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Space and ground segment performance of the FORMOSAT-3/COSMIC mission: four years in orbit

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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) mission 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 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 1400 to 1800 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 transitions the program from the current experimental research system to a significantly improved real-time operational system, which will reliably provide 8000 radio occultation soundings per day. The follow-on mission as planned will consist of 12 satellites with a data latency of 45 min, which will provide greatly enhanced opportunities for operational forecasts and scientific research. This paper will address the FORMOSAT-3/COSMIC system and mission 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.

1 Introduction

The FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) (FS-3/C) mission is a joint Taiwan-US 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

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data in near-real-time to over 1400 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 to Earth (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).

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, 2008; Kuo et al., 2000, 2004, 2008). The success of the FS-3/C mission has initiated a new era for near real-time operational global navigation satellite system (GNSS) RO soundings (Yunck et al., 2000).

However, the 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) mission. FS-7/C-2 will incorporate the next generation GNSS-RO receiver, an improved spacecraft design, and a greater ground network for data download as a follow-on constellation mission to FS-3/C (Chu et al., 2008; Fong et al., 2008c, 2009a,b).

FS-7/C-2 is intended to provide continuity of GPS-RO data as well as provide the next generation of GNSS-RO data users. The objective of the FS-7/C-2 mission 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 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 spacecraft and ground system.

2 FS-3/C system and mission overview

The FS-3/C space segment is comprised of six Low-Earth-Orbit (LEO) satellites in a constellation-like formation. The FS-3/C satellite constellation was successfully launched into the same orbit 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 to have six orbit planes at 800 km final mission altitude with 30° 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.

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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) and Kongsberg Satellite Services Ground Station (KSAT), which are currently set as the two primary stations for the mission; and the 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, 2009a,b).

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 collected GOX and TIP 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 min data latency requirement in order to be assimilated into the numerical weather prediction (NWP) models.

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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 constellation was intended to be a two-year experimental mission with a five-year spacecraft design life. 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. In addition, the authors believe 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. 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 solar array drive mechanism failure at 711 km orbit that led to the inhibited propellant thrust firing for the continuous orbit raising and tracking 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 mission payload GOX duty cycle on, and spacecraft ADCS (Attitude

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Determination and Control Subsystem) attitude performance vs. spacecraft sun beta angle. The GOX payload should be on during normal operation period except during the constellation deployment phase. In Fig. 1, it is observed that all spacecraft continue to operate with the GOX 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 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 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 its battery has shown significant degradation. FM5 has provided good spacecraft performance, however its GOX payload shows low SNR problems, causing good data to be hard to generate even when the GOX is on. FM6 has a similar GOX low SNR problem. FM6 experienced loss of communication 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. Due to a battery 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 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 are being operated at a duty cycle of 100% and two other

GOX (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 occultating precision orbit determination (POD) antenna seems to affect the data quality the most. Four spacecraft (FM1, FM3, FM5, and FM6) have exihibited 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 SNR decreased to where the GOX operating temperature was not over its red high limit that will shut down the GOX power by the autonomous control system. The RO profiles decreased to less than 100 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 recovered on its own and began to operate in 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 on values shown in Fig. 1, it is possible to compile the GOX payload duty cycle on statistics for one to four years, which are shown in Fig. 3. It is observed that the FM2 and FM3 power shortages are the main cause of the degraded average GOX duty cycles annually. After the completion of the orbit transfer, FM4 and FM5 are demonstrating the best performance. The drop in FM6 GOX 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 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 operation team has observed the GOX payload unexpectedly turn off while the spacecraft was 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 frequent recurring event on all 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 upexpected payload off is categorized as a diveation from the normal payload off that are (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 TT & C passes. 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 (compared to the nominal 14 V), but slightly higher than 10 V. Since the input voltage requirement for the tank pressure transducer is above 11 V, 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. In addition, when the value of bus voltage is below the Power Control Module (PCM) design value of 10 V, 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 significant 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 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)

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stations, or typically called Ground Station, 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). 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. 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 and Data Acquisition Station (FCDAS) as well as Wallops Command and 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 mission data is distributed from data servers at the ground stations across the open internet via Secure File Transfer Protocol (SFTP) to the SOCC and CDAAC. Figure 4 shows the flow of data between the RTS, SOCC and CDAAC. 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 15 min after spacecraft loss of signal (LOS) 97% of the time.

