CGMS

Prepared by IROWG
27 March 2025
IROWG/09/2024

Summary of the Tenth International Radio Occultation Workshop (IROWG-10)

Held in Boulder, CO, US

From Thursday, 12th September to Wednesday, 18th September 2025

Starting at 08:30 hours on 8th September

Ending at 12:10 hours on 14th September

EXECUTIVE SUMMARY

This report summarises the IROWG-10 meeting held on 12-18 September, 2024 in Boulder, Colorado, the United States, in conjunction with the COSMIC/JCSDA Workshop celebrating the anniversary of the GPS/MET and COSMIC missions. It provides the recommendations from the four IROWG sub-groups: Numerical Weather Prediction (NWP), Climate, Innovation and Space Weather. The key recommendations for CGMS – endorsed by the IROWG community at the plenary session – are listed below. Further recommendations by the subgroups (NWP, Climate, Space Weather, and Innovation) can be found in the working paper. All given workshop presentations can be found at the IROWG-10 webpage. This CGMS working paper built upon the IROWG-10 outcome is available at https://irowg.org/documents/.

- **IROWG recommends that a reliable replacement for the FORMOSAT-7/COSMIC-2 tropical and subtropical radio occultation observations be in place by 2030 at the latest. As FORMOSAT-7/COSMIC-2 is past its nominal end of life, there is a high risk of serious degradation to numerical weather prediction (NWP) accuracy due to the degradation of the current RO observing system, as FORMOSAT-7/COSMIC-2 satellites stop acquiring observations over the coming years.**

  FORMOSAT-7/COSMIC-2 reached nominal end of life in June 2024. While all six satellites continue to operate nominally, most currently have subsystems with single points of failure such that a malfunction of the subsystem will lead to loss of RO measurements from the affected satellite. The potential impact on NWP accuracy and climate monitoring is a growing concern, underscoring the urgency of establishing a robust long-term solution.

- **IROWG notes that the current radio occultation observational network is highly beneficial to NWP and is among the top two or three observational systems in terms of forecast impact. IROWG therefore recommends the continuation and expansion of the RO observational network. Initial results from ROMEX suggest that increasing the numbers of daily radio occultation profiles with global coverage provides significant additional positive impact on the accuracy of NWP forecasts.**

The RO Modeling Experiment (ROMEX) study, using different numbers of RO profiles up to 35,000 profiles per day (the maximum available in the experiment) in leading international NWP models, demonstrates the increasing benefits of RO with increasing numbers of profiles, supporting the IROWG recommendation which is to acquire at least 20,000 occultations per day with uniform spatial and local time coverage (HLPP 1.2.8).

Besides uniform spatial and local time coverage also refresh should be considered.

- **IROWG recommends that Level 0 (raw) data from RO missions be permanently archived and that the government agencies that purchase the data be responsible for its archiving with an open data policy. All data acquired by RO instruments should be archived without pre-filtering or editing and without intentional degradation.**

  The full record of acquired Level 0 observations should be available, without data removed based on quality metrics or other criteria. Archived raw data are re-used for scientific research and in reanalysis. Intentionally degraded commercial Level 0 data are sub-optimal for such purposes and therefore represent less "value for money" compared to the data as it is acquired. For reference: Level 0 data are defined according to the CEOS definition of raw data. There are Level 0 RO data that are collected but not archived anywhere (at least, not by governments).

- **IROWG recommends that relevant agencies undertake a ROMEX-like study for space weather.**

  Ionospheric RO data have begun to be assimilated in operational models. A ROMEXlike study for the space weather domain (ROMEX-SWx) would help to quantify the benefits of RO measurements in improving global ionospheric specification. To lay the groundwork for this effort, a precursor workshop on Observation System Simulation Experiment (OSSE) capabilities in the space weather domain is desirable prior to the first ROMEX-SWx workshop. As with ROMEX, the active support of government agencies will be crucial for the success of ROMEX-SWx.

- **IROWG recommends improving planetary boundary layer (PBL) profiling from GNSS-RO through technology and retrieval developments, and utilization of information from the PBL in NWP data assimilation as well as the further exploitation of RO-derived water vapor.**

  Recently published work on assimilating PBL height into global reanalyses represents a significant development for exploiting lower-troposphere information from GNSS-RO that can also be considered for NWP. Intercomparisons of retrievals within the PBL (refractivity, water vapor pressure, and other direct products) between different processing centers should be analyzed to gain fundamental insight into PBL products, with particular attention to the role of signal-to-noise ratio, which varies significantly between GNSS-RO instruments.

Initially discussed at IROWG-10 and finalized post-workshop, the following document was submitted to CGMS WGII for consideration:

- **IROWG proposes a Best Practices (BP) draft document "IROWG best practices in support to radio occultation observations for long-term climate studies":** This document started within the climate sub-group at IROWG-9 but that also addresses numerical weather prediction applications, endorsed by IROWG-10. It might be used to support CGMS-51 Plenary Action A51.08 to "develop…a CGMS statement on the optimum composition of hybrid architectures (combining reference platforms, small satellites and procurement of commercial data)..."

- **Roadmap towards full exploitation of the GNSS Polarimetric Radio Occultations**: was developed by the Innovation Sub-Group of the IROWG. It may be of great interest to agencies in WGII and may merit publication on the CGMS web site.

