CGMS IROWG INTERNATIONAL RADIO OCCULTATION WORKING GROUP

Prepared by IROWG
23 September 2013
IROWG/DOC/2013/02

STATUS OF THE GLOBAL RADIO OCCULTATION OBSERVING SYSTEM (UPDATE 2013)

Prepared by the International Radio Occultation Working Group (IROWG)
(http://www.irowg.org)

This document analyzes the current and future GNSS Radio Occultation (RO) observing system, focussing on the period up to 2030, and assesses how much coverage could be achieved in comparison to requirements of the NWP and ionosphere communities.

There are currently about 3,000 occultations available per day in Near Real Time (NRT). These are primarily provided by the operational GRAS on Metop-B and Metop-A (which continues to provide data in the same orbit), in total about 1,300 occultations. About 1,700 occultations are provided by non-operational missions: the COSMIC-1/FORMOSAT-3 constellation (about 1,300), GRACE (about 100), and TerraSAR-X (about 180).

Several other flying research missions have the potential to provide further occultations in NRT; data provision is however not reliable. The C/NOFS mission just stopped providing data; Oceansat-2/ROSA (2009 launch) has not been configured correctly, thus preventing any data usage; SAC-D/ROSA (2011 launch) test data has so far not been made available; Megha-Tropiques/ROSA (2011 launch) data processing is still under development, and other research missions providing NRT data are under-performing in terms of available occultations. Only part of these missions are designed and configured to include higher altitude monitoring (above ~100 km) for ionospheric nowcasting purposes.

Truly operational data are expected to be provided by the COSMIC-2/FORMOSAT-7 (equatorial) constellation from 2016 onwards, with at least 4,000 occultations per day, building on COSMIC-1/FORMOSAT-3 heritage, and by EPS-SG satellites from 2021, with at least 2,000 occultations per day. This leaves a strong under representation of mid-latitude and polar observations that will only be solved with the implementation of the COSMIC-2/FORMOSAT-7 (polar) constellation, which however is not fully funded to-date.

Once demonstrated, the operational GNOS mission planned on China's FY-3 satellite series should provide additional data in NRT (about 1300 for two satellites). The first instrument is planned for launch in 2013. Experience shows that for new missions at least 1-2 years are necessary to build up the RO data processing capability, hence a pre-requisite for early data delivery is international collaboration and exchange of data and processing software. Here, China was welcomed as a further participant at the recent OPAC-5 & IROWG-3 workshop. Plans of the Russian space agencies will also be looked at with interest. Research missions have often shown to be unable to provide reliable NRT data streams. Cooperation between ISRO and EUMETSAT on Megha-Tropiques ROSA data processing is however noted.

The NWP and IROWG communities have identified a need for at least 10,000 and preferably 16,000 occultations per day, regularly distributed in time and space. This cannot be achieved before 2020 without both COSMIC-2/FORMOSAT-7 constellations in equatorial and polar orbit. The operational EPS mission will add about 1,300 to the Global Observing System, and the new Chinese mission may further add about 1,300 once its data quality is proven. Arrangements have to be made in order to assure an operational baseline of at least 10,000 to 16,000 occultations after the end of COSMIC-2/FORMOSAT-7.

Status of the Global Observing System for Radio Occultation (Update 2013)

1 INTRODUCTION

The current and planned Radio Occultation (RO) constellation as of September 2013 is summarized below. The different missions are separated into four categories:

- **Operational:** missions that include e.g., dedicated Near-Real-Time (NRT) data availability requirements (timeliness, number of occultations), re-launch strategies;
- **Research/NRT**: research or other missions that provide NRT data access on a best effort basis;
- **Research:** research missions that could potentially provide NRT access with dedicated infrastructure;
- **Other:** missions that do not fall into the other 3 categories for different reasons, primarily because the instrument and processing setup is being developed, or because a possible RO instrument addition is being investigated.

Launch and operation schedules are based on WMO (World Meteorological Organisation) information provided in the OSCAR (Observing Systems Capability Analysis and Review Tool) **[1]**, as well as information gathered from the IROWG (International Radio Occultation Working Group) researchers involved in the various missions, the ROM SAF (Radio Occultation Meteorology Satellite Application Facility) monitoring pages **[2]**, from the UCAR (University Corporation for Atmospheric Research) data archive **[3]**, and from more recent available publications.

