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Global GNSS Radio Occultation Mission for Meteorology, Ionosphere & Climate

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1. Introduction

The term “occultation” is widely used in astronomy when an object in the foreground optically occults objects in the background, and it refers to a geometry involving the emitter, the planet and its atmosphere if any, and the receiver changes with time.¹ Radio occultation (RO) is a remote sensing sounding technique in which a radio frequency signal emitted from a spacecraft passes through an intervening planetary atmosphere before arriving at the receiver, and is used to study the planetary atmosphere properties in the interplanetary mission (Fjeldbo & Eshleman, 1965). The atmospheric RO observations represent a planetary scale geometric optics experiment in which the atmosphere acts as a big optical lens and refracts the paths and propagation velocity of electromagnetic wave signals passing through it (Kursinski et al., 2000). The first RO experiment started with the Mars flyby by Mariner-IV in 1964 (Kliore et al., 1965). When Mariner-IV satellite passed behind and emerged from the other site of Mars, the extra carrier phase delay and amplitude variation of the microwave signals were observed. These observed data provided very first valuable atmospheric and ionospheric density information by using the inversion techniques (Melbourne et al., 2005). Since then a series of planetary experimental missions were planned to study the atmospheres and ionospheres of the planets and their moons (Yunck et al., 2000).

The limb sounding of the earth’s atmosphere and ionosphere using the RO technique can be performed with any two cooperating satellites before the United States’ Global Positioning System (GPS), the first Global Navigation Satellite Systems (GNSS), becoming operational (Lusignan et al., 1969). A few early RO experiments from a satellite-to-satellite tracking link had been conducted. These included the occulted radio link between ATS-6 (Applications Technology Satellite-6) and GEOS-3 (Geodetic and Earth Orbiting Satellite-3) and between the Mir station and a geostationary satellite (Liu et al., 1978; Yakovlev et al., 1996).

¹ <http://en.wikipedia.org/wiki/Occultation> [cited 1 July. 2009].

2. GNSS radio occultation mission

After GNSS becomes operational, substantial and significant progress has been made in the science and technology of ground-based and space-based GNSS atmospheric remote sensing over the past decade (Davis et al., 1985). The ground-based GNSS atmospheric remote sensing with upward-looking observations arose in the 1980s from GNSS geodesy. As the rapid increase of the GNSS geodetic ground networks around the world, great quantity of atmospheric integrated perceptible water (PW) were used in numerical weather prediction (NWP) for weather and climate modelling (Liou et al., 2000 & 2001; Elgered et al., 2003; Ha et al., 2003). However, one of the major limitations to the ground-based GNSS remote sensing is that it only provides integrated PW without vertical resolution, and it is restricted to land areas distributed with GNSS networks. The space-based GNSS atmospheric limb sounding offers a complementary solution to these issues (Yunck et al., 2003).

The space-based GNSS RO atmospheric remote sensing technique, which makes use of the L-band radio signals transmitted by the GNSS satellites, has emerged as a powerful approach for sounding the global atmosphere in all weather over both lands and oceans (Yunck et al., 1990 & 2003; Wu et al., 1993; & Liou et al., 2002). Figure 1 shows a schematic diagram illustrating radio occultation of GNSS signals received by a low-earth-orbit satellite. The GPS/Meteorology (GPS/MET) experiment (1995-1997) showed that the GNSS RO technique offers great advantages over the traditional passive microwave measurements 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).

Fig. 1. Schematic diagram illustrating radio occultation of GNSS signals.

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 (SAC-C) (in 2001), the Challenging Minisatellite Payload (CHAMP) (in 2001), and the twin

Gravity Recovery and Climate Experiment (GRACE) missions (in 2002). The GNSS RO sounding data have been shown to be of high accuracy and high vertical resolution. Table 1 lists GNSS RO sounding data characteristics. All these missions set the stage for the birth of the FORMOSA SATellite mission-3/Constellation Observing Systems for Meteorology, Ionosphere, and Climate mission, also known as FORMOSAT-3/COSMIC mission (Kursinski et al., 1996; Rius et al., 1998; Anthes et al., 2000; Hajj et al., 2000; Kuo et al., 2000; Lee et al., 2001).