1. INTRODUCTION

This IROWG report presents the minutes / full recommendations of the combined JCSDA/COSMIC Workshop and the Tenth Workshop of the International Radio Occultation Working Group (IROWG-10). The meeting was organized by the University Corporation for Atmospheric Research (UCAR) Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) and Joint Center for Satellite Data Assimilation (JCSDA) and held at the UCAR Center Green campus in Boulder, Colorado, U.S. from 12-18 September, 2024. IROWG wants to express its gratitude for the perfect organization of this meeting, which was the largest IROWG workshop so far.

The workshop set a new record with approximately 180 abstracts submitted and over 150 participants attending in person. Attendees included representatives from all major radio occultation (RO) processing centers, space agencies, commercial data providers, weather prediction centers and research institutes and universities. The program featured more than 60 oral presentations and over 100 posters.

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 to facilitate discussions in response to previous IROWG internal recommendations and/or bolster collaborations within the IROWG community.

The structure of this report is as follows: Section 2 gives a brief overview of the organization of the workshop and the sub-groups; Section 3 lists the recommendations provided by the different subgroups; and Section 4 concludes with the main recommendations for CGMS.

2. IROWG-10 SETUP

IROWG-10, held in conjunction with the COSMIC/JCSDA Workshop, was a comprehensive event featuring oral presentations, posters, discussion sessions, and splinter meetings. The workshop opened with an address by Colorado Governor Jared Polis and marked key milestones

in radio occultation history, celebrating the 60th anniversary of the first radio occultation (Mariner IV, Mars, July 1965), the 30th anniversary of the first terrestrial RO (GPS/MET, launched April 1995), and the upcoming 20th anniversary of COSMIC-1 / FORMOSAT-3 (launched April 2006). Invited guests and speakers provided historical retrospectives alongside scientific presentations.

Beyond these commemorative moments, the workshop featured a diverse range of sessions covering various aspects of radio occultation research and applications. It included more than 60 oral presentations and over 100 posters, spanning the eight regular sessions:

- Missions and Programs
- Methodology
- Data Assimilation Advances, Errors, and Validation Studies
- Data Impact Studies
- Novel and RO Complementary Techniques
- Atmospheric Physics and Climate
- Climate Monitoring and Research
- Space Weather

Two special sessions on the findings and NWP results from:

- RO Modelling Experiment (ROMEX): an international collaborative effort first discussed and endorsed at IROWG-9. The First ROMEX Workshop took place on April 17–19, 2024, at EUMETSAT Headquarters in Darmstadt, Germany, with outcomes presented at CGMS-52. The ROMEX session at IROWG-10 served as a mid-term report, facilitating further discussions among participant groups.

And a splinter meeting was dedicated to

- Proposal for a new BUFR format: introduce offline development efforts and seeking feedback for further refinement before submission to WMO and CGMS.

In addition, IROWG-10 hosted two discussion sessions for internal action review and follow-ups and subgroup discussions.

The workshop fostered a stimulating atmosphere for scientific exchange, collaboration, and mutual learning among the radio occultation community and RO data users. It provided an excellent platform for dialogue between data producers, researchers, and applied users. Participants' contributions enriched discussions, fostering a dynamic environment for networking and strengthening collaborations. Further details, including the agenda, activities, and presentation materials, are available on IROWG-10 website.

The workshop also announced that the Eleventh IROWG Workshop (IROWG-11) will be held on September 10–16, 2026, at Seggau Castle, Austria, in conjunction with the OPAC-8 Workshop, hosted by the University of Graz. More details will be available on the official workshop website: http://irowg.org/workshops/irowg-11/. Additionally, Uli Foelsche (co-chair) announced that he will be stepping down from his role, with an election for his replacement to take place in the near future.

3. SUB-GROUP RECOMMENDATIONS / DISCUSSIONS

3.1 Numerical Weather Prediction (NWP) Sub-Group

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

Members: Benjamin Ruston (UCAR/JCSDA), Jennifer Haase (SIO), Ying-Jhen Chen (CWA), Zih-Mao Huang (CWA), Hsiao-Chun Lin (UCAR/COSMIC), Shu-chih Yang (NCU), Hailing Zhang (UCAR), Stig Syndergaard (DMI), Rob Kursinski (PlanetiQ), Chi Ao (JPL), Kuo-Nung Wang (JPL), Hui Shao (UCAR/JCSDA), Bill Kuo (UCAR), Billy Gullotta (UCAR), Chris Barsoum (Aerospace), Guo-Yuan Lien (CWA), Shu-Ya Chen (NCU), Yong Chen (NOAA/STAR), Chad Galley (JPL), Josep M. Aparicio (ECCC), Eum-Hee Kim (KMA), Hyaung-Wook Chun (KMA) , Jonathan Brandmeyer (PlanetiQ), Dominique Raspaud (Météo-France), Jeremiah Sjoberg (UCAR), Harald Anlauf (DWD), Pawel Hordyniec (UPWR), Nghi Do (UCSD), Yasutaka Murakumi (JMA), Shu-Peng Ben Ho (NOAA/STAR), Delaynie Peters (Texas Abm Corpus Christi), William Miller (U. Maryland), Xuanli Li (EMC), Ben Davis (UCSD), Rick Anthes (UCAR), Christian Marquardt (EUMETSAT)

3.1.1 Recommendations to CGMS

The first and highest priority recommendation from the subgroup was about the observational network. We drafted an initial version, and this generated a lot of discussion both within the group and at the plenary at the end of the meeting. The final text after the plenary was as follows.

