CGMS

CGMS-51 IROWG-WP-01
April 10, 2023

Prepared by IROWG
Agenda Item: WGII/3

REPORT OF IROWG ACTIVITIES: OUTCOME AND RECOMMENDATIONS FROM THE IROWG-9 WORKSHOP

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

Executive Summary

This report summarises the IROWG-9 meeting held on September 8-14, 2022 in Leibnitz, Austria, in conjunction with the 7th International Workshop on Occultations for Probing Atmosphere and Climate (OPAC). It provides the recommendations from the four IROWG sub-groups: NWP, Climate, Receiver Technology/Innovative Occultation Techniques and Space Weather.

The key recommendations for CGMS – endorsed by the IROWG community at the plenary session – are:

- IROWG strongly supports an open data policy towards the purchase of commercial RO data and recommends that all agencies follow this model. IROWG stresses the importance of free and unrestricted access to essential RO data including archived raw or low-level (level 0) data.
- IROWG recommends operational Global Navigation Satellite System (GNSS) RO missions for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage.
- IROWG continues to support the previous recommendations that GNSS-RO data - with at least 20,000 occultations per day - are globally distributed and provide full sampling of the diurnal cycle (local time). This is important for NWP, Climate, and Space Weather. IROWG also recommends further investigation of the value of increased target observation quantities, to provide a sound basis for future statements on the desirable number of observations and insights on satellite mission planning and coordination.
- IROWG recognizes the importance of space weather applications of RO data. IROWG recommends that RO and non-RO missions that use dual-frequency GNSS receivers for their orbit determination needs should make available to the operational and research communities all necessary low-level (level 0) data and metadata required to produce accurate overhead TEC data from the GNSS receiver.
- IROWG encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilisation in NWP data assimilation as well as the further exploitation of RO-derived water vapour.

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

Full workshop minutes and this CGMS working paper from IROWG-9 will be made available at http://irowg.org/workshops/irowg-9/. All given workshop presentations can be found at https://opacirowg2022.uni-graz.at/en/.

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 Hui Shao. Affiliations are listed at the end of this document.

1. INTRODUCTION

This IROWG working paper reports on the ninth workshop of the International Radio Occultation Working Group (IROWG-9), which was held in conjunction with the 7th International Workshop on Occultations for Probing Atmosphere and Climate (OPAC). The meeting was organised by the Wegener Center for Climate and Global Change, University of Graz and held in Seggau Castle, Leibnitz, Austria, from September 8-14, 2022. IROWG wants to express its gratitude for the perfect organisation of this meeting, which was the first face-to-face IROWG meeting since the pandemic across the world.

The workshop was attended by more than 100 scientists, including representatives from all the major RO processing centres, space agencies, the weather prediction centres assimilating RO data, the research community, and representatives of commercial data providers. 81 oral presentations, three opening talks, a key-note talk, and 21 posters were presented. Recommendations were developed in dedicated working sub-groups, and then presented and agreed upon in a plenary discussion on the last day. Additionally, the workshop was used by several researchers for dedicated specialist/splinter meetings, such as BUFR format revision, level 0 data format discussion, and aircraft radio occultation operator development and version control discussion. These meetings were hosted as part of the responses to previous IROWG internal recommendations.

The structure of this report is as follows: Section 2 gives a brief overview of the organisation of the workshop and the sub-groups, Section 3 lists the recommendations provided by the different subgroups, and Section 4 concludes the main section of the report. The status of actions and recommendations is covered in the Appendix. The Appendix also covers good practice documents being proposed for IROWG.

2. IROWG-9 SETUP

IROWG-9 (in conjunction with the 7th International Workshop on Occultations for Probing Atmosphere and Climate) was a full workshop, including presentations, posters and sub-group discussions. The presentations/posters and the sub-groups were organised according to the following specific topics, namely:

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

IROWG-9 participants were asked to summarise 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-RO community, to providers of RO data, or within the IROWG. These were discussed in the open plenary on the last day. Furthermore, the subgroups assessed the status of the relevant CGMS actions. The participants agreed to highlight main recommendations for CGMS-51; these were endorsed by all participants.

IROWG-9 also hosted an inauguration for the transition of the chairmanship of IROWG. Sean Healy stepped back as IROWG co-chair. His service for the IROWG community is well received and appreciated. Hui Shao took the co-chair position and will work with Uli Foelsche (co-chair) and Anthony Mannucci (Rapporteur) to continue the IROWG service.

