Constellation Deployment for the FORMOSAT-3/COSMIC Mission

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***Abstract*—The FORMOSA Satellite Series No. 3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC) spacecraft constellation consisting of six low-earth-orbiting satellites is the world's first operational Global Positioning System (GPS) radio occultation mission. The mission has been jointly developed by the National Space Organization of Taiwan and the University Corporation for Atmospheric Research of the U.S. in collaboration with the Jet Propulsion Laboratory, NASA, and the Naval Research Laboratory for three onboard payloads, including a GPS Occultation Receiver, a triband beacon, and a tiny ionospheric photometer. The FORMOSAT-3/COSMIC mission was successfully launched from Vandenberg into the same orbit plane of the designated 516-km circular parking orbit altitude on April 15, 2006. After the six satellites completed the in-orbit checkout activities, the mission was started immediately at the parking orbit for in-orbit checkout, calibration, and experiment of three onboard payloads. Individual spacecraft thrust burns for orbit raising were performed to begin the constellation deployment of the satellites into six separate orbit planes. All six FORMOSAT-3/COSMIC satellites are maintained in a good state of health except spacecraft flight model no. 2, which has had power shortages. Five out of the six satellites had reached their final mission orbits of 800 km as of November 2007. This paper provides an overview of the constellation spacecraft design, constellation mission operations, constellation deployment timeline evolution, associated spacecraft mass property and moment of inertia results, orbit-raising challenges, and lessons learned during the orbit-raising operations.**

***Index Terms*—Constellation deployment, Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), FORMOSA Satellite Series No. 3 (FORMOSAT-3), geodesy, Global Positioning System (GPS) radio occultation (RO), satellite.**

I. INTRODUCTION

THE MAIN idea of radio occultation (RO) scheme emerged in the early days of interplanetary flight [1]–[5]. It is well known that the limb sounding of the atmosphere and ionosphere using the RO technique can be performed with any two cooperating satellites. A few early RO experiments from a satellite-to-satellite tracking link had been conducted before the Global Positioning System (GPS) becomes operational. These included the radio link between GEOS-3 and ATS-6 [6] and between the Mir station and a geostationary satellite [7]. The GPS RO technique, which makes use of the radio signals transmitted by the GPS satellites, has emerged as a powerful approach for sounding the global atmosphere in all weather over both lands and oceans [8]–[11]. The GPS/meteorology (GPS/MET) experiment (in 1995–1997) showed that the GPS RO technique offers great advantages over the traditional passive microwave measurement of the atmosphere by satellites and became the first "proof-of-concept" RO mission to Earth [12]–[18]. The extraordinary success of GPS/MET mission had inspired a series of other RO missions, e.g., the Ørsted (in 1999), the SUNSAT (in 1999), the Satellite de Aplicaciones Cientificas-C (in 2001), the Challenging Minisatellite Payload (in 2001), and the twin Gravity Recovery and Climate Experiment missions (in 2002). The GPS RO sounding data have been shown to be of high accuracy and vertical resolution. All these missions set the stage for the birth of the FORMOSA Satellite Series No. 3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC) mission [15]–[18].

The FORMOSAT-3/COSMIC mission is the world's first operational constellation system of six low-earth-orbiting (LEO) microsatellites assigned mainly for the GPS RO remote sensing of the atmosphere and ionosphere at various altitudes with global coverage. The primary scientific goal is to demonstrate the value of near-real-time GPS RO observation in operational numerical weather prediction. The mission provides about 2500 soundings per day in near-real-time vertical profiles of temperature, pressure, refractivity, and water vapor in neutral atmosphere, and electron density in the ionosphere [19]–[26]. In the near future, other Global Navigation Satellite Systems (GNSSs), such as the Russian GNSS and the planned European Galileo system, will be used to extend the region of applications by use of the GPS RO technique [27], [28].

The FORMOSAT-3/COSMIC mission was successfully launched from Vandenberg Air Force Base (VAFB) in California at 1:40 coordinated universal time (UTC) on April 15, 2006. The FORMOSAT-3/COSMIC mission is jointly

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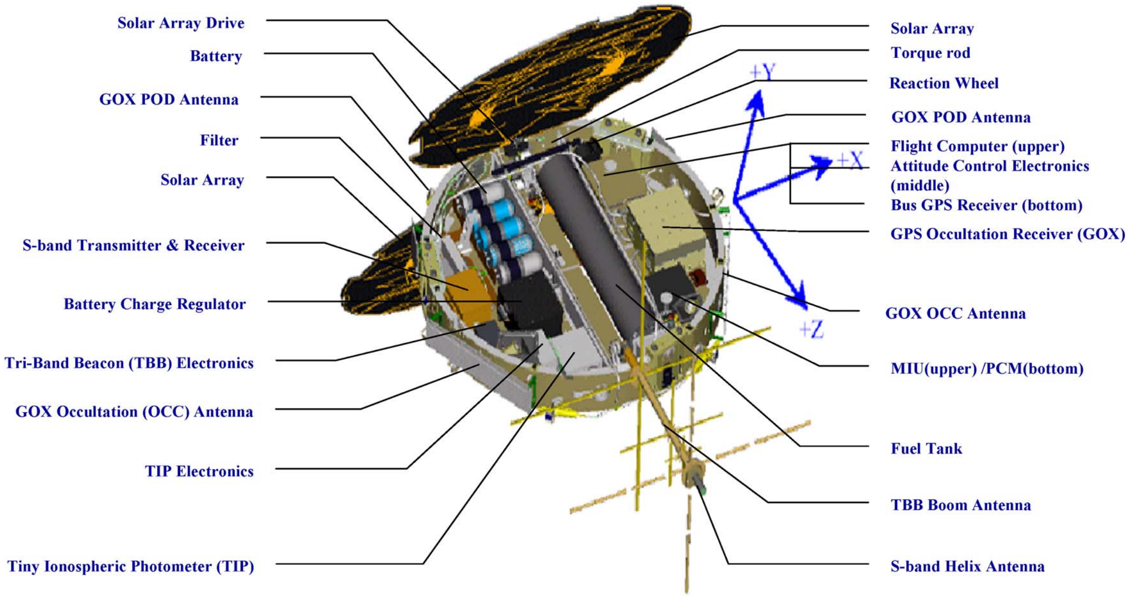


Fig. 1. FORMOSAT-3/COSMIC spacecraft main components.