1. ROWG notes that the current observational network is very beneficial, and that degrading this brings negative impacts. IROWG recommends that the degradation of current capabilities should be avoided, and achieving this via agency-funded missions avoids the risks associated with commercial data purchases. Initial results from ROMEX suggest that substantial increases in data volume can be beneficial to NWP forecasts.

   a. IROWG notes that the risk of degrading the current RO observing system as COSMIC-2 nears the end of its life is high, which would result in a serious degradation of NWP accuracy. Therefore, **IROWG recommends the development of a reliable long term plan for global coverage**, including the continuity of the tropical and subtropical coverage now provided by COSMIC-2 which will require a replacement in place by 2030 at the latest.
   b. IROWG also notes that the current radio occultation observational network is highly beneficial to NWP (among the top two or three observational systems with the current (September 2024) number and distribution of RO profiles per day.). Initial results from ROMEX suggest that increases in daily radio occultation profiles with global coverage can provide significant additional impact on the accuracy of NWP forecasts.

c. Past experience has shown that agency-funded missions have succeeded in maintaining a stable, continuous, long term, traceable and reliable baseline of observations, together with the development of world class expert teams. Commercial data purchases have so far succeeded in efficiently adding a supplementary amount of data and exploring technology enhancements. **IROWG recommends that the successes of commercial and agency-funded missions be evaluated as part of the design of a global long term approach to RO data provision**

This recommendation also came with the following additional notes:
Note: Science data (NASA CSDA) has not been purchased w/ open licence. Add to NWP Best Practice document for commercial.

We highlight that agency funded missions can provide stable, continuous, 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. It is helpful to have this baseline based upon multiple different satellite instruments / platforms.

The other recommendations received much less discussion, so we reproduce these here without further notes.

2. 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**.

   Commercial data has shown to provide good quality data and is much appreciated to contribute to improving forecasts. IROWG appreciates the NOAA and EUMETSAT approach of sharing commercial data on a global licence and hope that other agencies continue to follow this approach.

3. **IROWG recommends open communication and providing test data about changes to incoming data and its quality, especially with regards to new commercial data purchases.** Such communication should be as early as possible - at least one month before a change in operational data feeds.

4. **Buying agencies should not procure artificially degraded data.** Although adding small amounts of noise is unlikely to degrade NWP forecasts at present, this will typically become the observation of record and it will be impossible to test whether future NWP systems can extract further benefit from them.

5. For reanalysis and other purposes, it is helpful to have archives of large RO quantities.

IROWG recommends 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 by public agencies and be subject to regular reprocessing activities.

Updates to previous recommendation to CGMS

We have closed a previously made IROWG recommendation made to support open data policy. An open data policy has been adopted by CGMS, and therefore we don't feel the need to continue making this recommendation:

We continue to strongly support an **open data policy** towards the purchase of commercial RO data, and we recommend that all agencies follow this policy. This includes the exchange of test data and reporting on data quality.

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.

3.1.2 Recommendations within IROWG

IROWG has noted a number of important **research topics** which deserve attention in the coming years.

- IROWG encourages the **renewed lab measurements of the k1, k2 coefficients** as used in the calculation of refractivity.
- IROWG encourages studies to investigate **whether additional benefit can be extracted from RO measurements in the lower troposphere**. With a particular thought on how SNR affects this usefulness.
- Observation operators for **polarimetric and aircraft RO** are currently or have been developed. IROWG encourages **experimentation** with these new observations and operators.
- IROWG notes GNSS-R measurements are "home" to other working groups
- IROWG encourages further investigations into the impact of geographic distribution and also time distribution (homogeneous).

The IROWG chair asked us to discuss the following previously made IROWG recommendation in our subgroup: *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.*

<u>The following ideas came up:</u>

- Super-refraction - high SNR can be used to detect super-refraction.
- There is a need to update QC methods and observation uncertainties in the lower troposphere to make more effective use of RO data in the lower troposphere.
- Suggestion of a comparison of data in the lower troposphere (following a model of ROTrends). Rob Kursinski and Chi Ao volunteered to further investigate this in collaboration with the climate sub-group.
- PlanetIQ are exploring demonstrations of how high SNR allows better retrieval in the lower troposphere.

- This is a clear need for RO observations for NWP forecasts of tropical cyclones, since tropical cyclone intensity changes can be highly sensitive to the tropospheric water vapour distribution around the storm. There is strong evidence that RO observations in the environment of tropical cyclones improves the track forecasts.

Furthermore three different topics were discussed in our subgroup as raised by the chairs:

Discussion next (timing) IROWG: No objections were raised to meet in 2 years. Suggested to hold subgroup / ROMEX meetings in between.

Discussion next co-chair: Candidate should probably better come from other WG

Discussion AI activities: Some internal AI activities ongoing looking into using sat. observations.

3.1.3 NWP Subgroup Actions

1. IROWG members to read the CGMS best practice document.
   Consider possible additions to best practice document or whether we need to create our own best practices of (new) RO data for NWP. Consider the needs of best practice for data purchase, data processing, testing and communication of data changes.
2. EUMETSAT will attempt to organise another ROMEX workshop before CGMS. Update: Currently scheduled for 25-27 Feb 2025 at EUMETSAT in Darmstadt, Germany
3. People should run extra ROMEX sensitivity experiments. We should avoid making the timeline too ambitious.
4. Should consider whether it would be possible to create a dataset from ROMEX which has approximately equal temporal coverage, and consider which users could evaluate assimilation of these data.