Characteristics of GNSS Radio Occultation Data
<ul style="list-style-type: none">• Limb sounding geometry complementary to ground and space nadir viewing instruments• Global 3-D atmospheric weather coverage from 40 km to sea level surface• High accuracy temperature measurement (equivalent to <1 K; average accuracy <0.1 K)• High precision temperature measurement (0.02-0.05 K)• High vertical resolution (0.1 km surface – 0.1 km tropopause)• Only system from space to resolve atmospheric boundary layer• All weather-minimally affected by aerosols, clouds or precipitation• Independent height and pressure• No first guess sounding requirement• Independent of radiosonde calibration• No instrument drift• No satellite-to-satellite bias• Compact sensor, low power, low cost• A typical RO sounding showing very sharp tropopause• No other instrument from space provides such high vertical resolution profile

Table 1. Characteristics of GNSS radio occultation data

3. FORMOSAT-3/COSMIC mission

3.1 Mission

The FORMOSAT-3² satellite constellation was launched successfully from Vandenberg Air Force Base in California 1:40 UTC on April 15, 2006 into the designated 516 km circular parking orbit altitude. Table 2 shows the mission characteristics. The FORMOSAT-3 mission is the world’s first demonstration of GPS RO occultation near real-time operational constellation mission for global weather monitoring. The primary scientific goal of the mission is to demonstrate the value of near-real-time GPS RO observation in operational numerical weather prediction. With the ability of performing both rising and setting occultation, the mission provides about 1,600~2,400 atmospheric and ionospheric soundings per day in near real-time that give vertical profiles of temperature, pressure, refractivity, and water vapor in neutral atmosphere, and electron density in the ionosphere with global coverage (Anthes et al., 2000 & 2008; Liou et al., 2006a, 2006b, & 2007; Fong et al., 2008a & 2009a).

² In this chapter the FORMOSAT-3/COSMIC mission was referred to as the FORMOSAT-3 mission for simplicity.

The retrieved RO weather data are being assimilated into the NWP models by many major weather forecast centers and research institutes for real-time weather predictions and cyclone/typhoon/hurricane forecasts (Kuo et al., 2004; Anthes et al., 2008). The mission results have shown that the RO data from FORMOSAT-3 are of better quality than those from previous missions and penetrate much further down into the troposphere, mission results could be referred to Liou et al. (2007), Anthes et al. (2008), Fong et al. (2008a, 2008b, 2008c & 2009a), and Huang et al. (2009). In the near future, other GNSS, such as the Russian Global Navigation Satellite System (GLONASS), and the planned European Galileo system, could be used to extend the applications by the use of RO technique (Chu et al., 2008; Fong et al., 2009a & 2009b). The great success of the FORMOSAT-3 mission expected to operate through 2011, has initiated a new era for near real-time operational GNSS RO soundings (Fong et al., 2009b; Kuo et al., 2004, 2008a & 2008b).

Number	Six identical satellites
Weight	~ 61 kg (with payload and fuel)
Shape	Disc-shape of 116 cm diameter, 18 cm in height
Orbit	800 km altitude, circular
Inclination Angle	72°
Argument of latitude	52.5° apart
Power	~ 81 W orbit average
Communication	S-band uplink (32 kbps) and downlink (2 Mbps)
Sounding	1,600 ~ 2,400 soundings per day
Data Latency	15 minutes to 3 hours
Design and Mission life	5 years
Launch date	April 15, 2006

