THE NEXT GENERATION GNSS RADIO OCCULTATION CONSTELLATION MISSION

Chen-Joe Fong[*1], Jer Ling[2], Nick L.Yen[3], Vicky Chu[4], G.-S. Chang[5], Kendra Cook[6],
Cucurull Lidia[7], Dave Ector[8], Dan Mamula[9], and Peter Wilczynski[10]
[1-5]National Space Organization (NSPO), F8, No. 9, Prosperity 1st Road, HsniChu 30078, Taiwan
[6]C^2 International, LLC, 709 S Main St., Kimball, SD 57355, USA.
Also Integrity Applications Incorporated, 5160 Parkstone Drive, Chantilly, VA 20151, USA
[7-8]National Oceanic and Atmospheric Administration (NOAA), Camp Spring, MD 20746, USA
[9-10]National Oceanic and Atmospheric Administration (NOAA), SSMC1, 1335 East West Hwy, Silver Spring, MD 20910, USA

[1]FORMOSAT-7 System Lead; Tel: +886-3-578-4208#9202; E-mail: cjfong@nspo.narl.org.tw

[2]FORMOSAT-7System Management Lead; Tel: +886-3-578-4208#8441; E-mail: jl@nspo.narl.org.tw

[3]FORMOSAT-3 Program Director; Tel: +886-3-578-4208#1053; E-mail: longine@nspo.narl.org.tw

[4]FORMOSAT-7 Acting Program Director; Tel: +886-3-578-4208#1581; E-mail: vicky@nspo.narl.org.tw

[5]Director General, also FORMOSAT-7 Program Director; Tel: +886-3-578-4208#8102;
E-mail: gschang@nspo.narl.org.tw

[6]COSMIC-2 Consultant; Tel: +1-703-652-4809; E-mail: kcook@c2iconsulting.com

[7]COSMIC-2 Chief Scientist; Tel: +1-720-427-3588; E-mail: lidia.cucurull@noaa.gov

[8]COSMIC-2 Chief System Engineer; Tel: +1-720-427-3588; E-mail: dave.r.ector@noaa.gov

[9]COSMIC-2Program Manager, Tel: +1-301-713-2789#142; E-mail: dan.mamula@noaa.gov

[10]Deputy Director, Satellite and Ground Systems Program, NESDIS; Tel: +1-301-807-3524;
E-mail: peter.wilczynski@noaa.gov

KEY WORDS:FORMOSAT-7, COSMIC-2, GNSS, Radio Occultation

ABSTRACT: FORMOSAT-3/COSMIC (the Constellation Observing System for Meteorology, Ionosphere, and Climate) is a joint U.S.-Taiwan mission that was launched in April 2006. The constellation consists of six satellites in Low Earth Orbit (LEO) at 72-degree inclination. It is the world's first operational Global Positioning System Radio Occultation (GPS-RO) mission for global Earth weather forecasting; climate monitoring; and atmospheric, ionospheric, and geodetic research. The GPS-RO data has been demonstrated to be extremely valuable to the climate, meteorology, and space weather communities. FORMOSAT-3/COSMIC has proven to increase the accuracy of the predictions of hurricane behavior, significantly improve long-range weather forecasts, and monitor climate change with unprecedented accuracy. FORMOSAT-3/COSMIC unfortunately has reached the end of its 5-year design life in 2011, and the critical real-time satellite observing capability has already begun to degrade and become inoperative. As a result and in an effort to reduce the global GPS-RO data gap, the U.S. and Taiwan intend to jointly develop and launch FORMOSAT-7/COSMIC-2, a high-reliability next generation follow-on satellite system to FORMOSAT-3/COSMIC. It is intended to provide continuity of the next generation of Global Navigation Satellite System (GNSS) RO data to users. FORMOSAT-7/COSMIC-2 is expected to be a much improved system consisting of a new constellation of 12 satellites for an operational mission. The mission payload will be a TriG GNSS-RO receiver and will collect more data points per receiver by adding Europe's GALILEO system and Russia's Global Navigation Satellite System (GLONASS) tracking capability. The constellation is comprised of 6 satellites at 72-degree inclination, and 6 satellites at 24-degree inclination, which will enhance observations in the equatorial region over what is currently being collected with FORMOSAT-3/COSMIC. This constellation will produce more than 8,000 soundings per day, compared to the approximate 2,000 soundings per day currently produced by FORMOSAT-3/COSMIC. This paper discusses the FORMOSAT-7/COSMIC-2 system in more detail, including details on the constellation configuration and technologies that are used to meet the program objectives. Current status of the program is also provided.

