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Prepared by IROWG
Agenda Item: WGII/3

REPORT OF IROWG ACTIVITIES: OUTCOME AND RECOMMENDATIONS FROM THE IROWG-8 WORKSHOP

Prepared by IROWG[1] (www.irowg.org)

Executive Summary

This report summarizes the IROWG-8 meeting held on April 7-13, 2021 as a virtual conference, hosted by NOAA and UCAR. It provides the main recommendations from the four IROWG sub-groups: Numerical Weather Prediction; Climate; Receiver Technology and Innovative Occultation Techniques; and Space Weather. The key recommendations for CGMS – endorsed by the IROWG community at the plenary session – are:

- IROWG reaffirms that all providers of RO observations should classify these as essential in the sense of WMO Res 40. IROWG stresses the importance of free, timely and unrestricted access in real time to essential RO data, and free and unrestricted access to archived raw data (including auxiliary data).

- IROWG continues to recommend that WMO and CGMS should coordinate any GNSS-RO data purchases. Specifically, we suggest convening a meeting of all agencies considering procuring these data, in order to discuss if, how and when the current 20,000 daily target will be met with global and full local time coverage.

- IROWG recommends that CGMS encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilization in NWP data assimilation – and the further exploration of RO-derived water vapor as a climate variable.

- Per CGMS priority HLPP 1.1.4 (optimized system for atmospheric and ionospheric RO observations), IROWG recommends that CGMS encourages on-going and future GNSS RO and non-RO missions, including potential commercial providers of RO observations, to incorporate a complete set of ionospheric measurements.

Full workshop minutes and this CGMS working paper from IROWG-8 will be made available at http://irowg.org/workshops/irowg-8/. All given workshop presentations can be found at https://cpaess.ucar.edu/meetings/2021/irowg-8.

Action/Recommendation proposed: CGMS is invited to take note and comment.

[1] International Radio Occultation Working Group, represented by the rapporteur Anthony Mannucci and the co-chairs Ulrich Foelsche and Sean Healy. Affiliations are listed at the end of this document.

1 INTRODUCTION

This IROWG working paper reports on the 8th workshop of the International Radio Occultation Working Group (IROWG-8). The meeting was organized by NOAA and UCAR and was originally planned to take place in the Washington area in the USA. Due to the COVID situation it had to be re-scheduled as a virtual conference, taking place from April 7-13, 2021. IROWG wants to express its gratitude for the excellent organisation of this meeting, which turned out to be the best virtual meeting and one of the most successful in recent years.

The workshop minutes and full recommendations will be available at:
http://irowg.org/workshops/irowg-8/. All the workshop presentations are at:
https://cpaess.ucar.edu/meetings/2021/irowg-8

One and a half years had passed since IROWG-7 (September 2019) and important progress has been achieved in this period.

372 scientists from 39 countries registered for the virtual conference, and up to about 200 participated on the individual days, including representatives from all the major RO processing centers, space agencies, the weather prediction centers assimilating RO data, the research community, and representatives of commercial data providers. 69 talks and 35 posters were presented. Recommendations were developed in dedicated sub-working groups, and then presented and agreed upon in a plenary discussion on the last day.

The structure of this report is as follows: Section 2 gives a brief overview of the organization of the workshop and the sub-groups, Section 3 summarizes science highlights and subgroup-discussions (in order of the presentations on the last day of IROWG-8), Section 4 summarizes the plenary discussion, Section 5 lists the main recommendations which were agreed upon by IROWG, and Section 6 concludes the main section of the report. The status of actions and recommendations is covered in the Appendix.

2 IROWG-8 SETUP

IROWG-8 was a full workshop, including presentations, posters and sub-group discussions. The presentations/posters and the sub-groups were organized according to the following specific topics, namely:

- Numerical Weather Prediction (NWP);
- Climate;
- Receiver Technology and Innovative Occultation Techniques;
- Space Weather.