3.2 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), Stephen Leroy (AER, USA), Johannes Nielsen (DMI, Denmark), Marc Schwärz (WEGC, Austria), Endrit Shehaj (MIT, USA), Andrea Steiner (WEGC, Austria), Matthias Stocker (WEGC, Austria), Panagiotis Vergados (JPL, USA), Anna Hall (U. Washington, USA), Paul Staten (IU Bloomington, USA), Sara Vannah (AER, USA), Jun Zhou (UMD, USA), Xin Jing (UMD, USA), Cong Dong (U. Washington, USA), Guojun Gu (UMD, USA), Walid Bannoura (NOAA-NESDIS, USA), Jens Wickert (GFZ, Germany), Kevin Nelson (JPL, USA), Feiqin Xie (TAMUCC, USA), Aodhan Sweeney (U. Washington, USA), Yuying Wang (York University, CANADA), Lauren Hill-Beaton (GSFC, USA), Jihyeok Park (KAIST, Korea)

3.2.1 Recommendations to CGMS

1. **Ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage through a coordinated and sustained effort. 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. This could be achieved with satellites in sun-synchronous and low inclination orbits in at least four evenly-spaced orbital planes providing observations 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 minimized. 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. We need more climate-tailored measures 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 provides 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, a monthly mean record utilizing the effective horizontal resolution of about 300 km with at least 10 RO profiles within 300x300 km2 grid with a 3-hour resolution of the diurnal cycle 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 optimal coverage of the diurnal cycle and mesoscale resolution. Further needs for higher RO observation density include the analysis of atmospheric blocking situations with middle and upper troposphere data, analysis of extreme climate events (i.e., heat waves), analysis of thermodynamic imprints of deep convective systems (i.e., tropical cyclones), volcanic eruptions, and many other phenomena.

Regarding the status of RO coverage, the current and future MetOp satellite series only cover certain local times. The six-satellite COSMIC-2 mission is in low inclination orbits and covers only low to mid-latitudes between 40°N to 40°S, expected to start losing spacecraft in 2027. We are facing an imminent observational gap in mid- to high latitudes for most local times.

There is an urgent need for the installation and sustainability of satellite missions 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 RO missions to fill the gaps in data 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 CGMS recommendation WGIIA50.04 on long-term data access, we recommend that government agencies providing data, whether generated internally or purchased from commercial entities, ensure that all information necessary for independent processing towards climate data products is freely available (following WMO Unified Data Policy Resolution 1, GCOS requirements), including long-term archiving of all measured and acquired data without filtering, sub-selection, and "intentional degradation" (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 two data streams of RO climate data products: one regularly updated data version (interim CDR) and one uniformly reprocessed version (CDR).** The reprocessed version should always cover the full data time period until more recent processing versions are available. Acknowledging the increasing computing requirements and growing data volume, we encourage developing the capabilities for future archiving and distribution of large amount 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-organized workshop). **IROWG recommends that processing centers increase efforts on uncertainty estimation and make the methods and results 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).

5. **Promote funding of reprocessing activities of RO climate data records** from different independent RO processing centers along with the principles for reprocessing climate data records of the WCRP Observation and Assimilation Panel (WOAP). 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 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-centre 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. Continuity of funded efforts is desired.

6. **We recommend to assess the uncertainty in the refractivity coefficients that impacts the accuracy and traceability of RO climate time series and trends.** Significant progress was made at JPL in implementing an experiment to measure the refractivity of air, but such experiments currently lack the precision needed by the climate group. Required steps to improve precision have been identified by 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 continuous status reporting from JPL.

7. **We acknowledge the success of the 3G meeting which brought together the GNSS RO the GRUAN and the GSICS communities in May 2014 in Geneva and recommend organizing such meetings periodically by WMO** with the scope of enhancing collaboration among these 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 2026 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.

3.2.2 Recommendations within IROWG

1. **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 centers 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 characterizing 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.

2. **Continue to assess RO water vapor 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 vapor (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.

3. **Encourage research into assessing the sources of bending angle uncertainties from different receivers and processing centers (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 centers. Note that changes in the bending angle uncertainties over time affect the estimate of long-term trends from RO data. Such effects need to be assessed and quantified within the working sub-group.

4. **Issues of ionospheric correction and high altitude initialization should be further investigated to optimize 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.

5. **We recommend that the IROWG community continues to compare RO products with other observations and to foster contributions to IPCC Assessment Reports and other international climate reports.** We encourage the RO data centers to publish reprocessed climate data records to be provided to the upcoming IPCC report (deadline: late 2025 to be updated).

6. **Continue participation in the wider scientific community** (e.g., CMIP, GEWEX, APARC, 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.

7. **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.

