Summary of the Ninth International Radio Occultation Workshop

Held in Seggau Castle, Leibnitz, Austria

From Thursday, 8th September to Wednesday, 14th September 2022

Starting at 09:00 hours on 8th September

Ending at 12:10 hours on 14th September

1. 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 recognizes the recent efforts and activities at EUMETSAT and NOAA for global licensing of their commercial data purchase and supports continuing efforts. 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 that all use a common base of shared data. IROWG encourages institutions to purchase full datasets (with all observations and low-level data) and to make these available to the global community. IROWG also 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.

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.

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 the impact versus numbers of occultations in operational NWP, 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.

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.

The GNSS data and metadata should include dual-frequency code and phase measurements, antenna phase centre variations, spacecraft attitude orientation, and solar array motion. The data should have sample intervals of (10 sec or higher) and low latency if possible (goal of 15 minutes).

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.

Good practices:

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).

1. INTRODUCTION

This IROWG report presents the minutes / full recommendations of the combined 7th International Workshop on Occultations for Probing Atmosphere and Climate (OPAC) and the ninth workshop of the International Radio Occultation Working Group (IROWG-9). 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 are not covered here.

IROWG 2022 – the Joint OPAC-7 & IROWG-9 Workshop – follows the objectives of the previous workshops in 2019 (virtual), 2016, 2013, 2010, 2007, 2004, and 2002 for again fostering the advancement and use of this great utility: It aimed at providing a casual forum and stimulating atmosphere for scientific discourse, cooperation initiatives, and mutual learning and support amongst members of all occultation-related communities and users of occultation data. IROWG-9 integrated perfectly with these aims as its goals are to promote the exchange of scientific and operational information between RO data producers, the research community and the applied user community.

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 with the main recommendations for CGMS.

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. 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 are 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. SUB-GROUP RECOMMENDATIONS / DISCUSSIONS

a. Numerical Weather Prediction (NWP) Sub-Group

Co-chairs: Neill Bowler (UK Met Office) and Katrin Lonitz (ECMWF)

Members: Amy McVey (Verisk - atmospheric and environmental research), Joe Andrews (Skykraft), Harald Anlauf (DWD), Richard Anthes (UCAR), Kristen Bathmann (Spire), Yong Chen (NOAA), William Gullotta (NOAA), Jennifer Haase (University of California), Sean Healy (ECMWF), Pawel Hordyniec (University of California), Ying-Hwa (Bill) Kuo (UCAR), Rob Kursinski (PlanetiQ), Anthony Mannucci (JPL), Christian Marquardt (EUMETSAT), Martin McHugh (NOAA), William Miller (CISESS), Dominique Raspaud (Meteo France), Benjamin Ruston (JCSDA), Hui Shao (JCSDA), Stig Syndergaard (DMI), Kuo-Nung Wang (JPL), Jan-Peter Weiss (UCAR), Feiqin Xie (Texas A&M University), Hailing Zhang (COSMIC/JCSDA)

Recommendations to CGMS

2. 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.

3. 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.

4. 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.

5. 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 ROMEX experiment, 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 vs. 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.

Recommendations/Actions within IROWG

1. For reanalysis and other purposes, it is helpful to have archives of large RO quantities. IROWG encourages institutions to **purchase full datasets** (with all observations and low-level data) and to make these available to the global community. The procured data should also be archived and be subject to regular reprocessing activities.

2. IROWG recommends an action to every operational processing centre to **provide a clear set of detailed documentation on their procedures** (QC, smoothing, etc.). These should be produced in a timely manner (i.e. as release notes to be a part of the data release).

3. IROWG has noted that several important **research topics** deserve attention in the coming years:

   a. IROWG encourages the community to investigate **whether additional benefits can be extracted from RO measurements in the lower troposphere**. With a particular thought on how SNR affects this usefulness. (high priority)

   b. Observation operators for **polarimetric and aircraft RO** are currently being developed. Once these operators are ready, IROWG encourages **experimentation** with these new observations and operators. (high priority)

   c. IROWG recommends that agencies investigate **the potential of GNSS-R measurements** (both nadir and grazing angle), working with scientists from relevant other communities as needed. (medium priority)

   d. IROWG encourages the **renewed lab measurements of the k1, k2 coefficients** as used in the calculation of refractivity. (low priority)

Actions to IROWG 7/8 from CGMS:

Action IROWG-8-01: Form a sub-committee to discuss a revision to the BUFR format.

Done. Various meetings have been held online, with an open meeting being held at IROWG-9 to continue this discussion.

Action IROWG-8-02: Form a sub-committee to discuss a low-level data exchange format (level 0b).

Done. Various meetings have been held online, with an open meeting being held at IROWG-9 to continue this discussion.

