CGMS-40 EUM-WP-01
v6, 23 October 2012

Prepared by IROWG
Agenda Item: II/7
Discussed in WGII

REPORT FROM THE 2ND INTERNATIONAL RADIO OCCULTATION WORKSHOP

Prepared by IROWG (http://www.irowg.org)

This paper summarizes the outcome of the 2nd International Radio Occultation (RO) Working Group Workshop (IROWG-2). The workshop was organized by the University Corporation for Atmospheric Research (UCAR), the UCAR Joint Office for Science Support (JOSS), NOAA, and EUMETSAT. The meeting was in Estes Park, Colorado, US, from 28th of March to 3rd of April 2012.

For work in the immediate future CGMS 40 is invited to emphasise the following three main IROWG-2 recommendations:

- A need for an operational continuity plan for RO – including troposphere and ionosphere – to provide a daily availability of at least 10000 occultations;
- An urgent need for data gap filling using research / opportunity satellites, or commercial sources (if available) is required for the near term, but this is not a replacement for a long-term continuity plan to provide operational GNSS RO data;
- The potential of GNSS RO for anchoring climate re-analysis needs to be further addressed, this also requires updated laboratory measurements of refractivity coefficients.

Additionally, the sub-groups at IROWG-2 also recommend:

- Options to fly RO instruments on opportunity missions should be further pursued;
- Assure that GNSS operators are aware of the needs of RO applications, providing sufficient signal strength on the Earth limb;
- Support research towards implementing a LEO-LEO mission to fully explore the climate capabilities of RO;
- Engage CGMS agencies to organize a workshop to foster closer collaboration between the ionospheric and neutral atmospheric researchers.

CGMS is invited to comment.

Report from the 2nd International Radio Occultation Workshop

1 INTRODUCTION

This paper summarizes the outcome of the 2nd International Radio Occultation (RO) Working Group Workshop (IROWG-2). The workshop was organized by the University Corporation for Atmospheric Research (UCAR), the UCAR Joint Office for Science Support (JOSS), NOAA, and EUMETSAT. The meeting was held in Estes Park, Colorado, US, from 28th of March to 3rd of April 2012.

The CGMS meeting 37 in October 2009 endorsed the establishment of the IROWG. Dave Ector (NOAA) and Axel von Engeln (EUMETSAT) were selected as co-chairs and Mitch Goldberg (NOAA) as rapporteur to CGMS. In order to have a first IROWG workshop in 2010, the co-chairs and the rapporteur decided to join with the already scheduled workshops of OPAC-4 and the GRAS-SAF Climate in September 2010. IROWG-1 was thus “only” providing a platform for discussions and recommendations, while the talks that were given were organized by OPAC-4 and the GRAS SAF.

Here we report on the 2nd workshop IROWG-2, which included a full conference agenda with many talks in addition to the platform for discussions and recommendations. It was attended by more than 70 scientists, including all the major centres providing and all major centres assimilating RO data. There were more than 60 talks given and about 20 posters presented. Recommendations were worked out in dedicated sub-working groups and presented in a panel discussion. Additionally, IROWG-2 was also used by several researchers for dedicated splinter meetings, which are not covered here.

The structure of this paper is as follows: Section 2 gives a brief overview of the organization of the workshop and the sub-groups, Section 3 lists the main recommendations which were agreed upon by IROWG, Section 4 contains the proceedings of the sub-groups, and Section 5 concludes.

Two further CGMS working paper are also provided to the CGMS meeting 40 that present the *Status of the global Radio Occultation Observing System* and *Climate related Processing and Potential of Radio Occultation Data* **[1,2]**.

2 IROWG-2 SETUP

IROWG-2 was a full workshop, including presentations, posters and sub-group discussions. Both, the presentations/posters and the sub-group discussions were focussed on specific topics, namely:

- Numerical Weather Prediction;
- Climate;
- Research to Operations;
- Payload Technology;
- Innovative Occultation Techniques;
- Space Weather.

IROWG-2 participants were asked to summarize relevant activities within the scope of the sub-group in dedicated sub-group meetings and express recommendations which could either be relevant to CGMS, to the GNSS (Global Navigation Satellite System, e.g. GPS) signal providers, to the GNSS RO community, or to providers of RO data. These were discussed in the open plenary.

The participants agreed to highlight three main recommendations, which were endorsed by all participants, and additionally present within this document one main recommendation per sub-group that is relevant at CGMS level. The full set of recommendations per sub-group and further information is made available in a dedicated IROWG publication, available on our website www.irowg.org.

