

Radio Occultation Activities At NASA

CGMS-39 White Paper, October 2011

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1. Overview

NASA/JPL has been involved in radio occultation science since its early demonstration and development on planetary missions in the 1970s. NASA modified a TurboRogue geodetic GPS receiver to create the first GPS radio occultation instrument for the GPS/MET proof of concept mission in 1995. National Science Foundation and University Corporation For Atmospheric Research (UCAR) were partners on GPS/MET. The initial atmospheric profiles obtained in 1995 were successful, leading to follow-on development and mission deployment.

GPS/MET provided valuable information for NASA to develop a dedicated GPS radio occultation (RO) instrument, the “BlackJack.” The BlackJack design is the basis for operational assimilation of RO data on the following missions: COSMIC, CHAMP, SAC-C, C/NOFS, GRACE, and TerraSAR-X. The BlackJack instrument successfully demonstrated the following technologies:

- 1) ***24/7 tracking – overcoming GPS signal encryption***
GPS/MET dual-frequency tracking only occurred during a few 2-week periods when GPS signal encryption was intentionally disabled. The BlackJack design is capable of continuously tracking two GPS frequencies, as needed for operations.
- 2) ***Doubling data volume – rising occultations***
Acquiring occultations from a forward viewing antenna doubles the quantity of data from a single instrument, at the cost of an additional antenna input and increased processing load on the instrument.
- 3) ***Mid-to-lower troposphere data – open loop tracking***
Tracking the signal dynamics using predicts rather than tracking loop feedback enables improved data quality where the signal dynamics is highest: in the mid to lower troposphere (below ~8 km altitude). Required for rising occultations.
- 4) ***Track modernized GPS signals – in-flight programmability***
The signals transmitted by the GPS constellation tend to evolve over time. BlackJack signal processing hardware is reprogrammable in flight, permitting SAC-C in 2005 (and later COSMIC) to track the new unencrypted L2C signal with post-launch firmware upgrades, enabling higher quality data and reduced noise.

A guiding principle for radio occultation development at NASA is to enable as many hosting opportunities as possible by using flexible *onboard* signal processing architectures. High quality data are then available on a variety of platforms, despite significant limits on power and data downlink bandwidth. The science driver for widespread deployment is increased science data volume, which improves operations and

science return. The new Trig instrument currently under development builds on this principle while expanding science applications, as described below.

The implementation of open loop tracking, first demonstrated on SAC-C and currently implemented operationally on SAC-C and COSMIC, is an example of the guiding design principle. Planetary occultations first employed open loop tracking in the 1970s. This was achieved using ground-based receivers with access to large recording bandwidth. The science data was recovered in a post-processed mode. However, wide-bandwidth recording and subsequent processing on the ground requires large downlink bandwidths that are not always available from a space-borne platform. To increase hosting opportunities, the BlackJack design produces data at a relatively modest 50 Hz rate, which requires more sophisticated algorithms onboard the satellite compared to wide-bandwidth recording (e.g. 1 kHz or higher).

The open loop (OL) implementation for BlackJack is based on the algorithm described in Hajj et al. (2004; see also Ao et al. 2009), although other implementations are possible (Sokolovskiy, 2001). OL occultations were first enabled on a regular basis on SAC-C on June 28, 2004 to acquire statistics. The first successfully processed OL retrieval was obtained on July 17, 2004, as shown in Figure 1. Essentially the same system is implemented on the COSMIC receiver, which is a BlackJack-heritage IGOR receiver manufactured by Broad Reach Engineering. COSMIC acquires OL data since launch in 2006.

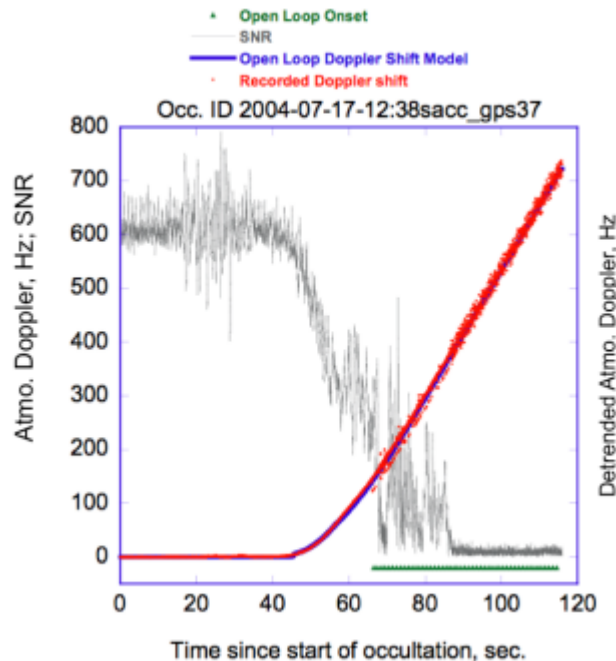


Figure 1. First open loop occultation retrieved from SAC-C.