8. **We recommend to have intercomparison studies of the PBL (refractivity, water vapor pressure, and other direct products), and of the determination methods of the PBL height.**

3.2.3 Previous Actions 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.

3.3 Innovation (renamed from Receiver Technology and Innovative Occultation)

Chair: R. Kursinski (PlanetiQ, USA)

Rapporteur: J. Braun (UCAR, USA)

Members: Rob Kursinski (PlanetiQ, USA), John Braun (UCAR, USA), Ramon Padulles (ICE/CSIC-IEEC, Spain), Estel Cardellach (ICE/CSIC-IEEC, Spain), Feiqin Xie (TAMU-CC, USA), Kuo-Nung (Eric) Wang (JPL, USA), Stig Syndergaard (DMI, Denmark), Chi Ao (JPL, USA), Jade Morton (CU, USA), Josef Innerkofler (WEGC/UniGraz, Austria), Tom Meehan (JPL, USA), Garth Franklin (JPL, USA), Franciois Vandenberghe, (JCSDA, USA), Kate Lord (SIO, USA), Noah Barton (SIO,USA), Kuo-Nung (Eric) Wang (JPL, USA), Anitia Paz (ICE/CSIC-IEEC, Spain), Bing Cao (SIO, USA), Ming Chen (University of Maryland, USA), Yong Chen (NOAA, USA), Guojuan Gu (UMD, USA)

The subgroup voted on whether to merge this subgroup with others or keep it separate. All 17 voting members unanimously opted to retain the subgroup, and 82.4% supported renaming it to **Innovation**. Therefore, the subgroup is renamed to Innovation from now on. Additionally, members ranked the recommendations raised during the discussion by importance (see table below), and the resulting recommendations are illustrated in the following sections.

Ranked recommendations from Innovation Subgroup

Ranking	Topic	Importance 10 is highest priority 1 is lowest priority
1	Encourage technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilization in NWP data assimilation	9.06
2	Promote development of Polarimetric RO observations (orbital and airborne) and exploitation of those observations	8.94
3	Identify Radio Frequency Interference (RFI) sources and develop strategies for mitigation	7.35
4	Develop GNSS observations from airborne platforms for operations and testing new technology	7.29
5	Encourage the development of synergistic GNSS radio occultation (grazing angle) and GNSS reflectometry	6.59
6	Encourage CGMS to coordinate purchase of commercial RO data	6.59
7	Advance LEO-LEO occultation development towards a demonstration mission	6.53
8	Improve removal of residual ionosphere correction for GNSS-RO	5.41
9	Formation of IROWG working group on “level0” data formats	3.76

3.3.1 Top Recommendations

1. Encourage technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilization in NWP data assimilation
    - Current Status: NWP is still not optimally using RO data in lower troposphere, generally discarding data higher than PBL area
    - Progress since IROWG-09
        - Operational duct detection in COSMIC-2
        - Increased duct measurements from PiQ
        - Improved retrievals from JPL combining RO with passive sounders, and grazing angle observations
        - 1DVAR retrievals from JPL to constrain from IWV
        - GMAO assimilating PBL height
        - Stephen Leroy has initiated PBL research group
        - Six oral presentations at IROWG-10 (Monday afternoon) from: Zhen, Xie, Wang, Ao, Syndergaard, Vannah
        - Multiple posters also presented
    - Future Needs
        - Improve data assimilation methods to leverage PBL observations
        - How to use PBL observations considering refractivity bias in current RO observations
    - Recommendation:
        - Encourage an intercomparison project for PBL observations
2. Promote development of Polarimetric RO observations (orbital and airborne) and exploitation of those observations
    - Promote development of Polarimetric RO observations (orbital and airborne) and retrievals and use of those observations
    - Current Status
        - PRO data now collected by PAZ, Spire, and PiQ
        - Not all this data is available
    - Progress since IROWG-09
        - Cal-Tech workshop hosted workshop with JPL and ICE in November 2023

        - Advances in the Use of Global Navigation Satellite System Polarimetric Radio Occultation Measurements for NWP and Weather Applications (https://doi.org/10.1175/BAMS-D-24-0050.1)
    - Cardellach leading PRO working group at IROWG-10 (see report)
    - New BUFR format contains PRO observation data set
    - PRO data has been used to evaluate NWP cloud parameterization schemes
    - ARO data has been collecting data for atmospheric rivers and hurricanes for past two years. This data has not been fully analyzed yet.
    - CU has high gain, dual-pol station on Hawaii collecting base band data for past few years, for mountain top RO.
    - Simple forward operators have been developed, including ECMWF, ICE

3.4.2 High Priority Recommendations

1. Identify Radio Frequency Interference (RFI) sources and develop strategies for mitigation
    - Current Status
        - RFI is becoming a more significant problem
    - Progress since IROWG-09
        - ML methods have been developed at CU
        - JPL RFI algorithm is being used for operational processing at UCAR
        - L5 is getting worse
        - Cross talk between satellites is potentially increasing

2. Develop GNSS observations from airborne (ARO) platforms for operations and testing new technology
    - Current status
        - ARO now being routinely collected as part of atmospheric river intensive observations and hurricane reconnaissance projects
        - TAMUCC has demonstrated ARO on commercial planes (add reference)
    - Progress since IROWG-09
        - JEDI operator has been written
        - BUFR format is documented
        - Realtime data delivery is ready for demonstration during NOAA campaigns
        - OL tracking needs to be improved
    - Recommendations
        - Innovation group believes ARO is sufficiently developed so that it should be considered for operational implementation