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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 s) 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 1 September 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 ho 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 1000 GPS-RO soundings per day. Approximately ninety percent of these are processed and delivered (via GTS) to operational centers within 3 h; the remaining ten percent have higher latency due to the satellites' inability to downlink every orbit (∼100 min). The COSMIC RTSs are down-linking and forwarding the payload data to the CDAAC in less than 15 min 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 min.

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The average latency of COSMIC data is currently approximately 75 min 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 × 6 satellites) of operation in orbit of the FS-3/C mission. There are many lessons learned from the four year operations, which can be used to improve similar future missions (Fong et al., 2008a,b,c, 2009a,b).

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 payload are performing well and reliabily at the instrument level based on the assessment of the available data as discussed in Sect. 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 SNR problem, (2) GOX OCC Low SNR problem, and (3) GOX SNR Decrease at High Temperature.

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5.3 Spacecraft system lessons learned

The spacecraft state of health is directly related 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 (<100 kg), 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 Data Dropouts, (2) Spacecraft Design Philosophy, (3) Spacecraft Downtime, (4) Computers Resets/Reboots, and (5) ADCS (Attitude Determination and Control Subsystem) Performance.

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 Fig. 5 (Fong et al., 2010; Yen et al., 2009, 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.

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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 8000 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 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

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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 min. FS-7/C-2 threshold latency of 45 min 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 min 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 compliment McMurdo. For the low-inclination orbit plane, a host of new equatorial 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. 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 crosslink via the National Aeronautic 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

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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 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, 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 Conclusions

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

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will continue to operate into the next few years. The success of the FS-3/C mission has initiated a new era for near real-time operational 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. NSPO and NOAA will proceed with the FS-7/C-2 joint mission implementation.

Acknowledgements. The authors would like to thank the spacecraft team for providing four-year statistical trend data in various subsystems. They would like to thank the contributions of the FS-3/C program, the FS-7/C-2 program, mission operation, flight operation, ground operation, constellation deployment, and anomaly resolution teams; the Taiwan science teams; and the cooperation partners with the NSC, NARL, CWB, NSF, UCAR, NCAR, JPL/NASA, NRL, USAF, OSC, and NOAA.

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

SC 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 at 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

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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.

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

	FM1	FM2	FM3	FM4	FM5	FM6	Total
Atmosphere	398 245	294 198	284 970	474 713	348 475	316 335	2 116 936
Ionosphere	368 049	354 054	343 353	561 426	309 966	329 116	2 265 964

Table 4. GOX Payload Performance Summaries.

SC 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.

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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

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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	– the 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 among 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 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 2500 occultation profiles per day on average based on the estimate from a "near-perfect" constellation situation (~3000 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 requirement shall be carefully implemented in the success criteria consider the downtime for each segment. – Improved S/C performance – Improved PL performance – Improve ground processing software

Note: PL = Payload

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Table 7. Payload Lessons Learned.

Items	Implementation	Observation/Major Finding	Lessons Learned
GOX POD Low SNR problem	– GOX instrument, POD cable link, and the POD antenna are assembled into the spacecraft without sufficient system level ground testing.	– 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 and 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 program
GOX OCC Low SNR problem	– 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 °C – Started from 2008-Day 082 whenever in higher beta angle (|Beta| > 40°) period – Higher minus beta angle has negative impact to the RO 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 able to cool down the GOX temperature below 35 °C when beta < −50° – The lesson learned is that the Payload thermal requirement and the related thermal analysis/ testing should be properly implemented

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Table 7. Continued.