3 MAIN RECOMMENDATIONS

IROWG-2 participants noted that the main IROWG-1 recommendations have made progress in the mean time; however, further work is required to fully address them. The urgency of the tasks requires re-stating several of them here in an updated form.

The following three main recommendations have been agreed upon by all participants at IROWG-2:

3.1 Operational Continuity Plan for RO – including Troposphere and Ionosphere

We recommend that CGMS devise a detailed **GNSS-RO Continuity Plan** with the operational agencies, outlining how we move towards a fully operational GNSS RO constellation providing **at least 10000 observations per day**.

GNSS RO has been demonstrated to be a critical element in the global data observing system for Numerical Weather Prediction (NWP), providing high positive impact to forecast skill in all the major national weather forecasting centres. GNSS RO also provides a very important data record for the global climate observing system, providing essential climate variables of benchmark quality. In addition, this data is critical for space weather observation and input to space weather prediction systems that are currently being developed.

The **continuity of GNSS RO observations in the future is not guaranteed by operational programs**. As of 2012, GRAS remains the only operational program for GNSS RO and this accounts for only about 25% of the occultations assimilated by operational NWP centres. Research programs may be able to supplement operational RO programs temporarily; as well as, exploring the potential of RO at higher spatial sampling, but they carry much higher risk.

Thus **research programs are not the answer for a fully operational GNSS RO constellation**. The amount of investment in GNSS RO and other satellite programs overall should be correlated to the positive impacts they have on NWP, climate, and chemistry, and GNSS RO impacts in NWP are comparable to that of the other major operational instruments. Proper GNSS RO continuity requires a constellation of properly spaced LEO satellites, providing a minimum of 10000 soundings per day. **It is of highest importance for NWP, climate, and space weather to assure the continuity of RO measurements**, especially following the COSMIC-1/FORMOSAT-3 constellation mission.

3.2 GNSS RO Data Gap Filling is Required

A concern shared by all attendees at the IROWG-2 is the impending GNSS RO data gap as coverage from COSMIC-1/FORMOSAT-3 is rapidly declining as it nears its end of life. The present plan for the next GNSS RO constellation is the first 6 satellites from the COSMIC-2/ FORMOSAT-7 mission that will nominally be operational in 2016. COSMIC-2/FORMOSAT-7 is a low inclination (24 degree) mission that will provide an unprecedented density of low latitude coverage critically needed for tropical storms and space weather monitoring and prediction. It will, however, not provide mid- and high-latitude coverage required for NWP, climate, and space weather at those latitudes. Thus, under the present plans, we are looking at a gap from about 2012 to 2016 in terms of low latitude coverage by a constellation and a substantially longer term gap of unknown duration at mid- and high-latitudes.

In light of the upcoming drop in the number of available radio occultations due to COSMIC-1/ FORMOSAT-3 nearing its end-of-life, **it is becoming critical to fill the impending data gap** with GNSS RO from any and all available mission data sources particularly in the 2012 – 2016 timeframe.

While data from RO science missions will require extra effort to be incorporated into operations due to non-standard payloads and configurations, and data volume per satellite is expected to be 1/3rd to 1/5th the data volume expected from an operational mission, **it has been shown that this data can have significant positive impact in weather forecasting**. Science missions that are expected to have the capability to provide data to partially fill this gap include e.g., Oceansat-2, Megha-Tropiques, SAC-D-Aquarius, TanDEM-X, Kompsat-5, and PAZ. **Effort and funding should be set aside for these missions to make the data available for weather forecasting in near real-time.**

It is however also important to note that data from the 3 ROSA GPS RO instruments currently flying on Oceansat-2, Megha-Tropiques, SAC-D-Aquarius have not been made available to the community and early quality assessments demonstrated problems in tracking the GPS L2 frequency at least on Oceansat-2.

We also note that several data buy (commercial) missions are currently being discussed, and if any of these launches in the 2014-2016 time frame, these might be able to help fill the data gap. They would however still require government funding to purchase such data when it becomes available.

3.3 Potential of GNSS RO use for anchoring Climate Re-analysis

The climate community has been slow to adopt GNSS RO, even with its proven accuracies and extremely low measurement uncertainty. GNSS RO has the two properties necessary to make it a benchmark of the climate, specifically the atmosphere: (a) traceability to the international definition of the second (SI), and (b) adequate coverage in space and time.

These same properties suggest that it should also be of great advantage to anchoring climate re-analyses, which typically suffer from drift because of shortcomings in the removal of biases from observational data, inadequate physical processes in the core model, and temporal inhomogeneity of the assimilated data. RO data need not be bias-corrected - like strongly calibrated radiosondes - and thus should serve as an important anchor to reanalysis to prevent drift.

