Subject	**Outcomes and Recommendations from the IROWG-10 Workshop**
In response to CGMS action/recommendation	N/A
HLPP reference	N/A
Executive Summary	This report summarizes 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. All given workshop presentations can be found at the IROWG-10 webpage. This CGMS working paper built upon the IROWG-10 outcome will be made available at https://irowg.org/documents/. IROWG also convened the Second ROMEX workshop on 23-25 February at EUMETSAT, Darmstadt, Germany. A working paper will be submitted separately to CGMS.
Action/Recommendation proposed	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. 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.

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

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

1 INTRODUCTION

This IROWG working paper reports on the 10th workshop of the International Radio Occultation Working Group (IROWG-10), which was held in conjunction with the COSMIC/JCSDA Workshop. 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 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 recommendations for consideration by CGMS WG II; Section 4 lists the recommendations provided by the subgroups.

2 IROWG-10 SETUP

IROWG-10, held in conjunction with the COSMIC/JCSDA Workshop, was a full workshop featuring oral presentations and posters across the following 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

The workshop included two special sessions for

- RO Modeling Experiment (ROMEX): ROMEX is an international collaborative effort that was discussed and subsequently endorsed by IROWG during its 9th workshop (IROWG-9). IROWG hosted the First ROMEX Workshop on April 17–19, 2024, at EUMETSAT Headquarters in Darmstadt, Germany. The outcomes were presented to CGMS-52, also in Darmstadt. The ROMEX session at IROWG-10 served as a mid-term report, providing an opportunity for further discussions among ROMEX participant groups.

- GPS/MET and COSMIC Anniversary: The workshop celebrated the 30th anniversary of the GPS/MET mission and the 20th anniversary of the COSMIC mission with invited guests and speakers, featuring both historical reviews and scientific presentations. A special highlight was an address by the Governor of Colorado.

In addition to these sessions, IROWG-10 organized three discussion sessions focused on:

- Internal action review and follow-ups
- Proposal for a new BUFR format (the proposed BUFR format will be submitted to WMO and CGMS once it is ready)
- IROWG subgroup discussions (Section 3)

IROWG-10 fostered a stimulating atmosphere for scientific discourse, collaboration, and mutual learning among occultation-related communities and users of RO data. It provided an excellent platform for exchanging insights between RO data producers, researchers, and applied users. The valuable contributions from participants enriched the discussions and created a dynamic environment for networking, learning, and strengthening collaborations. Further details, including the agenda, activities, and presentations/posters, are available on the IROWG-10 website.

3 MAIN RECOMMENDATIONS FROM IROWG-10 PLENARY TO CGMS

This section lists main recommendations for CGMS-53, endorsed by all participants during the IROWG-10 Plenary discussions.

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.

4 SUB-GROUP RECOMMENDATIONS

The subgroup meetings were structured around the following specific topics:

1. Numerical Weather Prediction (NWP)
2. Climate
3. Innovation (renamed from *Receiver Technology and Innovative Occultation Techniques* based on subgroup discussions)
4. Space Weather

Workshop participants were asked to summarize relevant activities within each subgroup's scope and provide recommendations applicable to CGMS, the GNSS-RO community, RO data providers, or IROWG itself. Additionally, the subgroups reviewed the status of relevant CGMS actions. The entire list of recommendations will be made available in the full meeting minutes. Here we focus on the main recommendations per subgroup, which we regard as the highest priority, even though not all of them could be promoted as IROWG key recommendations, which have been listed in Section 3.

4.1 Numerical Weather Prediction (NWP)

a. IROWG 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.

The rationale for this statement is that agency funded missions can provide stable, continuous, long-term, traceable and reliable observations. The expertise of publicly funded data-processing centers 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.

b. IROWG recognizes 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 centers has been a demonstration of effective inter-agency collaboration.

Commercial data have shown to provide good quality and are much appreciated to contribute to improving forecasts. **IROWG appreciates the NOAA and EUMETSAT approach of sharing commercial data on a global license and hopes that other agencies continue to follow this approach**.

c. IROWG recommends open communication and **providing test data about changes to incoming data** and their 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**.

d. **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.

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

f. **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.

g. IROWG continues to strongly support an **open data policy** towards the purchase of commercial RO data, and recommends that all agencies follow this policy. This includes the exchange of test data and reports on data quality.

h. IROWG encourages the renewed lab measurements of the k1, k2 coefficients as used in the calculation of refractivity.

4.2 Climate

a. 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 with satellites 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. Climate requirements should be taken into consideration when purchasing commercial data.

b. 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).

c. 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.

d. 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).

e. **Promote funding of various 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 centers.

f. 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 needed precision 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.

g. 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.

h. We recommend that operational data providers additionally supply **occultation prediction products**, aiding coordinated ground-based collocated measurements.

4.3 Space Weather

a. 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**.

- 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.

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

Ionospheric RO data are now being assimilated in NOAA operational models on an experimental basis. Space Weather ROMEX study can help articulate the benefit of RO measurements in improving global ionospheric specification.

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

Growing concerns related to RFI. This is particularly evident in the data from COSMIC-2 Signal-to-Noise Ratios (SNRs), where clear signs of interference can be observed.

RFI hotspots have been detected in various regions, including the Middle East, raising further concerns.

d. IROWG recommends that **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.

e. **All RO missions** should provide level 0 **data and metadata to derive topside TEC**, and to the extent possible, level 0 data and metadata to derive TEC occultations.

f. 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 reducing ionospheric residual errors in neutral atmospheric retrievals. These efforts are best handled within NWP and/or Climate sub-groups.
- The Space weather group offers to provide support to either NWP subgroup or climate subgroup to address the issue of reducing ionospheric residual error in neutral atmospheric retrievals.
- IROWG held a mini workshop on this topic many years ago. IROWG recommends to re-initiate this joint workshop.

4.4 Innovation

a. 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 the 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 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

b. 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 these data are 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 have been used to evaluate NWP cloud parameterization schemes
  - ARO data has been collecting data for atmospheric rivers and hurricanes for the past two years. These data have not been fully analyzed yet.
  - CU has high gain, dual-pol station on Hawaii collecting base band data for the past few years, for mountain top RO.
  - Simple forward operators have been developed, including ECMWF, ICE

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