IROWG-8 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) RO community, to providers of RO data, or within the IROWG. These were discussed in the open plenary. Furthermore, the subgroups assessed the status of the relevant CGMS actions.

Sean Healy will be stepping back as IROWG co-chair; an election process for a new co-chair was therefore initiated.

The next IROWG-workshop (IROWG-9) will be held in September 2022 in Seggauberg, Austria, in conjunction with the OPAC-7 meeting (Occultations for Probing Atmosphere and Climate).

3 SCIENCE HIGHLIGHTS AND WORKING-GROUP-DISCUSSIONS

Note that this is a summary; the entire list of recommendations will be made available in the full meeting minutes. Here we focus on the main recommendations per subgroup, which we regard as highest priority, even though not all of them can be promoted as IROWG key recommendations.

Receiver Technology and Innovative RO Techniques
Chair: Rob Kursinski (PlanetiQ), Rapporteur: John Braun (UCAR)

GNSS-RO can provide very high vertical resolution, all-weather, thermodynamic profiling of the planetary boundary layer (PBL) that is difficult to achieve from any other remote sensing technique. The unique contribution from GNSS-RO for spaceborne PBL profiling of temperature and water vapor as well as PBL height has been recognized in the U.S. 2017–2027 Decadal Survey for Earth Science and Applications from Space. Nonetheless, important issues do exist with RO profiling of the PBL which include:

- a persistent negative refractivity bias within the moist PBL
- increased noise in the lowermost troposphere data from COSMIC-2 despite its unprecedented high signal to noise ratios (SNR),
- limited utilization of lower troposphere RO data by NWP systems, as evidenced by high data rejection rates at low altitudes.
- depth of penetration

Ducting or super-refraction can cause RO-derived refractivity to be negatively biased in the PBL. Unbiased refractivity retrievals can be achieved when ducting is present, but doing so requires knowing whether or not ducting is present on a profile-by-profile basis–which is supported by observing deep occultation events, which require very high SNR observations.

Innovative techniques like polarimetric RO, LEO-LEO, grazing angle GNSS-R, and airborne observations deliver very promising results, which could be operationally exploited.

Radio Frequency Interference (RFI), e.g. through GPS jammers, has been identified as a major and increasing problem.

High-priority subgroup recommendations:
1) Encourage technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilization for NWP data assimilation - including formation of a working group focused on PBL related issues.
2) Advance LEO-LEO occultation development towards a demonstration mission. The subgroup recommends that CGMS adopt an action asking international space agencies (in particular CAS (Chinese Academy of Sciences) and ESA, where development work based on proposals towards initial LEO-LEO demonstration missions is ongoing) to support mission preparation projects that implement the next steps towards a LEO-LEO microwave and infrared-laser occultation (LMIO) demonstration mission.
3) Develop NWP forward operators for polarimetric RO, LEO-LEO, grazing angle GNSS-R, and airborne observations and promote the use of these new data for NWP and science applications

Numerical Weather Prediction
Co-Chairs: Hui Shao (JCSDA), Neill Bowler (Met Office), Ben Ruston (NRL)

Recent results confirm that the 20,000 target is well founded, and very likely to further increase the impact of GNSS-RO in NWP systems.

A number of operational NWP centers have now demonstrated the positive impact of increasing the number of observations, with the assimilation of FORMOSAT-7/COSMIC-2 and, in some cases, commercial data in 2020-21. For example, NASA GMAO have shown that the assimilation of both COSMIC-2 and Spire data leads to GNSS-RO being the third most important observing system, based on the Forecast Sensitivity to Observation Impact (FSOI) metric. Some impact on tropospheric humidity is also being reported – thanks to the high quality of COSMIC-2 data. In addition, new OSSEs by NASA GMAO suggest that there are still benefits moving from assimilating 50,000 to 100,000 profiles per day. Overall, the results presented at IROWG-8 reinforce the case for the current 20,000 daily target, which we note is achievable if the agency-led missions are augmented with commercial data.

