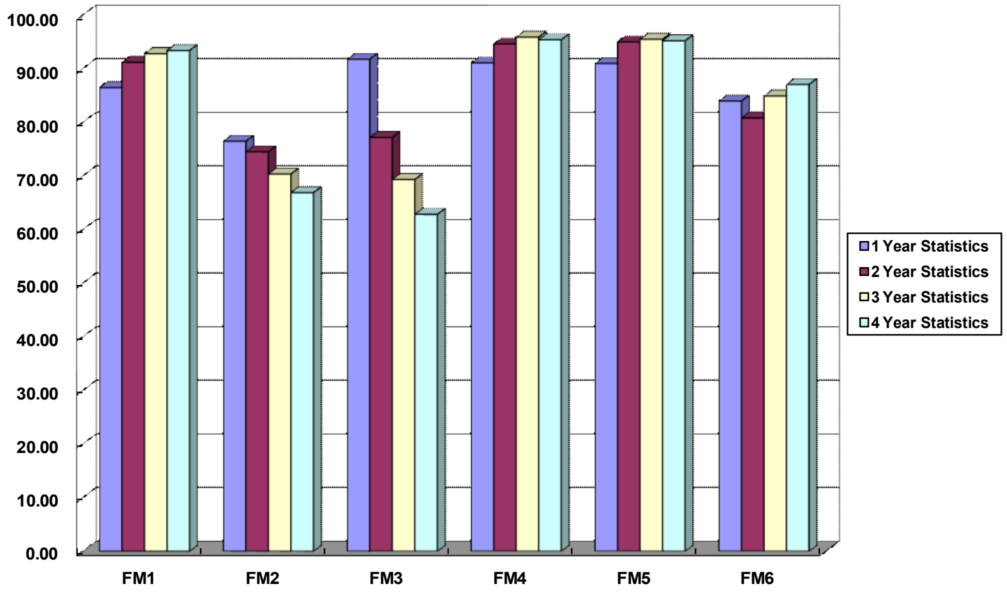
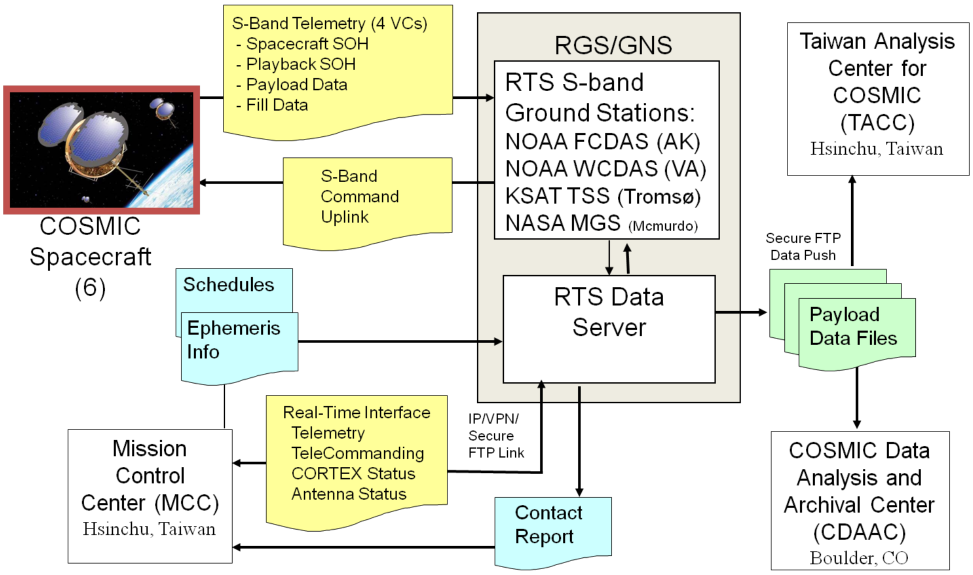


Figure 3. GOX P~~p~~ayload D~~d~~uty C~~c~~ycle O~~o~~n S~~s~~tatistics for O~~o~~ne to F~~f~~our Y~~y~~ears~~.~~