In order to take full advantage of RO data in reanalysis, though, it is necessary to model the RO observable (bending angle, Doppler delay) given state variables of the atmosphere (temperature, pressure, specific humidity) with an accuracy of 1 part in 10,000. Arguments based on theory and dated laboratory measurements of refractivity coefficients have been used to argue for a model with such accuracy, but it is incumbent that **modern laboratory studies on refractivity coefficients be undertaken to verify such a claim**.

This objective is urgent because the climate research community overwhelmingly defaults to use climate reanalyses for climate monitoring and trend research. Several numerical weather prediction centres are undertaking or have recently published second generation reanalyses with variational bias correction, but they do not agree in their trends over the past three decades. Incorporation of GNSS RO as an anchor is a necessary part of the solution to this problem.

4 SUB-GROUP RECOMMENDATIONS

The following sections highlight one recommendation relevant at CGMS level from each sub-group, additional information is provided in a background section. The full set of recommendations is available on our website www.irowg.org.

4.1 Numerical Weather Prediction (NWP) Sub-Group

Chair: S. Healy (ECMWF)

Rapporteur: B. Ruston (NRL Monterey)

Main Sub-Group Recommendation:

We recommend CGMS to encourage its member agencies to promote and support efforts for **operational GNSS RO continuity programs** in the future.

Background:

We note that the GOS 2025 vision from the WMO recommends at least 8 satellites, and the draft implementation plan (EGOS-IP, section 6.3.3.2) includes the action on “CGMS with WMO commissions, satellite agencies and data processing centres” to

> *“Ensure and maintain a radio-occultation constellation of at least 8 GNSS receivers onboard 8 platforms on different orbits, and organize the real-time delivery to processing centres.”*

We welcome this action, and hope that it will be used in support of proposed GNSS RO constellations, but we note that the 8 platform requirement is ambiguous. This requirement does not state whether these are operational or research satellites, how many occultations each satellite provides per day, or how the measurements are distributed geographically. We recommend that GCMS revisit the GOS 2025 vision/implementation plan and can carry forward our recommendation – based on the latest research – if they agree.

The current 1 operational and 9 research satellites provide around 2200 occultations per day. There is no evidence of saturation with the current system, and it will not meet future demand. About 2/3rd of the current data volume is obtained from research satellites; these have already exceeded their design life and are showing significant signs of aging and downtime. Also, higher resolution NWP systems in the near future will require accrued volumes of data to deliver their full potential.

A simulation study is underway, which aims to quantify the number of occultations where the NWP forecast benefit of GNSS RO measurements will saturate. The latest results presented at the IROWG-2 workshop suggest that the impact of an observing system of 8000 occultations per day is not saturated. Therefore, our recommendation is that 10000 operational profiles per day should be the minimum aim for the future operational GNSS RO constellation. This is also in line with recommendations from the recent *Fifth WMO Workshop on the Impact of various Observing Systems on NWP* (May 2012, Sedona, Arizona, US) and the recently updated GOS 2025 vision.

We recommend that CGMS devise a detailed “GNSS-RO Continuity Plan” with the operational agencies, outlining how we move towards a fully operational GNSS RO constellation providing at least 10000 observations per day.

4.2 Climate Sub-Group

Chair: S. Leroy (Harvard University)

Rapporteur: I. Culverwell (Met Office)

Main Sub-Group Recommendation:

GNSS RO has been demonstrated to be a very important data record for the global climate observing system providing essential climate variables of benchmark quality. The continuity of GNSS RO observations in the future is not sufficiently guaranteed which is of main concern regarding the provision of continuous climate products. **It is of highest importance to assure the continuity of RO measurements**, especially after COSMIC-1/FORMOSAT-3.

Background:

While GNSS RO is ideally suited as a climate benchmark by virtue of its traceability to the international definition of the second, adequate sampling density and distribution is also necessary to assure its utility as a climate benchmark. GNSS RO is most accurate in the region of the upper troposphere/lower stratosphere, but in this region the dominant contributor to uncertainty is sampling error. Studies have shown that, in this region, at least 1,000 soundings per day are necessary in order to reduce sampling error enough to consider GNSS RO a climate benchmark. Moreover, it is also necessary to obtain data sufficiently distributed in local time to remove bias in GNSS RO climatologies induced by the atmospheric diurnal cycle. While the requirement on sampling density should not be difficult to meet, the requirement on sampling in local time requires evenly distributed longitudes of ascending nodes for the constellation of GNSS RO satellites. This is unlikely to be accomplished with anything but an operational constellation of GNSS RO satellites.