We encourage CGMS members to consider any forthcoming missions of opportunity to fly additional GNSS-RO receivers, noting the recent progress with the Sentinel-6 Michael Freilich mission.

The NWP group notes that measurements made with GPS, GLONASS, Galileo and QZSS signals have now been successfully used in operational NWP (via commercial data provision); and that rapid operational implementation of new data is more likely if results and experience are shared between NWP centres.

High-priority subgroup recommendations:
1) The NWP group reaffirms providers of RO observations should classify these as essential in the sense of WMO Res 40. IROWG stresses the importance of free, timely and unrestricted access to essential RO data including archived raw and auxiliary data.
2) The NWP group continues to recommend that WMO and CGMS should coordinate any GNSS-RO data purchases, by convening a meeting of agencies actively considering procuring data. Sufficient commercial data should be purchased, with a world license for near-real time data, to meet the target of 20,000 globally available occultations per day.

3) There is a need to include additional information in a BUFR template. The NWP subgroup emphasizes the need for receiver IDs and a measure of SNR. This new template should accommodate new observation types, e.g., airborne GNSS-RO, and polarized RO (GNSS-PRO). Definition of a new GNSS-RO template should proceed even if specifics on how to calculate elements is ongoing.

Space Weather
Chair: Bill Schreiner (UCAR), Riccardo Notarpietro (EUMETSAT)

The high spatial and temporal resolution of COSMIC-2/FORMOSAT-7 data allows for studying the ionosphere (at low to mid latitudes) in much more detail than ever before, thereby breaking new ground for ionospheric research.

The space weather sub-group (SWSG) increased the priority of the recommendation to incorporate ionospheric measurements into satellites carrying RO instruments. In particular, the sub-group specifically endorses the merit of ionospheric upgrades to EPS being implemented for ionospheric data, as done in the Metop-A end-of-life test. In addition, the sub-group acknowledges that the Sentinel-6 hardware is capable of acquiring ionospheric observations in addition to the atmospheric RO, and endorses plans for implementing ionospheric capabilities via software upgrade to the Sentinel-6 receiver.

High-priority subgroup recommendations:
1) Per CGMS priority HLPP 1.1.4 (optimized system for atmospheric and ionospheric RO observations), the Space Weather sub-group of IROWG recommends CGMS encourage on-going and future GNSS RO and non-RO missions, including potential commercial providers of RO observations, to incorporate a complete set of ionospheric measurements (including negative and positive elevation angles – i.e. also data from zenith viewing precise orbit determination (POD) antennas …).
2) The SWSG recommends that CGMS expend all reasonable effort to acquire high quality near real-time GNSS RO space weather measurements, including all raw data, meta data, and documentation needed for future reprocessing, at all latitudes with full local time coverage.
3) The SWSG acknowledges the value of direct broadcast for low-latency ionospheric data, and endorses agency efforts to make use of direct broadcast channels for ionospheric data, wherever the missions are designed to provide such capability (e.g.: EPS-SG), to further decrease the latency of the ionospheric observations.

Climate
Chair: Andrea Steiner (WEGC), Rapporteur: Panagiotis Vergados (JPL)

The value of GNSS-RO data for climate monitoring is increasingly acknowledged by the broader climate science community. IROWG has been invited by the IPCC to contribute, and this chapter will appear in the upcoming assessment report.

The high spatio-temporal resolution of COSMIC-2/FORMOSAT-7 data allows for studying the tropical atmosphere in unprecedented detail, thereby breaking new ground for atmospheric research, e.g. related to different types of atmospheric waves and the diurnal cycle in the stratosphere.