The NASA approach to GNSS instrument development is focused on maximizing science return. The instrument design permits a large degree of software control over the digital

signal processing. Digital Signal Processors (DSPs) perform needed low-level computations requiring high speed dedicated hardware, but these DSPs can be software controlled to a very large degree. Tracking loops are closed in software, not hardware, for maximum flexibility in trading off closed versus open loop tracking. In addition, the BlackJack class of receivers includes field-programmable logic devices that can accommodate new GPS signal codes and other characteristics. The TriG receiver now under development extends and enhances this flexibility for even greater science return and potentially new kinds of science data (e.g. reflections) that could also lead to operational improvements. The benefits of the Trig design are further described below.

2. RO and Operations

The National Centers for Environmental Prediction (NCEP) currently assimilates data from the following NASA-developed RO instruments: COSMIC (6 satellites), SAC-C, GRACE, C/NOFS, and TerraSAR-X. A subset of these satellites (COSMIC, GRACE, TerraSAR-X) are assimilated by the European Center for Medium-Range Weather Forecast (ECMWF). Germany's DWD, Japan's JAXA, and other agencies are using these mission data also. For completeness, we mention here that several agencies receive Metop-A data from the GRAS radio occultation instrument. The continuous data record from the CHAMP satellite's BlackJack instrument played a significant role before de-orbiting in 2010 to establish the value of RO in operations (Healy and Thépaut, 2006; Cucurull et al., 2007). The GeoForschungsZentrum (GFZ) played a valuable role providing downlink resources to prepare SAC-C for transition to operations.

A detailed discussion of the value of RO to Numerical Weather Prediction (NWP) is beyond the scope of this paper. In the NCEP system, 8 hours of forecast skill improvement are observed at day 4 (500 hPa geopotential height; Cucurull, 2010). In the ECMWF system, RO has been found to improve significantly the estimated biases of observing systems such as hyperspectral passive infrared (AIRS, IASI). Similar results have been found at NCEP (Cucurull et al. 2011, pers. comm.) Recent comments at the COSMIC meeting in Taiwan 2011 suggest the value of RO data arises from the high vertical resolution of the profiles and the lack of bias correction needed for RO, both of which complement assimilation of satellite radiances (Marbouty and Healy, 2011).

The diverse platforms that provide data to NWP centers verify that the NASA instruments are compatible with a wide variety of spacecraft and mission goals. This compatibility portends well for continued use of RO as part of operational NWP systems. Only FORMOSAT-3/COSMIC is a dedicated RO constellation. RO can be accommodated on a wide variety of missions because of its autonomous operational characteristics and relatively low resource requirements.

To increase hosting opportunities, NASA has invested in creating flexible ways to acquire RO instruments. Design information has been transferred to commercial partners to off-load the manufacturing process, which permits NASA to focus on its core competency in research and design. Instruments currently being used for operations are sourced in various ways: JPL built the CHAMP, SAC-C and GRACE instruments; the IGOR class of BlackJack designs is manufactured by Broad Reach Engineering (COSMIC and TerraSAR-X); and Spectrum Astro built the instrument used on C/NOFS, with software

modifications by the Aerospace Corporation. Whatever the manufacturing origin, it is highly recommended that RO instruments be delivered by organizations with significant experience in RO scientific applications.

The diversity of hosting platforms requires that NWP centers adopt flexible processes for editing and quality control of RO data. Each satellite or constellation will, in general, require customized settings. Two configuration parameters that need to be addressed are the 1) acceptable altitude range, and 2) the assumed data precision, preferably altitude dependent. The lowest altitude for RO data is determined by the instrument's tracking approach: open or closed loop. The closed loop tracking receivers (CHAMP, GRACE, C/NOFS) provide their most reliable data above about 8 km in the tropics. Open loop tracking (SAC-C, COSMIC, TerraSAR-X) often provides science data down to the surface. However, OL algorithms are still in a process of refinement regarding the lowest 1-2 km altitudes. As satellites within a constellation age and change, it is also possible that individual satellites within the constellation should be treated distinctly.