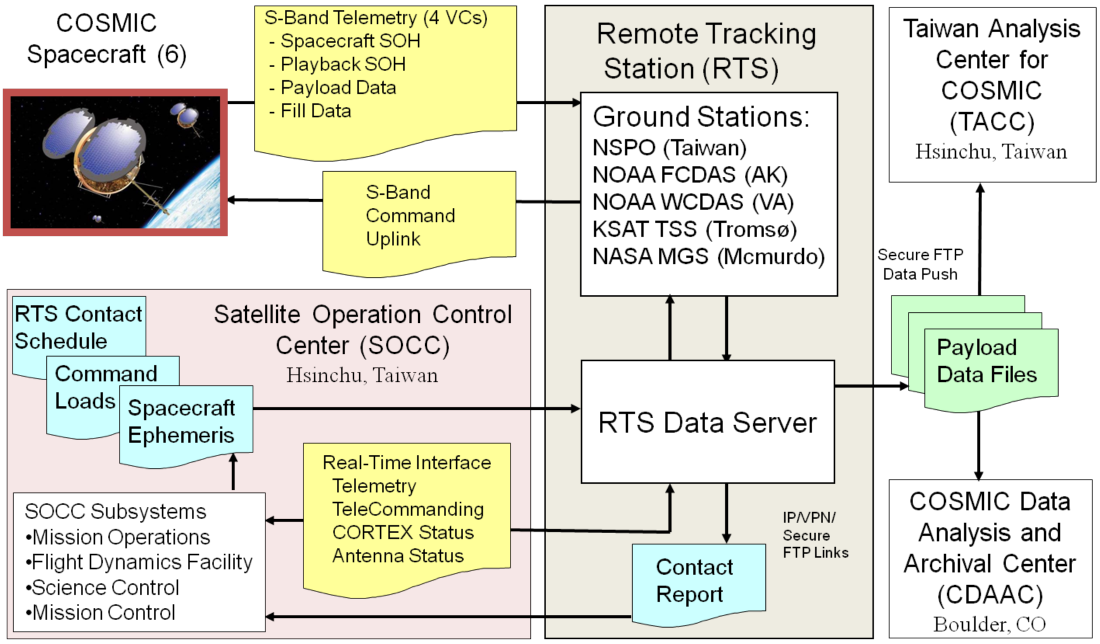


Figure 4. FS-3/C Ground System Data Flow.