2 OPERATIONAL MISSIONS

The current operational and planned mission schedule is shown in Figure 1.

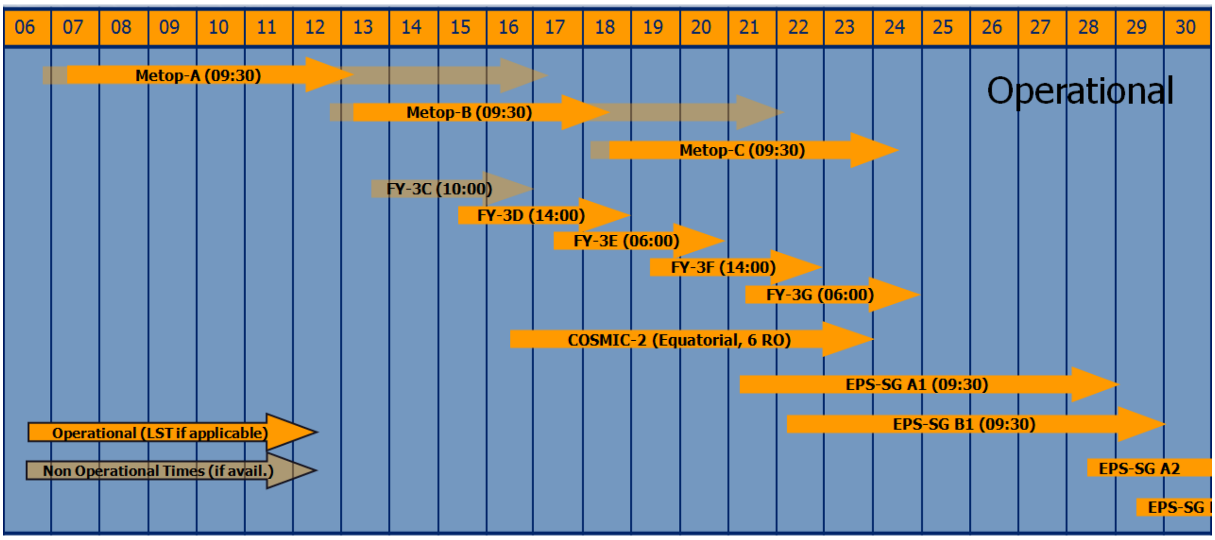

Figure 1 Operational RO missions, the local solar equator crossing time (LST) is given in brackets where applicable. Commissioning periods, pre-operational service, or extended service after the end of full operational service is indicated in lighter orange where available.

Currently, about 650 occultations per day are available from the operational EPS (EUMETSAT Polar System) GRAS instrument onboard of Metop-B, and another 650 from the data provided by the GRAS instrument on Metop-A, which continues to provide data service in the same orbit. Metop-B took over the operational service from Metop-A in April 2013, both instruments are however functioning without any problems. Only the timeliness (data delivery time) is slightly worse for Metop-A since it uses just one downlink station in the Arctic (Metop-B uses an Arctic and Antarctic one). Both satellites provide data in the 09:30 Equator crossing Local Solar Time (LST) mid-morning orbit. No ionospheric sounding is provided.

GNOS is a new RO instrument developed by China that is planned to be flown among other instruments on the two parallel series of FY-3 satellites, capable of tracking both GPS and the Chinese BeiDou GNSS signals. It has been introduced from FY-3C (2013 – 2016) onwards. The first RO instrument on FY-3C will be pre-operational, the later ones are planned for operational use. The FY-3 satellites could provide each at least 500 operational occultations per day from GPS and up to 200 from BeiDou.

The COSMIC-2/FORMOSAT-7 program has been approved and is funded by Taiwan and the USA for the first set of 6 RO satellites/instruments, which are planned to be launched into a low latitude/inclination (24 degrees) orbit in 2016. These 6 satellites have an operational requirement of at least 4,000 occultations per day. Data latency is specified at 45 minutes average. Deployment of the satellites to the final constellation will take about 2 years from launch.

