

Earth Observations with Orbiting Thermometers – Prospective FORMOSAT-3/COSMIC Follow-On Mission

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ABSTRACT

In the previous century, the rapid development of electronics and computers enable the sounding balloons to probe into the sky to collect atmospheric data to forecast the weather and monitor the climate changes. Those balloon soundings are limited above the landmass and much fewer above oceans and the Polar Regions. In the 21st Century, as the booming of micro-satellite constellation, FORMOSAT-3/COSMIC constellation has brought the atmospheric measurements from local to global and even penetrated into the ionosphere to collect data for space weather. The remarkable impacts of the globally collected data from FORMOSAT-3/COSMIC have been demonstrated. The temperature structure over the Polar Regions has been constructed at the first time and the measurements have improved the regional weather model. It has also proven that the forecast accuracy including the severe weather such as accumulated rainfalls and the forecast of hurricane and typhoon paths, etc., can be enhanced. FORMOSAT-3/COSMIC Follow-On mission is a project to carry on FORMOSAT-3/COSMIC mission, which design life ends in 2011. The mission will collect more data so that the sounding distribution is denser. The effective coverage area of one sounding in the contemplated 12- or 18-micro satellites constellation of the Follow-On mission can be reduced from 550 km x 550 km (FORMOSAT-3/COSMIC's capability) to 250 km x 250 km. In this paper we will address the lessons learned from FORMOSAT-3/COSMIC constellation, both in space and ground segments, and how to proceed to the Follow-On mission to become an operational constellation as the most accurate orbiting thermometers to measure the atmosphere and ionosphere more optimally and efficiently.

INTRODUCTION

FORMOSAT-3 mission, also known as COSMIC (Constellation Observing Systems for Meteorology, Ionosphere, and Climate), is the third project of FORMOSAT series implemented by National Space Organization (NSPO) at Taiwan, ROC. It is an international collaboration of Taiwan and the United States and the satellites have been successfully launched on April 15, 2006. The constellation has collected over 1020000 atmospheric sounding data and 1270000 ionospheric profiles as is of May 31, 2008 since launch. The most observable impacts are on Polar Regions; the scientists have identified the errors of Antarctica regional model¹ and first collected the temperature structure over the Antarctica². There is also remarkable contribution to weather forecast. Several weather centers such as NCEP (National Centers for Environmental Prediction) of the United States, ECMWF (European Centre for Medium-Range Weather Forecasts), UKMO (UK Meteorology Office), Météo France, and JMA (Japan Meteorological Agency) have injected the assimilation data into the weather forecast model to improve the accuracy of weather prediction. Numerous case studies have shown the data

make positive impacts on the path prediction of typhoon and hurricane.^{1,3,4} FORMOSAT-3/COSMIC data have also demonstrated the evidence on the plasma cave theory.^{5,6} Scientists keep analyzing the data to explore atmospheric river, sign of earthquake, and so on.

The topics of climate change, unusual severe weather and global warming issues have drawn international attention. These topics are not only widely discussed in the regional and international workshops, but also advocated its great impacts to the nature in the public media. As Dr. D. E. Hinsman, Director of the WMO (World Meteorological Organization) Space Programme, addressed in the Final Report of "Workshop on the Redesign and Optimization of the Space based Global Observing System" held at WMO Headquarters, Geneva, 21-22 June 2007, that "the Radio Occultation (RO) sounding provides accurate temperature information for the high troposphere and the lower stratosphere domains, and call for the international collaboration to form global constellation for RO soundings with high number of small satellites."

The FORMOSAT-3/COSMIC is with the following features:

- 6 satellites are in six orbital planes to take the data near evenly distributed globally.
- The data is transmitted to the ground station every revolution of each spacecraft.
- The ground data processing is prompt to make ~ 86% of data with latency less than 3 hours fed into weather forecast model.

The average 135-minute data latency make FORMOSAT-3/COSMIC as a quasi-operational constellation. There would be no doubt the FORMISAT-3/COSMIC Follow-On project should aim to be an operational weather satellites. The goals of the Follow-On project are:

- Constellation to achieve the data distributed globally more quickly.
- Better data latency.
- More robust satellite to support the mission.
- Capable payload to receive signal not only from GPS signal but also from GALELIO or GLONASS.