Data precision depends on antenna aperture and beam pattern, pre-amplifier system temperature, and insertion losses, all of which vary significantly among the different platforms. Use of an ultra-stable oscillator can improve data precision by enabling the zero-difference retrieval method (e.g. GRACE). Data precision has a strong influence on the useful upper altitudes of the retrievals. Despite these numerous significant variations, the highly accurate "self-calibrating" nature of RO enables a multi-mission data set that can be accommodated with relatively minor changes at the NWP centers.

NASA is a partner with UCAR on operating the FORMOSAT-3/COSMIC constellation. Post-launch support includes software uploads to the receiver, instrument and spacecraft anomaly resolution support, and experiments. Recent support as of this writing is focused on increasing occultation throughput as receiver power is cycled frequently to conserve satellite batteries. Recent experiments have enabled occultations using the new L2C transmission, an unencrypted signal that produces higher precision data. NASA operates the occultation instrument (GOX) on SAC-C.

NASA maintains an algorithms group that is a leading RO science data processing center ("GPS Earth Observatory"; <http://genesis.jpl.nasa.gov>). The algorithms group produces science products and simulation tools to ensure that hardware development and instrument algorithms meet science requirements. Examples are the successful implementation of open loop tracking (Ao et al., 2010) and analysis of the lower-troposphere refractivity bias (Ao et al., 2003; Ao, 2007). GEO produces retrievals for GRACE and SAC-C instruments primarily, formerly for the CHAMP satellite, and for the COSMIC constellation and TerraSAR-X missions as resources permit. GEO manages the SAC-C RO instrument and distributes the raw data. GEO capabilities are critical to maintaining science quality as instrument and mission resources and conditions vary throughout the mission timeline.

3. Future Directions

NASA is currently developing a new instrument focused on meeting the needs of NASA's planned Earth science missions, and increasing science return from

transmissions of Global Navigation Satellite Systems (GNSS), broadly defined to include reflections and other possible applications. The following features of the new receiver, “Trig”, will benefit the operational community:

- Frequency agility to receive GPS L1/L2/L5, Galileo E1/E5 and GLONASS, increasing the number of assimilated observations.
- Multi-element actively steered antenna arraying capability that increases data precision while accommodating a wide variety of constraints on the antenna form factor.
- 50-100 Hz data rate in open loop mode to accommodate a variety of mission link budgets.
- Access to 1000 Hz raw data onboard to accommodate custom algorithms that can be developed and executed in a Linux-based science processor.
- 24 dual-frequency channels to acquire “all-satellites-in-view” for two full GNSS constellations.

A Trig block diagram is shown in Figure 2.

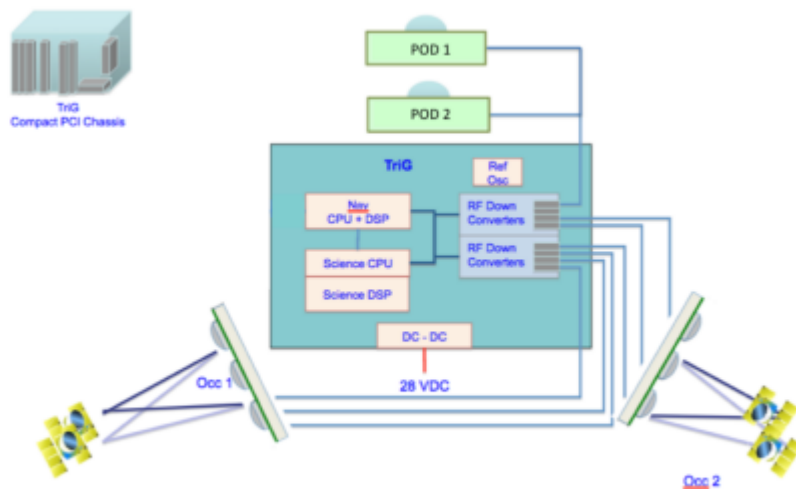


Figure 2. Trig block diagram. The multi-element occultation antennas can be actively steered by the receiver. The navigation (NAV) and science processors consist of a CPU and DSP. *Legend:* POD—precise orbit determination antenna; DSP—digital signal processor; RF—radio frequency.