- Explore ways to broadly implement on commercial airlines

3. Encourage the development of synergistic GNSS radio occultation and GNSS reflectometry
   - Current Status
     - GNSS-RO+R data now collected by Spire, and PiQ
     - GNSS-R now collected with grazing angle (RHCP) and near nadir reflections (LHCP)
       - GNSS NNR group is growing and is somewhat separated from RO community.
   - Progress since IROWG-09
     - NOAA has OSW CWDP pilot evaluation ongoing using Spire data
     - Lots of work for atmospheric, ionosphere, altimetry, water surface boundary mapping, water surface, ocean, inland water bodies, sea ice and some glaciers
     - CGMS recommended that GNSS-R methods participate in other CGMS groups (ocean surface winds and land surface)
4. Encourage CGMS to coordinate purchase of commercial RO data
   - Current status
     - EUMETSAT, NOAA, NASA and DoD
   - Progress since IROWG-09
     - NOAA RODB-02 is now in DO4
   - Need to stabilize the price and quantities to be purchased
5. Advance LEO-LEO occultation development towards a demonstration mission
   - Encourage international space agencies (in particular NASA, ESA and CAS, where LEO-LEO and GNSS-RO&-Reflectometry proposals are pending) to support mission preparation and implementation projects towards LEO-LEO microwave occultation and GNSS-RO&-Reflectometry demonstration missions. This should include recommending new OSSEs & EDAs for the LEO-LEO observations.
   - Progress since IROWG-09 and current Status
     - Limited progress since IROWG-9
     - Chinese administration had mission proposal, which was not funded.
     - Wegener Center/ROM SAF postponed work on forward operator for LEO-LEO.
     - JPL has worked on LEO-LEO technique supported by NASA decadal survey PBL incubation and internal JPL project to demonstrate transmit/receive capability with SDR
       - Eric has developed forward simulation operator (FSO)
     - PIQ sang praise to NOAA about very innovative leo-leo technology (hallelujah)

  - ICE has implemented forward operator for hydrometeoric PRO which is applicable for LEO-LEO frequencies.
- Recommend development of NWP-compatible forward operator and perform OSSEs & EDAs for LEO-LEO observations

6. Improve removal of residual ionosphere correction for GNSS-RO
   - Current status
     - Didn't discuss much
     - Ionospheric scintillations during solar maximum are degrading RO profiles of the atmosphere
     - Solar storm in May 2024 degraded the occultation processing causing many profiles to not pass QC.
   - Progress since IROWG-09
     - Awareness that ionosphere during solar maximum can degrade neutral atmosphere
   - Recommendations
     - Identify ways in which ionosphere can degrade neutral atmosphere profiles
     - Identify potential approaches to mitigate that degradation
7. Formation of IROWG working group on "level0" data formats
   - Current status
     - Nominal working group formed during IROWG-09
   - Progress since IROWG-09
     - Not much, maybe a google drive

3.4 Space Weather Sub-Group

(Acting) Chair: Irfan Azeem (NOAA, US)

(Acting) Rapporteur: Erin Lynch (NOAA, US)

Members: Paul Straus (Aerospace), Riccardo Notarpietro (EUMETSAT), Jan-Peter Weiss (UCAR),Tony Mannucci (NASA JPL), Deepali Aggarwal (Clemson University), Tom Meehan (JPL), Jude Salinas (NASA), Nick Pedatella (UCAR), Jaehee Chang (KAIST), Doug Hunt (UCAR), Irina Zakharenkova (UCAR), Iurii Cherniak (UCAR), Lindsey Hayden (UCAR), Charles Quilis Alfonso (BTH), Marc Gasbarro (NOAA), Jade Morton (University of Colorado, Boulder), Vu Nguyen (Spire)

3.4.1 Recommendations to CGMS

1. **IROWG recommends that relevant agencies undertake a ROMEX-like study for space weather.**

   Ionospheric Radio Occultation (RO) data is now being integrated into NOAA's operational Global Total Electron Content (GloTEC) model on an experimental basis. This integration has demonstrated a promising potential for improving the accuracy of global ionospheric specification, which are critical for understanding space weather events that can impact satellite communication, GPS systems, and other space-dependent technologies. Given the growing importance of space weather, it is essential that a thorough, dedicated study be undertaken to explore the full potential benefits of these RO measurements. This initiative is expected to provide a robust basis for evaluating the impact and value of RO data in space weather applications.

   IROWG recommends that a Radio Occultation Modeling Experiment (ROMEX)-like study for ionospheric applications could be instrumental in assessing and quantifying how ionospheric RO data can enhance global ionospheric specification and forecasting. The purpose of this Ionospheric-ROMEX study would be to assess the impact of RO data on the accuracy and reliability of ionospheric specification. Comparative analyses of model outputs with real-world space weather events should be conducted to gauge the effectiveness of the RO data in improving global ionospheric nowcasting capabilities.

2. **IROWG recommends CGMS to support a workshop to better coordinate efforts of the CGMS/SWCG Ionospheric RO Optimization task group and the IROWG space weather sub-group.**

   The advancement of an ionospheric Radio Occultation (RO) Observing System Simulation Experiment (OSSE) framework is a critical priority that requires advocacy and collaboration among relevant agencies. This OSSE framework will facilitate comprehensive studies to determine the occultation density and data latency requirements essential for achieving specified levels of accuracy in assimilative ionospheric models. Such advancements will play a pivotal role in improving predictive capabilities and operational outcomes for space weather monitoring and forecasting.