This paper will address how the Follow-On project is designed to achieve the goals listed above.

FORMOSAT-3/COSMIC APPLICATION

The FORMOSAT-3/COSMIC RO data is applied to a variety of research areas in meteorology, climate, space weather, and geodesy. More than 2000 atmospheric/ionospheric soundings are acquired daily, providing measurements of global 3-D atmospheric structure up to 40 km and ionospheric structure up to 800 km altitude.

With the FORMOSAT-3/COSMIC data, ECMWF of Europe shows the accuracy of their forecast is improved by about 11% in the southern hemisphere at 100 mb.⁴ The NCEP of the United States and the Central Weather Bureau (CWB) of Taiwan show the similar analysis results. FORMOSAT-3/COSMIC is also the first satellite can observe the atmospheric boundary layer, which contains information on low-level water vapor.¹

One of the most visible achievements are that the capability to take measurements over the Polar Region. It is found the region forecast model over the Antarctica was colder than actual and the scientists have begun to

make the temperature correction based on the addition of data from FORMOSAT-3/COSMIC occultation measurements.⁷ The data collected from June to September of 2006 have been used to construct the temperature profile of Antarctica through the stratosphere. These are the first continuous profiles of temperature sturcture over Antarctic winter. Scientists have found the vertex effect of ozone depletion.²

The author constructs the temperature structure by data retrieved from the FORMOSAT-3/COSMIC and shows it in Figure 1 as an example. The data are from the points within 5-10 km at around 1200 UT in April 2008.

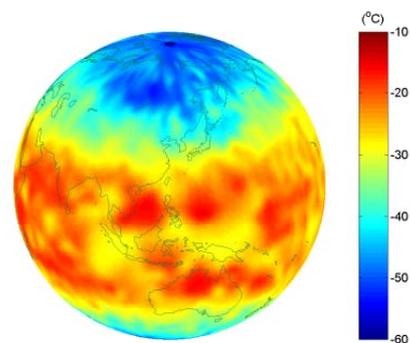


Figure 1: Atmospheric Temperature Structure over the Globe. The Data Are from the Points within 5-10 km at around 1200 UT in April 2008.

The global ionospheric density distribution can be obtained by cumulating monthly occultation observations in two-hour and taking the median value in each 2.5-by-2.5 degree grid (longitude-by-latitude) in every 1 km altitude range. Figure 2 shows 50 km integrated electron content in series of altitude intervals at around 1200 LT in July-August, 2007.

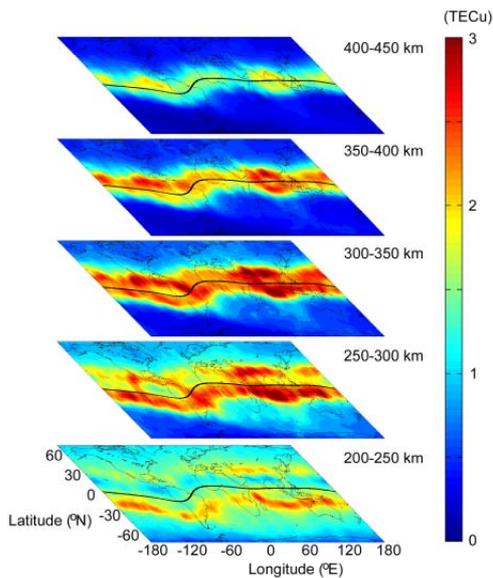


Figure 2: 50 km Integrated Electron Content in Series of Altitude Intervals at around 1200 LT in July-August, 2007.

FOLLOW-ON CONSTELLATION AND OCCULTATION POINTS

As we begin to analyze the new mission, let's review the number of the current FORMOSAT-3/COSMIC mission has achieved. The RO payload carried by FORMOSAT-3/COSMIC is called GOX (Gps Occultation eXperiment), it receives GPS signals. Currently, the constellation can collect about 3000 measurements per day as all six GOXes are at 100% duty. After data being processed, the retrieved good atmospheric sounding is about 70 % of measurements. In other words, there are approximately 2100 soundings per day. Converted to the equivalent area covered by one sounding, it would be 500 km x 500 km. It should be noted that the length of a front is about several hundred to several thousand kilometers and the radius of a cyclone is about several hundred kilometers. The coverage scale for FORMOSAT-3/COSMIC may or may not take one measurement at the point of interest area. Therefore, the Follow-On mission should have more soundings distributed more homogeneously over the globe to make the system to be an operational constellation to weather centers.