3. MAIN RECOMMENDATIONS FROM IROWG-9 PLENARY

This section lists main recommendations for CGMS-51, endorsed by all participants during the IROWG-9 Plenary discussions.

a. IROWG strongly supports an open data policy towards the purchase of commercial RO data and recommends that all agencies follow this model. IROWG stresses the importance of free and unrestricted access to essential RO data including archived raw or low-level (level 0) data.

IROWG recognizes the recent efforts and activities at EUMETSAT and NOAA for global licensing of their commercial data purchase and supports continuing efforts. The free and open exchange of data leads to the greatest improvements in forecast quality, due to the ability to rigorously compare processing methods and assimilation techniques when using a common base of shared data. IROWG encourages institutions to purchase full datasets (with all acquired observations and including low-level data) and to make these available to the global community. IROWG recognizes the need to ensure the long-term availability and continuity of the commercial data. Climate requirements should be taken into consideration when purchasing commercial data. This may necessitate targeted launches of satellites in order to fully cover the diurnal cycle at middle and high latitudes.

b. IROWG recommends operational Global Navigation Satellite System (GNSS) RO missions for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage.

IROWG reaffirms our support for publicly funded high-quality observations and also acknowledges the contributions of commercial data providers, pending validation of their climate data quality, including complete long-term access by independent processing centres to the complete set of acquired data without any data removal due to pre-screening. The backbone missions can provide stable, long-term, SI-traceable and reliable observations. The expertise of publicly funded data-processing centres is invaluable in assessing and archiving commercial data provision. They also help to reduce the risk to the global observing system if one or more commercial providers were to go out of business, or if the market became dominated by a single player.

c. IROWG continues to support the previous recommendations that GNSS-RO data - with at least 20,000 occultations per day - are globally distributed and provide full sampling of the diurnal cycle (local time). This is important for NWP, climate, and space weather. IROWG also recommends further investigation of the value of increased target observation quantities, to provide a sound basis for future statements on the desirable number of observations and insights on satellite mission planning and coordination.

The ROMEX experiment was proposed to investigate operational NWP impact versus numbers of occultations, as an international collaboration between NWP centres and data providers. ROMEX seeks to acquire RO data from all missions, including commercial missions, to obtain a very large amount of actual RO data for a limited period of time (approximately 3 months) for testing of impact, as well as to provide a unique research data set. It is expected that this will provide a sound basis for future statements on the desirable number of observations and validate the results of Ensemble Data Assimilation (EDA) studies and Observation System Simulation Experiments (OSSEs) for future satellite mission planning.

d. IROWG recognizes the importance of space weather applications of RO data. IROWG recommends that RO and non-RO missions that use dual-frequency GNSS receivers for their orbit determination needs should make available to the operational and research communities all necessary low-level (level 0) data and metadata required to produce accurate overhead TEC data from the GNSS receiver.

Overhead TEC data is a valuable space weather data type that is potentially available from a wide variety of orbiting platforms, including those that are not specifically purposed for space weather or radio occultation. Producing overhead TEC data requires that GNSS observables be downloaded from the onboard GNSS receiver. The downloaded GNSS data and metadata should include, at a minimum, dual-frequency code and phase measurements, and, if possible: antenna phase centre variations, spacecraft attitude orientation, and solar array motion. The data should have sample intervals of 1 sec or higher and low latency if possible (goal of 15 minutes).

e. IROWG encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilisation in NWP data assimilation as well as the further exploitation of RO-derived water vapour.

The unique contribution from GNSS-RO for spaceborne PBL profiling of temperature and water vapour as well as PBL height has been recognized in the U.S. 2017–2027 Decadal Survey for Earth Science and Applications from Space. NWP centres are encouraged to investigate whether additional benefits can be extracted from RO measurements in the lower troposphere, with a particular thought on how signal-to-noise ratio affects this usefulness. Atmospheric radio-refractivity is heavily dependent on water vapour. GNSS-RO data in the lower troposphere therefore contain a lot of water vapour information, which has so far only been partly exploited.

4. SUB-GROUP RECOMMENDATIONS AND DISCUSSIONS

IROWG-9 participants were asked to summarise 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. The entire list of recommendations are made available in the full meeting minutes. Here we focus on the main recommendations per subgroup, which we regard as the highest priority, even though not all of them can be promoted as IROWG key recommendations.

