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Space-Based Global Weather Monitoring System: FORMOSAT-3/COSMIC Constellation and Its Follow-On Mission

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The FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) mission consisting of six low-Earth-orbit satellites is the world's first demonstration of Global Positioning System radio occultation in a near real-time operational constellation for global weather monitoring and research. The mission has produced over 1800–2200 high-quality good atmospheric sounding profiles per day. Currently, the atmospheric soundings data are assimilated into operational numerical weather prediction models for global weather prediction, including typhoon/hurricane forecasts. The radio occultation data have been shown to have a positive impact on weather predictions at many national weather forecast centers. The goal of a proposed follow-on mission is to transfer from the current experimental research mission to a significantly improved real-time operational mission, which will reliably provide no less than 8000 soundings per day. We envision a new and improved mission to be a constellation of 12 satellites with data latency less than 1.5 h, which will provide greatly enhanced opportunities for operational forecasts and scientific research. In this paper, we describe highlights of the results of the current mission, the follow-on mission definition trade analysis results, and the new spacecraft constellation system design with the next-generation radio occultation receiver onboard.

I. Introduction

THE FORMOSAT-3 mission, also known as COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) consisting of six identical microsatellites is an experimental science mission for demonstrating the usefulness of Global Positioning System (GPS) radio occultation (RO) in operational numerical weather prediction, climate monitoring and research, and space weather forecasting. As demonstrated by the "proof-of-concept" GPS/meteorology experiment aboard Microlab-I satellite and later by the CHAMP, SAC-C (Satellite de Apliciones Cientificas-C), and GRACE (Gravity Recovery and Climate Experiment) missions, GPS RO data are shown to be of high precision, accuracy, and vertical resolution [1–4]. These missions set the stage for the FORMOSAT-3/COSMIC mission. In this paper, we refer to the FORMOSAT-3/COSMIC mission as the FORMOSAT-3 mission for simplicity. The FORMOSAT-3 satellites are equipped with three onboard payloads including a GPS occultation receiver (GOX), a triband beacon (TBB), and a tiny ionospheric photometer (TIP), respectively. The retrieved soundings (about $1800 \sim 2200$ per day on the average) are being assimilated into the numerical weather prediction (NWP) models by many major weather forecast centers and research institutes for real-time weather predictions and cyclone/typhoon/hurricane forecasts [5]. The success of the FORMOSAT-3 mission expected to operate through 2011, has initiated a new era for operational GPS RO soundings [6,7].

As addressed in the final report of "Workshop on the Redesign and Optimization of the Space-Based Global Observing System," the World Meteorological Organization had recommended continuing RO observations operationally and the scientific community had urged continuation of the current mission and planning for a follow-on operational mission [8]. The proposed follow-on mission is a greatly improved operational and research mission with redundancy and robustness, consisting of a new constellation of 12 satellites. The new mission will seek to establish international standards so that future RO missions deployed by any country can be assimilated into the same systems. The primary payload of the satellite will be equipped with the Global Navigation Satellite Systems (GNSS) RO receiver and will collect more soundings per receiver by adding GALILEO and GLONASS (Global Navigation Satellite System) tracking capability, which will produce a significantly higher spatial and temporal density of profiles. These will be much more useful for weather prediction models and severe weather forecasting, including typhoons and hurricanes, as well as for research. In this paper, highlights of the current FORMOSAT-3 mission are presented, followed by an overview of a future follow-on mission and mission definition trade analysis results.

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Table 1 FORMOSAT-3 mission characteristics

Number	Six identical microsatellites
Weight	61 kg (with payload and fuel)
Shape	Disk shape of 116 cm diam, 18 cm in height
Orbit	800 km altitude, circular
Inclination angle	72 deg
Argument of latitude	52.5 deg apart
Power	81 W orbit average
Communication	*S*-band uplink and downlink
Design and mission life	5 yrs
Launch date	01:40 UTC 15 April 2006

II. FORMOSAT-3 Mission Overview and Status

Table 1 shows the current FORMOSAT-3 mission characteristics. The FORMOSAT-3 satellites were successfully launched into the same orbit plane at 516 km altitude at 01:40 UTC on 15 April 2006. The final constellation configuration was designed to have six orbit planes at 800 km final mission altitude with 30 deg separation for evenly distributed global coverage [7,9–13].

A. Spacecraft Constellation Status

All six FORMOSAT-3 satellites, except spacecraft flight model numbers 2 and 3 (FM2 and FM3) are currently in a satisfactory state of health at $700 \sim 800$ km final orbit. FM2 has a power shortage issue with only one working solar panel and FM3 currently remains at an orbit of 711 km due to a stuck solar array drive. Five out of six satellites have reached their final mission orbit of 800 km since the end of November 2007 [7]. As for the primary payload, four GOX are operated at a duty cycle of 100% and two other GOX (FM2 and FM3) are operated based on sun beta angle due to power shortage and stuck solar array drive.