1. INTRODUCTION

FORMOSAT-3/COSMIC(the Constellation Observing System for Meteorology, Ionosphere, and Climate) mission,is a joint U.S.-Taiwan experimental “science mission”for demonstrating the usefulness of Radio Occultation (RO) in operational numerical weather prediction, climate monitoring, and space weather forecasting. The FORMOSAT-3constellation consisting of six satellites in Low Earth Orbit (LEO) at 72-degree inclinationwas launched in April 2006. The launch of the FORMOSAT-3 mission marked the beginning of a new era of Global Positioning System (GPS) atmospheric remote sensing by using Radio Occultation (RO) technique.

The FORMOSAT-3[*] is the world’s first operational GPS-RO mission for global Earth weather forecasting; climate monitoring; and atmospheric, ionospheric, and geodetic research (Liou, 2007). The FORMOSAT-3mission has retrieved 2.7 million soundings, serving more than 1,600 registered users from 57 countries. On average, FORMOSAT-3 provides 1,500 ~ 2,000 GPS-RO soundings per day, uniformly distributed around the globe. Approximately 90% of the data are available within 3hours of observations to support operational numerical weather prediction. Several worldwide weather operation centers have ingested FORMOSAT-3 data into their operational weather forecast models and forecasting abilities have been significantly improved. These include the NOAA National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), the Central Weather Bureau (CWB) of Taiwan, the United Kingdom Meteorological Office, the Japan Meteorological Agency (JMA), the United States Air Force Weather Agency (AFWA), the Canadian Meteorological Centre (Canada Met), Météo-France, the Bureau of Meteorology of Australia and others (Liou, 2007). The FORMOSAT-3 constellation has successfully improved global weather analyses and predictions, the accuracy of weather prediction models, and the understanding of tropical, mid-latitude and polar weather systems and their interactions.

NOAA/NCEP started assimilating observations from the FORMOSAT-3 mission into its global data assimilation system in May 2007. Results demonstrated that the use of GPS RO observation provides information on the state of the atmosphere not contained in other satellite instruments. This is due to the unique characteristics of the GPS RO measurements: unbiased observations, high accuracy, high vertical resolution, and equal accuracy over land than over ocean, and all-weather capability. The benefits of FORMOSAT-3 are very significant in terms of weather forecast skill. The assimilation of GPS RO observations improved anomaly correlation scores for the geopotential heights and reduced model biases and root-mean-squared errors of temperature and wind fields. From Figure 1 it was observed that 8 hours improvement at Forecast Day 4 and more than 5 hours improvement during Forecast Day 7. There are particularly significant improvements over the oceans and in Southern Hemisphere. These benefits are expected to increase with a larger constellation of GPS RO satellites. (Cucurull, 2008).

Unfortunately, the FORMOSAT-3 mission has reached the end of its 5-year design life in 2011, and the critical real-time satellite observing capabilities have already begun to degrade as satellites reach their end of life and become inoperative (Fong, 2011). The World Meteorological Organization (WMO) has recommended continuing RO observations operationally and the scientific community urges the continuation of the current mission and the planning for a follow-on operational mission. As a result and in an effort to reduce the global GPS-RO data gap, Taiwan and the U.S. collaborate to jointly develop, launch and operate a follow-on satellite mission to FORMOSAT-3, referred to as FORMOSAT-7/COSMIC-2 mission, through their agencies the National Space Organization (NSPO) and the National Oceanic and Atmospheric Administration (NOAA), respectively. Figure 2 depicts the joint mission collaborative framework (Cook, 2011).

2. FORMOSAT-7CONSTELLATION AND MISSION OVERVIEW

The objectives of the FORMOSAT-7[**]mission are similar to that of FORMOSAT-3: to reliably provide data for numerical weather prediction; to perform space weather monitoring; and to trend climate change. FORMOSAT-7/COSMIC-2 will meet its objectives by intercepting Global Navigation Satellite System (GNSS) signals including U.S.’s GPS, Europe’s Galileo, and Russian’s Global Navigation Satellite System (GLONASS) signals with an advanced satellite-based RO receiver and inferring the deviations in each signal's straight-line path caused by temperature, pressure, moisture, and electron density gradients, as illustrated in Figure 3 (Yen, 2010).