developed by the National Space Organization (NSPO) and the University Corporation for Atmospheric Research (UCAR) in collaboration with the Orbital Sciences Corporation (OSC) for the satellite bus, the Jet Propulsion Laboratory (JPL), and the Naval Research Laboratory (NRL) for three onboard payloads, including GPS Occultation Receiver (GOX), triband beacon (TBB), and tiny ionospheric photometer (TIP). The TIP payload instrument is routinely collecting data at night and observes the equatorial anomaly arcs and other density anomalies through the measurements of 1356 Å radiation. The nadir-pointing TBB enables observations of the line-of-sight total electron contents and scintillations along the radio links of the FORMOSAT-3/COSMIC–TBB ground stations. The data from these two instruments complement the ionospheric observations from the GOX and are used to improve the retrieval of electron density profiles at night and over TBB ground stations. These data are also valuable for the evaluation of ionospheric models and the use in space weather data assimilation systems [29]. The FORMOSAT-3/COSMIC mission preliminary results could be referenced to Cheng *et al.* [30], Liou *et al.* [31], Fong *et al.* [32]–[34], and Yen *et al.* [35]. In this paper, we present a new fundamental concept of the FORMOSAT-3/COSMIC spacecraft constellation and flight dynamic design, constellation deployment plan, constellation mission operations, constellation deployment results, orbit-raising challenges, and lessons learned.

II. SPACECRAFT CONSTELLATION AND FLIGHT DYNAMICS DESIGN OVERVIEW

The FORMOSAT-3/COSMIC mission takes advantage of nodal precession to conduct orbit-raising maneuvers at the appropriate times so that the effect of different altitudes makes the orbital planes drift. An overview of the spacecraft system, propulsion subsystem size, and the attitude control subsystem (ACS) design related to constellation deployment and ground flight dynamics design is described as follows [39], [41].

TABLE I
FORMOSAT-3 /COSMIC CONSTELLATION SPACECRAFT BUS KEY DESIGN

Mass	~ 54 kg (Dry Weight)
Power:	~ 81 Watts (bus and payload)
Shape	Disc-shape of 116cm diameter, 18cm in height
Science Data Storage	128 MB
Distributed Architecture	Motorola 68302 Microprocessor
Attitude Control	Magnetic 3-axis Control Pointing Control = 5° Roll & Yaw, 2 ° Pitch
Propulsion	Hydrazine Propulsion Subsystem
S-Band Communications	HDLC Command Uplink (32 kbps) CCSDS Telemetry Downlink (2 Mbps)
Single String Bus	Constellation Redundancy

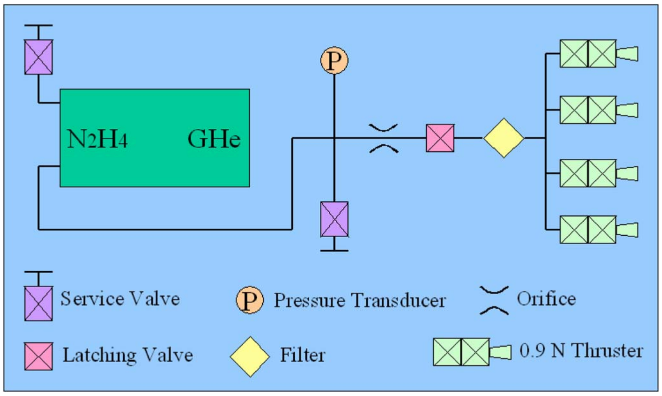
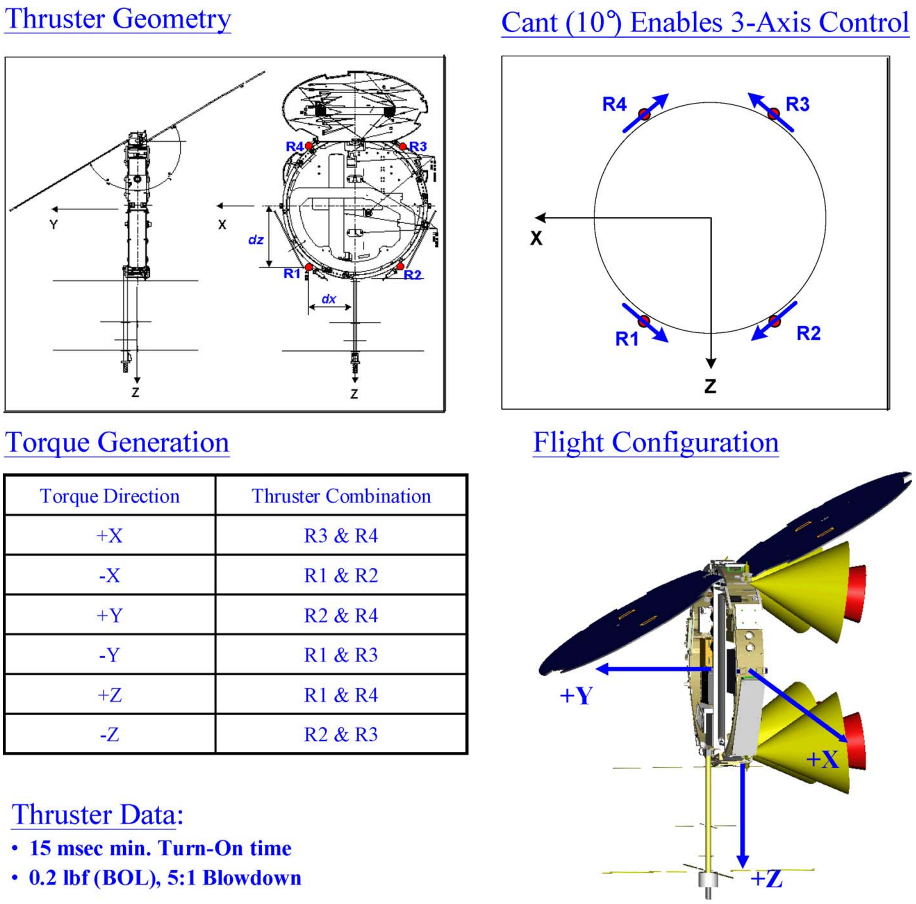


Fig. 2. Spacecraft RCS block diagram.

A. Spacecraft System

Fig. 1 shows the FORMOSAT-3/COSMIC spacecraft inflight configuration and its major components. The major subsystem elements of the spacecraft system are payload, structure and mechanism, thermal control, electrical power, command and data handling, and radio frequency communication subsystems; reaction control subsystem (RCS); ACS; and flight software subsystem. The spacecraft bus provides structure, RF power, electrical power, thermal control, attitude control, orbit raising, and data support to the instrument [34], [35], [39]–[41].