Spacecraft flight model number 6 (FM6) lost its communication on 8 September 2007. There was no warning that indicated a spacecraft problem before the FM6 outage event. Many emergency recovery attempts were tried by the operations team, without success. However, after 67 days, the FM6 resumed contact and recovered back on its own after a computer master reset event occurred over the South Atlantic Anomaly region. The FM6 transmitter's RF spectrum looked normal with no sign of degradation, and all the spacecraft subsystems were found to be in good health status. The FM6 started to provide data again on the next day. After analysis, two possible root causes were identified: 1) an intermittent hardware failure of the field programmable gate array inside the mission interface unit, or 2) an intermittent short circuitry of the pin grid matrix related to thermal effects. Science data from FM6 after it recovered appeared to be good [14].

B. New FORMOSAT-3 Constellation System Architecture

After two years in orbit, in mid-April 2008 the FORMOSAT-3 program had switched from two commercially operated ground stations at Fairbanks, Alaska and Kiruna, Sweden to two new ground stations in Fairbanks and Tromso, Norway. The program plans to use the new stations for the reminder of the mission. Figure 1 shows the new system architecture. The new FORMOSAT-3 constellation system consists of the six microsatellites, the spacecraft operations control center (SOCC) in Taiwan, several tracking, telemetry, and command (TT&C) ground stations, two data receiving and processing centers, and the fiducial network. There are two TT&C local tracking stations, one located in Chung-li and the other in Tainan of Taiwan, respectively. Currently, there are a total of three new remote terminal stations (RTS) to support the passes: the aforementioned two new RTS, Fairbanks Command and Data Acquisition Station, Kongsberg Satellite Services Ground Station, and a third RTS located in McMurdo, Antarctica. This ground station is expected to reduce the data latency of some RO products. These three RTS are currently set as primary stations for the FORMOSAT-3 mission.

C. Data Monitoring and Distribution

The SOCC uses the real-time telemetry and the back orbit telemetry to monitor, control, and manage the spacecraft state of health. The downlinked science data are transmitted from the RTS via the National Oceanic and Atmospheric Administration (NOAA) to the two data receiving and processing centers: 1) COSMIC Data Analysis and Archive Center[††] (CDAAC) which is located in Boulder, Colorado, and 2) Taiwan Analysis Center for COSMIC[‡‡] (TACC) located at the Central Weather Bureau (CWB) in Taiwan [7,10–13]. The fiducial GPS data are combined with the occulted and referencing GPS data from the GOX payload to remove the clock errors through double differencing. All collected science data are processed by CDAAC and then transferred to TACC and other facilities for operations, science, and data archival. The processed atmospheric profiles are being distributed in near real-time (NRT) to international weather centers from CDAAC through NOAA/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS). These data are currently provided to weather centers within 90 min (data latency requirement is 180 min) after satellite on-orbit science data collection to be ingested by the operational weather forecast models.

D. Global Positioning System Radio Occultation Events Statistics: Over Millions of Soundings

All six satellites have generated a total of more than 2500 RO data per day. However, only 60–75% of the RO data received today could be retrieved into useful NRT atmosphere profiles for numerical weather prediction. The retrieved RO data of about 1800–2200 good atmospheric soundings per day have been used to study atmospheric and ionospheric structures and total electron content, and were assimilated into numerical atmospheric and space weather predictions models to improve the accuracy of prediction. We have collected over 3 million RO sounding data (1.507331×10^6 for atmosphere and 1.712929×10^6 for ionosphere) profiles as of 31 December 2008, as shown in Fig. 2.

E. Operations Lessons Learned on FORMOSAT-3

After the FORMOSAT-3 launch, many satellite engineering performance and operational challenges and lessons learned have been published in the literature [7,10–13]. By examining the spacecraft performance, we have determined that the attitude excursion is one of the main causes of the data loss. The on-orbit attitude performance of current FORMOSAT-3 is within 2 deg for pitch axis and within 5 deg for roll and yaw axes (1σ value). The FORMOSAT-3 satellites experienced bad attitude more than expected, and this problem has reduced the number of data collected and has sometimes caused a spacecraft to power contingency condition. The follow-on mission will acquire a better attitude control system so that the roll/pitch/yaw attitude will meet the new requirements [15].

III. Highlights of the Mission Results

The scientific goals for the FORMOSAT-3 mission are to 1) demonstrate the value of NRT RO observations in operational NWP to improve global and regional weather forecasting, 2) improve global space weather monitoring and forecasting, 3) provide data sets for climate and global change research, and 4) advance our knowledge of Earth's gravity field [16]. Here, we highlighted some of the FORMOSAT-3 scientific results.

A. Open-Loop Tracking Technique and Detection of the Atmospheric Boundary Layer

A new open-loop tracking technique was implemented on the FORMOSAT-3 mission and it has assured most of the retrieved soundings to penetrate to altitudes of 1 km or lower above the Earth's

[††]Data available at http://cosmic-io.cosmic.ucar.edu/cdaac/index.html [cited 15 Oct. 2008].

[‡‡]Data available at http://tacc.cwb.gov.tw/en/index.htm [cited 15 Oct. 2008].