1. Numerical Weather Prediction (NWP) Sub-Group

a. IROWG strongly supports an **open data policy** towards the purchase of commercial RO data and recommends that all agencies follow this model. IROWG believes that the free and open exchange of data contributes to the greatest improvements in forecast quality, due to the ability to compare processing methods and assimilation techniques.

b. IROWG reaffirms our support for **a publicly funded backbone of government funded high-quality observations**. The rationale for this statement is that agency funded missions can provide stable, long-term, traceable and reliable observations. The expertise of publicly funded data-processing centres is invaluable in assessing and archiving commercial data provision. They also help to reduce the risk to the global observing system if one or more commercial providers were to go out of business, or if the market became dominated by a single player. The CGMS baseline also provides a reference point against which the commercial companies can compare and innovate.

c. IROWG **recognises the rapid progress** that has been made in the **exploitation of commercial observations**. The progression to the routine operational assimilation of these data at a number of centres has been a demonstration of effective inter-agency collaboration. IROWG recommends to continue this work.

d. IROWG supports the statements that CGMS has given on the desirable number of observations for the baseline and target observing systems. Some members expressed the view that the **target observation quantities** should be **increased**. It was agreed that we would await results from the proposed **RO Modeling Experiment (ROMEX)**, which seeks to acquire all RO data from all missions, including commercial missions, to obtain a very large number (32,000 or more per day) of real RO data for a limited period of time (approximately 3 months) for testing of impact versus number of occultations in operational NWP, as well as to provide a unique research data set. It is hoped that this will provide a sound basis for future statements on the desirable number of observations and validate the results of EDA studies and OSSEs.

Climate Sub-Group

a. **Ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage. Operational GNSS RO missions for continuous global climate observations need to be established and maintained as a backbone to ensure continuity with at least 20,000 occultations per day, in at least four evenly-spaced orbital planes with uniform global coverage. Level 0 data need to be freely available for reprocessing**. The community is currently short of 20,000 evenly-distributed occultations per day, but IROWG acknowledges the recommendation of CGMS to achieve this target. For climate studies, the effects of local time-related sampling errors should be examined and minimised. We acknowledge the contributions of commercial data providers, pending validation of their climate data quality, including long-term and full access to the data by independent processing centres. We need more climate-tailored data, fulfilling GCOS climate quality requirements, and to ensure the long-term availability and continuity of the commercial data. Climate requirements should be taken into consideration when purchasing

commercial data. This may necessitate targeted launches of satellites in order to cover the diurnal cycle at middle and high latitudes.

b. Acknowledging a relevant CGMS recommendation WGIIR50.04 on long-term data access, we recommend that **data providers ensure that all information necessary for independent processing towards climate data products is freely available (following WMO Unified Data Policy Resolution 1), including long-term archiving of *all* measured and acquired data *without* filtering (i.e. including the data not passing quality control), starting with level 0 data, and public data access, thus assuring full climate traceability.** This needs to include information on instrument/software updates and full documentation of the processing chains that keep track of any introduced changes/updates (e.g., POD-induced uncertainties). We also recommend that the impact of instrument software updates on climate products be evaluated beforehand. All level 0 data providers should make available phase data, amplitude data, and satellite orbit data in a well-documented format (such as NetCDF).

c. **Data providers should ensure parallel data streams of RO climate data products: one regularly updated data version and one uniformly reprocessed version.** The reprocessed version should always cover the full data time period until a new processing version takes over. Acknowledging the increasing computing requirements and growing data volume, we encourage developing the capabilities for future archiving and distribution of large amounts of RO data, e.g., using cloud computing. We note that there are ongoing activities at NASA to migrate all Earth data onto commercial storage solutions: one such funded program to migrate RO data is ACCESS 2019.

d. In the retrieval processing chains, traceable uncertainty estimation and documentation needs to receive increased attention (as for example raised via Action G-3 on IROWG members by the "3G" community at the WMO-organised workshop)[1]. **IROWG recommends that processing centres increase efforts on uncertainty estimation and make uncertainty calculations publicly available through peer-reviewed publications. One method of uncertainty quantification is to produce ensembles of processed observations ("perturbed retrieval ensembles")** that include different processing assumptions and initialization information where the SI-traceability chain may be less robust (in accordance with the GCOS-143 Document).[2]

e. **Promote funding of various reprocessing activities of RO climate data records** from different RO processing centres along the principles for reprocessing climate data records of the WCRP Observation and Assimilation Panel (WOAP[3]). Documentation of the historical evolution of processing systems for the provision of climate data records is important. **This should include gridded data together with uncertainty estimates (such as the "perturbed retrieval ensembles" mentioned in (d) above) and algorithm descriptions from multiple centres**. This will help to promote the use of RO data by the climate community. Furthermore, it is recommended that efforts to provide data in the Obs4MIPs format and archive should be continued and extended.