Items	Implementation	Observation/Major Finding	Lessons Learned
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 decreases even the temperature not over its red high limit.	– Turn on GOX at definite time for one orbit at low beta angle, GOX On 4 hr Off 4 h 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

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Table 8. Spacecraft System Lessons Learned.

Items	Implementation	Observation/Major Finding	Lessons Learned
SSR/MIU GOX Data Dropouts	– GOX data dropouts avoidance design was not implemented in the design requirements and the data dropouts scenario was not detected at 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 recover from them – Temporary loss of the payload performance is much significant for 1 out of 6 spacecrafts in the FS-3/C constellation than 1 out of more than 30 spacecraft 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 in the spacecraft as well as in the constellation for the sufficient operational service availability in the follow-on mission

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Table 8. Continued.

Items	Implementation	Observation/Major Finding	Lessons Learned
Spacecraft Downtime	– Due to the single string design, the spacecraft may often encounter anomalies and cause the spacecraft downtime for various durations depending on the types of the anomalies. – SC 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 and that they have occupied around 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 SC downtime.
Computers Resets/ Reboots	– FS-3/C 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 or external back-up unit for anomaly region and the contingency	– 262 out of 304 events are computer resets/reboots as-of-4-1-2010 – Most of the time and geo-locations the spacecraft anomalies occurred are closely correlated to the space radiation environment. – Single event effects (SEEs) in the South Atlantic polar region are identified as the most probable root cause. – SC recovered automatically following system level Failure Detection and Correction (FDC) strategies. – Use High reliable Processor/FPGA – Use system FDC strategies.	– The SEE anomalies made SC lost valuable telemetry and payload data. A design with nonvolatile memory is recommended to secure critical S/C housekeeping and payload data for future missions. – A higher level red-tolerant or rad-hardening design should be considered in the future – The FDC design makes the C & DH (and SC) can recover from anomalies automatically. A similar function should be implemented in the future

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Table 8. Continued.

Items	Implementation	Observation/Major Finding	Lessons Learned
ADCS Performance	– The ADCS equipped only coarse attitude sensor and without rate sensor. – The sun sensor processing algorithm generated incorrect sun vector data from time-to-time.	– The attitude performance is not stable and impact 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 be considered in the future

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.

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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: $\pm 1^{\circ}$ (3 σ) Pitch: $\pm 1^{\circ}$ (3 σ) 3-Axis Gyro, 3-axis MAG, CSSAs, RWA × 3, Torque × 3, Star Tracker × 1	3-axis nonlinear control Roll/Yaw: $\pm 5^{\circ}$ (1 σ) Pitch: $\pm 2^{\circ}$ (1 σ) Earth Sensor × 2, CSSA × 8, RWA × 1, Torque × 3, GPS Bus Receiver PL × 1	Improved PL Performance Better Attitude Performance Simplified Operation Simplified Orbit Transfer
Science Data Storage	250 MB	128 MB (32 M for GOX)	Simplified Operations
Avionics Architecture	Centralized Architecture Radiation – Hardness	Distributed Architecture (Multiple Avionics Boxes)	Simplified Integration Harnessing & 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	Cost Reduced
Payload Interface	Main PL: TriG Rcvr Science PL VIDI & Radio Beacon	Primary PL: GOX Secondary PL: TIP, TBB	Modular Design Cost Reduced