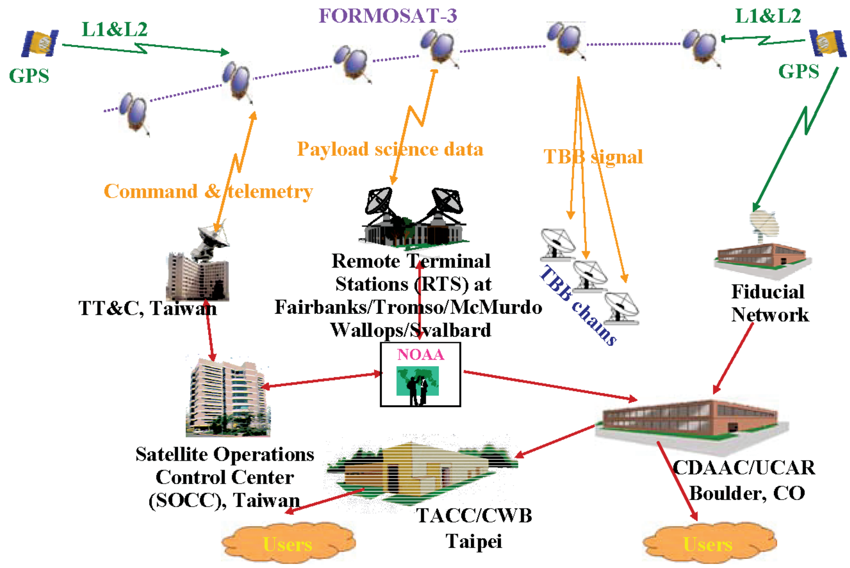
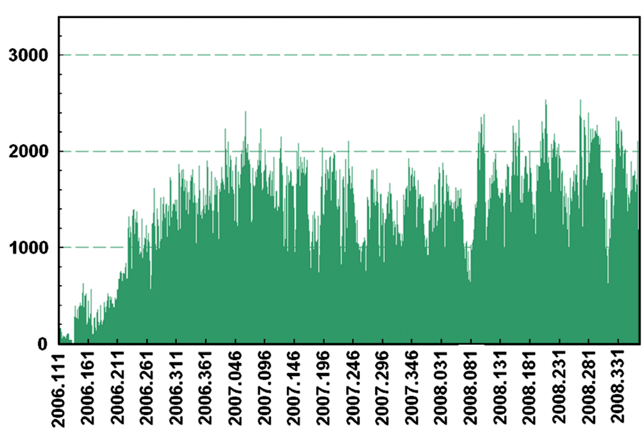
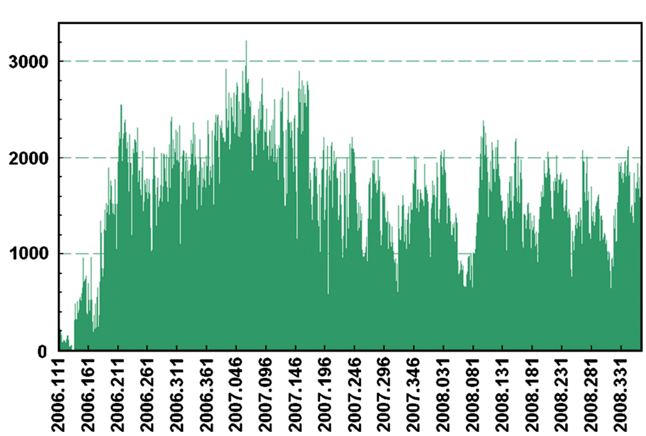


Fig. 1 New FORMOSAT-3 constellation system architecture.

surface [6,17]. About 70–90% of the soundings reach altitude within 1 km above the surface on a global basis. With this technique, the FORMOSAT-3 constellation mission for the first time can monitor the atmospheric boundary layer (ABL) on a global scale and provide the top height of ABL, which is an important parameter for understanding transport processes in the lower troposphere and for numerical weather prediction and climate monitoring [6,18,19].



a) Atmospheric occultation events



b) Ionospheric occultation events

Fig. 2 Number of daily occultation events since launch as of 31 December 2008 for a) atmosphere profiles and b) ionosphere profiles.

B. Data Assimilation to Numerical Weather Prediction Model and Impacts on Storm Forecasts

The assimilations of FORMOSAT-3 observation into operational weather prediction systems have shown a positive impact on forecasts at a number of global and national weather centers, such as Denmark Meteorological Institute in Denmark, European Centre for Medium-Range Weather Forecasts in Reading, United Kingdom, Institut D’Estudis Espacials de Catalunya in Barcelona, Spain, Met Office in Exeter, United Kingdom, National Center for Atmosphere Research, NOAA’s NESDIS, and Joint Center for Satellite Data Assimilation in the United States, and many other weather forecast and research centers in Japan, Korea, China, India, and Taiwan [6,13]. Thus, the primary goal of the FORMOSAT-3 mission, to demonstrate a significant positive effect on global NWP, has been met.

C. Lowest Altitude Penetration of Radio Occultation Retrievals

Huang et al. [20] studied the global distribution statistics of the lowest height of the retrieved profiles for FORMOSAT-3 and CHAMP (Challenging Minisatellite Payload) satellites for the period from 1 January to 10 May 2007. The lowest height of the tangent point of the RO signals is limited by high terrain. The retrieved profiles were separated into two groups: one over the ocean and the other over land. The lowest heights reached by the profiles of the land group for FORMOSAT-3 and CHAMP were analyzed. It was noted that they are mostly below 0.5 km over the surface in the southern polar region. In most other land regions, the lowest heights reached are all below 1 km. Those with lowest heights reached above 1 km are mostly located in mountainous areas such as the Himalaya mountains, the Tibetan plateau, and the Andes mountains because high mountains prevent RO signals with lower tangent point heights from being tracked [6,20].