Action IROWG-7-01: Data providers to document data processing QC processes (including a month of QC statistics, e.g. rejection percentage at each QC step) and spatial sampling information and provide to IROWG.

Close.

Data providers have struggled to provide us with the requested information.

New action items from IROWG-9

The science of radio occultation depends upon accurate geodetic data for precise orbit determination. IROWG discussed the need for a variety of services to be available which meets this need.

J. Haase conducted a survey of the ground-station infrastructure which is used by the RO community. Many of the respondents indicated that they are reliant on IGS for this information, although some used other organisations. A summary of the survey is as follows:
GNSS ground based infrastructure is required for several direct and indirect steps for RO and space weather data processing. They are described as essential, extensively used, and relied on by all centres that responded. Five processing centres relied exclusively on publicly supported and open GNSS ground station data through their derived clock, orbit, and Earth orientation products (EOP), which were provided by six of the IGS analysis centres. Three RO processing centres used a combination of proprietary and publicly supported ground stations for derivation of their own GNSS orbit and clock products. Real-time ground station data used directly for low-Earth orbit (LEO) determination and near real-time clocks came from publicly supported ground stations rt.igs.org, auscors.ga.gov.au, www.euref-ip.net, mgex.igs-ip.net, www.igs-ip.net and self-maintained real time stations (CDAAC, GDGPS, EUMETSAT-GMV, Spire-Hexagon/Veripos). For space weather data processing, broadcast orbits and differential code biases DCBs are generally sufficiently accurate, except there is a dependency on IGS ground networks for the IGS MGEX near real-time DCB and orbits for the GLONASS constellation. PlanetiQ's GNOME spacecraft data bits are used rather than ground based data streams for Space Weather. Because of the current mix of extensively used publicly and privately supported GNSS ground stations and the improved accuracy brought by IGS final orbit products for climate quality post-processed RO products, it is essential to support GNSS ground infrastructure.

Action IROWG9-01:
The sustainability of ground-station infrastructure should be discussed at IROWG-10.

b. Climate Sub-Group

Chair: Andrea Steiner (WEGC, Austria)

Rapporteur: Panagiotis Vergados (JPL, USA)

Members: Julia Danzer (WEGC, Austria), Eric DeWeaver (NSF, USA), Ulrich Foelsche (Univ. Graz, Austria), Hans Gleisner (DMI, Denmark), Ben Johnston (UCAR, USA), Florian Ladstädter (WEGC, Austria), Kent Lauritsen (DMI, Denmark), Stephen Leroy (AER, USA), Anthony Mannucci (JPL, USA), Francisco Martin (EUMETSAT, Germany), Johannes Nielsen (DMI, Denmark), Sebastiano Padovan (EUMETSAT, Germany), Bahareh Rahimi (Univ. Graz, Austria), Bill Randel (UCAR, USA), Ben Santer (UCLA, USA), Torsten Schmidt (GFZ, Germany), Marc Schwärz (WEGC, Austria), Endrit Shehaj (ETH, Switzerland), Andrea Steiner (WEGC, Austria), Matthias Stocker (WEGC, Austria), Panagiotis Vergados (JPL, USA), Axel von Engeln (EUMETSAT, Germany), Kamilya Yessimbet (WEGC, Austria), Zhen Zeng (UCAR, USA).

Visitors:

Recommendations to CGMS

1. **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 (TBD) 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 centers (see details in recommendation 2). 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.

   It has been demonstrated that GNSS RO is a very important data record for global climate observations of benchmark quality and stability. The continuity of GNSS RO observations with adequate coverage in the future is not sufficiently guaranteed with research/commercial missions alone, which is a main concern regarding the provision of continuous climate products. For reference, in alignment with the NWP Sub-Group, a monthly mean record utilizing the effective horizontal resolution of about 300 km within 6-hour time windows requires at least 20,000 occultations per day. GNSS RO is also valuable for checking the reliability of climate data records estimated from other satellite-based instruments (e.g., MSU/AMSU, which provide incomplete local time coverage and require instrument bias corrections, inter-satellite calibration, accounting for orbital drift effects, and merging of MSU and AMSU). While large-scale climate monitoring and research questions can be successfully tackled with less than 20,000 occultations daily, the study and improved understanding of many regional-scale and large-scale climate processes critically depends on coverage of the diurnal cycle and mesoscale resolution. Further needs for higher RO density include the analysis of atmospheric blocking situations with middle and upper troposphere data, the representation in RO data of extreme climate events such as heat waves, analysis of thermodynamic imprints of deep convective systems such as tropical cyclones, volcanic eruptions, and many other phenomena.