In all latitude bands except the highest latitudes, the COSMIC-1/FORMOSAT-3 project has satisfied the requirements of sampling density and uniform distribution in local time. The COSMIC-1/FORMOSAT-3 project is steadily degrading, and in the next year or two it is expected that it will meet neither requirement. In the interim only a few GNSS RO missions of opportunity will deliver data, only one or two of which will be operational. Because their primary scientific missions are so different, they will not be deployed in formation as is needed for uniform sampling in local time. Any climatology of GNSS RO data is likely to be biased as a consequence.

The absence of a constellation of GNSS RO satellites in the near future will also weaken the utility of operational infrared sounders for climate research. The infrared sounders are highly sensitive to clouds whereas GNSS RO is not, and the two can be used in conjunction to distinguish between trends and anomalies in the radiative forcing of climate. Without GNSS RO, the lapse rate, upper tropospheric water vapour, and cloud feedbacks will remain ambiguous during the “gap” in GNSS RO data.

4.3 Research to Operations Sub-Group

Chair: K. Lauritsen (DMI/ROM SAF)

Rapporteur: B. Schreiner (UCAR)

Main Sub-Group Recommendation:

RO measurements are a valuable information source for NWP and climate. Within NWP, the number of RO instruments has not reached saturation level. Hence IROWG recommends to CGMS that **operational and research organizations consider adding GNSS RO payloads on all suitable non-commercial and commercial satellite systems**. For example, the operational centres should consider adding a GNSS RO payload to the Jason-CS and Sentinel missions.

Background:

Since IROWG-1 there has been some progress related to making GNSS RO data from research missions available for NWP centers in NRT (Near Real Time). There has also been some progress in making documentation and low level readers available. There is however room for additional progress and accordingly several of the recommendations from IROWG-1 have been kept in similar form and were only updated.

The main considerations for transitioning research missions into operations that have led to the recommendation are as follows:

- Put GNSS RO on all available satellite systems;
- Operational agencies should support research missions for NRT applications;
- Improve and expand GNSS ground networks;
- Provide level0 data, data formats, software to read data, and receiver configuration information;
- Continue improvements to receiver tracking firmware.

4.4 Payload Technology

Chair: G. Franklin (JPL)

Rapporteur: G. Franklin (JPL)

Main Sub Group Recommendation:

Recommend to GNSS satellite operators and designers to transmit significant power levels beyond the limb of the Earth, defined as 0 Degree ground elevation angle, for at least two civil (non-encrypted) signals at different radio frequencies. This will enable valuable GNSS RO contributions to weather forecasts, climate benchmarking, and space weather monitoring.

Background:

GNSS systems were initially designed for positioning on the Earth surface, so they designed the antenna pattern to focus the signal on the visible Earth disk. GNSS RO applications have used GNSS signals that spill past the Earth limb (and for ionospheric applications even up to LEO orbit altitude) making it important for signal providers to take this under consideration.

4.5 Innovative Occultation Technique

Chair: R. Kursinski (Broadreach Engineering)

Rapporteur: K. Zhang (RMIT)

Main Sub Group Recommendation

CGMS member space agencies are asked to **support research towards implementation of LEO-LEO occultation demonstration** to pave the way towards developing an authoritative metrologically-controlled reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs). Initial mountaintop demonstrations have been made at cm, mm and micrometer wavelengths. The next step within the next 2 years should be an airborne occultation demonstration. Specifically, CGMS is asked to encourage international space agencies (NASA, ESA, NSF, NOAA, EUMETSAT and others) to hold an interagency workshop as soon as possible to define how they can cooperate in implementing an the airborne demonstration and a LEO-LEO research and demonstration mission.

Background:

While GNSS RO proves to be increasingly successful and is strongly endorsed, e.g. in the US NRC Decadal Survey and within the EUMETSAT Polar System, it only measures bending angles, refractivity which leaves a temperature-water vapour ambiguity in the troposphere and limits water vapour information to below the 240 K level in the troposphere (approximately 9 km in the tropics). LEO-LEO occultations measuring both refraction and absorption of coherent microwave and infrared signals would provide a much more complete set of atmospheric variables that includes thermodynamics (temperature, pressure, water vapour), dynamics (line-of-sight winds), climate/chemistry (ozone, carbon dioxide, methane, and other greenhouse gases and trace species) as well as cloud, aerosol and turbulence information. These “next-generation RO” data will have negligible ionospheric residual errors and provide the key upper air WMO/GCOS Essential Climate Variables (ECVs), independent of models, as a dataset of climate benchmark quality.

A LEO-LEO observing system complementing GNSS RO would thus provide an authoritative reference standard in the global free atmosphere (above the boundary layer) for these essential variables to which all other observing systems and weather and composition assimilation and forecasting systems could “anchor”. The climate community as well as the NWP and atmospheric chemistry communities can benefit strongly from this information, including the long-term operational use of such a reference observing system in the 21st century.