D. Model Errors Identification in Antarctica

Because of the small number of weather stations in Antarctica, there are relatively few weather data in this area. This provides a great opportunity for FORMOSAT-3 to provide data for forecast model initialization and verification of this area. It was found that forecast model temperatures over Antarctica were lower than observed and meteorologists have begun to make the temperature correction based on the addition of data from FORMOSAT-3 measurements [6]. The data have been used to construct the first continuous profiles of temperature during the Antarctica winter and to study the vortex effect on ozone depletion [21]. The ability to take many accurate soundings over Antarctica is providing new scientific insights in that area.

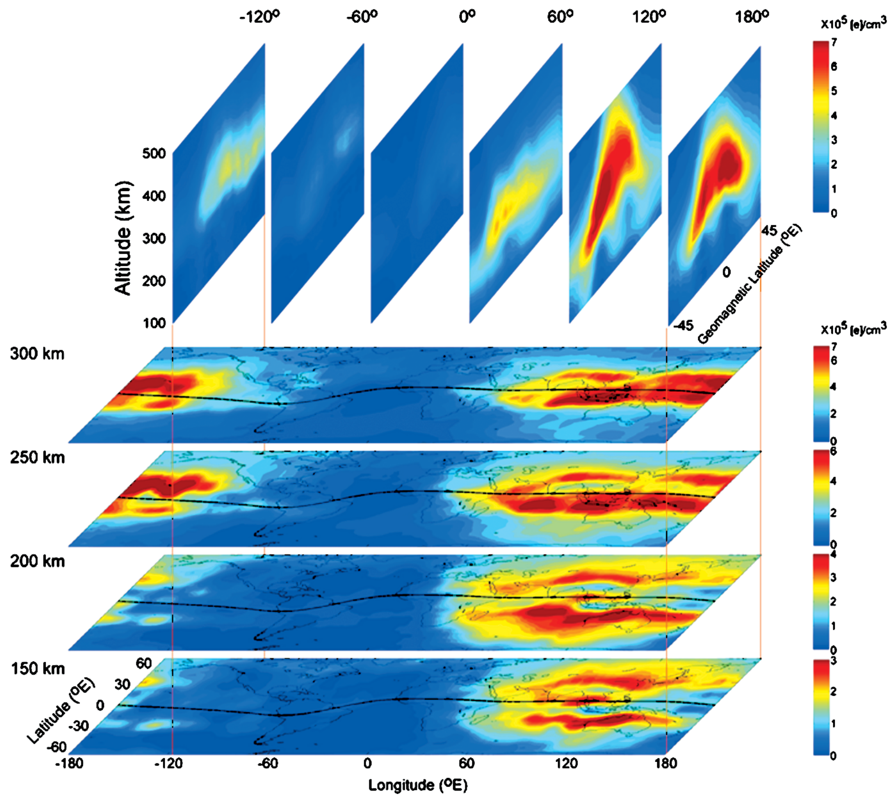


Fig. 3 Sample of 3-D ionospheric electron density distribution reconstructed by FORMOSAT-3 RO data.

E. Applications to Climate Change

The FORMOSAT-3 RO observations provide an unequaled accuracy, consistency, and stability in the height range of 8–25 km above sea level to meet the stringent climate monitoring requirements of 0.5 K accuracy and 0.04 K/decade stability [6,19]. Also, the RO temperature record from CHAMP, SAC-C, and FORMOSAT-3 missions show no obvious changes or jumps in temperature anomalies between these missions. These results verify that accurate RO temperature soundings in the height range of 5–40 km are mission independent [6].

F. New Findings in Observing Gravity Waves

We have emphasized new directions in applying the RO method to measure the vertical gradients of the refractivity in the atmosphere, to determine the temperature regime in the upper stratosphere, and to investigate the internal wave activity in the atmosphere. Because the amplitude of the RO signal is proportional to the second derivative of the phase, the correlation between the phase acceleration and the intensity variations in the RO signals opens a way to locate the layered structures in the propagation medium based on simultaneous observations of the radio wave intensity and the phase variations in transionospheric satellite-to-satellite links. The joint analysis of the phase and amplitude data are provided for measuring the horizontal wind perturbations and energy associated with the atmospheric internal waves [9,22,23].

G. Ionospheric Space Weather Achievements

The FORMOSAT-3 satellite constellation has created a new era of observing ionospheric space weather. Taking advantage of dense and global three-dimensional observation coverage, the enhancement of electron density in the four equatorial ionization anomaly zones can be observed [24,25]. The four-peaked structure of total electron content observation is the most significant at F-region heights and suggests that the feature is most likely produced by physical processes [24]. FORMOSAT-3's capability to observe vertical plasma distribution across a 24 h period further shows important results of local time diurnal variation of the longitudinal four-peaked structure in the equatorial ionosphere [25]. Recently, the 3-D observation has been adopted to investigate pre-earthquake ionospheric anomalies. Hsiao et al. [26] employed FORMOSAT-3 to observe anomalies in the ionospheric electron density structure before the 26 December 2006 M7.0 Pingtung earthquakes in Taiwan. We found that, around the epicenters, the F2-peak height descends and the ionospheric electron density between 300 and 350 km altitude significantly decreases within 5 days before the earthquakes.