Regarding the status of RO coverage, the current and future MetOp satellite series only cover limited local times (09:30/21:30 equator crossing times). The six-satellite constellation of the COSMIC-2 mission, launched in June 2019 as follow-on to the now decommissioned COSMIC-1 mission, is in low inclination orbit and covers only low to mid-latitudes between 40°N to 40°S. We are facing an imminent observational gap in mid- to high latitudes for most local times. Thus there is an urgent need for satellite missions in high inclination orbits to provide full global and local time coverage in order to ensure global climate monitoring. RO obtained by the private sector may be useful in filling gaps in local time coverage and numbers of soundings, but these data are not useful for climate benchmarking and trend analyses unless they are made publicly available, provide level 0 data, and do not filter out any data. We also note that the needs of the NWP and the climate communities do not fully coincide regarding use of commercial data. We urge that space agencies take climate requirements into account and make purchased commercial RO data publicly available for climate research, even at long latency, or make arrangements for the deployment of agency-funded targeted RO missions to fill in the gaps in coverage. Overall, the aim should be to take advantage of all available GNSS constellations and RO missions, potentially including the private sector data after careful validation.

2. **Acknowledging a relevant CGMS recommendation on long-term data access (WGIIR50.04), 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).

3. **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.

4. 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]

5. **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 4) 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. 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.

6. **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.

7. **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**

[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

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

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.

8. **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.

Recommendations within IROWG

We recommend that IROWG continues to contribute to the development of GNSS RO as a climate monitoring system by a) assessing the structural uncertainty of RO retrieval data, including differences between processing centres and between different RO instruments and missions, **b)** supporting the generation of multi-center ensembles of RO climate data records, **c)** studying the effect of changing spatial coverage with latitude, including characterising the errors related to incomplete spatial and temporal coverage, and **d)** clearly communicating the usability and limitations of RO products (e.g., N, T, H_2O) to the climate community.

1. **Continue to assess RO water vapour products in terms of climate quality, information content, and random and systematic uncertainties, including characterization of the stability, inter-center homogeneity, and added value/impact to reanalyses; guided by GEWEX and GCOS requirements.** RO data provide unique high vertical resolution information on tropospheric humidity that is much needed to improve our understanding of the coupling of thermodynamics and large-scale circulation in the lower troposphere. Such information is critical for estimating climate sensitivity and changes in the water cycle. This activity encourages the development of an inter-center comparison project of water vapour (including random and structural uncertainty estimation). Any information about tropospheric humidity would be of specific interest to future IPCC reports. Such information may also be useful in constraining the (currently large) differences between simulated and observed covariance relationships between tropical temperature and moisture changes.[5]

2. **Encourage research into assessing the sources of bending angle uncertainties from different receivers and processing centres (which include SNR, clock noise, ionospheric residuals, calibration techniques etc.) and their impact on the estimates of long-term changes**, which is likely to extend the benchmarking capability of GNSS RO more robustly into the troposphere and higher into the stratosphere. We acknowledge the ROM SAF effort within the IROWG to investigate the lower troposphere measurement and algorithm uncertainty among various processing centres. Note that changes in the bending angle uncertainties over time affect the estimate of long-term

[5] https://journals.ametsoc.org/view/journals/clim/34/15/JCLI-D-20-0768.1.xml

trends from RO data. Such effects need to be assessed and quantified within the working sub-group.

3. **Issues of ionospheric correction and high altitude initialization should be further investigated to optimise the climate utility in the entire stratosphere.** We acknowledge progress in these areas, e.g. the kappa correction, and recommend that these efforts continue. We recommend evaluating the accuracy of the kappa correction and other ionospheric corrections and including the information on ionospheric correction terms in the output data files. Observational detection of the signature of ionospheric residual errors requires homogeneous RO data sets that cover the diurnal cycle and a full solar cycle.

4. **We recommend that the IROWG community continues to compare RO products with other observations and foster contributions to IPCC Assessment Reports and other international climate reports.**

5. **Continue participation in the wider scientific community** (e.g., CMIP, GEWEX, SPARC, CLIVAR, ITWG, GRUAN, GSICS, Obs4MIPs, MSU/AMSU community) and collaboration for the promotion of RO data and the complementary use of different data sets. We acknowledge ongoing IROWG activities and efforts.

6. **Ensure a complete archive of navigation data bits in a standard format.** We recommend making this information available to the community. We recommend that current providers come up with a common nav bit format.

Actions to IROWG-8 from CGMS:

IROWG climate sub-group actions: CLOSED

IROWG-04: RO measurements from past and current missions that have not yet been fully processed (e.g., GPS/MET, KOMPSAT-5, FY-3C) should be made available to the scientific community so that the climate utility of these data can be evaluated. These data could help to fill the gap after COSMIC-1 as well as increase past coverage.