---

[*] In this paper the FORMOSAT-3/COSMIC-2 mission is referred to as the FORMOSAT-3 mission for simplicity.

[**] In this paper the FORMOSAT-7/COSMIC-2 mission is referred to as the FORMOSAT-7 mission for simplicity.

FORMOSAT-7 is a much improved constellation system consisting of a new constellation of 12 satellites for an “operational mission” transition from FORMOSAT-3. The FORMOSAT-7 mission is a high-reliability next generation follow-on satellite system to FORMOSAT-3. The FORMOSAT-7 mission architecture is shown in Figure 4. The constellation is comprised of 6 satellites at 72-degree inclination, and 6 satellites at 24-degree inclination, which will enhance observations in the equatorial region over what is currently being collected with FORMOSAT-3. In addition, NSPO will develop one self-reliant satellite as an in-orbit spare satellite. This constellation will produce more than 8,000 soundings per day, compared to the approximate 1,500~2,000 soundings per day currently produced by FORMOSAT-3 due to the increase of the number of satellites in the FORMOSAT-7 constellation and the system’s ability to track three navigation systems’ signals versus FORMOSAT-3’s ability to track one.

Figure 5 illustrates the comparison of sounding distribution over a 3-hour period between FORMOSAT-3 and FORMOSAT-7. The constellation configuration was chosen because it provides the most uniform global coverage. Figure 6 compares the constellation configuration of FORMOSAT-3 and FORMOSAT-7. The more dense GNSS-RO distribution will enhance the societal and scientific impacts for weather/climate research and forecasting worldwide, with particularly enhanced benefits in the equatorial region. The expected average data latency of radio occultation profiles for the FORMOSAT-7mission is 45 minutes.

The spacecraft design and mission payload instrument are improved from the current FORMOSAT-3 system with operational robustness. The mission payload is a TriG GNSS-RO receiver and will collect more RO data points by adding GALILEO and GLONASS tracking capability, which will produce a significantly higher spatial and temporal density of profiles over tracking GPS signals alone. These will be much more useful for weather prediction models and for severe weather forecasting (including typhoons and hurricane forecasting), as well as for related research in the fields of meteorology, ionosphere, and climate. The planned science payloads of the first six satellites are the VIDI (Velocity, Ion Density and Irregularities Instrument) Instruments and RF Beacon instrumentfor space weather application. The planned science payloads of the second six satellites will be provided by NSPO.

Similar to the current FORMOSAT-3 satellites, the current plan is to use 2 launch vehicles with 6 satellites on each vehicle – either in the class of Minotaur-IV plus, or Falcon-9. They will be launched and then positioned into their final orbits.In order to achieve the data latency requirement of 45 minutes, it is planned that there will 2 data downlinks per orbit, which will reduce the data latencyconsiderably. Consequently, FORMOSAT-7requires more satellite ground stations for receiving the data. As with FORMOSAT-3, the data collected by FORMOSAT-7will be downlinked to the tracking station, then transferred to the U.S. Data Processing Center (DPC) as well as to the Taiwan Data Processing Center (TDPC). The processed products will then be provided to NOAA Global Transmission System (GTS) for distribution to the worldwide weather prediction centers. The NSPO Satellite Operations Control Center (SOCC) will provide command and control of the FORMOSAT-7 constellation. In summary, the current FORMOSAT-7mission baseline is shown in Table 1. Table 2 shows the satellite design requirements comparison for FORMOSAT-7 and FORMOSAT-3.

3. FORMOSAT-7 CURRENT STATUS

Both of the U.S.-Taiwan parties signed theTECRO-AIT agreementthat is the authorizing document for the joint programin May 2010. The joint mission is anticipated to be a collaborative mission and both parties will implement the mission with work share based on equitable contribution. Each party will contribute to the funding in proportion to their respective participation in such activities. The Joint FORMOSAT-7 Program Office had held the Feasibility Design Review (FDR) in May 2010, the Mission Definition Review (MDR) in August 2010, the Systems Requirements Review (SRR) in April 2011, and the Systems Design Review (SDR) in June of 2011, respectively. Three major documents, which are including the Joint Level One Performance Requirements Document (JL1PRD), the Joint Management Control Plan (JMCP), and Joint Mission Requirements Documents (JMRD), are complete and are inthe final approval process. Also the Joint Systems Requirements Document (JSRD) has been drafted and iscurrently being edited and approved.