H. Global Three-Dimensional Visualization Atmospheric and Space Weather Database

The 3-D ionospheric and atmospheric vertical profile can be reconstructed up to 800 and 40 km, respectively, by using the global GPS RO measurements observed by FORMOSAT-3. The global data map of ionospheric density distribution, atmospheric temperature, and pressure structures can be routinely obtained by accumulating monthly RO occultation observations in 2-h intervals and taking the median value in each 2.5×2.5 deg grid (longitude by latitude) and in every 1-km altitude range. Based on the ionospheric RO data, we have created a global 3-D visualization atmospheric and space weather database,[§§] which will be disseminated to the science communities in the near future. The 3-D database includes: 1) the global temperature for climate change research and application, 2) the global atmospheric pressure, and 3) the global space weather 3-D ionospheric tomography database. We have processed over 200,000 3-D figures after the 2-year in-orbit data as of 31 December 2008. Figure 3 shows a sample of 3-D ionospheric electron density distribution.

IV. Follow-On Mission Trade Analysis Results

Here, we discuss follow-on mission major trade analysis results performed during the advanced study mission definition phase. The major trade analysis results include the mission orbit properties, the orbit inclination angle, the sounding data distribution, the proposed

[§§]Data available at http://www.cchsiao.idv.tw/f3cindexc.htm [cited 18 Nov. 2008].

follow-on constellation spacecraft configuration, and the number and density of occultation data points. Then, we discuss the data latency analysis that will impact to the overall space system architecture design and ground communication network. At the end, we show the follow-on mission system architecture and preliminary spacecraft conceptual design [12,15].

A. Mission Orbit Properties

The follow-on mission requires the satellite at low Earth orbit from 500 to 900 km. The engineering consideration on the altitude is mainly for the constellation deployment period. Constellation deployment period is a function of inclination angle, eccentricity, and difference of the parking orbit altitude. If the altitude difference of parking orbit and mission orbit is larger, the mission will achieve its final constellation sooner. Therefore, we propose 500 km as the parking altitude and 800 km as the mission altitude. As for the shape of the orbit, a circular orbit is preferred for simplification. The optimal performance of the radio occultation payload is to have highest gain pointing to the Earth surface.

B. Orbit Inclination Angle

The following four important factors depend on the orbit inclination angle.

1) Generally speaking, if the satellite is at high-inclination-angle orbit, it requires fewer ground receiving stations to achieve the full data dumps per revolution.

2) The constellation period depends on the cosine of the inclination angle. Therefore, the inclination angle cannot be too close to 90 deg.

3) The relationship between total occultation number and inclination angle is as shown in Fig. 4. It is understandable that the number of occultation is higher if the inclination angle is higher because the GNSS system is orbiting at a higher inclination angle.

4) Data distribution and spatial density will be analyzed further because the mission requires the data to be distributed homogeneously over the globe.

The analysis of inclination angle vs sounding data distribution has been studied and published by authors [12,15]. It is realized that the inclination angle of 72 deg of FORMOSAT-3 will make the measurements in low latitudes a little bit sparse. Therefore, there will be a need to add some satellites at a low inclination orbit.

C. Sounding Data Distribution and Spatial Density

We define the equivalent area covered by one occultation or horizontal spatial density as the average area in square kilometers associated with a single sounding, for example, one sounding per N km ($\times N$ km). As we take a closer look at the dependence of data distribution and density with inclination angle, a high inclination angle favors the data collection at high latitudes and a low inclination angle favors the data distribution at low latitudes. Taking a 72 deg inclination as an example (see Fig. 5), the data distribution at low latitudes is sparser than at high latitudes. Within the latitude zone of -10–$+10$ deg, there is one sounding per 1530×1530 km, and

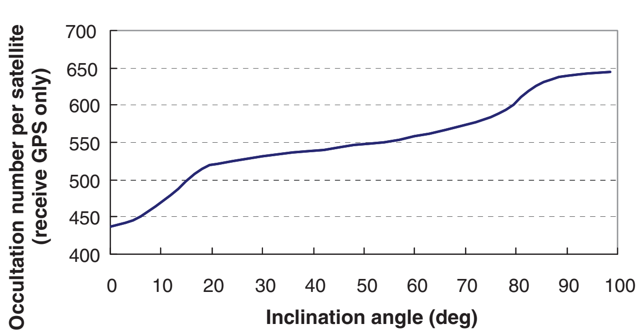


Fig. 4 Relationship between total occultation number and inclination angle for one satellite receiving GPS only.