Table 2. The FORMOSAT-3 mission characteristics

3.2 System architecture

Figure 2 shows the FORMOSAT-3 system architecture. After two years’ in orbit operations, starting from mid-April 2008, the FORMOSAT-3 program switched and changed from two commercially operated ground stations at Fairbanks, Alaska and Kiruna, Sweden, operated by United Service Network (USN), to two new ground stations in Fairbanks and Tromso, Norway, operated by National Oceanic and Atmospheric Administration (NOAA). The constellation operation plans to use the new stations for the remaining five-year mission. The FORMOSAT-3 constellation system consists of the six microsattellites, a Satellite Operations Control Center (SOCC) in Taiwan, several tracking, telemetry and command (TT&C) ground stations, two data receiving and processing centers, and a fiducial network. There are two TT&C Local Tracking Stations (LTS), one located in Chungli, Taiwan and the other in Tainan, Taiwan, respectively. Currently there are four Remote Terminal Stations (RTS) to support the passes: Fairbanks Command and Data Acquisition Station (FCDAS), and Kongsberg Satellite Services Ground Station (KSAT), which are currently set as primary stations for the FORMOSAT-3 mission, and the Wallops station at Virginia, USA and the McMurdo station located in McMurdo, Antarctica. The latter two RTS stations provide partial support for the mission (Fong et al., 2009a; Rocken et al., 2000).

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 RO data is transmitted from the RTS via National Oceanic and Atmospheric Administration (NOAA) to CDAAC (COSMIC Data Analysis and Archive Center) located at Boulder, Colorado, USA, and TACC (Taiwan Analysis Center for COSMIC) located at Central Weather Bureau (CWB) in Taiwan. The fiducial GNSS data is combined with the occulted and referencing GNSS data from the GOX payload to remove the clock errors. All collected science data is processed by CDAAC and then transferred to TACC and other facilities for science and data archive (Wu et al., 2006).

Fig. 2. The FORMOSAT-3 system architecture

The processed results are then passed to the National Environmental Satellite, Data, and Information Service (NESDIS) at NOAA. These data are further routed to the weather centers in the world including the Joint Center for Satellite Data Assimilation (JCSDA), National Centers for Environment Prediction (NCEP), European Centre for Medium-range Weather Forecast (ECMWF), Taiwan CWB, UK Meteorological Office (UKMO), Japan Meteorological Agency (JMA), Air Force Weather Agency (AFWA), Canadian Meteorological Centre (Canada Met), French National Meteorological Service (Météo France), etc. They are made ready for assimilation into weather prediction models. The data is currently provided to weather centers within 180 minutes data latency requirement in order to be ingested by the operational weather forecast model (Fong et al., 2009b).

4. FORMOSAT-3 satellite design

Figure 3 illustrates the FORMOSAT-3 satellite designed by Orbital Science Corporation in a deployed configuration and its major components. The FORMOSAT-3 satellite avionic block

diagram is shown in Figure 4. The major subsystem elements of the spacecraft system are Payload Subsystem, Structure and Mechanisms Subsystem (SMS), Thermal Control Subsystem (TCS), Electrical Power Subsystem (EPS), Command and Data Handling Subsystem (C&DH), Radio Frequency Subsystem (RFS), Reaction Control Subsystem (RCS), Attitude Control Subsystem (ACS) and Flight Software Subsystem (FSW). The spacecraft bus provides structure, RF power, electrical power, thermal control, attitude control, orbit raising, and data support to the instrument (Fong et al, 2008a, 2008b & 2009a). Table 3 shows the spacecraft bus key design features.

Fig. 3. The FORMOSAT-3 satellite in deployed configuration and its major components.

Structure	Metal Matrix (AlBeMet)
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

Table 3. The FORMOSAT-3 spacecraft bus key design.

Fig. 4. The FORMOSAT-3 satellite avionic block diagram.