[1] https://www.wmo.int/pages/prog/www/WIGOS-WIS/reports/3G-WIGOS-WS2014.pdf

[2] Mears, C. A., F. J. Wentz, P. Thorne, and D. Bernie, 2011: Assessing uncertainty in estimates of atmospheric temperature changes from MSU and AMSU using a Monte-Carlo estimation technique. *J. Geophys. Res.*, **116**, D08112, doi:10.1029/2010JD014954.

[3] http://www.wcrp-climate.org/documents/WOAP_ReprocessingPrinciples.pdf

Multi-center ensembles of independently processed RO datasets will be useful in quantifying the structural uncertainty. Derived parameters such as tropopause heights are also important climate records.[4] Continuity of funded efforts is desired.

f. **Uncertainty in the refractivity coefficients 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 such experiments currently lack the precision needed by the climate group. Required steps to improve precision have been identified by NASA/JPL, however further financial support is needed. **IROWG is pleased to see these initial laboratory refractivity experiments and encourages CGMS agencies to support this activity.** We recommend continuous coordination among IROWG, bringing in metrology experts and assessing decadal trends in the coefficients' definition. We also recommend status reporting from JPL.

g. **We acknowledge the success of the 3G meeting which brought together the GNSS RO community, the GRUAN community and the GSICS community in May 2014 in Geneva and recommend organising such meetings periodically by WMO** with the scope of enhancing collaboration among communities and assessing progress. Recent activities regarding the link between GRUAN and RO are noted, the one between GSICS and RO could be deepened. We will target the year 2023 for the next meeting and identify a sponsor within WMO to host the workshop.

h. **We recommend that operational data providers additionally supply occultation prediction products, aiding coordinated ground-based collocated measurements**. We note products provided for GRAS by EUMETSAT, and COSMIC-2 by NOAA/STAR.

Receiver Technology and Innovative RO Techniques

1. **Encourage technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilisation in NWP data assimilation.**

2. **Advance LEO-LEO occultation development towards a demonstration mission**
   IROWG recommends to **support mission preparation projects** that implement the next steps towards LEO-LEO microwave and infrared-laser occultation (LMO/LMIO) demonstration missions. Such next steps within the next two to three years include LMO/LMIO instrument developments towards flight instrumentation, microsat platform design and preparation, and dedicated Phase A/B studies towards mission implementation. IROWG also recommends that CGMS encourage space agencies to support R&D towards implementation of LEO-LEO demonstration in a broader sense, in order to pave the way towards developing an authoritative reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs) on thermodynamics, composition (greenhouse gases) and climate, as well as transferring

[4] https://www.science.org/doi/10.1126/science.1084123

the unique accuracy, precision and high resolution of the LEO-LEO observations into the NWP forecasts and reanalyses via assimilation.

3. **Promote development of retrievals and use of polarimetric RO observations (i.e. PAZ/orbital or airborne).** Polarimetric RO measurements are sensitive to hydrometeors along the occultation raypath. With the launch of both PAZ and FORMOSAT-7/COSMIC-2 missions and the operational collection of grazing angle reflections by Spire satellites and plans for PlanetIQ to add such a capability in 2024, new opportunities in data analysis are now possible. These observations include polarimetric RO observations, high SNR data, deep tracking data, and grazing angle reflections. The IROWG community should capitalise on these observations to explore and demonstrate the scientific value of these emerging technologies.

Space Weather Sub-Group

a. Per CGMS priority HLPP 1.1.4 (optimised system for atmospheric and ionospheric RO observations), **on-going and future GNSS RO missions (including commercial providers) should incorporate the following key ionospheric monitoring capabilities in their sensors:** (a) low data latency (<30 minutes, 15 minutes goal); (b) continuous tracks of data spanning tangent altitudes from below 90 km up into the zenith hemisphere to the maximum extent; (c) slant total electron content (TEC) with 3 TECU & 0.3 TECU absolute and relative accuracy, respectively; (d) amplitude and phase scintillation indices; (e) high rate (50Hz or higher, as dictated by the GNSS signal being observed) observations at ionospheric tangent altitudes when scintillation is present. **When considered as a whole, RO systems should make ionospheric measurements with approximately uniform geographic and local time coverage over the globe.**