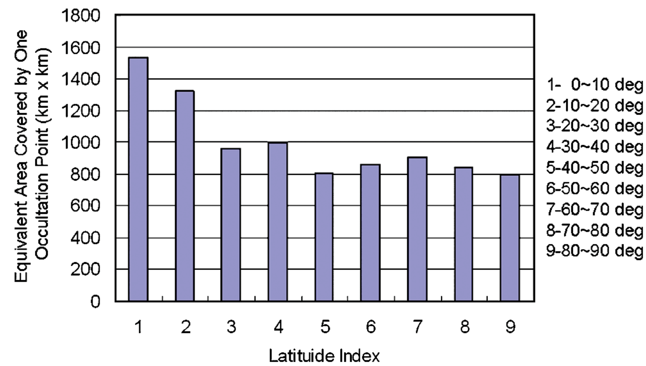


Fig. 5 Dependence of data distribution vs latitude for a 72 deg inclination angle. The equivalent area covered by one occultation is defined as the average area in square kilometers associated with a single sounding, for example, one sounding per N km ($\times N$ km).

within the latitude zone of 80–90 deg (northern and southern hemisphere), there is one sounding per 800×800 km.

Figure 6 shows our analysis for inclination angles of 0, 12, 24, 60, 72, 90, and 98.6 deg. The angle of 98.6 deg corresponds to a 800 km sun-synchronous orbit. One can see the trend for 72, 90, and 98.6 deg are similar, and the trend for 0, 12, and 24 deg are similar. Therefore,

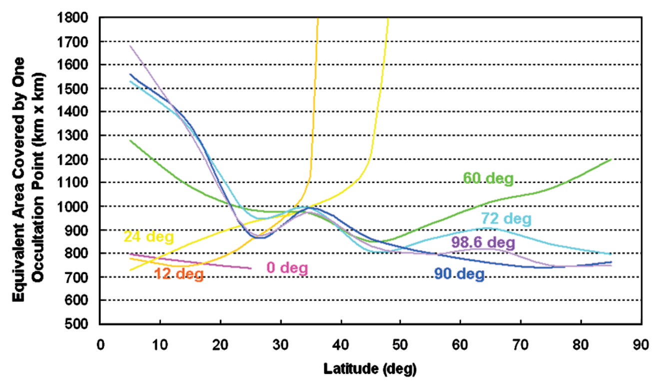


Fig. 6 Dependence of data distribution with inclination angle. The equivalent area covered by one occultation is defined as the average area in square kilometers associated with a single sounding, for example, one sounding per N km ($\times N$ km).

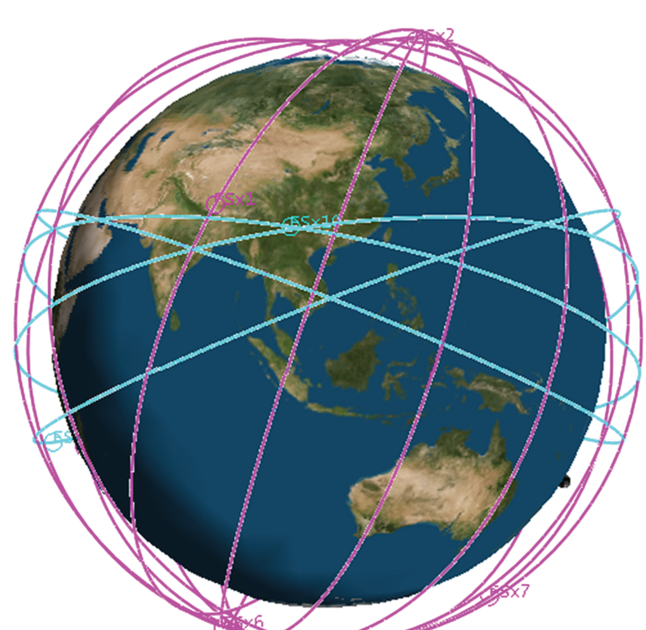


Fig. 7 FORMOSAT-3 follow-on constellation with 12 satellites.

Table 2 Expected atmospheric profiles vs different constellation and different receiver capability

Satellites in constellation	GPS	GALILEO	GLONASS	GPS + GALILEO	GPS + GALILEO + GLONASS
High inclination, 72 deg	350	336	273	686	959
Low inclination, 24 deg	350	329	231	679	910
12(=8 + 4)	4200	4004	3108	8204	11,312

the approaches for global distribution homogeneously are 1) to pick the inclination in the middle, and 2) to choose a satellite constellation combined with high inclination and low inclination. For this project, we start with the latter approach because FORMOSAT-3 is a constellation with 72 deg inclination angle and it is running well in terms of payload, spacecraft, and data centers.

D. Follow-On Spacecraft Constellation

We propose a follow-on mission consisting of a 12 satellites constellation (see Fig. 7). Eight satellites are at high inclination angle of 72 deg at eight orbital planes (see the pink lines in Fig. 7) and are separated by 22.5 deg when constellation deployment is complete. Four more satellites are at a low inclination angle of 24 deg at four orbital planes (see the blue lines in Fig. 7) and separated by 45 deg when constellation deployment is complete. The satellites at high inclination angle will be launched in one cluster and be placed to one parking orbit. The mission operations team will then perform the spacecraft thrust burns so that their orbital plane can be separated through the differential precession rate with the differential orbit altitude. The satellite at low inclination angle will go through the similar launch and constellation deployment process. The overall deployment period will be about 19 months for high inclination satellites and about 7 months for low inclination satellites, respectively.