   To further this objective, IROWG recommends efforts to facilitate a closer coordination between the IROWG Space Weather Subgroup and the CGMS Space Weather Coordination Group (SWCG) Task Group on Ionospheric RO System Optimization. A CGMS-supported

workshop could serve as a platform for gathering expert insights and fostering dialogue among stakeholders. It will also contribute to defining the parameters and structure of a space weather RO benefit study similar in scope to ROMEX. Collaborative planning between these entities will be vital for conceptualizing and organizing a space weather-focused ROMEX. This cooperative approach will ensure alignment of objectives, efficient use of resources, and the development of a strategic pathway for optimizing ionospheric RO systems to meet emerging needs.

Additional points made during the plenary discussions:

- Advocacy amongst agencies is needed to fund the development of an ionospheric RO OSSE framework which would enable studies to address the necessary occultation density and latency requirements for achieving certain levels of specification accuracy and assimilative models.
- The workshop will also help inform the definition of a space weather RO benefit study akin to ROMEX.
- Close coordination between the two teams is needed to plan how a space weather ROMEX could be organized.

3. IROWG strongly recommends close coordination with CGMS to protect GNSS bands from man-made RFI.

Recent observations underscore the urgency of this issue. For example, data from the COSMIC-2 mission have revealed noticeable degradation in Signal-to-Noise Ratios (SNRs), with clear evidence of interference affecting the quality and reliability of GNSS-based data. This interference poses significant challenges to the accuracy of satellite-based atmospheric measurements, which are crucial for weather forecasting, climate monitoring, and scientific research. RFI hotspots have been detected in various regions, including the Middle East, raising further concerns. These findings highlight the need for immediate action to address the root causes of interference. To mitigate these risks, IROWG recommends the following actions:

1. Strengthen international collaboration and communication between CGMS, IROWG, and other relevant stakeholders to monitor and address RFI incidents.
2. Develop and implement technologies and strategies to detect, locate, and mitigate sources of RFI.
3. Advocate for increased awareness and regulatory measures at national and regional levels to protect GNSS spectrum from unauthorized activities.

4. IROWG recommends a workshop to facilitate coordination between relevant groups to examine approaches for reducing ionospheric residual errors in neutral atmospheric retrievals.

IROWG-9 identified steps to reduce ionospheric residual errors in neutral atmospheric retrievals. These efforts are best handled within NWP and/or Climate sub-groups. A mini workshop on this topic was held many years ago. IROWG recommends the re-initiation of this joint workshop, bringing together experts from both NWP and climate communities, to foster collaboration, share updated research findings, and explore new methodologies for reducing ionospheric residual errors.

This workshop would serve as a platform for addressing current challenges, promoting interdisciplinary dialogue, and developing actionable strategies for improving neutral atmospheric retrievals. It would also provide an opportunity to revisit previous recommendations, assess progress made since the original mini-workshop, and adjust the approach based on recent developments in the field.

By reinitiating this workshop, IROWG aims to catalyze a concerted effort to tackle ionospheric residual errors, ensuring that future atmospheric retrievals are as accurate and robust as possible, with significant implications for both NWP and climate modeling applications.

3.4.2 Recommendations within IROWG

1. IROWG proposes rewording of the previous recommendation on ionospheric RO capabilities (changes are shown in italics):
   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*, lasting at least 8 min*;
   c. *sensor contribution to* slant total electron content (TEC) *with should enable* 3 TECU & 0.3 TECU absolute and relative accuracy, respectively;
   d. amplitude and phase scintillation indices;
   e. high rate (50 Hz or higher, as dictated by the GNSS signal being observed) observations of *amplitude and phase (both)* ~~*scintillations*~~ at ionospheric tangent altitudes *when either amplitude or phase* 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 *on a daily basis*.

   Note from IROWG-10 plenary: this recommendation is to create a new action

2. IROWG proposes rewording of the previous recommendation to IROWG regarding ionospheric RO data assimilation. The revised recommendation language is as follows:
   IROWG should encourage development/improvement of ionospheric data assimilation models to take full advantage of all available (including commercial providers) GNSS data, i.e. RO, topside TEC, and GNSS-R (both grazing angle and nadir) from all providers including commercial providers for specification and prediction of the ionosphere, including both its large-scale properties such as the F-layer and bottom side, and small-scale properties related to ionospheric scintillation effects. Data sets from FS7/C2 and commercial providers 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.

3. **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.

4. **IROWG should encourage the development of more accurate retrievals of ionospheric electron density profiles.** There was already a presentation at IROWG-8 and there has been one also at IROWG-9.
5. **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, as collected on orbit.**
6. **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 on a daily basis.**
7. **IROWG recognizes the importance of space weather applications of RO data. IROWG recommends that non-RO missions that use dual-frequency GNSS receivers for precise orbit determination 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).
8. **All RO missions should provide level 0 data and meta data to derive topside TEC, and to the extent possible, level 0 data and meta data to derive TEC occultations.**

3.4.3 Recommendations within Sub-group

1. Coordinate with space weather activities throughout the CGMS Space Weather Coordination Group (SWCG), the WMO Expert Team on Space Weather (ET-SWx), and the SWCG Ionospheric RO System Optimisation Task Group. Whenever possible, members of each of these teams should attend each other's meetings. See action IROWG9-01.
2. **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.

3. 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.
4. **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.
5. **Undertake studies which address the necessary occultation density and latency to achieve certain levels of specification accuracy with assimilative models.**
6. **Investigate the possibility of determining accurate thermospheric density from GNSS receiver tracking data. (UCAR is doing this and NOAA is funding a study to explore this capability)**

3.4.4 Status of Actions from Previous IROWG and New Actions

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 #2 above.
OPEN: This action is being addressed by the Space Weather Coordination Group (SWCG) Ionospheric RO Task Group.