High-priority subgroup recommendations:
1) Ensure continuity and long-term availability of climate quality RO measurements with global coverage over all local times. Operational GNSS RO missions for continuous global climate observations need to be established and maintained as backbone to ensure continuity with at least 20,000 occultations per day.
2) Acknowledging CGMS recommendation R46.01 on long-term data storage, we recommend that data providers ensure that all information necessary for independent processing towards climate data products is freely available (following WMO resolution 40), including long-term archiving and public data access, thus ensuring full climate traceability.
3) We recommend assessment of the uncertainty in the refractivity coefficients that impacts the accuracy and traceability of RO climate time series and trends. Significant progress was made at JPL in implementing an experiment to measure the refractivity of air, but currently is lacking the accuracy needed by the climate group. Required steps to improve accuracy have been identified by NASA/JPL, however further financial support is needed to implement these steps. IROWG is pleased to see these initial refractivity experiments and encourages CGMS agencies to support this activity.

4 SUMMARY OF PLENARY-DISUCSSIONS

All of the sub-groups recognized the importance of Level 0 (raw) data. It was stressed that raw data should be included in data purchase plans from commercial providers. **Action within IROWG**: A working group will be formed to develop an exchange format for raw data that is common to the different receiver types and that can be used for data exchange among users.

Radio Frequency Interference (RFI), e.g. through GPS jammers, has been identified as a major problem – receiver developers need to address this issue.

Technology and retrievals for the PBL, and their utilization for NWP have been discussed: **Action within IROWG**: Form a working group on PBL – how best to extract profile information.

Significant discussion occurred on the provision of commercial data. Dallas Masters of Spire recommended that NOAA purchase Level-2 data to increase access to data from multiple constellations. Several members of the community, however, reiterated that, for climate monitoring purposes, Level-2 data are not sufficient and raw data must be available.

The recommendations of the IROWG regarding coordination of data purchases acquired more urgency due to a large increase in the production of commercial RO data, particularly from Spire. GeoOptics is the sole provider of operational radio occultation data products under NOAA's Delivery Order-2 contract (1300 profiles/day). The near real-time data are only available to US Government users.

The Numerical Weather Prediction (NWP) sub-group recommended that CGMS agencies convene a meeting to discuss coordinated data purchases. This suggestion was well received.

The IROWG is addressing action item A47.31 (WGII) by developing material that shows gaps in RO data coverage from current and planned agency-led missions. These gaps occur particularly in local time above 40° latitude. Ben Ho of NOAA agreed to provide maps showing geographic and local time distributions for agency-led radio occultation profiles.

Regarding action A48.02 (WGII), the NWP sub-group suggested that agencies send representatives to an IROWG meeting so that detailed information on quality control methods and statistics used by the different agencies can be discussed, leading to their improved documentation.

IROWG should verify that the WMO OSCAR database properly documents the abilities of current and future missions to obtain ionospheric data.

NWP and climate requirements are not exactly the same – care is needed when purchasing commercial data and climate requirements need to be considered.

New RO data probe the lower troposphere better than before.
Action within IROWG: Establish a task force for the lower troposphere. Explore RO-derived water vapor further as a climate variable.

A dedicated launch of satellites carrying RO receivers was suggested by the climate sub-group to address the gap in local time coverage that has emerged since the demise of COSMIC-1 and the limited latitudinal coverage of COSMIC-2. The existing RO constellation does not serve the needs of climate monitoring. Dedicated launches, either by agency-led missions or by commercial data providers, are an effective approach to fill the gap.

5 MAIN RECOMMENDATIONS FROM IROWG-8

5.1 IROWG reaffirms that all providers of RO observations should classify these as essential in the sense of WMO Res 40. IROWG stresses the importance of free, timely and unrestricted access in real time to essential RO data, and free and unrestricted access to archived raw data (including auxiliary data).

This is important for NWP, Climate and Space Weather. For applications in climate science it is particularly important that all information necessary for independent processing towards climate data products is freely available. Data latency is particularly important for Space Weather applications (requirement of 30 minutes (median), with a goal of 15 minutes).