Torque Direction	Thruster Combination
+X	R3 & R4
-X	R1 & R2
+Y	R2 & R4
-Y	R1 & R3
+Z	R1 & R4
-Z	R2 & R3

- **15 msec min. Turn-On time**
- **0.2 lbf (BOL), 5:1 Blowdown**

Fig. 3. RCS thruster geometry and torque.

Table I shows the FORMOSAT-3/COSMIC constellation spacecraft bus key design features.

B. Spacecraft Propulsion for Thrust Burn

The spacecraft propulsion subsystem (also named as the RCS) is a blowdown monopropellant hydrazine (N_2H_4) propulsion subsystem with gaseous helium (GHe) as the pressurant. The designed blowdown ratio is 5 : 1 with a maximum expected operating pressure of 400 psia at 50 °C. The initial tank pressure is pressurized to about 330 psia at 20 °C. The RCS is utilized to provide impulses for attitude control during orbit raising and to transfer the satellite from the injection orbit to an intermediate orbit if required and, finally, to the mission orbit of the constellation. Fig. 2 shows the block diagram of the RCS. The FORMOSAT-3/COSMIC RCS consists of a propellant tank, gaseous helium and hydrazine service valves, a latching valve, a filter, an orifice, four thrusters, pressure transducer, and a set of pipelines. The spacecraft RCS characteristics are summarized as follows [37], [41]:

1) thrust force: 1.1 [beginning of life (BOL)]–0.2 N [end of life (EOL)];
2) specific impulse: 217–194 s;
3) propellant mass: ~6.65 kg;
4) thrust type: OFF pulsing (duty cycle $\leqq$ 50%).

Fig. 3 shows the locations of the four thrusters (R1, R2, R3, and R4), which are located in the four quadrants of the x–z plane of the satellites. These four thrusters are canted by 10° to enable three-axis control capability. By modulating the off-pulsing duration of the four thrusters, control torque is generated for the attitude control around X, Y, and Z axes of the satellite. The estimated thrust and specific impulse over the entire blowdown pressure range are shown in Fig. 4.

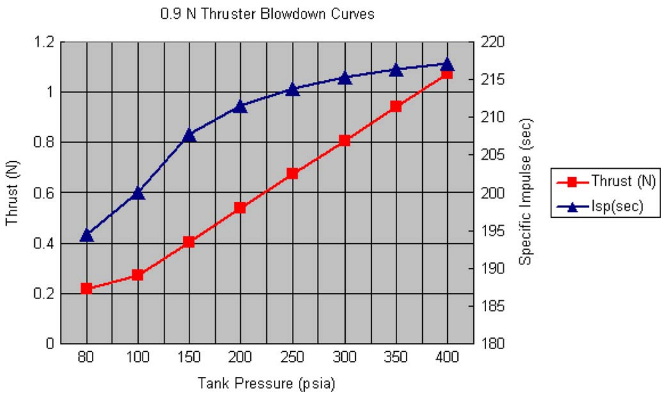


Fig. 4. RCS blowdown curve.

C. Spacecraft Attitude Control for Constellation Deployment

The function of the spacecraft ACS is to control the attitude of the satellite in the safe, stabilization, nadir, nadir-yaw, and thrust modes. The sensors for attitude estimation include earth horizon sensors, coarse sun sensors, and a magnetometer. The

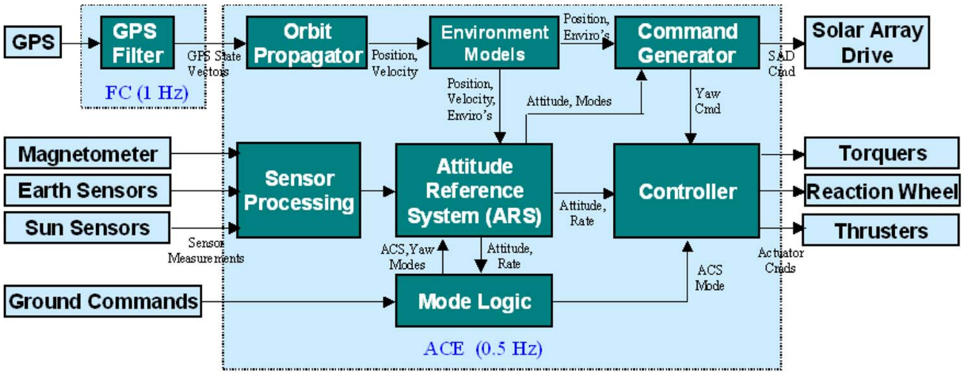


Fig. 5. Functional block diagram of the spacecraft ACS.

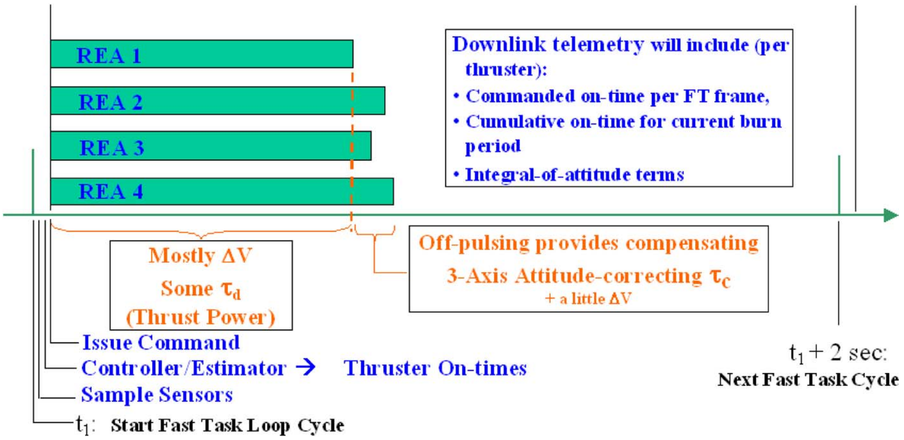


Fig. 6. Off-pulsing concept of ACS thrust mode.

actuators for attitude control include magnetic torquers, a reaction wheel, and thrusters [37], [41].

Fig. 5 shows the functional block diagram of the spacecraft ACS, where FC stands for flight computer and ACE means the attitude control electronics. In Fig. 5, the Attitude Reference System (ARS) includes attitude and rate estimators using a Kalman filter algorithm with measurements from the sensors. The ACS controller processes the attitude and rate estimation from ARS through the control gains/algorithm and distributes the torque commands to the actuators. The ACS also receives the satellite position and velocity data from the bus GPS receiver. Based on this information, it then propagates and computes necessary information for the navigation purpose, the ARS, and the commanded angles for the solar array drive (SAD).