The follow on to the EPS program (-SG, Second Generation) is based on 2 RO instruments flying at the same LST as the Metop satellites, with an operational requirement of at least 1,100 occultations per day and satellite. EPS-SG will observe at least GPS and Galileo satellites, with a potential for GLONASS and BeiDou as well. It has an option for 3 recurrent A and B satellites, potentially providing RO data beyond 2040. EPS-SG includes ionospheric sounding up to 500 km.

3 RESEARCH / NRT

Research/NRT missions that provide data are shown in Figure 2.

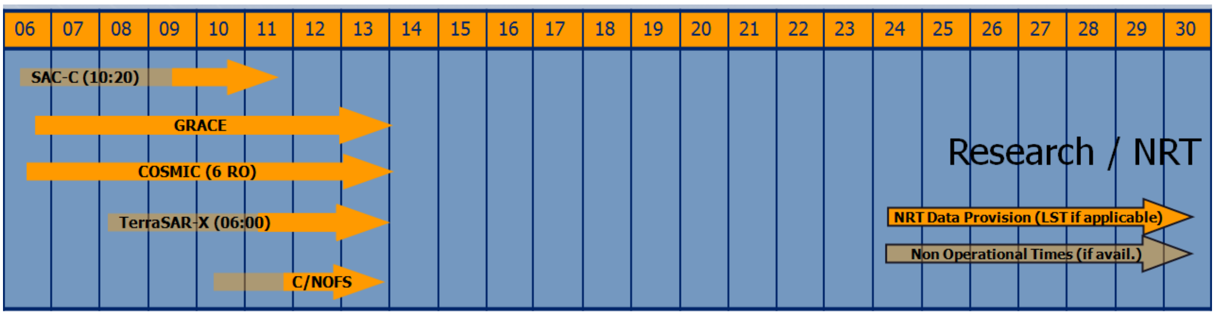

Figure 2 Research/NRT missions, the local solar equator crossing time (LST) is given in brackets where applicable. Periods with data that was not available in NRT (but is still useful for climate) are shown in lighter orange.

Research/NRT is here understood as "best effort" service, thus data is mostly available within 3 hours after observation, but e.g., for the TerraSAR-X and GRACE missions there is no 24/7 operational service available. Moreover, there is not systematically a follow-on satellite.

In total, three Research/NRT missions provide data (in total about 1,600 to 1,700 occultations per day, most of them from the COSMIC-1/FORMOSAT-3 mission - about 1,300 provided by UCAR, Boulder, CO, USA). GRACE provides < 100 occultations per day and TerraSAR-X about 180 occultations per day (both provided by GFZ, the German Research Centre for Geosciences, Potsdam, Germany). TerraSAR-X on-board memory only allows operating one of the occultation antennas (setting is activated at the moment). The C/NOFS mission is no longer providing data; the SAC-C satellite has been lost.

All Research/NRT missions are close to / beyond their initial lifetime, hence the timeline ends currently 2013. The COSMIC-1/FORMOSAT-3 data volume is fluctuating and shows degradation, with one satellite lost. Currently, the COSMIC-1/FORMOSAT-3 team is trying to get as many occultations out as possible, e.g. by workarounds where satellites are dormant while in the Earth shadow (since batteries on-board are degraded) and reactivating them once enough energy is collected on the solar arrays. GRACE and in particular TerraSAR-X are however expected to last several more years.

4 RESEARCH

Research missions are shown in Figure 3.