ACTION CLOSED, data (KOMPSAT-5, FY-3C) have been made available to the community. GPS/Met data will be made available to the community.

c. Receiver Technology and Innovative RO Techniques

Chair: R. Kursinski (PlanetiQ, USA)

Rapporteur: J. Braun (UCAR, USA)

Members: Rob Kursinski (PlanetiQ, USA), Estel Cardellach (ICE/CSIC-IEEC, Spain), Michel Tossaint (ESA, Netherlands), Kuo-Nung (Eric) Wang (JPL, USA), Jennifer Haase (UCSD, USA), Tom Meehan (JPL, USA), Sun Yueqiang (NSSC, China), Liu Conglinang (NSSC, China), Chen-Joe Fong (NSPO, Taiwan), Gottfried Kirchengast (WEGC/UniGraz, Austria), Wei Xia-Serafino (NOAA,USA), John Braun (UCAR, USA), Ramon Padulles (ICE/CSIC-IEEC, Spain), Bin Zhang (University of Maryland, USA), Riley Fitzgerald (MIT, USA), JaeGwan Kim (National Met. Satellite Center, Korea), Chi Ao (JPL, USA), Laurent Lestarquit (CNES, France), Changyong Cao (NOAA, USA), Stig Syndergaard (DMI, Denmark), Saverio Paolella (EUMETSAT, Germany), Pawel, Doug Hunt (UCAR, USA), Loknath Adhikari (University of Maryland, USA), Pawel Hordyniec (RMIT, Australia), Dallas Masters (Spire Global, USA), Feng Ding (NASA GSFC, USA), Feiqin Xie (TAMU-CC, USA), Martin McHugh (NOAA, USA), Yong Chen (NOAA, USA), Josef Innerkofler (WEGC/UniGraz, Austria), Veronika Proschek (WEGC/UniGraz, Austria), Jens Wickert (GFZ, Germany), Zhen Zeng (UCAR, USA)

Top Recommendations to CGMS

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

   GNSS-RO can provide very high vertical resolution, all-weather, thermodynamic profiling of the planetary boundary layer (PBL) that is difficult to achieve via any other remote sensing technique. 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. 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 utilisation of lower troposphere RO data by NWP systems, as evidenced by high data rejection rates at low altitudes.
   - depth of penetration

   With regard to depth of penetration, results from Irisov et al. of Spire at IROWG-8 indicate that deep penetration can be achieved with relatively low SNRs. However, Ao et al. at IROWG-9 found the Spire RO profiles processed by Spire were overly smoothed vertically such that they had limited ability to detect the top of the PBL. In contrast, Ho et al. at IROWG-9 showed that detecting the PBL top using Spire data that was processed by UCAR produced results apparently comparable to COSMIC-2 data. Thus, further investigation in this area is needed by the community.

With regard to the negative bias in the PBL, it has long been recognized that 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 (e.g., Xie et al., 2006), but doing so requires knowing whether or not ducting is present on a profile by profile basis. Sokolovskiy et al. (2014) showed that determining whether ducting exists in each profile requires very high SNR observations. Thus, high SNR observations are apparently necessary to achieve unbiased profiling of the PBL particularly under warm, wet conditions where ducting can occur.

Preliminary results presented at ICGPSRO and IROWG-8 and 9 also show that higher SNR occultations enable higher vertical resolution which yield larger maximum bending angles which better capture the sharp transition between the free troposphere and PBL and lead to smaller BA biases. Higher SNR also apparently helps penetration depth as PlanetIQ data with SNRs up to 2500 v/v is demonstrating.

Regarding deep tracking data, very promising early results from COSMIC-2 were presented at the IROWG-07, 08 and 09 meetings demonstrating unprecedented very high 1 second SNRs, sometimes exceeding 2000 v/v, which were used to identify ducting and profile bending angle through the planetary boundary layer down to the surface. Similarly, PlanetIQ results with comparable or higher SNRs up to 2500 v/v have now also been used to identify ducting and profile through the PBL down to the surface. However, results to date have not yet diminished the bias significantly. This may well be due to not accounting for the effects of ducting but other possible explanations need to be fully explored and quantified.