Status of actions from previous IROWG meetings (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
CLOSED: A NOAA/SWPC member of the ET-SWx has been identified

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
CLOSED: Closed with a negative

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
CLOSED: Ongoing studies have demonstrated the potential of obtaining TEC from GNSS-R

New action items from IROWG-10

Action IROWG10-01:
Jade Morton to coordinate with the Innovation sub-group.
Due Date: October 1, 2026

Action IROWG10-02:
Irfan Azeem to organize an ionospheric RO session at an international meeting such as AGU, EWS, JPGU, etc. per recommendation within subgroup #4 above.
Due Date: October 1, 2026

Action IROWG10-03:
Jan Weiss to explore the origin of the 3 TECU/0.3 TECU accuracy requirement and validate with an OSE if needed.
Due Date: October 1, 2026

Action IROWG10-04:
Erin Lynch to request CGMS/SWCG to endorse a recommendation for information that missions with GNSS POD capabilities can provide to enable thermospheric density estimation per recommendation within subgroup #6 above.
Due Date: October 1, 2026

Action IROWG10-05:
Erin Lynch to request the WMO ET-Swx advocate for mobile phone providers to release TEC data.
Due Date: October 1, 2026

Action IROWG10-06:
Irfan Azeem to invite SWPC members of WMO ET-SWx to speak and participate in the IROWG Space Weather subgroup per recommendation within subgroup #3 above.
Due Date: October 1, 2026

Action IROWG10-07:
Irfan Azeem to organize subgroup virtual meetings every 4 months.
Due Date: October 1, 2026

4 CONCLUSIONS

With the success of IROWG-10, IROWG endorsed the high-priority recommendations for CGMS outlined below. Workshop presentations are available on the IROWG-10 webpage, and this meeting minutes, along with the IROWG working paper workshop for CGMS WGII, built upon IROWG-10, is or will be accessible on the IROWG document webpage.

1. IROWG recommends that a reliable replacement for the FORMOSAT-7/COSMIC-2 tropical and subtropical radio occultation observations be in place by 2030 at the latest. As FORMOSAT-7/COSMIC-2 is past its nominal end of life, there is a high risk of serious degradation to numerical weather prediction (NWP) accuracy due to the degradation of the current RO observing system, as FORMOSAT-7/COSMIC-2 satellites stop acquiring observations over the coming years.

FORMOSAT-7/COSMIC-2 reached nominal end of life in June 2024. While all six satellites continue to operate nominally, most currently have subsystems with single points of failure such that a malfunction of the subsystem will lead to loss of RO measurements from the affected satellite. The potential impact on NWP accuracy and climate monitoring is a growing concern, underscoring the urgency of establishing a robust long-term solution.

2. IROWG notes that the current radio occultation observational network is highly beneficial to NWP and is among the top two or three observational systems in terms of forecast impact. IROWG therefore recommends the continuation and expansion of the RO observational network. Initial results from ROMEX suggest that increasing the numbers of daily radio occultation profiles with global coverage provides significant additional positive impact on the accuracy of NWP forecasts.

The RO Modeling Experiment (ROMEX) study, using different numbers of RO profiles up to 35,000 profiles per day (the maximum available in the experiment) in leading international NWP models, demonstrates the increasing benefits of RO with increasing numbers of profiles, supporting the IROWG recommendation which is to acquire at least 20,000 occultations per day with uniform spatial and local time coverage (HLPP 1.2.8).

3. IROWG recommends that Level 0 (raw) data from RO missions be permanently archived and that the government agencies that purchase the data be responsible for its archiving with an open data policy. All data acquired by RO instruments should be archived without pre-filtering or editing and without intentional degradation.

The full record of acquired Level 0 observations should be available, without data removed based on quality metrics or other criteria. Archived raw data are re-used for scientific research and in reanalysis. Intentionally degraded commercial Level 0 data are sub-optimal for such purposes and therefore represent less “value for money” compared to the data as it is acquired. For reference: Level 0 data are defined according to the CEOS definition of raw data. There are Level 0 RO data that are collected but not archived anywhere (at least, not by governments).

4. IROWG recommends that relevant agencies undertake a ROMEX-like study for space weather.

Ionospheric RO data have begun to be assimilated in operational models. A ROMEX-like study for the space weather domain (ROMEX-SWx) would help to quantify the benefits of RO measurements in improving global ionospheric specification.

To lay the groundwork for this effort, a precursor workshop on Observation System Simulation Experiment (OSSE) capabilities in the space weather domain is desirable prior to the first ROMEX-SWx workshop. As with ROMEX, the active support of government agencies will be crucial for the success of ROMEX-SWx.

5. IROWG recommends improving planetary boundary layer (PBL) profiling from GNSS-RO through technology and retrieval developments, and utilization of information from the PBL in NWP data assimilation as well as the further exploitation of RO-derived water vapor.

Recently published work on assimilating PBL height into global reanalyses represents a significant development for exploiting lower-troposphere information from GNSS-RO that can also be considered for NWP. Intercomparisons of retrievals within the PBL (refractivity, water vapor pressure, and other direct products) between different processing centers should be analyzed to gain fundamental insight into PBL products, with particular attention to the role of signal-to-noise ratio, which varies significantly between GNSS-RO instruments.

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