U.S. and European agencies (NSF, ESA, NASA) have undertaken technological and scientific preparatory activities for more than a decade, which should be continued with high priority towards a demonstration mission to begin such a benchmark climate record as soon as possible.

4.6 Space Weather Sub-Group

Chair: P.R. Straus (Aerospace Cooperation)

Rapporteur: A.J. Mannucci (JPL)

Main Sub-Group Recommendation:

The Group recommends that an **International Workshop be held to discuss several aspects of GNSS RO analysis involving the ionosphere**, probably to be funded by government agencies.

Background:

The suggested workshop shall include a cross-section of ionospheric space weather experts and scientists concerned with removing ionospheric effects from GNSS RO for neutral atmospheric parameters. The workshop will include the following three sessions: (A) removing ionospheric effects from RO for neutral atmospheric parameters; discussion of various ionospheric corrections currently being used; (B) discussion of various ionospheric data assimilation methods; (C) ionospheric effects, especially scintillation, on Radio Occultation using the extensive RO databases.

The rational for the three sessions is as follows:

Session A: Space weather (ionosphere) has a potentially significant impact on the operational use of radio occultation by introducing biases in the neutral atmospheric retrieval products that are routinely assimilated. Considerable ionospheric space weather expertise exists that could benefit the neutral atmosphere community to mitigate these impacts. Yet, this expertise is not integrated into the research and operations communities that assimilate GNSS RO data. We recommend that a working group (WG) be formed over the next 18 months to organize and conduct a workshop supported by the WMO and other operational agencies that brings together a cross-section of ionospheric space weather experts and the neutral atmosphere community. The WG will discuss the various ionospheric corrections currently being applied and possible improvements. Areas to be discussed include solar cycle, diurnal and seasonal variability, and sporadic-E climatologies. The extensive GNSS RO databases that currently exist are a valuable resource.

Session B: GNSS RO is not yet fully utilized by the operational space weather communities that are focused on ionospheric specification and nowcast. We further recommend the formation of a focus group with support from operational agencies to develop uniform metrics for evaluating assimilative ionospheric models that ingest GNSS RO data, and to advance modeling approaches for assimilating GNSS RO data for space weather nowcasts and forecasts.

Session C: An emerging use of GNSS RO is to measure L-band scintillation caused by ionospheric irregularities, from space. There is currently insufficient knowledge of how L-band scintillation measurements acquired in an occultation geometry translate to other geometries and frequencies of interest. We recommend the formation of a focus group with support from operational agencies to address how space-based scintillation measurements can be used operationally. A goal of the group is to understand how measurements from space can be compared to the extensive databases and models of scintillation developed from ground-based measurements. This should include a discussion of recommended flight receiver designs, acquisition approaches, algorithms for flight and ground processing of scintillation parameters, and the use of GNSS RO data for scintillation products.

5 CONCLUSIONS

The main recommendations of the second IROWG were summarised above. The full set of recommendations, relevant at CGM, at satellite operator, and at IROWG level can be found at http://www.irowg.org.

For work in the immediate future CGMS 40 is invited to emphasise the following three main IROWG-2 recommendations:

- A need for an operational continuity plan for RO – including troposphere and ionosphere – to provide a daily availability of at least 10000 occultations;
- An urgent need for data gap filling using research / opportunity satellites, or commercial sources (if available) is required for the near term, but this is not a replacement for a long-term continuity plan to provide operational GNSS RO data;
- The potential of GNSS RO for anchoring climate re-analysis needs to be further addressed, this also requires updated laboratory measurements of refractivity coefficients.

Additionally, the sub-groups at IROWG-2 also recommend:

- Options to fly RO instruments on opportunity missions should be further pursued;
- Assure that GNSS operators are aware of the needs of RO applications, providing sufficient signal strength on the Earth limb;

- Support research towards implementing a LEO-LEO mission to fully explore the climate capabilities of RO;
- Engage CGMS agencies to organize a workshop to foster closer collaboration between the ionospheric and neutral atmospheric researchers.

All given presentations, as well as minutes, CGMS working papers from IROWG-2 are available at http://www.irowg.org.

References

[1] Status of the global Radio Occultation Observing System, CGMS-40 EUM-WP-02
[2] Climate related Processing and Potential of Radio Occultation Data, CGMS-40 EUM-WP-03

Acknowledgements

IROWG notes and thanks for financial support to this second workshop the following organisations: UCAR, EUMETSAT, NOAA, CGMS, and WMO.