5.2 IROWG continues to recommend that WMO and CGMS should coordinate any GNSS-RO data purchases. Specifically, we suggest convening a meeting of all agencies considering procuring these data in order to discuss if, how and

when the current 20,000 target will be met with global and full local time coverage.

It is likely that commercial data will need to be purchased, with a world license for near-real time data, to meet the current target of 20,000 globally available occultations per day.

IROWG notes that commercial data are of operational quality and have been used successfully by several agencies, as demonstrated by the successful operational assimilation by the ECMWF, UK Met Office, and USAF of over 7000 daily, near real-time Spire Level 2 RO BUFR profiles over more than four months in 2020. The daily target of 20,000 – although possible within 2021 with the inclusion of commercial data – will be difficult to achieve without sharing the data. These data should be evenly distributed in local time and latitude.

Climate requirements should be taken into consideration when purchasing commercial data, and the potential climate quality of commercial data needs to be assessed.

A world license has numerous benefits, including avoiding data duplication, sharing of experience with data sets among different centres, fairness among countries, and reducing the timeline toward implementation.

IROWG will provide links to current real time statistics on the number of assimilated GNSS-RO data in various systems, and their performance.

5.3 IROWG recommends that CGMS encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilization in NWP data assimilation – and the further exploration of RO-derived water vapor as a climate variable.

GNSS-RO can provide very high vertical resolution, all-weather, thermodynamic profiling of the planetary boundary layer (PBL) that is difficult to achieve from any other remote sensing technique. The unique contribution from GNSS-RO for spaceborne PBL profiling of temperature and water vapor as well as PBL height has been recognized in the U.S. 2017–2027 Decadal Survey for Earth Science and Applications from Space.

Atmospheric radio-refractivity is heavily dependent on water vapor. GNSS-RO data in the lower troposphere therefore contain a lot of water vapor information, which has so far only been partly exploited.

5.4 Per CGMS priority HLPP 1.1.4 (optimized system for atmospheric and ionospheric RO observations), IROWG recommends that CGMS encourages on-going and future GNSS RO and non-RO missions, including potential

commercial providers of RO observations, to incorporate a complete set of ionospheric measurements.

- across all negative elevation angles as defined in the LEO local level frame from orbit altitude down to near the Earth's limb to allow for ionospheric profiling (for RO missions)
- across all positive elevation angles in the zenith direction for ionospheric/plasmaspheric sensing
- dual frequency signal amplitudes or SNRs, pseudoranges, phases, slant TECs, amplitude and phase scintillation indices
- with the maximum sampling rate allowed by the receiver (at least for all the time intervals for which the level of ionospheric scintillation is significant).

IROWG endorses the merit of ionospheric upgrades to EPS being implemented for ionospheric data, as done in the Metop-A End-of-Life test. In addition, the sub-group acknowledges that the Sentinel-6 hardware is capable of acquiring ionospheric observations in addition to the atmospheric RO, and endorses plans for implementing ionospheric capabilities via software upgrade to the Sentinel-6 receiver.

6 CONCLUSIONS

The "GPS" RO Technique is now a true "GNSS" RO Technique, where signals from all GNSS constellations are being exploited.

GNSS-RO data demonstrate a high impact in NWP. This impact clearly increases with the number of high-quality profiles – without any sign of "saturation".

GNSS-RO climate data advance climate change monitoring and contribute to the upcoming IPCC assessment report.

GNSS-RO data with high spatial and temporal resolution allow for unprecedented studies of atmospheric and ionospheric phenomena.

A better penetration into the lowest kilometres allows for studying the planetary boundary layer – including tropospheric water vapor.

Overall, the aim of the community is to ensure the long-term continuity of the GNSS-RO measurements, and to maximize the number of high-quality GNSS-RO observations, providing good spatial and local time coverage, which can be freely exchanged. Specifically, the researchers need access to the raw data, not just retrieved products. The provision and funding of long-term archiving of both the raw GNSS-RO data and all the meta-data is essential for climate studies, for reanalyses, and for any reprocessing activities. The researchers also need access to information about the instrument performance. Overall, it is important that multiple centers have all the information required for them to process and re-process GNSS-RO from both government sponsored and commercial missions. Therefore, there is strong support for a "backbone" of agency-funded GNSS-RO missions with long-term commitment.