Progress and Actions related to this recommendation:

The IROWG recommends that

- a working group be created to work toward enabling accurate, routine profiling of the PBL via RO. A key to achieving this is developing an understanding of the sources of uncertainty in RO profiling of the lowermost troposphere/PBL including (1) measurement quality associated with instrument SNR, signal tracking, high bandwidth sampling and filtering, (2) dependence on atmospheric conditions such as ducting, moisture variability, turbulence and larger scale horizontal inhomogeneity, (3) efficient 2D and 3D modelling of light propagation, and (4) advanced retrieval methods to extract the profiles.
- more research is needed to determine the quality of the profiles in the lowermost troposphere and the dependence on SNR.
- further development on forward operators and improved QC procedures in the lowermost troposphere, particularly in the presence of PBL ducting, are needed in the NWP community to improve RO data impact in the lower troposphere.
- funding resources be made available to support this working group and its research efforts

2. Advance LEO-LEO occultation development towards a demonstration mission

IROWG recommends that CGMS adopt an action asking international space agencies (in particular CAS, ESA, NOAA and NASA, 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 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 the unique accuracy, precision and high resolution of the LEO-LEO observations into the NWP forecasts and reanalyses via assimilation. Successful initial mountaintop demonstrations have been made at cm, mm and micrometre wavelengths. A Chinese mountaintop to mountaintop experiment is planned for 2023.

Progress and Actions Regarding progress on LEO-LEO observations: (1) a forum workshop was held in July 2019 in China on scientific questions and objectives, retrieval techniques and payloads; (2) ESA is looking at broadcasting GNSS signals from LEO, presenting a potential opportunity for LEO-LEO; (3) a key paper (Ward et al., 2019) was published demonstrating water vapour retrievals to 0.5% in clear, cloudy and rainy conditions by probing the 183 GHz water vapour line between mountaintops; and (4) PlanetiQ and China continue to pursue LEO-LEO implementations. The previously recommended LEO-LEO OSSE & EDA activity has stalled awaiting development of a forward model or operator (FO). We note that present RO and radiative transfer FOs already contain the pieces required to create the LEO-LEO FO, suggesting that its development may be relatively straightforward.

3. **Promote development of retrievals and use of polarimetric RO observations (ie PAZ/orbital or airborne)**

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 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.

A GNSS polarimetric radio occultation experiment orbiting aboard the PAZ satellite was activated on May 10, 2018. RO observables at two linear polarizations are being acquired and they have proved sensitive to heavy rain as well as other hydrometeors above the freezing layer. The initial hypothesis of the experiment was that these observables were induced by large flattened rain droplets, more likely in heavier precipitation. The additional strong signals coming from frozen hydrometeors seem to be always linked to strong precipitation scenarios. Refractivity O-B biases have been linked to strong polarimetric signals between 4 and 10 km altitude, and recent studies have indicated that the uppermost level reached by the polarimetric signal can serve as an effective proxy for the vertical air motion associated with convective precipitation processes. Very promising results presented by Padulles et al. at IROWG-09 revealed that profiles of differential phase delay measured by PAZ above the freezing level were strikingly similar to snowfall estimated completely independently by ERA5, indicating that the particles measured at sub-freezing temperatures by PAZ appear likely to be snowfall. Since the pol-RO signal is currently not assimilated, this suggests the use of the pol-RO as an independent metric to evaluate forecast model characteristics (e.g., assessment of impact of "rainy occultations" from "non-rainy occultations"). The unexpected ice-induced signals are both an opportunity for new science and a challenge for the retrieval algorithms, and further work is needed to properly understand the measurements and develop both scientific and operational meteorology applications.

Secondary Recommendations

1. **Develop NWP forward operators for polarimetric, LEO-LEO, GNSS-R, and airborne observations and promote the use of these new data for NWP and science applications**

   We recommend developing 1D and 2D NWP forward operators for polarimetric, LEO-LEO, GNSS-R, and airborne versions of these in order to evaluate the feasibility of developing useful observation systems and to evaluate the potential benefit of the observations to future NWP assimilation and scientific investigations.

   Actions Items:
   In order to support data analysis and interpretation and OSSE & EDA assessments, the IROWG community should argue to the global NWP centres (+) that there is a need for a forward operator for two types of observations:
   - LEO-LEO observations need a forward operator up to at least 183 GHz to account for absorption, scattering and polarimetric capabilities
   - Now that PAZ has demonstrated some very new and unique sensitivities, significant investment is needed in developing scientific applications for polarimetric observations (phase and amplitude). The investment includes studies to better understand the observations; the creation of a forward modelling operator for scattering observations; 1Dvar and 2Dvar retrieval applications; and others.

2. **Encourage continued development of synergistic GNSS radio occultation and GNSS reflectometry.**

   IROWG recommends strengthening the scientific and technical activities related to the exploitation of the potential to combine the application of the GNSS radio occultation technique with GNSS reflectometry (GNSS-R) at grazing angles of observation for global monitoring of several geophysical Earth Surface parameters (e.g., altimetric height of water and ice surfaces,). GNSS reflectometry measurements are potentially also appropriate for atmosphere/ionosphere sounding, in particular, those reflected signals in very slant geometries, such as collected unintentionally with standard RO receivers.