5. GNSS RO payload

5.1 Development of US GNSS RO receiver

In the United States, the development of space-based GPS RO receiver probing the atmospheric properties can be tracked to GPS/MET mission. Starting from 2000, the GPS occultation measurement instrument has evolved from TurboRogue geodetic receiver to a high-precision space-rated GPS receiver with dual-frequency tracking capability – “BlackJack” built by JPL. The Blackjack is an unclassified receiver, and uses a patented codeless processing technique that allows it to utilize the P-code signal without knowledge of the encryption code. The Blackjack is controlled through flexible and versatile software implementations of various receiver functions. Blackjack GPS flight receivers has been used on the following space missions such as SRTM (in 2000), SAC-C (in 2000), CHAMP (in 2000), JASON-1 (in 2000), VCL (in 2000), FEDSat (in 2001), ICESat (in 2001), and GRACE (in 2001) (Franklin et al., 2009). They have generated a lot of useful data in the areas of geophysical research.

FORMOSAT-3 carries the integrated GPS Occultation Receiver (IGOR or GOX) which is based on the NASA/JPL BlackJack space-borne GPS Receiver built by Broad Reach Engineering (BRE). The Pyxis receiver is the next generation of GNSS RO receivers based on the highly successful IGOR receiver. The Pyxis incorporates the lessons learned from the IGOR design and implements a number of improvements and upgrades. The addition of L2C and L5 frequencies and eventually Galileo frequencies provide increased Occultation Data and improved PVT resolution.

5.2 Development of European GNSS RO receiver

In Europe, Saab Ericsson Space (now RUAG), ESA, EUMETSAT built GRAS (GNSS RO Receiver for Atmospheric Sounding), which is an atmospheric sounding instrument carried by Metop satellites. GRAS has very low measurement noise. The mission is to provide data to operational meteorology and climate (Bonnedal, 2009). THALES develops ROSA (Radio Occultation Sounder for Atmosphere) to support international missions of OCEANSAT (India), and SAC-D (Argentina) (Fuggetta et al., 2009).

5.3 Development of advanced GNSS RO payload

Based on the 2007 National Research Council (NRC) publication report of "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," which is also referred to as Earth Sciences' Decadal Survey (SSB, 2007), and with the lessons learned and experience on GNSS RO receiver, the next generation of radio occultation instrument that will track additional new GNSS signals is under development. In addition to GPS signal, the developers also consider to include GLONASS (CDMA) and Galileo (E1, E5). The new advanced GNSS RO payload tentatively called TriG by JPL continues the evolution of hardware. The TriG hardware platform provides significantly more processing power than the IGOR platform to accommodate new signals and will have digital beam steering antenna capability, more channels, more memory available, and provide "wider" open loop tracking function (Franklin et al., 2009).³

6. Scientific contributions

Below we summarize the major scientific contributions of the current FORMOSAT-3 constellation mission using the GOX (or IGOR) payload (Yen & Fong, 2009; Anthes et al., 2008):

6.1 GNSS RO measurement technique

FORMOSAT-3 is the first mission that makes use of the revolutionary open-loop tracking technique. This allows more than 90% of the GNSS RO soundings to penetrate through the bottom 1 km over high latitudes, and more than 70% of soundings over the tropics. In comparison with earlier mission, such as CHAMP, only about 10% of the soundings penetrate below 1 km over the tropics.

FORMOSAT-3 is the first satellite mission that allows detection of the atmospheric boundary layer (ABL) from space. The RO soundings can be used to provide global measurements of ABL heights and their seasonal and geographical variations. These observations are crucial for the understanding of climate processes as well as tropical weather prediction.

During the early stage of constellation deployment, measurements from different FORMOSAT-3 satellites were used to determine the precision of RO measurements. Results from FORMOSAT-3 show that the precision of RO measurements is as high as 0.01%, and about an order of magnitude better than radiosonde system. Such a study was not possible before the launch of FORMOSAT-3.