b. **Non-RO missions that fly GNSS receivers for precise orbit determination should make available to the operational and research communities all necessary level-0 data and metadata required to produce accurate overhead TEC data.** Overhead TEC data is a valuable space weather data type that is potentially available from a wide variety of orbiting platforms, including those that are not specifically purposed for space weather or radio occultation. Producing overhead TEC data requires that GNSS observables be downloaded from the onboard GNSS receiver. The downloaded GNSS data and metadata should include, at a minimum, dual-frequency code and phase measurements, and, if possible: antenna phase centre variations, spacecraft attitude orientation, and solar array motion. The data should have sample intervals of 1 sec or higher and low latency if possible (goal of 15 minutes).

c. **All RO data providers should make level-0 data available together with appropriate documentation and software to read this data, to enable science users to process the data into higher level products.**

5. CONCLUSIONS

The IROWG-9 meeting was held on September 8-14, 2022 in Leibnitz, Austria. This was the first face-to-face IROWG meeting since the pandemic across the world. The IROWG-9 participants reported their programmatic and scientific progress and formed main recommendations for CGMS-51, as well as recommendations and actions within the IROWG. In addition, IROWG-9 hosted an inauguration for the transition of the chairmanship of IROWG. Sean Healy stepped back as IROWG co-chair. Hui Shao has taken the co-chair position and will work with Uli Foelsche (co-chair) and Anthony Mannucci (Rapporteur) to serve the IROWG community.

IROWG highly appreciates the recent efforts and activities at EUMETSAT and NOAA for global licensing of their commercial data purchase and supported continuous efforts. IROWG strongly supports an open data policy towards the purchase of commercial RO data and recommends that all agencies follow this model. IROWG emphasizes that free and unrestricted access to essential RO data, including archived raw or low-level (level 0) data, leads to the best NWP forecasts and the highest utility of RO data for climate purposes.

IROWG reaffirms our support for publicly funded high-quality observations and also acknowledges the contributions of commercial data providers, pending validation of their climate data quality, including complete long-term access by independent processing centres to the complete set of acquired data without any data removal due to pre-screening. IROWG recommends operational GNSS RO missions for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage.

IROWG continues to support the previous recommendations that GNSS-RO data - with at least 20,000 occultations per day - are globally distributed and provide full sampling of the diurnal cycle (local time). This is important for NWP, climate, and space weather. IROWG also recommends further investigation of the value of increased target observation quantities, to provide a sound basis for future statements on the desirable number of observations and insights on satellite mission planning and coordination. This will be done through the RO Modelling Experiment (ROMEX) effort, proposed during the IROWG-9. ROMEX seeks to acquire RO data from all missions, including commercial missions, to obtain a very large amount of actual RO data for a limited period of time (approximately 3 months) for testing of impact, as well as to provide a unique research data set. It is expected that this will provide a sound basis for future statements on the desirable number of observations and validate the results of Ensemble Data Assimilation (EDA) studies and Observation System Simulation Experiments (OSSEs) for future satellite mission planning.

IROWG recognizes the importance of space weather applications of RO data. IROWG recommends that RO and non-RO missions that use dual-frequency GNSS receivers for their orbit determination needs should make available to the operational and research communities all necessary low level (level 0) data and metadata required to produce accurate overhead TEC data from the GNSS receiver.

IROWG encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilisation in NWP data assimilation as well as the further exploitation of RO-derived water vapour.

6. APPENDIX

Status of CGMS Actions/Recommendations relevant to IROWG

There are currently no open actions for IROWG.

Proposed Good Practices

During the IROWG-9, the following good practices were proposed from the subgroup discussions and to be considered for WGII:

> IROWG recommends that data providers ensure that all information necessary for independent processing towards climate data products is freely available (following WMO Unified Data Policy Resolution 1), including long-term archiving of *all* measured and acquired data *without* filtering (i.e. including the data not passing quality control), starting with level 0 data, and public data access, thus assuring full climate traceability.
>
> IROWG proposes that a good practice for data providers is to include information on instrument/software updates and full documentation of the processing chains that keep track of any introduced changes/updates (e.g., POD-induced uncertainties).

Affiliations

Anthony Mannucci is with the Jet Propulsion Laboratory, California Institute of Technology, United States. Hui Shao is with the Joint Center for Satellite Data Assimilation, United States. Ulrich Foelsche is with the University of Graz, Austria.