JSRD will be flown down to various segment requirements. The Spacecraft Bus Systems Requirements Document (BSRD), and the Mission and Science Payload to Spacecraft bus interface requirements documents (IRDs), Ground Segment-to-Spacecraft IRD, and Launch Vehicle-to-Spacecraft IRD are incorporated into the technical package of spacecraft bus Request for Proposal (RFP).NSPO officially sent out a Spacecraft Request for Information (RFI) in July 2010 and Request for Quotation (RFQ) in March and May 2011, respectively (Chu, 2011). NSPO is anticipating releasing a Spacecraft Request for Proposal (RFP) in September 2011 and also is planning on completion of the spacecraft contractor selection process by end of 2011.

The FORMOSAT-7 program in Taiwan is executed and approved under the second phase of the 15-year "National Space Technology Long Term Development Program," and it's also listed as one of the two major axes depicted in the "Year 2010-2014 Space Technology Long Term Development Mid-Term Program." The detailed statement of work and responsibilities is specified the "Joint Management Control Plan." The responsibilities on the Taiwan parties include systems engineering and design, spacecraft bus development, satellite operation and control, and satellite data processing and utilization. The responsibilities on the U.S. parties include launch, ground systems, mission payload, and satellite data processing and utilization. The main execution strategies of this program will be focused in the following four areas: increase of the international research cooperation, establishment of core technology capabilities, strengthening of satellite data processing, and enhancement of data utilization.

In the area of the core technology capabilities buildup, NSPO also plans to develop an additional self-reliant spacecraft to be used as an on-orbit spare satellite as well as for technology qualification. NSPO will use this satellite as aspacecraft platform to test the NSPO-built newly developed avionic devices and navigation key components for the next generation follow-on mission. As in the area of GNSS-RO data processing and utilization, with the collaboration with US parties, NSPO will partner with CWB, Taiwan Typhoon and Flood Research Institute (TTFRI), GPS Scientific Application Research Center (GPS-ARC), and other institutes and organization, to build a Taiwan GNSS-RO data processing center to process, archive and distribute data from the FORMOSAT-7. This system will serve as a verification platform for GNSS-RO data, and enhance domestic independency of the GNSS-RO data processing and buildup capability, which will promote the program to have greater societal impacts to the livelihood and civil benefits in Taiwan.

4. CONCLUSION

FORMOSAT-3's contribution to weather prediction is considered to be "significant" by the Taiwan CWB and U.S. NOAA's National Weather Service (NWS, and represents an immense benefit to worldwide forecasting capability. This data is not available globally from other sources, and allowing this data to deteriorate due to the FORMOSAT-3 satellites' end-of-life will result in a significant diminution of performance of the NOAA and CWB's Numerical Weather Prediction (NWP) models. This will result in diminished weather prediction capability that may lead to increased costs and loss of life due to natural disasters. The realization of FORMOSAT-7 will continue to fulfill this important mission and further increase weather forecast capabilities.

ACKNOWLEDGEMENTS

The authors would like to thank the contributions of the FORMOSAT-3/COSMIC program, the FORMOSAT-7/COSMIC-2 program, systems engineering team; the Taiwan science teams; and the following cooperation partners: NSC, NARL, CWB, NSF, UCAR, NCAR, JPL/NASA, USAF, Aerospace Corp., and NOAA.

REFERENCES

Chu, V., Ling, J., Lin, T., Fong, C.-J., Huang, F.-T., and Chang, G.-S., 2011. FORMOSAT-7/COSMIC-2 System Overview. 5th FORMOSAT-3/COSMIC Data Users Workshop and International Conf. on GPS Radio Occultation (ICGPSRO) 2011, Taipei, Taiwan, S9-03. (Invited Paper)

Cook, K., Wilczynski, P., Fong, C.-J., Yen, N. L., and ChangG.-S., 2011. The Constellation Observing System for Meteorology Ionosphere and Climate Follow-On Mission. 2011 IEEE Aerospace Conf. Proceedings, Big Sky, MT.

Cucurull, L., 2008. Assimilation of GPS radio occultation measurements at NCEP. GRAS SAF Workshop on Applications of GPSRO measurements, 16-18 June 2008. (Invited Paper)

Fong, C.-J.,Whiteley, D., Yang, E., Cook, K., Chu, V., Schreiner, B., Ector, D.,Wilczynski, P., Liu, T.-Y., and Yen, N. L., 2011. Space and Ground Segment Performance and lessons learned of the FORMOSAT-3/COSMIC Mission: Four Years in Orbit.Atmos. Meas. Tech., 4, pp.1115–1132. doi:10.5194/amt-4-1115-2011.