³ <http://gnssro.geolinks.org/presentations>

6.2 Operational weather prediction and meteorological research

FORMOSAT-3 data were used to support operational weather prediction by many weather centers worldwide within a year after the data were released to the public. ECMWF started operational assimilation of RO data from FORMOSAT-3 on December 12, 2006, NCEP on 1 May 2007, and UKMO on 15 May 2007, and Météo France in September 2007. All these operational centers reported significant positive impacts with the assimilation of FORMOSAT-3 data. ECMWF showed that the temperature prediction at 100 hPa over the Southern Hemisphere was improved by 10% for the first two days of forecast, and the impacts remain positive through 10 day forecast.

FORMOSAT-3 data were found to be extremely valuable for the prediction of tropical cyclogenesis. The genesis of Hurricane Ernesto (2006), that took place in August 2006 over western Atlantic, was successfully predicted only when FORMOSAT-3 data were assimilated into the model. Because GNSS RO soundings are not affected by clouds and precipitation, RO data provided valuable information on the thermodynamic structure of the hurricane environment. The assimilation of FORMOSAT-3 data produced a much more realistic analysis of low-level moisture, which was crucial for the successful prediction of the genesis of the storm.

The study of the June 2007 Mei-Yu season showed that the assimilation of FORMOSAT-3 data significantly improved the analysis of the subtropical high-pressure system over the western North Pacific. As a result, more realistic moisture fluxes are predicted, and subsequently, more accurate rainfall prediction over the Taiwan area was produced. Typhoon forecast experiments during the 2008 typhoon season showed that the FORMOSAT-3 data improved the prediction of the typhoon track by about 15% over a three-day period. The data also improved the forecast of typhoon intensity, though as not as large as the track improvement.

6.3 Climate research

FORMOSAT-3 is the world's first GPS RO constellation mission that provides uniform global coverage. With six satellites and a 100-min orbit, it takes 16 days for FORMOSAT-3 to provide a uniform coverage for all latitude and all local times. In contrast, it would take 6 months for CHAMP mission to obtain uniform coverage in latitudes and local time. This provides a significant advantage in climate monitoring, as we minimize the aliasing of diurnal variations into signals of climate changes.

FORMOSAT-3 data have been used to evaluate the accuracy of traditional microwave satellite sounder data and radiosonde data, allowing systematic errors of these data to be detected. The comparison of FORMOSAT-3 data with other satellite and radiosonde data allows a robust climate record to be developed for long-term climate monitoring.

The comparison of retrieval results from four different GPS RO processing centers gives essentially the same trends and changes based on CHAMP and FORMOSAT-3 data. This highlights the robustness of GPS RO measurements for climate change detection.

6.4 Space weather – three dimensional observation

FORMOSAT-3 is a constellation formation that observes about 2500 vertical ionospheric electron density profiles per day that are globally and uniformly distributed. Having such a global and dense set of occultation observations, a three-dimensional ionospheric electron density can be constructed in a timely manner. A new era of ionospheric space weather

study has been envisioned and numerous new ionospheric structure and application can be investigated by this unique and powerful constellation.

7. FORMOSAT-3 follow-on mission

7.1 Supporting recommendations

As addressed in the Final Report of “Workshop on the Redesign and Optimization of the Space based Global Observing System,” the World Meteorological Organization (WMO) in 2007 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. The WMO also calls for the international collaboration to form global constellation for RO soundings with high number of small satellites in support of the Societal Benefits Areas (SBA) of the Global Earth Observation System of Systems (GEOSS) including weather and climate (GCOS, 2003, 2004, 2006a, & 2006b; WMO, 2007). Also from the Earth Sciences’ Decadal Survey (SSB, 2007), the committee on earth science and applications from space, Space Studies Board, recommended in the NRC decadal observing plan that NOAA should increase investment in identifying and facilitating the transition of demonstrably useful research observations to operational use. The committee also recommended that NOAA should transition to operations from three research observation. The three missions are vector sea-surface winds; GNSS radio occultation temperature, water vapor, and electron density soundings; and total solar irradiance. A GNSS RO mission is listed as one of the high-priority observations and missions identified by the committee.