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

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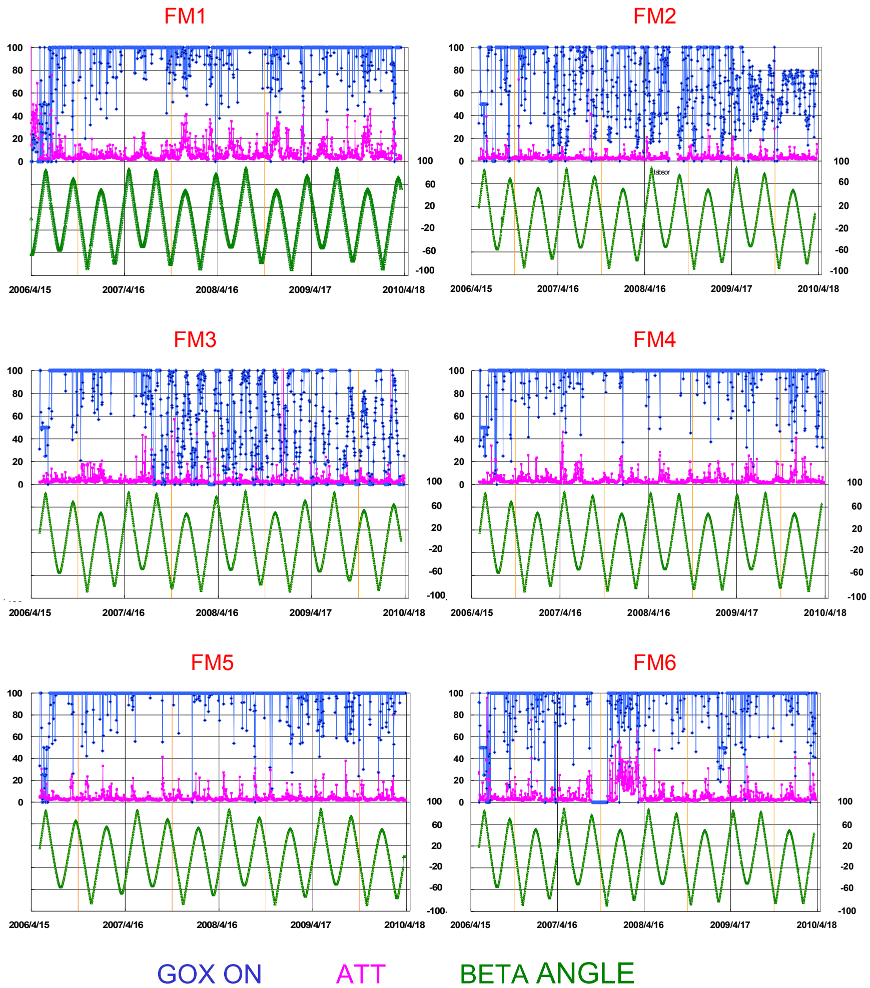

Fig. 1. Spacecraft System Performance after Four Years in Orbit.

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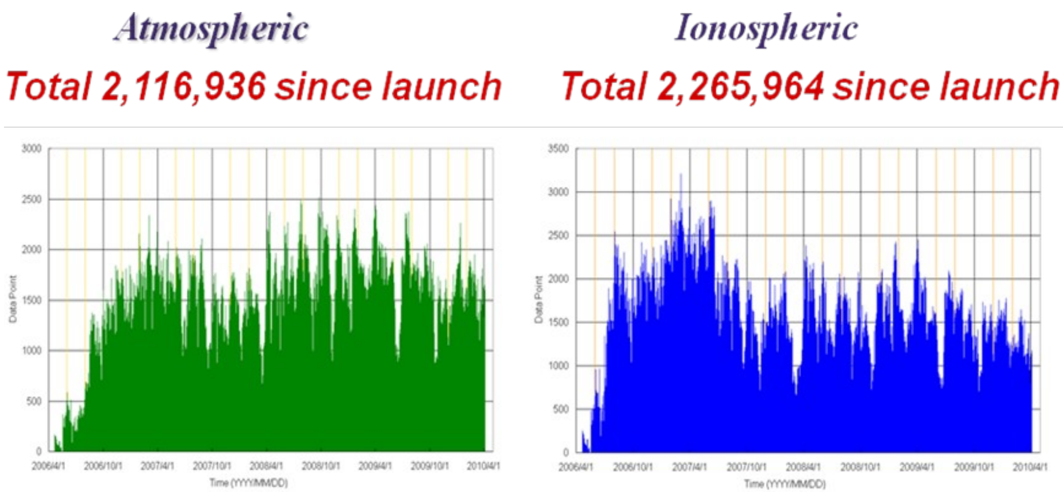

(a) (b)

Fig. 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.