E. Occultation Points

With the various uncertainties on the follow-on project, we also calculate the number of occultation points with 12 satellites in the constellation. They are listed in Table 2. Figure 8 shows the 6-h occultation point distribution with a 12-satellite constellation for the FORMOSAT-3 follow-on mission. The calculation is based on 28 GPS satellites, 27 GALILEO satellites, and 21 GLONASS satellites with the assumption of 350 effective atmospheric profiles per low Earth orbit per day if the satellites perform similarly to the FORMOSAT-3 satellites. Note that the estimation is based on the following ideal conditions: no spacecraft emergency, no anomaly on the ground segment, and no errors from the operation segment.

F. Data Latency

The data latency depends on the number and locations of the available ground stations in the world. In the analysis, the ground stations, which are located at Fairbanks, Tromso, and McMurdo, used for FORMOSAT-3 are assumed to receive the data from the high-inclination-angle satellites of the follow-on mission. For the low-inclination-angle satellite, we tentatively use TT&C stations located in Taiwan, Bangalore, and Mauritius for the RO number calculation and latency analysis. These three low-latitude ground stations can also support data dumps from the high-inclination-angle satellites. To maximize the use of the ground stations, the argument of latitude of the orbit needs to be phased properly to avoid more than one spacecraft flying over the same ground station at the same time. For a constellation of 12 satellites, the data latency due to storage and dumping is about 36 min on average. If we assume ground network and processing take about another 14 min, the total average data latency is about 50 min.

G. Effective Coverage Area

Currently, the FORMOSAT-3 constellation can collect about 2500 measurements per day when all six GOX are at 100% duty cycle. After the data are processed, the number of good atmospheric soundings is about 70% of the total measurements. In other words, there are approximately 1600–2200 good soundings per day depending on the GOX duty cycles. For this number of soundings, the spatial data density is about one sounding per 550 × 550 km. It should be noted that the horizontal scale of a tropical cyclone is about several hundred square kilometers. Therefore, FORMOSAT-3 may

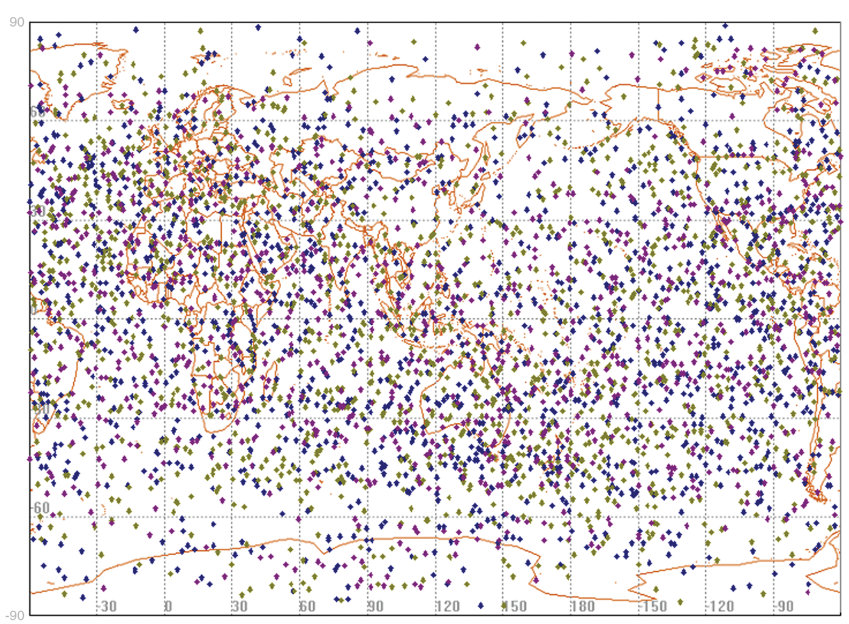


Fig. 8 Six-hour occultation point distribution with 12 satellite constellation for the FORMOSAT-3 follow-on mission.

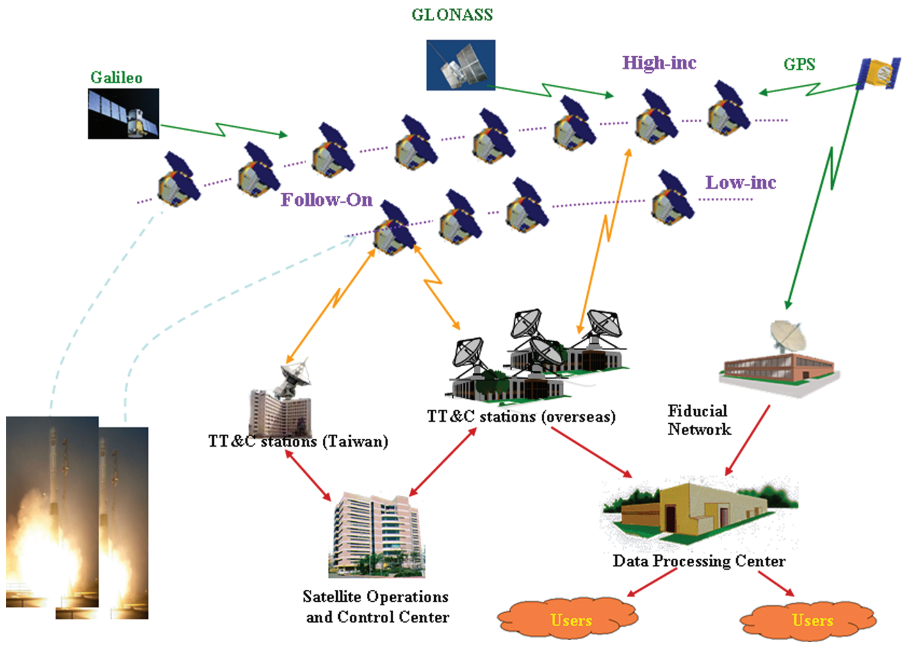


Fig. 9 FORMOSAT-3 follow-on mission system architecture with constellation of 12 satellites.