The FORMOSAT-3 Follow-on/COSMIC-II⁴ mission will be a much improved constellation system for research and operation mission. The primary payload of the Follow-on satellite will be equipped with the GNSS RO receiver and will collect more soundings per receiver by adding tracking capability to receive signals from European GALILEO system and Russian’s Global Navigation Satellite System (GLONASS), which will produce a significantly higher spatial and temporal density of profiles. These will be much more useful for weather prediction models and also severe weather forecasting including typhoons and hurricane, as well as for related research in the fields of meteorology, ionosphere and climate (Yen & Fong, 2009; Fong et al., 2009b).

7.2 Mission planning

The FORMOSAT-3 Follow-on mission is contemplated to be a 12 satellites constellation. Figure 5 shows the proposed follow-on mission spacecraft constellation configuration. The primary mission objective is to increase RO data profiles to efficiently transition into the global reliable operational constellation system for related research and operational numerical weather prediction. The effective cover area per radio occultation profile per day is expected to be 200 km x 200 km (compared to FORMOSAT-3 mission at 450 km x 450 km) when all 12 new satellites are deployed into the constellation formation. The denser RO distribution will enhance the impacts for weather/climate research and forecast in the world. The expected radio occultation profiles in the follow-on mission should be no less than 8,000 on the average per day with the averaged data latency within 90 minutes (Yen & Fong, 2009; Fong et al., 2009b).

⁴ In this chapter the FORMOSAT-3 Follow-on/COSMIC-II mission was referred to as the FORMOSAT-3 follow-on mission for simplicity.

Eight satellites are at high inclination angle of 72° at 8 orbital planes (see the pink lines in Figure 5) and separated by 22.5° when complete constellation deployment. Four more satellites are at low inclination angle of 24° at 4 orbital planes (see the blue lines in Figure 5) and separated by 45° when complete constellation deployment. The satellites at high inclination angle will be launched in one or two clusters and be placed to one parking orbit. The mission operations team will then perform the spacecraft orbit raising 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 nineteen months for eight high inclination satellites and about seven months for four low inclination satellites, respectively.

The system will start to collect data collection once the satellite has completed the in-orbit checkout at parking orbits. Herein, we do not exclude the possibility to send the spacecraft by co-share piggyback conjunction with other mission satellites. The advantage of the proposed constellation design is that the collected data will be homogeneously distributed world-wide evenly within a 3-hour period.

Fig. 5. The FORMOSAT-3 Follow-on constellation

Figure 6 shows the proposed follow-on mission system architecture that requires three launches. The mission includes space segment, launch segment, ground segment, and science segment.

7.3 Space segment

The primary payload of the follow-on satellite will be equipped with next-generation GNSS RO receiver to collect more soundings per receiver with GPS, Galileo and GLONASS tracking capability, which include 29 operational USA GPS satellites, several Russia’s GLONASS (planning to have 18 satellites), and European GALILEO system (plan to have 30 GNSS satellites by 2013). The new GNSS RO receiver will be able to receive the USA GPS

L1/L2/L5 signals, also to receive the GALILEO E1/E5/E6 signals, and to receive GLONASS's L1/L2/L5 signals as well (Yen & Fong, 2009; Fong et al., 2009b).

Fig. 6. The FORMOSAT-3 Follow-on mission system architecture

Figure 7 shows the proposed FORMOSAT-3 Follow-on mission spacecraft avionic diagram. The benefit and improvement for the follow-on spacecraft will improve payload performance, better attitude performance, simplified operation, simplified orbit transfer, increased data storage, and modular design for additional compatible science payloads. The follow-on spacecraft bus intended design vs. FORMOSAT-3 design is shown in Table 4.