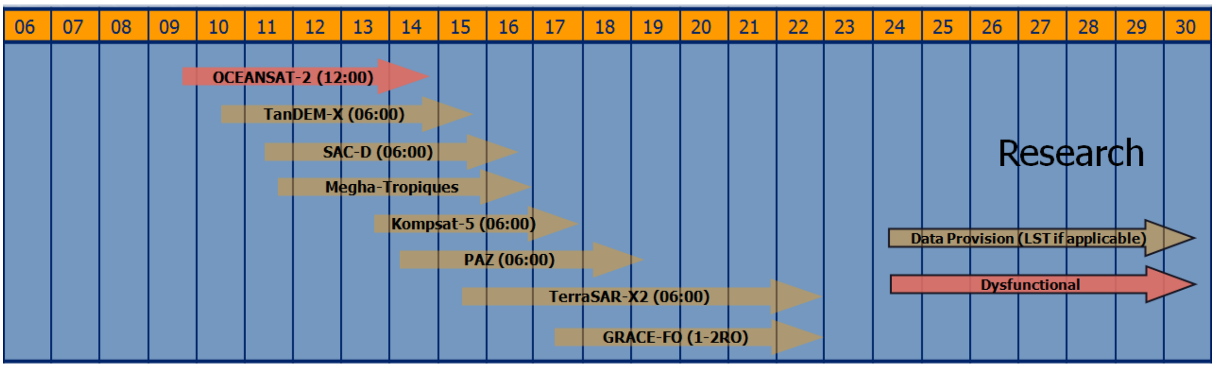

Figure 3 Research missions that could potentially provide NRT or data for climate assessments, the local solar equator crossing time (LST) is given in brackets where applicable.

Four research missions are currently flying:

- TanDEM-X (German) flies very close to TerraSAR-X, thus all occultations are closely collocated. These could be very valuable for inter-satellite evaluation of e.g. different on-board software algorithms (some experiments have already been performed), and for climate sensitivity studies of RO (the instrument is currently configured to obtain setting occultations);
- Three missions carry the ROSA receiver, but no full evaluation of the data quality of this receiver has been performed yet. In particular, the instrument data of:
    - Oceansat-2 (receiver operated by the Italian Space Agency ASI) has been analyzed early, showing severe problems with tracking the GPS L2 frequency. This renders it dysfunctional (hence data is not even useful for climate assessments). There is a strong belief that the receiver itself could be updated, but resources are not allocated;

- SAC-D (receiver operated by the Italian Space Agency ASI) has only been validated by ASI/Italian researchers; no data has so far been made available for further assessments. The instrument was however updated after discovering the Oceansat-2 tracking issues. SAC-D observes in setting and rising direction, with a potential of up to about 600 occultations per day. Raw data quality analysis showed standard performances on L1 and L2 tracking, but no data has so far been made available for further assessments (ASI indicated a release of the Data Policy during fall 2013);
- Megha-Tropiques (operated by the Indian Space Research Organisation ISRO) data has been analysed by ISRO and within a cooperation between ISRO and EUMETSAT. This cooperation showed that the data is currently unsuited for operational weather prediction; the current processing at ISRO focuses on the lower part of the atmosphere, hence no precise orbit processing is performed (which is required for processing at stratospheric altitudes); in addition, lower tropospheric processing shows biases with respect to NWP (Numerical Weather Prediction) models. As ISRO is just building up the processing capability, shortcomings are assumed to lie with the processing setup, rather than the instrument itself. Megha-Tropiques could provide about 500 occultations per day.

A just launched research missions is the Korean KOMPSAT-5 AOPOD (in a 550 km orbit at 06:00 Equator crossing time), with potentially about 250 occultations per day; NRT data provision options are investigated. The onboard software has however been modified from the original JPL (Jet Propulsion Laboratory) version and the instruments field of view is non optimal. Planned missions include the Spanish PAZ, flying in a 514 km orbit at 06:00 Equator crossing time. PAZ observes horizontally/vertically polarized GPS signals and will also attempt to sense intense precipitation events; it is planned to provide NRT data (about 200 occultations per day in cooperation with NOAA, UCAR). Further into the future are TerraSAR-X2 (515 km at 06:00 Equator crossing time) and the GRACE-FO satellites (485 km orbit, 89 Degree inclination, discussions are ongoing whether both satellites will carry an RO receiver) that could provide options for NRT RO data.

5 OTHER

The "Other" category encompasses missions that do not fall under the categories above for the following reasons: (1) investigating an RO option as a secondary mission (Jason-CS); (2) unclear funding situation (COSMIC-2/FORMOSAT-7, polar); (3) new RO receiver development (Meteor). Figure 4 shows a timeline of these missions.