The thrust mode is dedicated to the orbit-raising operation. When the orbit-raising operation is performed, the satellite first maneuvers itself to a yaw angle of 90° to align the thrust direction with the velocity direction. Then, as soon as the ACS enters the thrust mode, the thruster ignition starts up, and the attitude is controlled by the thrusters while orbit raising proceeds. When the operation is terminated or finished, the ACS enters the nadir-yaw mode and maneuvers itself to a preset yaw angle.

A proportional-integral-derivative (PID) controller is designed for the thrust mode to compute the desired three-axis control torque. Four thrusters are commanded, off-pulsing in each control cycle to provide both the impulse for orbit raising and the three-axis control torque to diminish the attitude errors. Fig. 6 shows the concept of the "off pulsing" in each control cycle. In orbit-raising operations, the thrust turn-on time in each control cycle is either kept constant as the "InitialThurstPower" value or increased by "AddThrustIncrement" seconds in every "AddThrustInterval" control cycles. The thrust mode control gains are adjusted in order to compensate for the changes in thrust level during the RCS blowdown process.

The PID controller will minimize the attitude control error and improve the orbit-raising performance, but it suffers from the relative instability issue. This is because the control system may diverge with a large thruster turn-on time when the PID integral terms are not yet converged to their steady-state values. Therefore, during orbit-raising operations, the PID controller requires a series of "calibration burns" in order to converge the attitude integral terms and to ramp up the thruster turn-on time to a larger value. Calibration burn is usually a smaller burn than the full-thrust burn. During the calibration process, the final values of the thrust turn-on time and the integral terms of a previous burn are used as the initial values for the next burn. In this way, it takes about six to eight calibration burns to reach the so-called full-thrust burn.

D. FDF and Orbit Dynamics

The main function of ground-based Flight Dynamics Facility (FDF) is to conduct various orbit dynamics analyses, including orbit determination, orbit-ephemeris propagation, orbit-maneuver planning, orbit-parameter trending, and orbit-event prediction. In the FORMOSAT-3/COSMIC mission, we use the commercial off-the-shelf software package called "Orbit Analysis System (OASYS)" in FDF for orbit analysis. The OASYS database includes the thrusting model of the onboard RCS and ACS, such as the thruster number, location, and direction; propellant mass and pressure; pressurant mass; blowdown curves for thrust and specific impulse; and thrust type, thruster duty cycle, and efficiency [36], [40].

The blowdown curves for thrust force (F) and specific impulse (I_{sp}), as shown in Fig. 4, are modeled as follows:

$$F = (0.001141 + 0.0006^{*} P)^{*} 4.448221 (\text{in newtons}) \tag{1}$$

$$I_{\mathrm{sp}} = 222.84 - 2268.4/P (\text{in seconds}) \tag{2}$$

where

F the thrust force;

I_{sp} the specific impulse;

P the propellant mass.

and used in the OASYS database for FORMOSAT-3/COSMIC orbit raising. Both equations are functions of the propellant tank pressure in the unit of psia.

The thrust power in each ACS control cycle is modeled as the duty cycle of the thruster and listed as *Duty Cycle* = *Thrust Power/Control Cycle*. In full-thrust orbit-raising burns, the thrust power in each control cycle is kept constant, as the duty cycle is in the OASYS model. However, in calibration burns, the thrust power in each control cycle is linearly ramped up to the end of the burn. In other words, the duty cycle in each control cycle also increases in the same way as the thrust power does. Unfortunately, there is no way in OASYS to correctly model the calibration burns with increasing thrust powers. Instead, an averaged thrust power (duty cycle) using the initial and final thrust powers of the burn is used in the OASYS database to model the thrusting of a calibration burn.

The OASYS is also used to conduct an orbit determination to compare the actual postburn orbit and the OASYS-planned postburn orbit after a thrust burn is completed. Based on the actual and OASYS-planned orbit altitudes, a thrusting efficiency is recalculated, which, in turn, provides another input for the next orbit-raising planning.

III. CONSTELLATION DEPLOYMENT PLAN

The FORMOSAT-3/COSMIC constellation deployment concept was to launch the entire cluster of satellites by a single launch vehicle. All six satellites were delivered to the same injection orbit plane of the designated 516-km circular parking orbit altitude, and they were in a cluster formation fly configuration after separation from the launch vehicle. Next, the six satellites were deployed into six different orbit planes at specific time intervals using the nodal precession method. In this method, the differences in the spacecraft orbit heights allow them to precess at different rates, thus separating the orbit planes [36], [37].

The nodal precession is a well-known gravity phenomenon, where the orbital plane drifts due to the oblateness of the Earth [36], [37]. The approach using the natural physics of the oblateness of the Earth, as well as time, allows the spacecraft to drift instead of requiring complex propulsion systems or even depending on individual launch vehicle to arrive at their orbit planes directly. Although this approach requires a lengthy orbit-deployment time, it significantly reduces the size of the propulsion subsystem design. The evolution of the constellation plan and the constellation deployment principle are described as follows.

A. Original Constellation Deployment Plan

The FORMOSAT-3/COSMIC mission operation plan changes as time passes, following launch. Originally, the FORMOSAT-3 constellation deployment plan included a tandem flight design during the deployment phase. The tandem flight satellites would maintain an along-track distance of 200–400 km. Two pairs [flight model no.1 (FM1) and FM2; FM3 and FM4] of satellites would fly in tandem in an intermediate orbit altitude (525 and 576 km) for the geodesy research [27]. However, spacecraft FM3 and FM4 have been very close together since the launch of the satellites. The data from April to October were able to provide adequate data for geodesy research at the parking orbit of 516 km. The constellation plan was thus changed to meet the need for more science dumps for intensive operation period campaign and tropical cyclone (typhoon, hurricane, etc.) prediction forecast studies [31]–[35].

The constellation plan at an 800-km orbit with 24° separation planes was for a shorter deployment time consideration (13 months after launch) and based on the assumption that spacecraft attitude control performance in lower altitude is worse than that in the mission orbit. However, this plan is not favorable for the ionospheric monitoring and climate seasonal variability studies due to nonuniform coverage globally. Shorter duration to complete the constellation deployment has become less of a concern since the spacecraft attitude performance is better than expected, and the data of the early phase (mostly at lower orbit) are much better than anticipated [36], [40].

B. New Constellation Deployment Plan

Scientists from Taiwan and the U.S. coherently favor 30° separation with approximately six months longer constellation deployment duration over 24° separation for global uniform coverage in local solar time. The original constellation mission operation plan was revised, manpower was reallocated, and the orbit-raising schedule was rearranged to accommodate the science team's request. This change in new constellation plan reflects integral teamwork among the operation team and data users and leads to greater mission success. The constellation deployment plan change from 24° to 30° separation was made in September 2006 after the completion of FM5 orbit transfer and during FM2 orbit raising. The decision was made to put the FM2 orbit transfer on hold in October 2006 and to allow its separation from FM5 further. The decision postponed the completion of the final constellation to December 2007 [40], [41].