   Multiple studies have shown that GNSS reflections acquired in geometries compatible with the typical RO antenna configuration are suitable for precise sea ice and ocean altimetry. On the one hand, CYGNSS raw data (downloaded to ground at high sampling rate before being processed by the onboard receiver) re-processed with software receivers could find coherent grazing angle reflected signals up to 25 deg elevation over the Central America coastal waters, providing a few cm level altimetric retrievals in a few tens of millisecond integration. As Spire has demonstrated, the open-loop model can be modified, through firmware updates, to collect altimetric tracks that provide in similar ranges of precision levels, mostly over sea ice from the RO payload. These firmware modifications do not affect the rest of the RO mission, except for data volume and if needed, correlation channels. These findings open new opportunities for RO missions, even existing orbiting ones, at relatively low incremental costs.

The GNSS grazing reflectometry can also provide additional information related to ducting at the top of PBL. In a study published in 2020 the reflected bending angle can reduce the negative bias and improve RO observation within the PBL without assistance by external information.

Great progress has been made in the field of GNSS reflectometry (GNSS-R) since the previous IROWG. In addition to the extensive GNSS-R data set being obtained from NASA/CYGNSS, the GNOS-2 payload launched aboard FY-3E, with 4 RO antennas, one near-nadir looking Reflection antenna, and another one for POD. Spire has launched GNSS-R scatterometry satellites. In 2023, several GNSS-R missions are scheduled to launch including Taiwan's Triton (formerly FS-7R) mission, ESA PRETTY mission, and a reflectometry mission using opportunistic signals at P-band (NASA/SNOOPI).

NOTE: Given that there exists a reflection community already within the IEEE society, and given that near-nadir reflectometry involves different technology, challenges and developer communities, the consensus within the WG continues to be that there is not a need to promote GNSS-R that involves near-nadir LHCP scenarios) within the IROWG. The RO community should pursue low grazing angle reflections that can be conducted with GNSS RO payloads using slightly modified firmware.

IROWG stimulates in this context also the GNSS industry **to develop combined GNSS RO/R receivers** and related hardware for future missions. Hereby, the application aboard small satellites is especially in focus to allow the installation of future multi-satellite constellations with GNSS remote sensing (GNSS-RO combined with GNSS-R) observations with high spatiotemporal resolution in a cost effective way.

IROWG recommends and stimulates the scientific investigation of the dependency of the coherent GNSS-R technique on the roughness of the reflecting surface and of potential additional geophysical applications of this method.

3. **CGMS recommends technology promoting ultra-low latency data products to support future space weather applications**

Additional Recommendations

1. **Formation of IROWG working group on "level 0" data formats**
   Standard practices for delivering low-level data are necessary. The most complete, fully traceable and rigorous approach is to supply true 'level 0' data (meaning all bytes delivered from the satellite needed for RO, possibly stripping unneeded virtual channel data and satellite headers) along with documented data readers. This is difficult for operators of large diverse constellations due to the proliferation of formats for different satellites and instruments over time. As a potential alternative, standardised low-level file format(s) should be defined that include all necessary information needed to create

RO profiles. The opnGns file format could be a part of this, but it is not complete. netCDF has been suggested as a part of this format; the simpler netCDF version 3 format might be a better choice as an archive data set. Data customers need to decide whether delivery of true level 0 data (and readers) or of standardised low level data is acceptable for a given situation.

2. **Use new GNSS signals and orbit design**
The navigation modulation of new GNSS signals and systems (GPS, GLONASS, Galileo, BeiDou, QZSS, and IRNSS) is yielding increasingly precise ranging data. The new navigation modulation such as binary offset carrier (BOC) has a more complex autocorrelation function that not only narrows the central peak of the autocorrelation function but also has anti-correlated response at certain time lags. This response makes acquisition of signals in the lower troposphere more challenging and could potentially impact the occultation performances there.

3. **Develop GNSS observations from airborne platforms for operations and testing new technology**
GNSS observations from airborne platforms (aircraft, balloons, and UAVs) offer unique datasets with distinct advantages for weather forecasting and studies of regional weather and climate processes. The techniques include radio occultation, reflectometry/reflection, grazing angle observations, altimetry, and polarimetry, for sensing the atmosphere (moisture, temperature, hydrometeors), land surface (soil moisture and dielectric constant), and ocean surface (surface roughness, wind, sea ice) and ionosphere (total electron content).

GNSS radio occultation from aircraft and balloons have now been demonstrated and significant high quality datasets have been collected. The higher spatial and temporal density of targeted observations over phenomena of interest (i.e., severe storms, tropical cyclones, stratospheric wave structures) can benefit NWP. **IROWG recommends** advancing towards operational systems for airborne data collection from platforms of opportunity (including commercial aircrafts and high-altitude balloons) and operational use of these observations in NWP using 2D airborne data assimilation operators that exploit the high density observations.