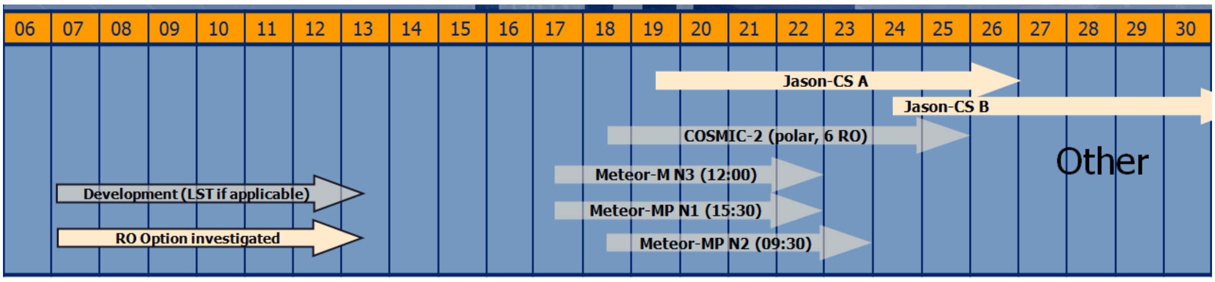

Figure 4 Other missions that could potentially provide NRT or data for climate assessments, the local solar equator crossing time (LST) is given in brackets where applicable.

Jason-CS: This is a discussed continuation of the Jason satellites for ocean altimetry, full funding is however not secured. It would be an attractive possibility to include RO since it is (a) operational; (b) already includes a POD (Precise Orbit Determination) receiver that is easily upgraded to include RO. First assessments estimate a potential of up to 1000 occultations per day based on several GNSS (Global Navigation Satellite Systems) observed. NOAA has offered to provide a JPL TriG receiver, investigations to add this instrument as a secondary mission are ongoing.

COSMIC-2/FORMOSAT-7 (polar): The second batch of COSMIC-2/FORMOSAT-7 receivers for polar orbit is planned with at least 6 RO receivers, all observing several GNSS. It could provide at least 4000 occultations per day. Funding is currently not secured for this 2nd set of 6 COSMIC-2/FORMOSAT-7 satellites. Deployment of the satellites to the final constellation will take about 2 years from launch.

Meteor: A new Russian RO instrument development that is planned to be flown among other instruments on the Meteor satellites. It is capable of tracking GPS and GLONASS, providing possibly at least 1000 operational occultations per day and satellite. No detailed information on this instrument or planned data availability is so far available, it is thus included in the "Other" section.

Commercial: This is a place-holder for commercial provider of RO data. It should be noted that there are currently no mechanisms in place to "buy" data for the global NWP community. No detailed launch schedules are available, it is thus not included in Figure 4.

6 IONOSPHERIC PROFILING

The main focus of the sections above was on neutral atmospheric profiling, not on ionospheric profiling. Figure 5 shows for completeness all instruments discussed above that provide or provided ionospheric profiling capability. No further attempt has been made to separate these by operational or research satellites since ionospheric forecasting would actually need real-time access to data.