C. Constellation Deployment Principle

The technical principles relevant to perform the constellation deployment related to Earth oblateness and right ascension ascending node (RAAN) phasing, argument of latitude (AOL) final phasing and contact conflict avoidance, and dispersion operation are described as follows [36], [37], [40], [41].

1) Earth Oblateness and RAAN Phasing: The total mass of a FORMOSAT-3 satellite is 61.05 kg, including the dry mass of 54.4 kg and the propellant mass of 6.65 kg. The overall altitude increase from injection orbit to mission orbit is 285 km. The estimated total delta-V required is 147 m/s, and the estimated propellant required is 4.6 kg. Fuel margin is 2.05 kg [36], [37], [40], [41].

Due to the oblateness of the Earth gravity, the RAAN of a LEO satellite will drift away at a rate, which is a function of the semimajor axis (SMA), inclination, and eccentricity of the orbit. The drift rate of RAAN ($\Delta\Omega/\Delta t$), also called "orbit precession rate," is modeled as follows for the FORMOSAT-3 near-circular orbit with an inclination of 72° and an eccentricity of zero [44]

$$\Delta\Omega \cong -6.3804 \times 10^{13} \Delta(a^{-7/2}) \cdot \Delta t \tag{3}$$

where

$\Delta\Omega$ the drift of the RAAN after a deployment time of Δt;
a the SMA of the orbit altitude in kilometers;
Δt the deployment time period in days.

The deployment strategy is to use the first raised spacecraft (FM5) as a reference point. The second spacecraft is then raised to its mission orbit when the difference of the RAAN between the first and the second spacecraft reaches the desired separation angle. The third spacecraft was then raised when the difference of the RAAN between the first and third spacecraft reaches the value of twice of the planned separation angle and so forth.

2) AOL Final Phasing and Contact Conflict Avoidance: As one ground station can support one pass from an elevation angle of 10° to 10°, if there are two satellites flying over the same ground station at the same time frame, the ground station could support only one satellite unless there were special arrangements. Therefore, a 52.5° phasing on AOL must be implemented to ensure that one orbit's worth of occultation science data are sent to the receiving stations. Among the six mission orbits of the FORMOSAT-3 constellation, the maximal difference in SMA (Δa in meters) and the maximal deviation (ΔL in degrees) of the AOL from its nominal value are deployed to fulfill the following equation so that multiple contacts at the same ground station at the same time are avoided [40], [41]:

$$\Delta a + 5^{*}\Delta L < 50. \tag{4}$$

The differentiation of the AOLs of the other five satellites against the reference orbit is achieved by controlling the altitude deployment profile in the final stage of the "maneuvering window." When the orbit altitude is different from the reference orbit (FM5), the AOL change rate is also different from the reference orbit. The different AOL change rate differentiates the AOL of the satellite against the reference orbit along with time. By manipulating the altitude deployment profile in the final stage, the AOL difference is targeted at the same time to maneuver the satellite into the mission orbit altitude. Then, both the RAAN and AOL differences are frozen and kept constant simultaneously.

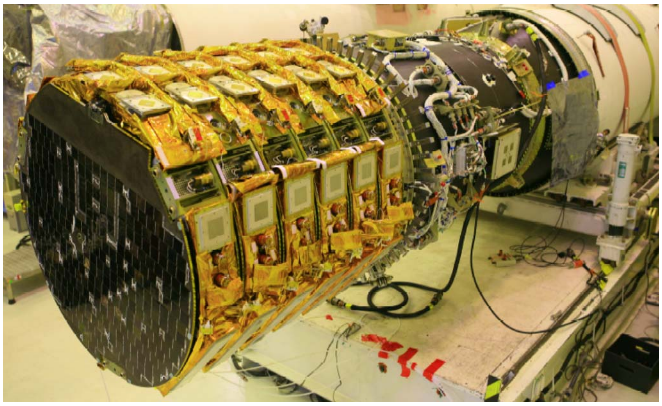


Fig. 7. Six FORMOSAT-3/COSMIC satellites in stowed configuration and stacked on the Minotaur launch vehicle.

3) Spacecraft Dispersion Operation to Increase Science Data Downloads: The dispersion operation is very similar to the AOL phasing. In order to increase the number of GOX data downlink, a spacecraft dispersion operation plan was executed to differentiate the AOLs of FM4, FM3, FM1, and FM6 in parking orbits. These four satellites were maneuvered to the same altitude around 519 km with an AOL difference of around 80° so that they can contact a ground station in turn to increase GOX science data downlink with no contact conflicts [36]–[38].

IV. CONSTELLATION MISSION OPERATIONS

The FORMOSAT-3/COSMIC constellation mission operations are divided into four phases: Phase I is the Launch and Early Orbit (L&EO) phase; phase II is the constellation deployment phase; phase III is the final constellation phase; and phase IV is the extended mission phase. Phase I includes launch, separation, ground initial acquisition, spacecraft bus checkout, and payload checkout. During phase II, the spacecraft are raised to the final mission orbit heights by means of nodal precession. The science mission is conducted already during phase II when there is no thrust burn. All spacecraft should reach their final orbits with the designed RAAN and AOL at phase III, and all science experiments are conducted continuously when there is no burn activity. The duration of phase IV is three years, commencing with the completion of phase III [35]–[40].

A. Launch and Injection Orbits

Fig. 7 shows a photograph of six satellites in stowed configuration and stacked on the Minotaur launch vehicle at the VAFB launch site. After successful launch, the FORMOSAT-3/COSMIC constellation has the following orbit characteristics [36], [37]:

1) SMA: 6893 km;
2) eccentricity (E): 0.00323;
3) inclination (I): 71.992°;
4) RAAN Ω: 301.158°.

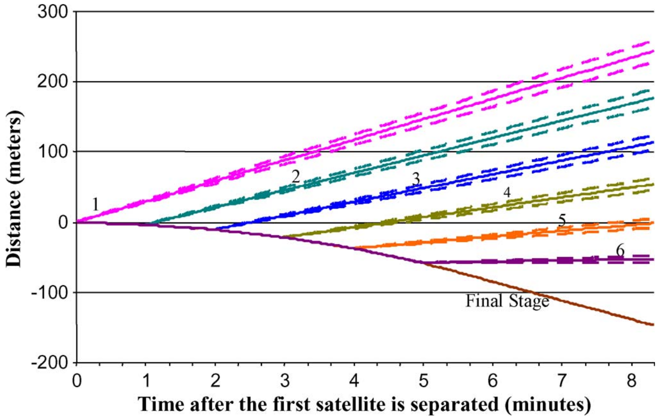


Fig. 8. Resulting spacecraft separation simulation result.