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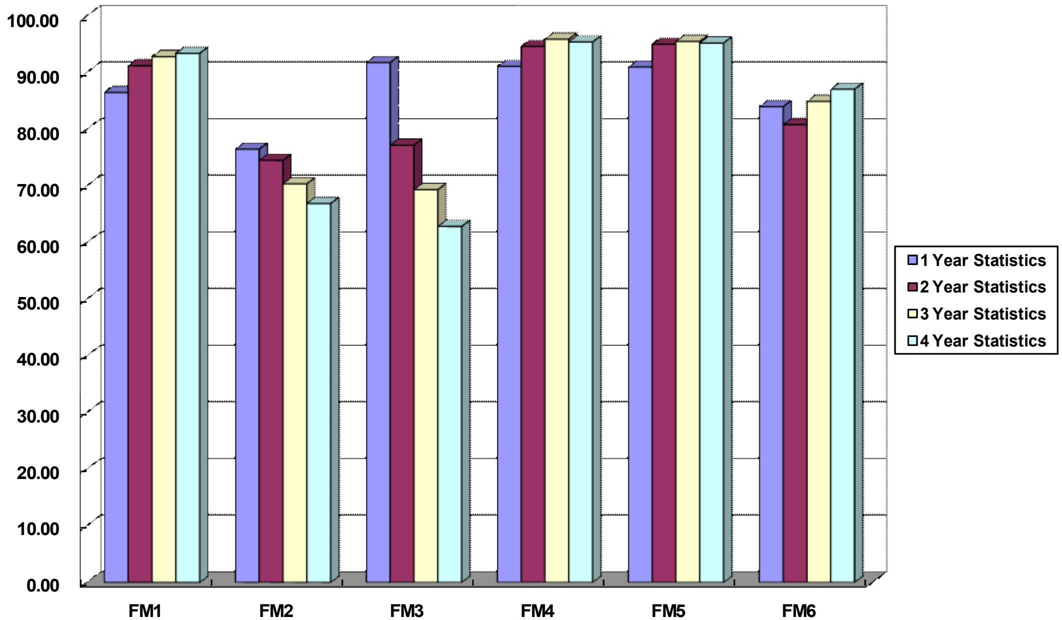

Fig. 3. GOX payload duty cycle on statistics for one to four years.