IROWG recommends pursuing opportunities to use observations from airborne platforms to advance new technologies (instrumentation, new signals, algorithms, and assimilation methods). These can lead to better understanding of the behavior and use of satellite systems at the limit of their resolution that benefit operations and research.

Specific examples include observations in the lower troposphere, PBL ducting, and in intense convection at fine spatial scales with dense sampling for GNSS-RO, in the presence of wave structures sampled by balloons in the UTLS, over small scale soil moisture variability for GNSS-R, . Collaboration in these areas benefits the community by sharing technology and expertise, speeding development, and reducing logistical constraints.

4. **Identify Radio Frequency Interference (RFI) sources and develop strategies for mitigation**

RFI is becoming a significant source of noise throughout the world and is particularly evident due to jamming near the war in Ukraine. This is impacting both RO and GNSS-R data quality. The IROWG community should study RFI sources and potential mitigation techniques that can be proactively implemented either in ground GNSS analysis, or through on-orbit hardware and/or software mitigation.

5. **Improve removal of residual ionosphere correction for GNSS-RO**
   Residual ionosphere after dual frequency calibration remains an important limitation for climate monitoring by GNSS RO. The possibility of using a single frequency ionosphere correction that utilises the 10X finer ranging resolution on some new GNSS signals to determine the residual bias that remains after applying dual frequency ionosphere correction should be evaluated.

6. **CGMS recommends that future GEO and MEO satellite observing systems have GNSS-RO technology added to enhance plasmasphere profiling**

Progress regarding previous IROWG recommendations

1. modify the firmware in the GRAS RO instruments onboard Metop-A, B and C, to continue the occultations to at least an altitude of 120 km
   Completed.
2. The provision of Ultra Rapid Orbits and Clock bias data for all GNSS systems
   IGS MGEX now has GPS, GLONASS, Galileo. A Wuhan site seems to provide the only ultrarapid Beidou clocks. However, it is not a fully robust 24/7 operational capability.
3. GLONASS 1 second clocks
   Groups (ROM-SAF, JPL) showing value of 1sec GLONASS clocks.
4. IROWG recommends to the Indian Space Research Organization to make a comprehensive IRNSS signal ICD available
   IRNSS ICD has been found!

d. Space Weather Sub-Group

Chair: Paul Straus (Aerospace, US)

Rapporteur: Riccardo Notarpietro (EUMETSAT, Europe)

Members: Paul Straus (Aerospace), Riccardo Notarpietro (EUMETSAT), Jan-Peter Weiss (UCAR), Irfan Azeem (NOAA), Kamila Kabo-bah (Earth Observation Research and Innovation Centre), Bruno Nava (International Centre for Theoretical Physics (ICTP)), Vu Nguyen (Spire), Francisco Sancho (EUMETSAT), William Gullotta (NOAA), Christopher Barsoum (Aerospace), Martin McHugh (NOAA), Argelia Gonzalez (NOAA)

Recommendations to CGMS

1. **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.**
2. **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.** The GNSS data and metadata should include dual-frequency code and phase measurements, 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).
3. **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.**

Recommendations within IROWG

1. **IROWG should continue to explore approaches for reducing ionospheric residual errors in neutral atmospheric retrievals.** Success in this challenging area of work would both improve the upper altitude limit and errors of useful neutral atmospheric products. This would mostly benefit climate applications. Next steps forward should include:

a. Further assessment of recently proposed approaches to reduce residual large-scale ionospheric errors based on the correction term that depends on the electron density distribution (e.g. the "kappa" technique);
b. Further assessment of recently-proposed approaches to reduce residual small-scale ionospheric errors (based on back propagation techniques, ray tracing, or other);
c. Development and use of new ionospheric re-analyses in neutral retrievals to assess possible benefits;
d. Determination of ionospheric model accuracy requirements that, if met, would likely lead to a reduction in ionospheric residuals;
e. Evaluation of existing datasets to determine the degree to which current ionospheric residuals conform to known aspects of ionospheric climatology.

It is noted that progress updates on (a) above were presented at ROMSAF-6/IROWG-7/IROWG-9.