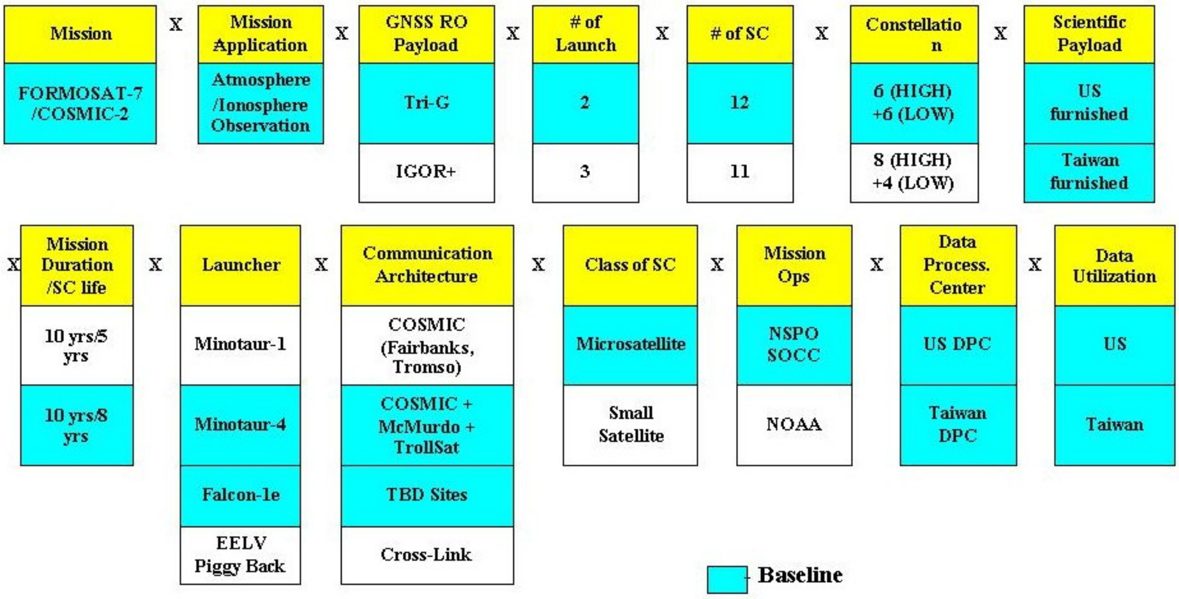
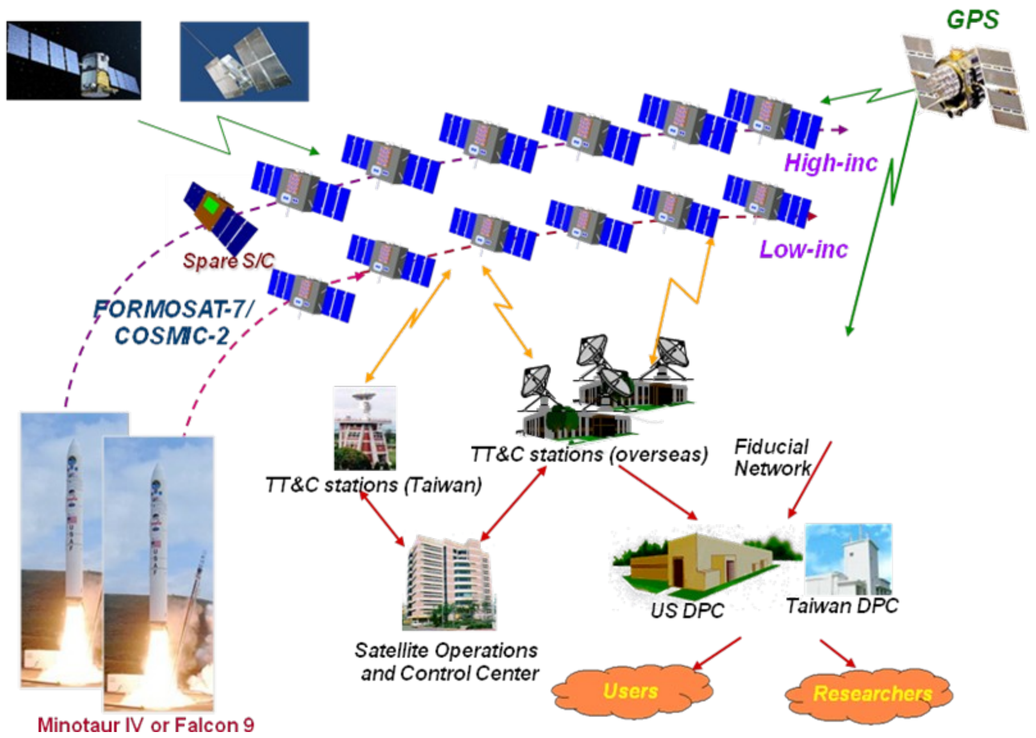