The six identical satellites are deployed into six mission orbits with the following orbit characteristics for $i = 1 \sim 6$:

1) SMA (SMA_i) : 7178 km;
2) eccentricity (E_i) :< 0.014;
3) inclination (I_i): 71.992°;
4) RAAN (Ω_i) : Ω_5, $(\Omega_5 - 30°)$, $(\Omega_5 - 60°)$, $(\Omega_5 - 90°)$, $(\Omega_5 - 120°)$, and $(\Omega_5 - 150°)$ $\pm 5°$;
5) (AOL, L_i): L_5, $(L_5 - 52.5°)$, $(L_5 - 105°)$, $(L_5 - 157.5°)$, $(L_5 - 210°)$, and $(L_5 - 262.5°) \pm 8°$.

B. Collision Avoidance

The separations of FORMOSAT-3 spacecraft from the final stage of the launch vehicle relied on the separation mechanism built into the structure of each spacecraft. All the six satellites were injected, heading along the velocity direction. The separation of each spacecraft from the spacecraft stack and the final stage of the launch vehicle obey the conservation laws of momentum and energy. As a result of calculation, the velocity after separation should be $V_{\mathrm{FM1}} > V_{\mathrm{FM2}} > V_{\mathrm{FM3}} > V_{\mathrm{FM4}} > V_{\mathrm{FM5}} > V_{\mathrm{FM6}}$ [27], [28].

We conclude that the spacecraft will not collide with each other because the velocity of spacecraft N is always faster than the velocity of spacecraft $N + 1$. When taking into account the variance and the accuracy of measurement, there may be approximately 12.5% variance in the energy of the spring in the case of FORMOSAT-3. To avoid collisions, the compression of the sets of springs for each spacecraft is different: $x_{\mathrm{FM1}} > x_{\mathrm{FM2}} > x_{\mathrm{FM3}} > x_{\mathrm{FM4}} > x_{\mathrm{FM5}} > x_{\mathrm{FM6}}$. The resulting separation simulation results are shown in Fig. 8. The separation intervals are set at 60 s. The higher dashed line represents $+12.5\%$ of specified spring energy, and the lower dashed line represents -12.5%. Distance $= 0$ represents an imaginary object which is the nonseparated final stage and spacecraft suite. The different slopes correspond to different velocities. If the lines do not intersect, no collision is expected to happen.

C. Separation Sequence

Ten days before launch, NSPO was informed that there is unexpected residual thrust in the final stage of the launch vehicle as the first separation is triggered. Additional simulation analyses were performed; the results indicated that the relative positions with respect to the six satellites and final stage are adequate to avoid collision. However, the effect of residual thrust did result in changes to the spacecraft sequence. The expected spacecraft sequence should be FM6$- >$ FM5$- >$ FM4$- >$ FM3$- >$ FM2$- >$ FM1 based on the designed installation of a separation spring without the fourth stage residual thrust. The satellite cluster sequence with the anticipated fourth stage residual thrust after launch became FM6$- >$ FM1$- >$ FM5$- >$ FM4$- >$ FM3$- >$ FM2. FM1 has lagged behind as expected in the cluster sequence since it has the least effect due to the fourth stage residual thrust. This sequence change has no practical impact on flight or mission operations [27], [28].

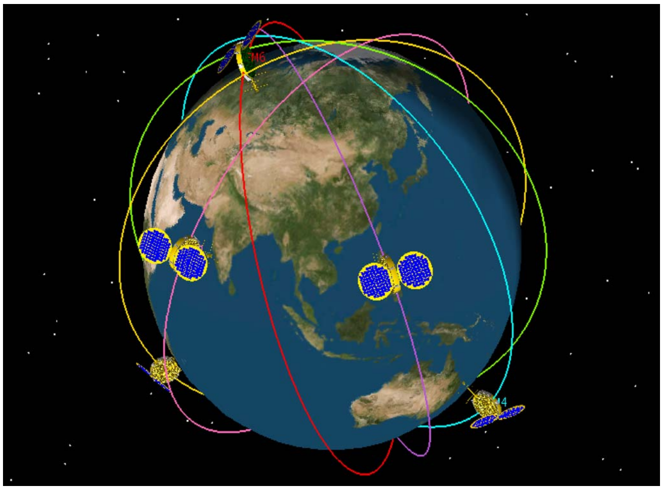


Fig. 9. FORMOSAT-3/COSMIC final constellation.

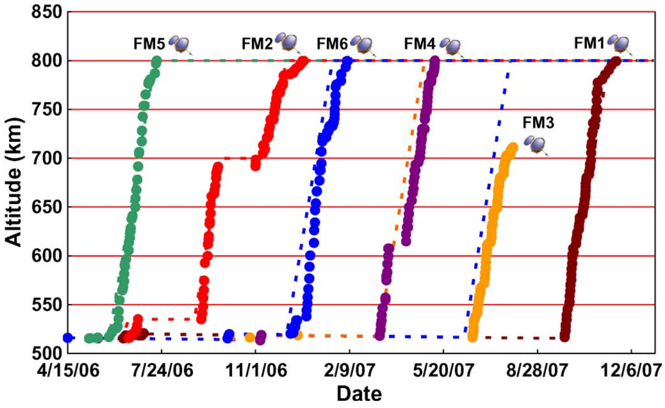


Fig. 10. FORMOSAT-3/COSMIC as-is burn history and deployment timeline.

D. Spacecraft Constellation Deployment

During the L&EO phase, the satellites were separated one by one into the same injection orbit with the same RAAN and RAAN drift rate. The strategy to differentiate the RAANs among the six orbits is to maneuver the six satellites into the mission orbit altitude of 800 km at different "maneuvering windows" (typically 45 days) in the year in order to get into the designated separate orbital planes through nodal precession. All satellites reach their final orbits with each designed RAAN and AOL at this phase [37], [41]. The FORMOSAT-3/COSMIC mission is the first "proof-of-concept" mission to use OSC

TABLE II
CONSTELLATION DEPLOYMENT STATUS WITH FIVE SATELLITES (FM5, FM2, FM6, FM4, AND FM1) AT FINAL ORBITS AS OF DEC. 2, 2007

Items SC No.	SMA (km)	Eccentricity	Inclination (deg)	RAAN (Ωi/5) (deg)	AOL (Li/5) (deg)
FM5	799.475	0.0046	71.973	0	0
FM2	799.449	0.0041	72.037	29.9	50.7
FM6	799.444	0.0051	71.982	62.0	104.4
FM4	799.471	0.0072	72.009	90.0	158.2
FM3*	711.047	0.0054	72.012	129.9	Time Variant
FM1	799.475	0.0046	71.973	145.9	262.53

*Note: On 3 Aug. 2007 the FM3 encountered solar array drive mechanism malfunction when reached 711 km orbit.

constellation deployment patent [43]. The detailed constellation deployment principles have been described in Section III-C, and the as-burn constellation results are described in Section V.