The analysis of inclination angle vs. measurement distribution has been studied and published by authors.⁸ It is realized the inclination angle of 72-deg of

FORMOSAT-3/COSMIC will make the measurements in low latitude area a little bit sparse. Therefore, there will be a need to add some satellites at low inclination. In the baseline of Follow-On mission, if the funding can support 12 micro-satellites, we would propose the following constellation with 3 orbit planes.

- Orbit plane 1 – one launch to deliver 4 satellites to high inclination angle (72 degrees for this analysis), and use small thrust burns to separate the Argument Of Latitude (AOL).
- Orbit plane 2 – another launch to deliver 4 satellites to high inclination angle (72 degrees for this analysis). The orbit plane 2 and orbit plane 1 is separated by 90 deg at equator. It is planned to use small thrust burns to separate the AOL.
- Orbit plane 3 – the other launch to deliver 4 satellites to low inclination angle (24 degrees for this analysis), and use small thrust burns to separate the AOL.

The Follow-On constellation will be as Figure 3. The orbit altitude could be 700 km ~ 850 km. In the analysis, 800 km is assumed here for easy comparison with FORMOSAT-3/COSMIC.

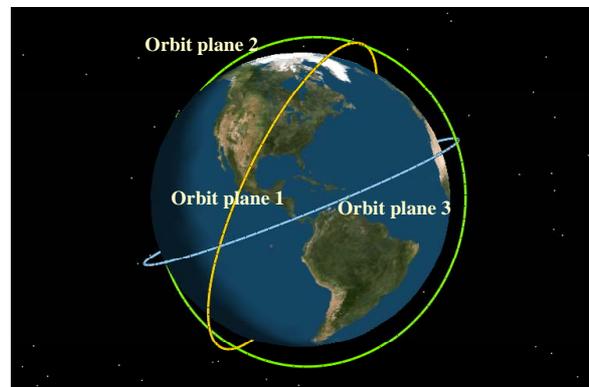


Figure 3: Follow-On Constellation

As for the RO receiver, Pyxis in one of the candidates. This receiver is manufactured by Broadreach and it is capable of receiving both GPS and GALILEO signals. We use its capability as the baseline of the analysis.

The analysis results are depicted in Figure 4, the measurements obtained by Orbit plane 1 and 2 are marked in blue dots and the measurements from Orbit plane 3 are marked as pink ones. One can see how low inclination satellites supplement the measurements at low latitudes. The calculation shows the system can provide about 8000 profiles per day. In other words, the equivalent covered area of one sounding is reduced to 250 km x 250 km.

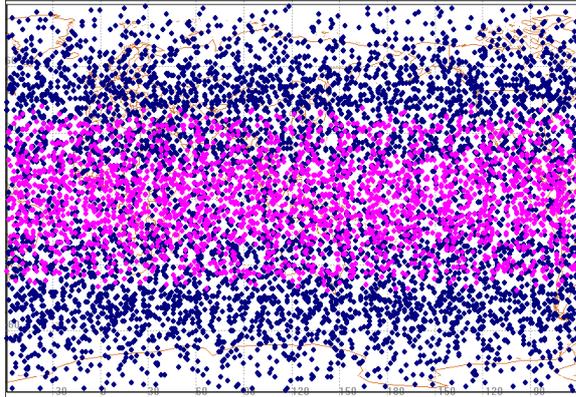


Figure 4: Occultation Point Distribution with 12-Satellite Constellation

With the variation of the possible concluded funding of the Follow-On project, we also calculate the occultation points at 7, 12, and 18 satellites of the constellation. They are listed in Table 1.

Table 1: Expected Atmospheric Profiles vs. Different Constellation and Different Receiver Capability

Satellites in constellation	GPS	GPS+GALILEO	GPS+GALILEO+GLONASS
7	2440	4790	6650
12	4160	8070	11110
18	6250	12110	16670

The calculation is based on 28 GPS satellites, 27 GALILEO satellites, and 21 GLONASS satellites with the assumption of 350 effective atmospheric profiles if the satellite is with similar performance with FORMOSAT-3/COSMIC. Please note that the estimation is based on the following ideal conditions: no spacecraft emergency, no anomaly on ground segment, and no errors from operation segment.