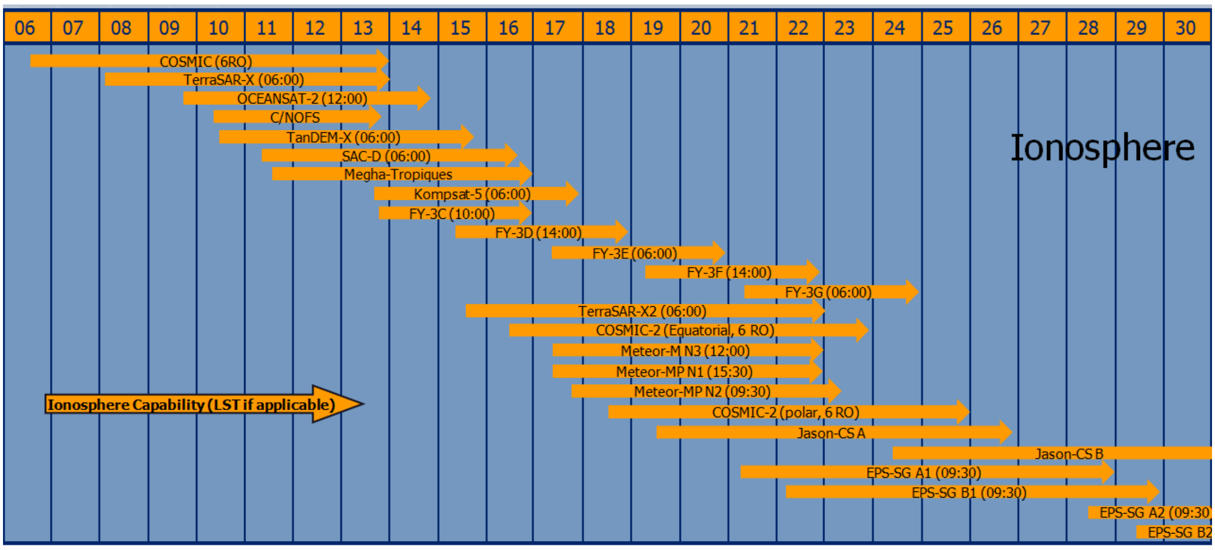

Figure 5 RO missions that provide ionospheric profiling capability, the local solar equator crossing time (LST) is given in brackets where applicable.

7 GNSS AVAILABILITY

The discussed number of occultations available for future RO instrument needs to be taken with some caution since the availability of GNSS signals is changing, new signals are being used, and new GNSS are being deployed. In particular the following open points can be identified:

- an update of the GPS signal structure at the end of 2020, as announced by the GPS authorities **[4**], would make observations from the EPS Metop satellites highly degraded, as the GRAS instrument is unable to receive the new codes on the L2 frequency. This may in particular limit the use of the GRAS instrument on Metop-C. Currently it appears unlikely that this update will happen already in 2020; updated projections are however not available.
- the EPS-SG program however relies on observations made at the GPS L1 and L5 frequencies, these frequencies are also planned to be used for Galileo, and, if available, for BeiDou and GLONASS. The availability of GPS L1, L5 frequencies is tied to the above mentioned update in the GPS signal structure, which is likely going to be delayed. Hence there is a risk of underperformance of the EPS-SG RO instruments for the early years (GPS is in the baseline for EPS-SG).
- the deployment of Galileo satellites might be delayed, thus the RO EPS-SG instruments could underperform during the first years of the mission (Galileo is in the baseline for EPS-SG). Other missions relying on Galileo (e.g., Jason-CS) will also be affected.
- the GLONASS constellation recently had some setbacks (e.g., the loss of three satellites at launch in July 2013).
- operators of the GLONASS constellation have announced that they will move to new frequencies and signals, exact timeliness are however not available. This might impact the EPS-SG RO instruments (which has the new GLONASS signals not in the baseline, but as an option).
- current GLONASS signals haven't been used for RO, hence the exact performance is unknown as well as whether further processing (e.g., double differencing which degrades the data quality) is required.
- Quasi-Zenith Satellite System (QZSS) could provide additional occultations, usually however located around the zenith position. There are at least 2 different systems available, e.g., by the Japanese, the Indians.
- BeiDou, the Chinese GNSS, is currently operating satellites in geostationary orbit and is planning to build up a global constellation.

8 CONCLUSIONS AND LESSONS LEARNED

Please note that this section is a repeat of the first page summary, with additional references included.

This document analyzes the current and future GNSS Radio Occultation (RO) observing system, focussing on the period up to 2030, and assesses how much coverage could be achieved in comparison to requirements of the NWP and ionosphere communities **[5,6,7]**.

There are currently about 3,000 occultations available per day in Near Real Time (NRT). These are primarily provided by the operational GRAS on Metop-B and Metop-A (which continues to provide data in the same orbit), in total about 1,300 occultations. About 1,700 occultations are provided by non-operational missions: the COSMIC-1/FORMOSAT-3 constellation (about 1,300), GRACE (about 100), and TerraSAR-X (about 180).