Liou, Y.-A., Pavelyev, A. G., Liu, S.-F., Pavelyev, A. A., Yen, N. L., Huang, C.-Y., and Fong, C.-J.,2007. FORMOSAT-3 GPS Radio Occultation Mission: Preliminary Results. IEEE Trans. on Geosci. and Rem. Sens., 45 (10), pp. 3813-38826. doi:10.1109/TGRS.2007.903365.

Yen,N. L., Fong, C.-J., Chu,C.-H., Miau, J.-J., Liou, Y.-A., and Kuo, Y.-H., 2010. Global GNSS Radio Occultation Mission for Meteorology, Ionosphere & Climate. In: Aerospace Technologies Advancements, edited by Arif,T. T., ISBN 978-953-7619-96-1, pp. 241-258, INTECH, online available from http://www.sciyo.com/. (Invited Paper)

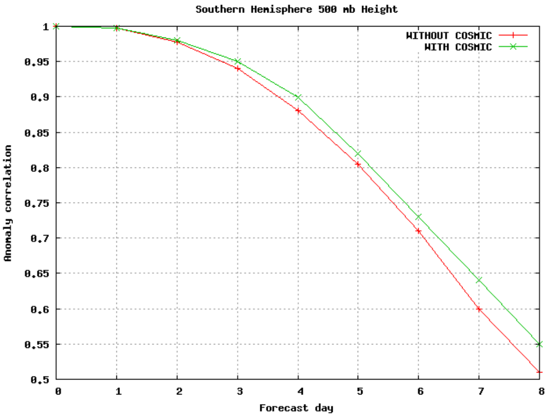

Figure 1. Prediction Accuracy Improvement on Global Prediction Model by Assimilating FORMOSAT-3 RO Data into NOAA/NCEP's Global Data Assimilation System.

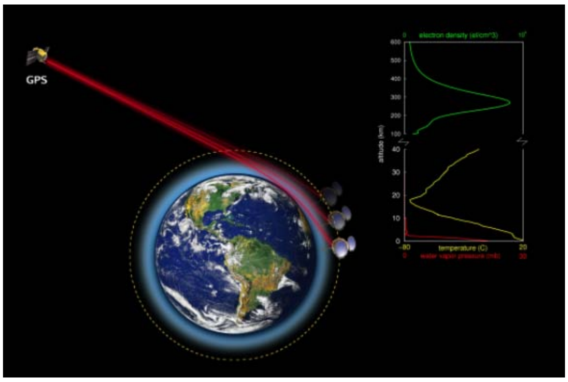

Figure 3. Illustration of FORMOSAT-3 GNSS Radio Occultation Technique.