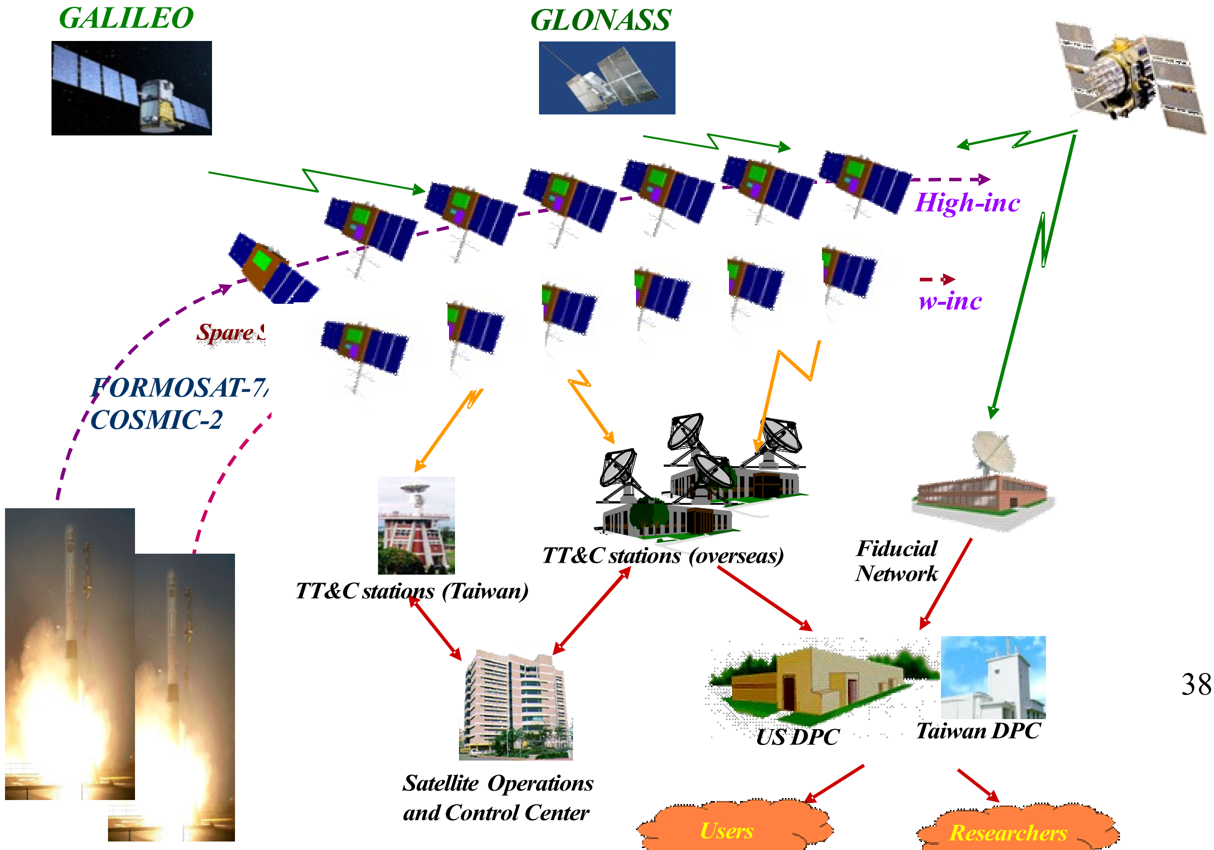