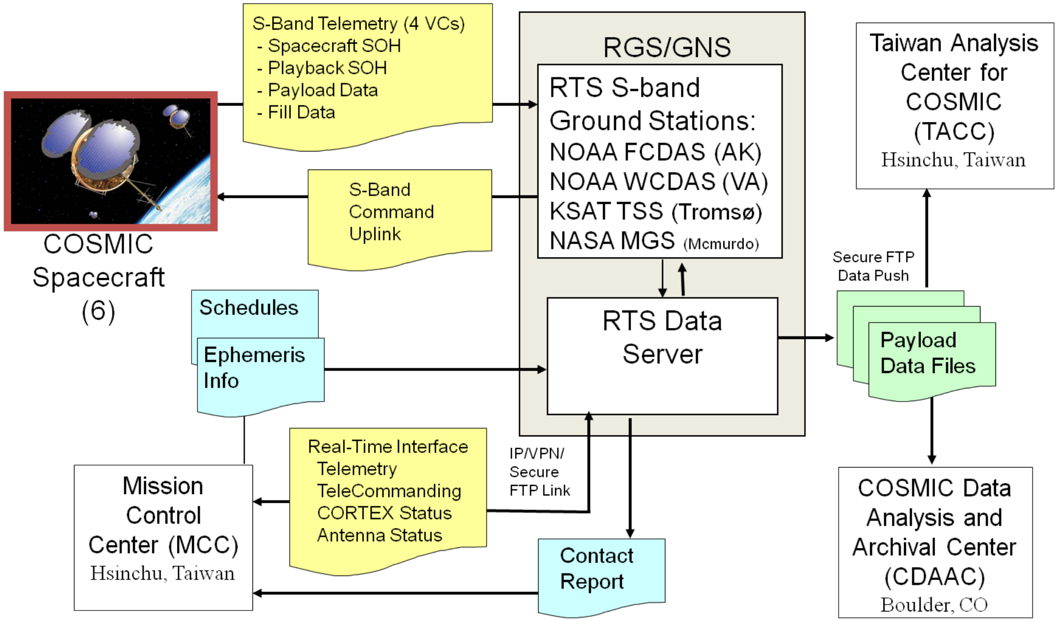

Fig. 4. FS-3/C Ground System Data Flow.

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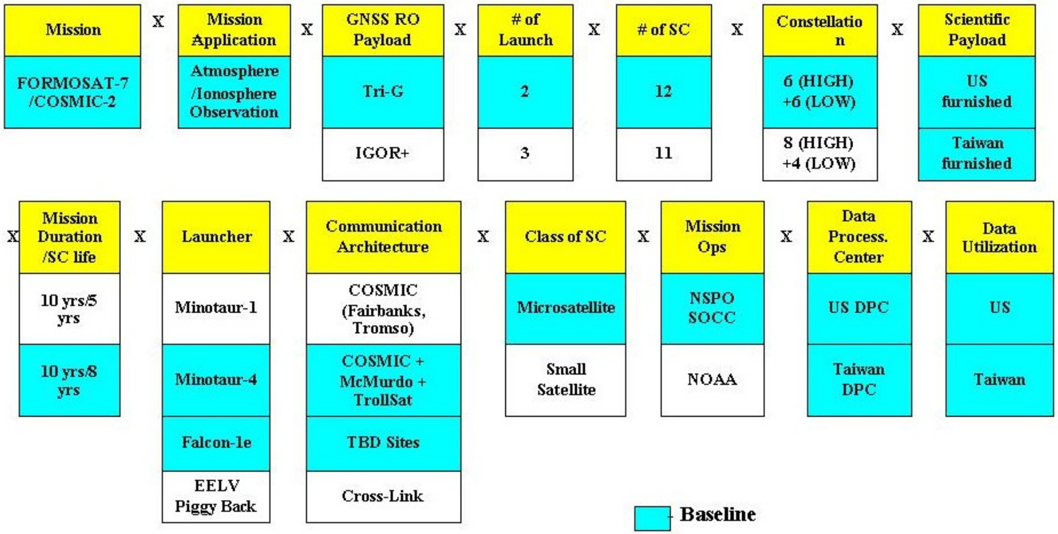

Fig. 5. FS-7/C-2 Mission Trades.