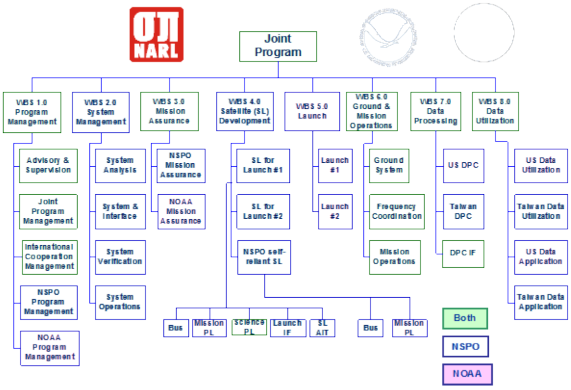

Figure 2. Joint Mission Collaboration framework of NSPO and NOAA

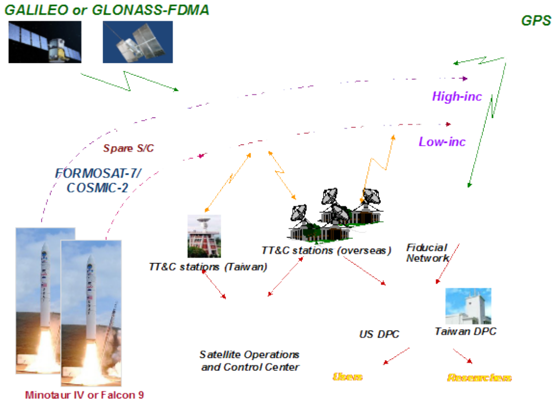

Figure 4. The FORMOSAT-7mission architecture

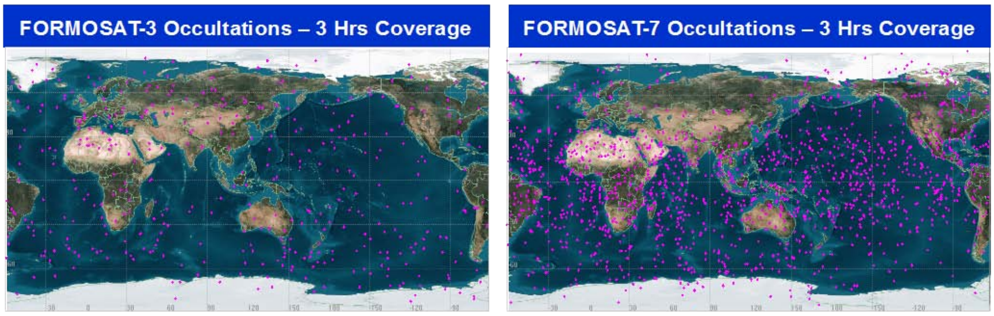

Figure 5. Sounding Distribution Comparison for FORMOSAT-3 vs. FORMOSAT-7.

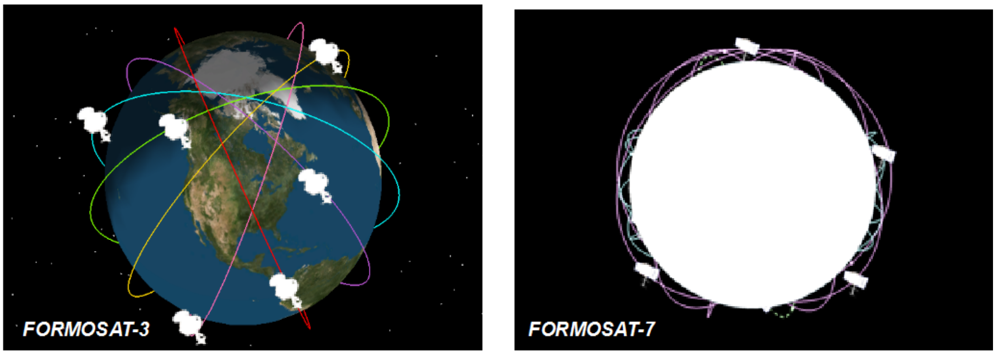

Figure 6. Constellation Configuration for FORMOSAT-3 vs. FORMOSAT-7.

Table 1 FORMOSAT-7Mission Baseline.

FORMOSAT-7	First Launch	Second Launch
Mission Objectives	To be achieved after Full Operational Capability: • 8,000 atmospheric sounding profiles per day • 45-min data latency	
Constellation	6 spacecraft to low-inclination-angle orbit (mission altitude 520~550 km)	6+1 spacecraft to high-inclination-angle orbit (mission altitude 720~750 km)
GNSS RO Payload	TriG	TriG
Scientific Payload	• Velocity, Ion Density and Irregularities Instrument • RF Beacon Instrument	To be determined
Launch Vehicle	Minotaur IV+ or Falcon 9	Minotaur IV+ or Falcon 9
Launch Schedule (as a goal)	2015 Q3-Q4	2017 Q3-Q4
Communication Architecture	Via ground station	

Table 2 FORMOSAT-7Satellite Design

Function	FORMOSAT-7 Design	FORMOSAT-3 Design
Spacecraft Bus Reliability	>0.66 for 5 Years	>0.68 for 2 years
Weight	150~200 kg	61 kg (w/ Propellant)
Attitude Control Performance	3-axis linear control Roll/Yaw/Pitch:+/-1° (3σ) Attitude Knowledge: better than 0.05° (3σ), all axis GPS Bus Receiver x 1	3-axis nonlinear control Roll/Yaw: +/-5° (1 σ) Pitch: +/- 2° (1 σ) GPS Bus Receiver PL x 1
Data Storage	Bus: > 256 Mbits Science: >2Gbit	128 Mbyte
Avionics Architecture	Centralized Architecture Radiation - Hardness	Distributed Architecture (Multiple Avionics Boxes)
Electrical Power	10 % Power Margin Lithium Ion Battery Voltage Based Algorithm	10 % Power Margin Ni-H2 Battery dMdC Charging Algorithm
Payload Interface	Mission PL: TriG Science PL: VIDI & RF Beacon	Primary PL: GOX Secondary PL: TIP, TBB