Figure 5. FS-7/C-2 Mission Trades


GPS
High-inc
Low-inc
Spare S/C
FORMOSAT-7/
COSMIC-2
TT&C stations (overseas)
TT&C stations (Taiwan)
Fiducial
Network
Satellite Operations
and Control Center
US DPC
Taiwan DPC
Users
Researchers
Minotaur IV or Falcon 9

1


GALILEO
GLONASS
High-inc
w-inc
Spare S
FORMOSAT-7/
COSMIC-2
TT&C stations (overseas)
TT&C stations (Taiwan)
Fiducial
Network
Satellite Operations
and Control Center
US DPC
Taiwan DPC
Users
Researchers

1

2

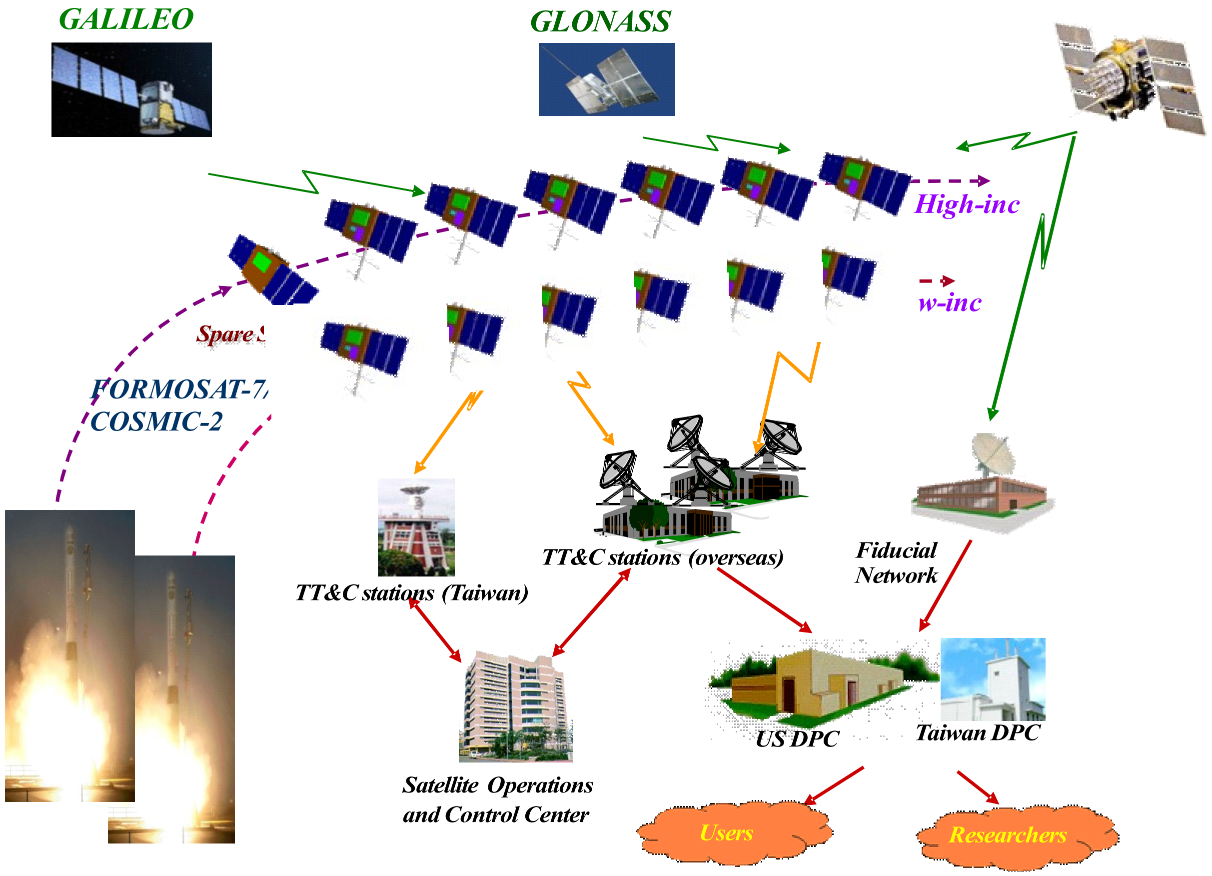


Figure 6. Proposed FS-7/C-2 Mission Architecture.

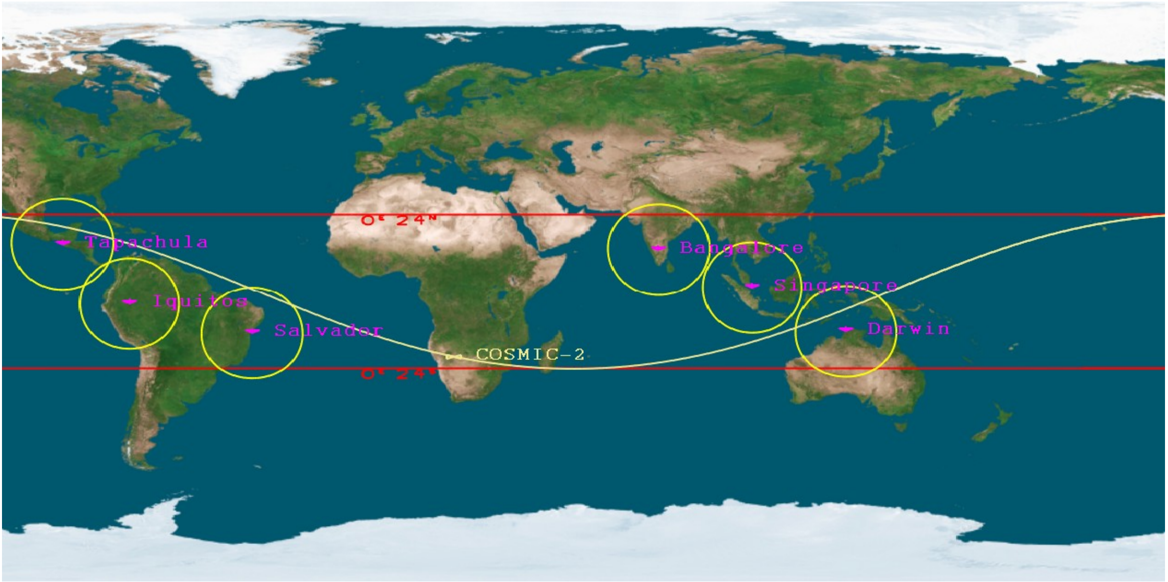


Figure 7. Potential FS-7/C-2 Equatorial Ground Station Locations.