Several other flying research missions have the potential to provide further occultations in NRT; data provision is however not reliable. The C/NOFS mission just stopped providing data; Oceansat-2/ROSA (2009 launch) has not been configured correctly, thus preventing any data usage; SAC-D/ROSA (2011 launch) test data has so far not been made available; Megha-Tropiques/ROSA (2011 launch) data processing is still under development, and other research missions providing NRT data are under-performing in terms of available occultations. Only part of these missions are designed and configured to include higher altitude monitoring (above ~100 km) for ionospheric nowcasting purposes.

Truly operational data are expected to be provided by the COSMIC-2/FORMOSAT-7 (equatorial) constellation from 2016 onwards, with at least 4,000 occultations per day, building on COSMIC-1/FORMOSAT-3 heritage, and by EPS-SG satellites from 2021, with at least 2,000 occultations per day. This leaves a strong under representation of mid-latitude and polar observations that will only be solved with the implementation of the COSMIC-2/FORMOSAT-7 (polar) constellation, which however is not fully funded to-date.

Once demonstrated, the operational GNOS mission planned on China's FY-3 satellite series should provide additional data in NRT (about 1300 for two satellites). The first instrument is planned for launch in 2013. Experience shows that for new missions at least 1-2 years are necessary to build up the RO data processing capability, hence a pre-requisite for early data delivery is international collaboration and exchange of data and processing software. Here, China was welcomed as a further participant at the recent OPAC-5 & IROWG-3 workshop **[8]**. Plans of the Russian space agencies will also be looked at with interest. Research missions have often shown to be unable to provide reliable NRT data streams. Cooperation between ISRO and EUMETSAT on Megha-Tropiques ROSA data processing is however noted.

The NWP and IROWG communities have identified a need for at least 10,000 and preferably 16,000 occultations per day, regularly distributed in time and space. This cannot be achieved before 2020 without both COSMIC-2/FORMOSAT-7 constellations in equatorial and polar orbit. The operational EPS mission will add about 1,300 to the Global Observing System, and the new Chinese mission may further add about 1,300 once its data quality is proven. Arrangements have to be made in order to assure an operational baseline of at least 10,000 to 16,000 occultations after the end of COSMIC-2/FORMOSAT-7.

References

[1] WMO Observing Systems Capability Analysis and Review Tool (OSCAR), available at: http://www.wmo-sat.info/oscar/spacecapabilities

[2] ROM SAF Monitoring Pages, available at: http://www.romsaf.org/monitoring/

[3] COSMIC CDAAC Data Analysis and Archiving Center at UCAR, available at: http://cdaac-www.cosmic.ucar.edu/cdaac/products.html

[4] Federal register Vol. 73, No. 185, pp.54792-54793; available online at http://www.gpo.gov/fdsys/pkg/FR-2008-09-23/html/E8-22197.htm

[5] Report from the 2nd International Radio Occultation Workshop, CGMS-40 EUM-WP-01, 2012, available at: http://www.irowg.org/docs/CGMS-40/Report_from_the_2nd_International_Radio_Occultation_Workshop.pdf

[6] Final Report of the Fifth WMO Workshop on the Impact of Various Observing

Systems on Numerical Weather Prediction, Sedona, Arizona, USA, 22-25 May 2012, WMO Integrated Global Observing System, Technical Report No. 2012 – 1, available at: http://www.wmo.int/pages/prog/www/OSY/Reports/NWP-5_Sedona2012.html

[7] Harnisch, F., S. Healy and P. Bauer and S.J. English, Scaling of GNSS radio occultation impact with observation number using an ensemble of data assimilations, 2013, available at: http://www.ecmwf.int/publications/library/ecpublications/_pdf/tm/601-700/tm693.pdf

[8] Joint OPAC-5 & IROWG-3 Workshop - 5th-11th September 2013, Austria, further information available at: http://www.uni-graz.at/opacirowg2013 and at http://www.irowg.org

Acknowledgements: Thanks to Jerome Lafeuille (WMO) for valuable input to this letter. Specific mission information was also obtained from E. Cardellach (ICE-CSIC/IEEC, Barcelona, Spain); G. Beyerle, J. Wickert, S. Heise (German Research Centre for Geosciences, Potsdam, Germany); C. Accadia, D. Klaes (EUMETSAT); R. Notarpietro (Polytechnic Turin, Italy).