E. Final Constellation and Extended Mission

The final constellation of FORMOSAT-3 has six orbit planes, as shown in Fig. 9. Each orbit is at an altitude of 800 km with an inclination angle of 72°. The separation angle among orbit planes is 30°, and the AOL separation between satellites in adjacent orbit planes is of 52.5°. The final constellation allows the six satellites to collect 2500 atmospheric sounding data on an average per day worldwide.

V. CONSTELLATION DEPLOYMENT RESULTS

A. As-Burn Constellation Results

The current constellation configuration as of December 2007 is five satellites (FM5, FM2, FM6, FM4, and FM1) successfully reaching the 800-km mission orbits. On August 3, 2007, FM3 encountered the SAD mechanism malfunction when reaching the 711-km orbit. This anomaly blocks the FM3 thrust-burn activity to be deployed at the 800-km mission orbit. The reasons for this anomaly are still under investigation. The current constellation status is shown in Fig. 10. The dashed line is the newly planned schedule, and the dots recorded the execution results of the thrusting. The relative orbital separation angle, AOL, and altitudes of these four satellites are shown in Table II.

B. Spacecraft Thrust-Burn Performance Statistics

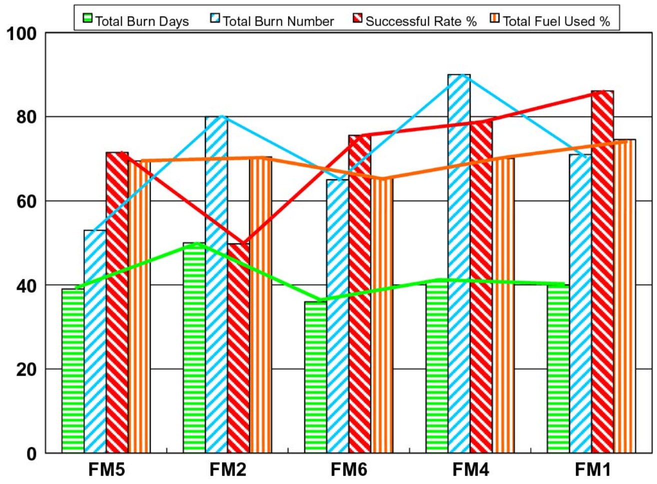


Fig. 11. Spacecraft thrust-burn performance statistics.

Fig. 11 and Table III show the spacecraft thrust-burn performance statistic results in strip chart and table formats, respectively. Starting from FM4 orbit transfer, the NSPO operation team uses the autopilot scheme to increase the burn success rate and reduce the burn working days. The data show that the FM5 burn working days number 39. However, it takes 75 calendar days to complete the burn activities. The operation team scheduled seven burns per day for FM4 and FM1 compared to three burns per day for FM5, as deployed earlier. The better spacecraft burn performance indicates that more successful rate has been achieved. The operation team has decreased the planned burn duration from 456 min for FM5 to 382.8 min for FM1 and also decreased the executed burn duration from 326.1 min for FM5 to 329.8 min for FM1. These results show that the thrust-burn success rate (= executed/planned burn) has been increased by the operation team from 71.5% for FM5 to 86.2% for FM1. Total burn number has increased from 53 times in FM5 to 71 times in FM1. In Table III, it can be seen that the average orbit-transfer height per burn has decreased from 5.4 km/burn for FM5 to 3.4 km/burn for FM1. In addition, the average burn duration per burn has decreased from 369.4 s/burn for FM5 to 238.4 s/burn for FM1.

C. Spacecraft Mass Property and MOI Results

We found that the propellant mass remains in the propellant tank are about 2.0 kg after the orbit-transfer operations are completed for each satellite. It is also expected that the spacecraft mass property [weight and center of gravity (CG)] and the moment of inertia (MOI) are changed accordingly when the propellant mass is changed. It was observed that the spacecraft CG has a change of -0.7-cm shift in Z-axis before and after orbit-transfer activities and has a CG shift in $-Y$ and $-X$ axes too. These changes will have a significant impact on the geodesy and earth gravity research. Table IV shows the spacecraft mass property and MOI results of the six satellites. The spacecraft remaining propellant mass was estimated and provided by propulsion subsystem. The error of the mass was estimated in the range of ±0.1 kg. Based on computation results, a very minor impact on MOI and CG results was observed due to this error range.

TABLE III
SPACECRAFT THRUST-BURN PERFORMANCE STATISTIC

Items SC No.	Total Burn Days (Days)	Total Burn Number (no.)	Planned Burn (Minutes)	Executed Burn (Minutes)	Successful Rate (%)	Total Fuel Used (kg)	Total Fuel Mass (kg)	Average SMA/burn (km/burn)	Average Duration/burn (sec/burn)
FM5	39	53	456	326.1	71.5	4.634	6.671	5.4	369.4
FM2	50	80	646.5	321.7	49.8	4.686	6.651	3.6	241
FM6	36	65	390	294.7	75.6	4.332	6.635	4.4	279.9
FM4	41	90	390.5	307.8	78.8	4.644	6.627	3.2	205.4
FM3	39	74	265.7	190.3	71.6	3.345	6.665	2.7	154.3
FM1	40	71	382.8	329.8	86.2	4.993	6.697	3.4	238.4