Recommendations within sub-group

1. **Encourage development/improvement of ionospheric data assimilation models to take full advantage of the FS7/C2 and other GNSS RO data (also from commercial providers) for specification and prediction of the low latitude ionosphere, including both its large-scale properties such as the F-layer and bottom side, and small-scale properties related to ionospheric scintillation effects.** These new data sets from FS7/C2 can be expected to lead to significant advances in the state of the art of ionospheric assimilative modelling, and associated improvements to operational space weather systems, if model development efforts are adequately funded.
2. Encourage development of more accurate 1DVAR retrievals of ionospheric electron density profiles (there was already a presentation at IROWG-8 and there has been one also at IROWG-9).
3. Coordinate with space weather activities throughout the CGMS Space Weather Coordination Group (SWCG) and the WMO Expert Team on Space Weather (ET-SWx). Whenever possible, members of each of these teams should attend each other's meetings. See action IROWG9-01.
4. **Verify that the WMO OSCAR database properly documents the abilities of current and future missions to obtain ionospheric data per Recommendations to CGMS #1-2 above.** Capabilities of both RO missions and missions flying dual frequency GNSS receivers should be documented in sufficient detail to understand the ionospheric products. The information in the database for each mission should include the extent to which the mission collects ionospheric profile and overhead TEC data, the mission data latency, and the extent to which ionospheric scintillation data are collected. In engaging with the WMO Space Weather Expert Team, we should request their help in this verification.
5. It is desirable to continue to **expand the sub-group membership in the areas of personnel associated with operational space weather support centres and members of the international science community involved in the development and evaluation of assimilative ionospheric and scintillation models**. Team members should advocate

for travel support from operational space weather support centres that will enable scientists to support future IROWG meetings.

6. **Space Weather sub-group team members should continue to advocate for and support greater incorporation of ionospheric radio occultation science topics** (such as the development of space weather data assimilation models) within existing ionospheric science venues such as AGU, AMS, CEDAR, URSI and IRI workshops. Collaborations within the sub-group membership involving evaluations of ionospheric models using GNSS RO data, or development/refinement of ionospheric or scintillation specification models using GNSS RO data sets, are also encouraged.
7. **Undertake studies which address the necessary occultation density and latency to achieve certain levels of specification accuracy with assimilative models.**
8. **Investigate the possibility of determining accurate thermospheric density from GNSS receiver tracking data. (UCAR is doing this)**

Status of actions from previous IROWG meetings (from IROWG-6)

Action IROWG6-01:
IROWG Space Weather sub-group (SWSG) should verify that the WMO OSCAR database properly documents the abilities of current and future missions to obtain ionospheric data per recommendation within subgroup #4 above.
OPEN

Action IROWG6-05:
IROWG SWSG members should review COSMIC-2 ionosphere TEC and scintillation data formats and provide comments back to SWSG. See:
TEC:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=podTc2
On-board S4:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scn1c2
HR phase/amp:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scnPhs
Ground-computed S4/SigmaPhi:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scnLv2
Spectrograms of HR phase/amp:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scnSpc
Due Oct 31, 2017
CLOSED. No comments received.

New action items from IROWG-7

Action IROWG7-01:
Efforts should also be made, in coordination with the WMO Space Weather Expert Team, to facilitate data access to raw data, products, metadata and documentation, and to define standard

data exchange formats for RO sensor ionospheric products. This is a continuation of IROWG-6 Action 06.
DUE DATE: Next IROWG

Action IROWG7-02:
Action: Check other sub-group and main IROWG recommendations for inclusion of level-0 data.
Due Now. Closed.

New action items from IROWG-9

Action IROWG9-01:
Irfan Azeem to investigate whether there is a NOAA/SWPC person that is involved in the WMO Expert Team on Space Weather (ET-SWx) that could attend the IROWG to increase the interchange between our group and others within WMO that are concerned with space weather.
Due Date: October 1, 2022

Action IROWG9-02:
Paul Straus to investigate whether or not there are ionospheric applications that might significantly benefit from direct broadcast (low latency) GNSS sensor data.
Due Date: Next IROWG

Action IROWG9-03:
Riccardo Notarpietro to explore the possibility of obtaining TEC from reflectometry and whether this should be a focus of future sub-group advocacy.
Due Date: Next IROWG

4. CONCLUSIONS

The workshop presentations are available at:
https://opacirowg2022.uni-graz.at/en/scientific-programme/

This summary and the CGMS working paper from IROWG-9 are/will be available at https://irowg.org/documents/

The suggested high-priority recommendations for CGMS 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 recognizes the recent efforts and activities at EUMETSAT and NOAA for global licensing of their commercial data purchase and supports continuous efforts. 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 that all use a common base of shared data. IROWG encourages institutions to purchase full datasets (with all observations and low-level data) and to make these available to the global community. IROWG also 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 cover the diurnal cycle at middle and high latitudes.

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 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, 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.

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 the impact versus numbers of occultations in operational NWP, 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.

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.

The GNSS data and metadata should include dual-frequency code and phase measurements, 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).

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

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