7.4 Ground segment

The NSPO SOCC will be responsible for the satellites flight operations during the mission. The SOCC will take charge of up linking commands, monitoring the state of health of satellite, analyzing the trending data, scheduling the passes of the TT&C stations, planning the constellation deployment, performing orbit thrusting and maintenance, conducting anomaly resolution, etc. SOCC will use Taiwan TT&C stations as well as the RTS for satellites telemetry and commanding (Yen & Fong, 2009; Fong et al., 2009b). More RTS stations or more antennas from the same RTS Station are desired in order to have data transmission at every orbit to reduce data latency. The current FORMOSAT-3 RTS stations at Fairbanks and Tromso are at good geo locations to cover every dump for the 72° inclination constellations, but need to add more antennas to fulfill 12 satellites data dump including 4 satellites at lower inclination angle. The EUMESAT ground stations, as example, have been considered as part of the receiving stations to reduce the data latency for the RO data retrieving. The SOCC uses the real time telemetry and the back orbit telemetry to monitor, control. The downlinked science data is transmitted from the RTS via NOAA to the two data receiving and processing centers.

Fig. 7. Proposed spacecraft avionic diagram of the FORMOSAT-3 Follow-on mission.

Function	Follow-on Design	FORMOSAT-3 Design	Benefit
Weight	~60 kg	61 kg (w/ Propellant)	Stacked or Single Launch Piggy-Back Launch
Attitude Control Performance	3-axis linear control Roll/Yaw: +/-1° (3σ) Pitch: +/- 1° (3σ) 3-Axis Gyro, 3-axis MAG, CSSAs, RWA x 3, Torque x 3, Star Tracker x 1	3-axis nonlinear control Roll/Yaw: +/-5° (1σ) Pitch: +/- 2° (1σ) Earth Sensor x 2, CSSA x 8, RWA x 1, Torque x 3, GPS Bus Receiver PL x 1	Improved PL Performance Better Attitude Performance Simplified Operation Simplified Orbit Transfer
Science Data Storage	>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 (Al)	Metal Matrix (AlBeMet)	Cost Reduced
Payload Interface	Main PL: GNSS RO Rcvr Science PL (Optional)	Primary PL: GOX Secondary PL: TIP, TBB	Modular Design Cost Reduced

Table 4. Proposed FORMOSAT-3 Follow-on spacecraft bus design vs. FORMOSAT-3 design.

7.5 Science segment

The data receiving and processing centers will be CDAAC and TACC. All collected science data is processed by CDAAC and then transferred to TACC and other facilities for operations, science, and data archival. The processed atmospheric profiles are distributed in near real time to international weather centers from CDAAC through NOAA/NESDIS. These data are currently provided to weather centers within 90 minutes after satellite on-orbit science data collection in order to be ingested by the operational weather forecast models. The data from fiducial network is part of inputs to data processing center.

8. Conclusion

The GNSS RO mission represents a revolution in atmospheric sounding from space, with precise, accurate, and all-weather global observations useful for weather, climate, and space weather research and operations. The FORMOSAT-3 constellation has been unanimously regarded by the major user community as “the world's most accurate, precise, and stable atmospheric thermometer in space.” The success of the FORMOSAT-3 mission has initiated a new era for the operational GPS RO sounding applications in the world.

With the success of FORMOSAT-3, there is a strong interest from both research and operational communities to maintain and enhance the existing FORMOSAT-3 mission. Observing system simulation experiments (OSSE) have been conducted to evaluate the impact of the GNSS RO follow-on mission on the prediction of typhoons in the vicinity of Taiwan. OSSE experiments based on Typhoon Shanshan (2006) indicated that the proposed follow-on configuration provided a significant improvement over the existing FORMOSAT-3 for typhoon prediction in terms of track, intensity and rainfall prediction. These preliminary results strongly support the use of the proposed follow-on design for the FORMOSAT-3 Follow-on mission.

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