TABLE IV
SPACECRAFT MASS PROPERTY AND MOI FOR SIX SATELLITES AS OF DEC. 2, 2007

Items	Total Mass (Full Tank)	Remaining SC Total Mass	Remaining Propellant +/- 0.1 kg	Center of Gravity (CG)	Moment of Inertia (MOI) Assume SAD = 0 deg		
SC No.	(kg)	(kg)	(kg)	(m)	kg m^2		
FM1	61.097	56.104	1.704 (94 psi/ 13.2 °C)	x= 0.0035084 y=-0.0043757 z=-0.0334029	Ixx= 7.1677273 Iyx= 0.0288131 Izx=-0.0071984	Ixy= 0.0288131 Iyy=10.0887230 Izy=-0.4359628	Ixz=-0.0071984 Iyz=-0.4359628 Izz= 5.2806052
FM2	61.295	56.609	1.965 (100 psi/ 12.68 °C)	x=-0.0034182 y=-0.0041841 z=-0.0364667	Ixx= 6.9711402 Iyx= 0.0292363 Izx=-0.0096030	Ixy= 0.0292363 Iyy= 9.8405863 Izy=-0.4376625	Ixz=-0.0096030 Iyz=-0.4376625 Izz= 5.2101918
FM3	61.295	57.950	3.320 (129 psi/ 27.86 °C)	x= -0.0015454 y=-0.0070990 z=-0.0367495	Ixx= 7.0538797 Iyx= 0.3262446 Izx= 0.1441285	Ixy= 0.3262446 Iyy= 9.8458681 Izy= -0.2834290	Ixz= 0.1441285 Iyz= -0.2834290 Izz= 5.1711034
FM4	61.020	56.376	1.983 (105 psi / 29.10 °C)	x = -0.0037843 y = -0.0073189 z = -0.0371947	Ixx= 6.8193710 Iyx= 0.0317362 Izx= 0.0744942	Ixy= 0.0317362 Iyy= 9.7484668 Izy=-0.4389625	Ixz= 0.0744942 Iyz=-0.4389625 Izz= 4.8734748
FM5	61.167	56.533	2.037 (98 psi/ 13.68 °C)	x=-0.0036067 y=-0.0045262 z=-0.037113	Ixx= 6.9437632 Iyx= 0.0275360 Izx=-0.0087138	Ixy= 0.0275360 Iyy= 9.8007081 Izy=-0.4379625	Ixz=-0.0087138 Iyz=-0.4379625 Izz= 5.2086237
FM6	61.315	56.983	2.303 (106 psi/ 18.40 °C)	x = -0.0032281 y = -0.0044101 z = -0.0360353	Ixx= 6.9827399 Iyx= 0.0289346 Izx=-0.0115537	Ixy= 0.0289346 Iyy= 9.8596525 Izy=-0.4397625	Ixz=-0.0115537 Iyz=-0.4397625 Izz= 5.2408835

In the FORMOSAT-3 satellite case, the TBB boom and the solar panels are two portions that are deployed after satellite separation from the launch vehicle. The propellant fuel is also changed after orbit transfer. For the MOI computation, we assume that the SAD is at 0° position. The CG is valid for any SAD position and therefore applies to the ACS nadir and nadir-yaw modes. The MOI and CG for six spacecraft were recomputed based on the aforementioned propellant mass.

VI. ORBIT-RAISING CHALLENGES AND LESSONS LEARNED

A. Thrust-Burn Failures and Challenges

NSPO experienced numerous thrust-burn failures during the spacecraft constellation deployment of FM5 [44]. By analyzing the spacecraft back-orbit data and using the animation result of the dynamic engineering development model simulator with real telemetry data, we observed and summarized that the thrust-burn failure was attributed to the incorrect thrust-burn modeling and the incorrect spacecraft mass property and MOI data. The thrust gain factor in the spacecraft model is designed to be adjustable by the spacecraft ground command. By adjusting the thrust PID gain "factor" for roll and yaw, the reduction factor for the thrust torque ($R \times F$), and the ACS common spacecraft database parameters, the thrust-burn activity was continued and performed successfully. The major impact of the thrust-burn failure is that the operation team could not perform the full burn (turn ON thruster 0.8 s in 2-s control cycle) by routine process as planned. This caused a significant schedule slip in the first orbit-transfer activities for FM5 [28], [41], [42].

B. Spacecraft Attitude Excursion Challenges

Another lesson learned from the follow-on FM2 and FM6 thrust-burn activities comes from the spacecraft attitude excursion challenge. From the thrust-burn history statistics, it was observed that the orbit-transfer activities were performed very successfully with a 100% success rate when the thrust-burn activity was planned during the spacecraft eclipse time period. However, it was also observed that the orbit-transfer activities were performed unsuccessfully with around a 50% success rate when thrust-burn activity was planned during the spacecraft daytime period. The source of this attitude excursion problem for daytime thrust-burn activity is the fact that the sensor-processing algorithm used for the spacecraft ARS to perform attitude control will sometimes generate incorrect sun vector solutions, depending upon the numbers of cosine sun sensors. As soon as the algorithm generates an unreliable sun vector output solution to the ARS, the ARS and the ACS will immediately generate a large attitude transient incident when responding to the error [32], [39], [40].

C. Automation of Ground Operation Procedure

It usually takes two station contacts for a thrust-burn: one contact to upload the burn commands and the other to check out the burn results. This constrains the thrust operation to two burns per day. To increase the number of burns per day, the operation team developed a Satellite Test and Operations Language (STOL) procedure to generate the burn command sequence. After checking out the burn results during a station contact, the STOL procedure could extract the postburn data of tank pressure, thrust power, and control integral terms from the telemetry. The tank pressure was used to calculate the thrust force level. The thrust power and integral terms were used as the initial conditions of the next thrusting. With these data from the telemetry, the STOL procedure could generate and upload the time-tag commands for the next burn during the same station contact. The STOL procedure increased the operation efficiency to one burn per orbit. Three burns or more (seven burns were achieved at once) are planned per day to increase the operation flexibility and efficiency [32], [39].

D. RTS Ground Support Limitation

The operation team needs to observe the results of the thrust burn from the real-time telemetry and then estimate the corresponding two line elements as the inputs to ground antenna pointing. During 00:00:00–06:00:00 UTC, Kiruna remote tracking station (RTS) is not staffed, so that they cannot support the update of the North American Aerospace Defense Command two-line elements. This constraint impacted the thrusting operations to be conducted after 06:00:00 UTC if the postburn contact station is Kiruna [32], [40].

VII. CONCLUSION

We have presented in this paper a new fundamental operation concept for the FORMOSAT-3/COSMIC spacecraft constellation deployment, orbit-raising results, operations challenges, and lessons learned. With five satellites (FM5, FM2, FM6, FM4, and FM1) successfully reaching the 800-km mission orbits as of November 2007, the FORMOSAT-3/COSMIC mission has verified the "proof of concept" of a novel way of performing constellation deployment by taking the advantage of nodal precession. This novel approach has dramatically reduced the spacecraft propellant mass and the complexity of the spacecraft RCS and ACS subsystem design. The success of the constellation deployment of the FORMOSAT-3/COSMIC mission has also provided a powerful demonstration of RO scheme in particular and for the remote-sensing applications of microsatellite constellations in general. All these technical principles have paved the way for the design of future GNSS RO remote-sensing systems.

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