DATA LATENCY ANALYSIS

The Follow-On mission is defined as an operational constellation and its main application is on weather forecast, therefore, the data latency is a key element in the program. Before we specify the data latency for the mission, let us examine the minimum resources we need to receive the data dump for every revolution as defined in FORMOSAT-3/COSMIC’s specification. The RAAN (Right Ascension of Ascending Node) and AOL (Argument of Latitude) of Orbit plane 1 and 2 are designed as shown in Figure 5.

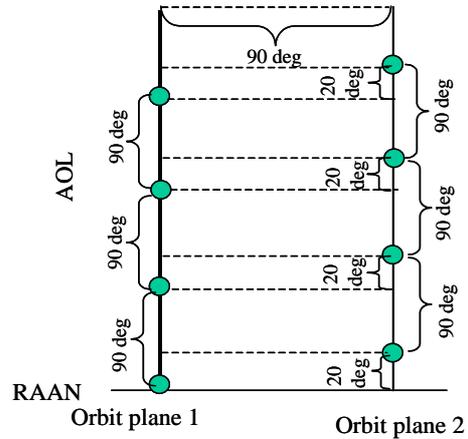


Figure 5: Phasing of Satellites at Orbit Planes 1 & 2.

We have learned that two ground stations at high latitude are required for this configuration, just like FORMOSAT-3/COSMIC constellation does. Currently, FORMOSAT-3/COSMIC constellation employs one ground station at Fairbanks of United States and one ground station at Tromsø of Norway. We use these two stations as the baseline for simulation. The result shows the minimum time from Acquisition Of Signal (AOS) time of one satellite to the AOS time of another satellite is 7.5 minutes. If we allocate 4 minutes for ground antenna to turn around, there will be 3.5 minutes for the spacecraft operations. The minimum AOS time interval happens about twice per day. In other words, in general, the AOS interval is longer than 10 minutes so that the operations time is normally longer than 6 minutes. The spacecraft operations time should be sufficient for NSPO team to monitor the spacecraft status and send command loads.

Figure 6 shows an example for the passes over a high-latitude ground station. The pass number per day is about 60. There is no pass for 20% of time (minute 240-480). 40% of time, the ground station handles 4 satellites in one orbit plane per revolution (minute 480-840 for orbit plane 1 and minute 0-240 & minute 1320-1440 for orbit plane 2). 40% of time, the ground station handles 8 satellites of two orbit planes per revolution (minute 840-1320). The rationale for 90-deg AOL separation in one orbit plane (as shown in Figure 5) is to reserve more operations time as the ground station only handles 4 satellites within one orbital plane (as shown in Figure 6).

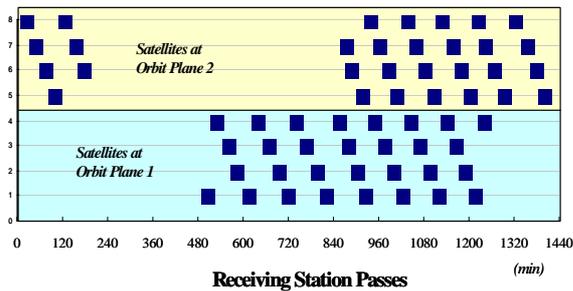


Figure 6: Passes over a High-Latitude Ground Station

If we want to add more station to reduce the data latency, a TT&C station in McMurdo would be the best choice. One satellite has 11~12 passes per day over this station. If we can have a dedicated TT&C station over this area, the station can handle 84 passes per day. Then the average data latency can be reduced from 50 minutes to 30 minutes. The analysis addressed in this paper is to generate a proposal to acquire the ground station. The database is from STK's facility tool. In the database, there is no other facility beyond the 60 degrees south latitude.

As for Orbit plane 3, those 4 satellites will be separated by 90 deg in the direction of AOL. Taiwan TT&C station sure is the main ground station for these low-inclination satellites, but it can only cover 6~7 passes per day for one satellite. If we consider the ground stations within 25-deg north and south latitude, the station located in Mauritius may cover another 4 passes, and the station located in Bangalore may cover the other 3 passes. With 3 low-latitude ground stations, each low-inclination satellite can have about 21 passes per day, that makes the latency of those low-inclination satellites to be around 35 minutes.