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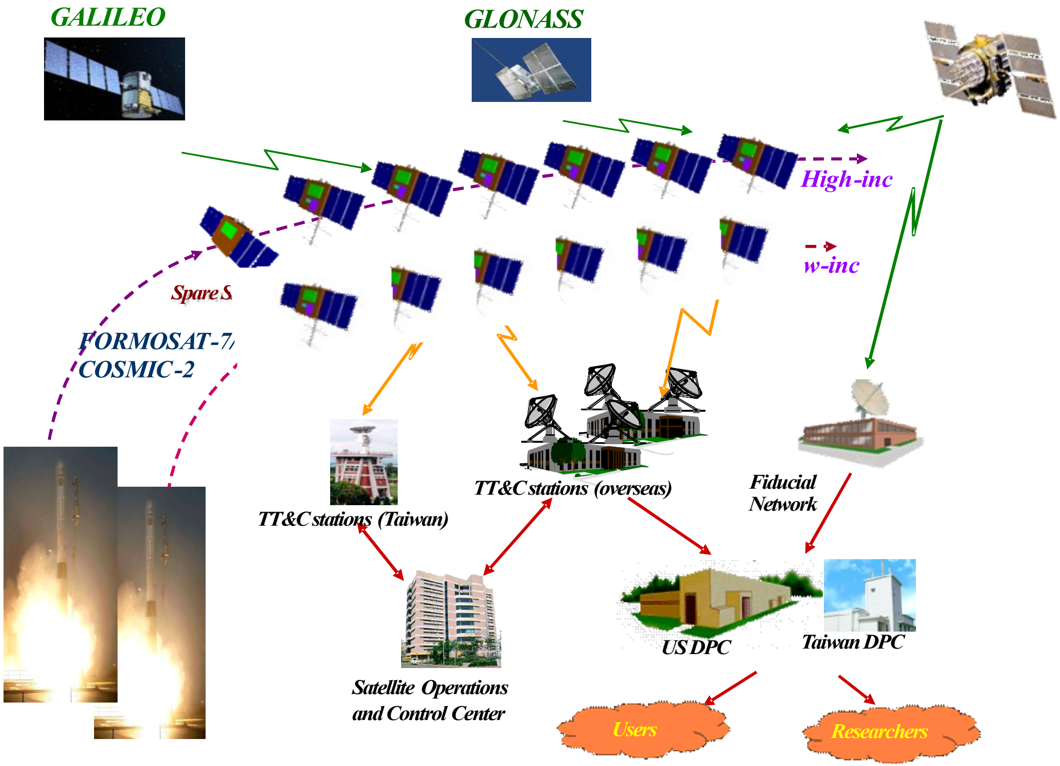

Fig. 6. Proposed FS-7/C-2 Mission Architecture.

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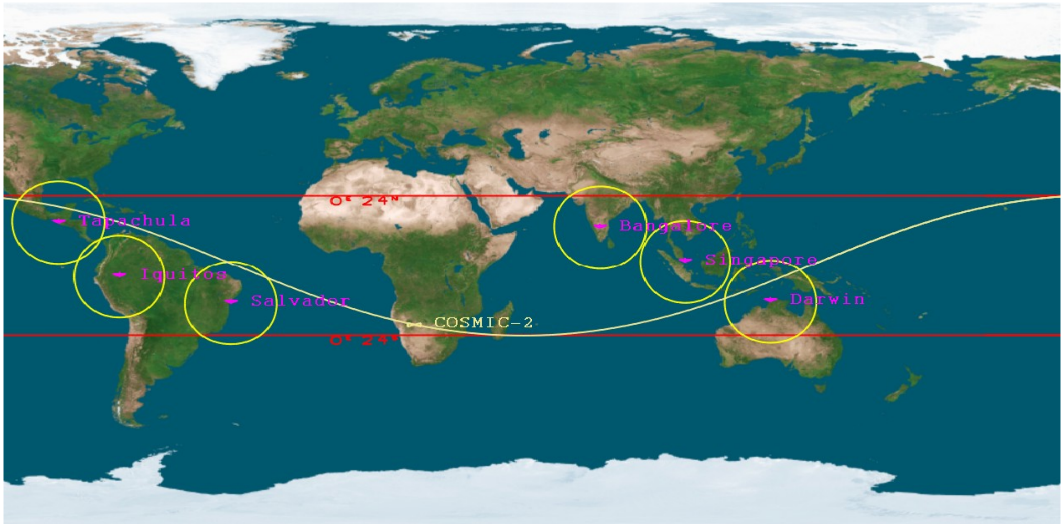

Fig. 7. Potential FS-7/C-2 Equatorial Ground Station Locations.

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