Accommodation of the Trig on a wide variety of platforms remains an important goal, to increase the quantity of data the operational community can assimilate. NASA has recently selected a reduced power “Trig-Lite” for a technology demonstration mission. Trig-Lite has the same frequency agility as the full Trig, but without the second Linux-based processor or active antenna arraying. Best estimates suggest that ‘Trig-Lite’ hardware will consume approximately one-half the power of a full Trig while being capable of producing retrievals similar to those currently being assimilated from

COSMIC, assuming the same antenna configuration.

The first engineering model of the Trig will be available in 2012. NASA has agreed, at NOAA's request, to provide Trig for the follow-on FORMOSAT-7/COSMIC-2 constellation. Flight models are scheduled for delivery in 2013 to the FORMOSAT-7/COSMIC-2 project. Trig is being developed with a commercial partner. It is recommended that, whatever the manufacturing source, science instruments be delivered by institutions with experience in the science applications.

NASA recognizes that hosting opportunities increase as resource requirements go yet lower. JPL is proposing a multi-GNSS instrument concept that requires only 3.5 W power, with mass less than 1 kg. Nearly the full functionality of the Trig can be achieved using these sensors if the hosting platforms provide near real-time (few second latency) two-way communication links to a ground based auxiliary processor. Commercial communications constellations currently under development meet this latency requirement, e.g. the Iridium NEXT constellation. The operational community will realize enormous benefits cost-effectively using such hardware hosted on communications constellations.

The Korean KOMPSAT-5 mission has purchased a modified IGOR receiver from Broad Reach Engineering, representing another hosted payload opportunity. NASA will support this mission for operational use if resources are made available. Launch is planned for late 2011.

4. Conclusions

NASA recognizes the potential of RO for operational use and has facilitated that use across multiple missions. NASA activities that have benefited operations include: instrument design that can be hosted on multiple platforms, open data policies, technology transfer to commercial partners, tests to support frequent data downloads (SAC-C) and post-launch support for FORMOSAT-3/COSMIC.

The next major step for operational use is FORMOSAT-7/COSMIC-2. NASA is collaborating with NOAA to help integrate the Trig for this follow-on to FORMOSAT-3/COSMIC. The design of the Trig itself, and variants being considered, are highly conducive to meeting a recommendation of the International Radio Occultation Working Group to "consider adding Global Navigation Satellite System (GNSS) RO payloads on all suitable satellite systems" (CGMS-38 NOAA-WP-15, Research To Operations Subgroup).

Science-driven instrument development, and close cooperation between instrument developers and scientists, is key to continued success. As NASA continues to develop new instrument technology and explore new science applications for RO and related GNSS science, the operational community will reap the benefits.

5. References

- Ao, C. O., G. A. Hajj, T. K. Meehan, D. Dong, B. A. Iijima, A. J. Mannucci, and E. R. Kursinski (2009), Rising and setting GPS occultations by use of open-loop tracking, *Journal of Geophysical Research-Atmospheres*, 114, D04101, doi:10.1029/2008jd010483.
- Cucurull, L., J. C. Derber, R. Treadon, and R. J. Purser (2007), Assimilation of global positioning system radio occultation observations into NCEP's global data assimilation system, *Monthly Weather Review*, 135(9), doi:10.1175/mwr3461.1.
- Cucurull, L. (2010), Improvement in the Use of an Operational Constellation of GPS Radio Occultation Receivers in Weather Forecasting, *Weather and Forecasting*, 25(2), doi:10.1175/2009waf2222302.1.
- Hajj, G. A., C. O. Ao, B. A. Iijima, D. Kuang, E. R. Kursinski, A. J. Mannucci, T. K. Meehan, L. J. Romans, M. D. Juarez, and T. P. Yunck (2004), CHAMP and SAC-C atmospheric occultation results and intercomparisons, *Journal of Geophysical Research-Atmospheres*, 109(D6), D06109, doi:10.1029/2003jd003909.
- Healy, S. B., and J. N. Thepaut (2006), Assimilation experiments with CHAMP GPS radio occultation measurements, *Quarterly Journal of the Royal Meteorological Society*, 132(615), doi:10.1256/qj.04.182.
- Marbouty, D. and S. Healy (2011) Importance of GPS-RO in NWP and climate reanalyses at the European Centre for Medium-range Weather Forecasts, presented at International Conference on GPS Radio Occultation, Taipei, Taiwan, April 2011.
- Sokolovskiy, S. V. (2001), Tracking tropospheric radio occultation signals from low Earth orbit, *Radio Science*, 36(3), doi:10.1029/1999rs002305.