In the previous paragraphs, we assume the high-latitude ground stations to support high-inclination satellites and the low-latitude ground stations to support low-inclination satellites. Let us consider to use low-latitude ground stations to support high-inclination satellites as the 2nd priority. The data latency for high-inclination satellites can be further reduced to 25 minutes.

In summary, the data latency over the entire constellation, including high and low inclination satellites with 6 ground stations we discussed before is approximately 36 minutes. Please note that the latency we described above only include the delay from the data collection to data dump. Considering the data transfer and processing time on the ground, which may be done within 14 minutes, the overall system can deliver the assimilation data within 50 minutes on the average.

The alternative approach would be using the existing communication satellites such as Iridium, Global Star, Intersat, Inmarsat, Eutelsat, Orbcomm, and so on. That will involve the services of these relay satellites can provide. It is still under investigation at this stage.

LESSONS LEARNED FROM FORMOSAT-3/COSMIC

FORMOSAT-3/COSMIC satellite engineering performance have been published in many different journals.^{9, 10, 11, 12} In summary, all six satellites are currently in service. Four GOXes are operated at a duty cycle of 100% and two GOXes (FM2 and FM3) operated based on sun beta angle due to power shortage and stuck solar array drive.

By examining the spacecraft performance, the attitude excursion is one of the main contributors for the data loss.⁸ The on-orbit attitude performance of current FORMOSAT-3/COSMIC is within 2 degrees for pitch axis and within 5 degrees for roll and yaw axes (1 value). The FORMOSAT-3/COSMIC satellites experienced bad attitude more than estimated to interrupt the payload collecting data and sometimes it drove the spacecraft to power contingency condition. The Follow-On project needs to acquire a better attitude control system so that the roll/pitch/yaw attitude will be controlled within 0.2 degrees (3 value).

The design of FORMOSAT-3/COSMIC is conservative so that as spacecraft has been back to normal situation, the payload still awaits the operators to manually turn it on. NSPO has accumulated sufficient experiences for such anomalies, the payload resume time can be shortened. In the Follow-On plan, several criterion or flags should be allowed to be pre-set on the spacecraft, so that the payload can resume the service once the anomaly has been recovered automatically.

About one year after launch, McMurdo was added to support the data dump occasionally. However, due to the limit of transmitter duty cycle, the operations team hesitates to dump the data to two ground stations within one revolution. In the Follow-On plan, the duty cycle of transmitters should be relaxed to allow 3 passes of data dumps per orbit.

It was understood that FORMOSAT-3/COSMIC consisting of 6 satellites, the operations should be designed as more automatically as possible. The geographical command serves as a handy tool, it can turn on transmitter and dump data when spacecraft is in the contact area of a ground station. Once those commands have been loaded to spacecraft, the operators do not have to load the time-tag commands to instruct spacecraft when to do what. However, some of the unexpected anomalies changed the scenario. Some bus GPS receivers behave abnormally and the geographical

commands for routine operations are not always reliable. Instead, the operators need to send time-tagged command load to the spacecraft every day. In the Follow-On project, the geographical command should be carried on with reliable GPS receiver.

In addition to the items discussed above, NSPO has built a database of lessons learned to exclude the defects passing to the next project. The database covers space segment, ground segment, operations segment, management, and international co-operations experiences. With the current achievements and enhancement from lessons learned, the Follow-On mission is not just a follow-on project of FORMOSAT-3/COSMIC, but is a next generation with upgraded performance.

CONCLUSION

It is a feasible project and the data product is worthy to pursue. With more satellites, more receiving ground stations, more efficient RO payload, and more robust system, it is foreseen the Follow-On mission being well-qualified to be an operational constellation to contribute to weather forecast, climate trending, and ionosphere monitoring. The applications of radio occultation have been demonstrated by FORMOSAT-3/COSMIC constellation and the scientists have obtained various valuable data, the Follow-On mission shall continue to provide the data steadily and freely. NSPO welcomes any kinds of support to this project to make the whole system better.

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