Commercial GNSS-RO missions have reached operational quality (at least in the UTLS), and could help to close the identified gaps in geographic and local-time coverage – provided that they are made available for the scientific community.

7 APPENDIX

Status of CGMS Actions/Recommendations relevant to IROWG

A47.31: CGMS baseline and RO: IROWG and 7th WMO Impact Workshop needs to validate the current baseline in terms of the coverage, number, quality and sampling of RO

- IROWG notes that the current CGMS baseline (6000 occultations from low inclination orbits distributed geographically and temporally; 1000 occultations from drifting high inclination orbits; and 7600 occultations from sun-synchronous orbits) does not necessarily reflect the IROWG recommendations regarding geographic and local time coverage.
- E.g., the requirement "7600 occultations from sun-synchronous orbits" (without further specification) **can** result in an adequate sampling of the diurnal cycle – or not (see below).
- It is mandatory, that RO data are globally distributed and provide a good sampling of the diurnal cycle. This can be either achieved with a dedicated constellation with orbits that drift sufficiently fast in local time (typically in six orbit planes, including high-inclination orbits), or with satellites in six or more sun-synchronous orbit planes that provide an adequate sampling of the diurnal cycle (or by a combination of these approaches).
- The current (and near future) situation is unsatisfactory: Due to the cancellation of its polar component, COSMIC-2 data are confined to latitudes below ~40° Metop as well as Metop-SG satellites are/will be limited to one orbit plane, and there is currently only one sun-synchronous satellite (FY-3D), which covers other local times than Metop(-SG). This leaves a serious gap in local time coverage at mid and high latitudes – even more pronounced for ionospheric data, which are not provided by the first generation of Metop satellites.
- This situation can/will be slightly improved (but certainly not mitigated) by including RO data from the upcoming FY-3E satellite with different equator-crossing time and data from Sentinel-6 in a drifting orbit. Initial Sentinal-6 data look very promising, and will – ultimately – cover all local times, however, it takes almost two months to achieve this.

- Actual profile numbers tend to be smaller than the nominal ones. Based on the nominal performance documented in the WMO OSCAR database, one would assume that the current constellation of operational RO missions would deliver at least 10 000 profiles per day (April 2021); however, the actual number of post-QC profiles (average of the past month) that can be assimilated at ECMWF is less than 8000.
- IROWG shares the concern, expressed in the recent WGIII risk assessment, that there is "Continuity risk for the number and geographic distribution of radio occultations; especially in the low- to mid- latitudes", since there is currently no plan for a successor of the COSMIC-2 mission.
- This baseline is currently not sufficient to meet the HLPP objective (1.2) to advance the atmospheric Radio Occultation constellation, with the long-term goal of providing 20,000 occultations per day on a sustained basis.

A48.02: Data providers to document data processing QC processes (including a month of QC statistics, e.g. rejection percentage at each QC step) and space sampling information and provide to IROWG.

- IROWG notes that this is a CGMS recommendation to data providers.
- IROWG suggests that the relevant agencies send representatives to the next IROWG meeting so that detailed information on quality control methods and statistics used by the different agencies can be discussed, leading to their improved documentation.
- The need for this has been recognised, and members of the community will take steps to document their procedures.
- Certain WG members (from EUMETSAT, Spire and NOAA-NESDIS) agreed to provide information on QC numbers in the next IROWG meeting.

Affiliations

Anthony Mannucci is with the Jet Propulsion Laboratory, California Institute of Technology. Sean Healy is with the European Center for Medium Range Weather Forecasts. Ulrich Foelsche is with the University of Graz, Austria.