take only one measurement in the area of highest interest. Therefore, the follow-on mission should have significantly more soundings distributed more or less homogeneously over the globe to make the system a significant improvement over FORMOSAT-3. The effective spatial data density in the contemplated 12 satellites constellation of the follow-on mission with GNSS capable of receiving GPS, GALILEO, and GLONASS signals can be reduced to one sounding per 250×250 km.

H. Follow-On Mission System Architecture and Spacecraft Design

The advanced program team at National Space Organization, Taiwan is currently at the stage of mission definition design phase. We show here some of the planned mission and spacecraft design features for the follow-on mission. Figure 9 shows the proposed FORMOSAT-3 follow-on mission system architecture with a constellation of 12 satellites that will require three launches. The primary payload of the follow-on satellite will be equipped with a next-generation GNSS RO receiver to collect more soundings per receiver by adding Galileo and GLONASS tracking capability. The follow-on spacecraft bus design vs current FORMOSAT-3 design is shown in Table 3. Figure 10 shows the proposed FORMOSAT-3 follow-on mission spacecraft configuration. The follow-on spacecraft will improve payload performance, better attitude performance,

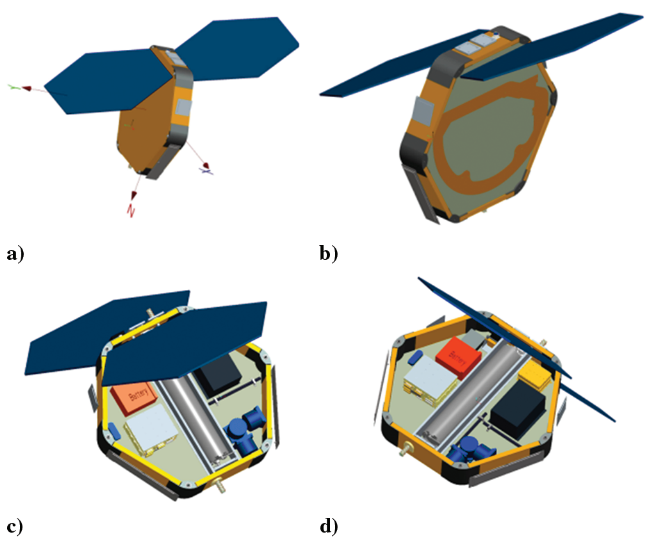


Fig. 10 Proposed FORMOSAT-3 follow-on mission spacecraft configuration; various view angles shown in Figs. 10a–10d.

Table 3 Proposed follow-on mission spacecraft bus design vs FORMOSAT-3 design

Function	Follow-on design	FORMOSAT-3 design	Benefit
Weight	<50 kg	61 kg, with propellant	Stacked or single launch piggyback launch
Attitude control performance[a]	3-axis linear control roll/yaw: ± 0.2 deg (3σ) pitch: ± 0.2 deg (3σ) 3-axis gyro, 3-axis magnetometer, RWA $\times$ 3, torque $\times$ 3, GNSS PL $\times$ 1	3-axis nonlinear control roll/yaw: ± 5 deg (1σ) pitch: ± 2 deg (1σ) Earth sensor $\times$ 2, CSSA $\times$ 8, RWA $\times$ 1, torque $\times$ 3, GPS bus receiver PL $\times$ 1	Improved PL performance better attitude performance simplified operation simplified orbit transfer
Science data storage	>1.5 G	128 M	Increased data storage 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	Metal matrix (AlBeMet)	Cost reduced
Payload interface	Main PL: GNSS RO Rcvr 2 science PL (optional)	Primary PL: GOX secondary PL: TIP, TBB	Modular design cost reduced

[a] RWA: reaction wheel assembly; CSSA: cosine sun sensor assembly; PL: payload

simplify operation, simplify orbit transfer, increase data storage, and modular design for additional science payloads (optional) and launch vehicle interface.

V. Conclusions

In this paper, we have described the FORMOSAT-3 mission status, highlights of the mission results, and the new constellation system architecture after two years in orbit operation. The success of the FORMOSAT-3 mission has initiated a new era for operational GPS RO soundings and is the world's first demonstration of the impact of near real-time GPS RO observations in operational global weather forecasting. We also show the proposed follow-on mission definition trade analysis results, especially the system architecture and spacecraft bus and GNSS RO payload design. The follow-on spacecraft design will have a robust design and improve the payload performance by using the next-generation GNSS RO payload and provide better attitude performance to reduce the spacecraft recovery time and payload down time. The follow-on mission will have a significantly improved impact on global weather prediction, and its promise for weather and climate research and space weather monitoring is equally far reaching.

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