Prepared by IROWG
22 April 2015
IROWG/MM/2015

Summary of the Fourth International Radio Occultation Workshop

Held at the Bureau of Meteorology, Melbourne, Victoria, Australia

From Thursday, 16th April to Wednesday, 22nd April 2015

Starting at 09:15 hours on 16th April

Ending at 13:00 hours on 22nd April

1 INTRODUCTION

This IROWG report presents the minutes / full recommendations of the IROWG Workshop No. 4 (IROWG-4) of the International Radio Occultation (RO) Working Group. The workshop was organized by the Bureau of Meteorology (http://www.bom.gov.au/) and the Centre for Australian Weather and Climate Research (http://www.cawcr.gov.au/) in Melbourne, Victoria, Australia; the meeting was held at the Bureau of Meteorology from the 16th to 22nd of April 2015.

IROWG-4 was attended by more than 50 scientists, including representatives from all the major RO processing centres and all major weather prediction centres assimilating RO data. Approximately 50 talks and 4 posters were presented (several presentations and posters were given by attending scientists on behalf of colleagues, because authors could not attend personally). Recommendations were developed in dedicated sub-working groups and presented and agreed upon in a plenary discussion on the last day. Additionally, IROWG-4 was used by several researchers for dedicated specialist/splinter meetings, which are not covered here.

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 main recommendations which were agreed upon by IROWG, and Section 4 concludes. The report is kept very brief due to the short time interval between IROWG-4 and CGMS-43.

This IROWG document provides the summary in a CGMS working paper format. The full minutes / recommendations / discussions of the sub-working groups within IROWG-4 will be made available at http://www.irowg.org. Presentations are already available at the website.

For reference, an appendix has also been added that gives a brief summary of relevant CGMS actions and recommendations that are impacted by IROWG.

2 IROWG-4 SETUP

IROWG-4 was a full workshop, including presentations, posters and sub-group discussions. The presentations/posters and the sub-group discussions were focused on specific topics, namely:

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

The possibility of commercial providers of RO data in the near future also led to several dedicated sub-group discussions, the recommendations of which were captured within the main recommendations.

IROWG-4 participants were asked to summarize **relevant activities** within the scope of the sub-group in dedicated sub-group meetings and express recommendations which could either be relevant to CGMS, to the GNSS (Global Navigation Satellite System, e.g. GPS) RO community, to providers of RO data, or within the IROWG. These were discussed in the open plenary.

The participants agreed to highlight four main recommendations for CGMS-43; these were endorsed by all participants. The full set of recommendations per sub-group and further information will be made available in a dedicated IROWG publication, available on our website www.irowg.org.

3 SUB-GROUP RECOMMENDATIONS / DISCUSSIONS

3.1 Numerical Weather Prediction (NWP) Sub-Group

Chair: Lidia Cucurull (NOAA, US)

Rapporteur: Josep M. Aparicio (EC, Canada)

Participants: Harald Anlauf (DWD, Germany), Richard Anthes (UCAR, US), Dave Ector (UCAR, US), Axel von Engeln (EUMETSAT, Europe), Christian Marquardt (EUMETSAT, Europe), Sung-Rae Chung (KMA, Korea), Hiromi Owada (JMA, Japan), Bill Schreiner (UCAR, US), Stig Syndergaard (DMI, Denmark), John Le Marshall (BoM, Australia), Sean Healy* (ECMWF, Europe), Chris Burrows* (UK Met Office, UK), John Braun (UCAR, US)

*Were not attending but provided comments

Background

Many of our recommendations are carried forward again. We acknowledge the significant progress made in COSMIC-2. The launch of the equatorial component is scheduled for May 2016. However, the polar component of COSMIC-2 has not yet been completely secured, resulting in a risk of a substantial gap in RO observations in the middle and high latitudes. To avoid this gap and to increase the substantial positive impact of RO observations on global weather prediction, **we recommend completion of the full COSMIC-2 program**. At this moment, **the completion of the polar component of COSMIC-2 is perceived as the least risky way to obtain global coverage of RO data in the short and medium term.**

The IROWG considers GNSSRO data as being essential, or basic, data, in the sense of WMO Res 40, therefore subject to free and open exchange. According to Res. 40: "Members shall provide on a free and unrestricted basis essential data and products which are necessary for the provision of services in support of the protection of life and property and the well-being of all nations, particularly those basic data and products, as, at a minimum, described in Annex 1 to this resolution, required to describe and forecast accurately weather and climate, and support WMO Programmes." This applies to all providers of essential data.

Recommendations to CGMS

1. GNSSRO has become a critical component of the WMO Integrated Global Observing System. It is our judgment, based on the success of COSMIC-1, that the only well-defined mission able to fill this operational role within the short to medium term is COSMIC-2 (for which funding is not yet complete). **Both, equatorial and polar components of COSMIC-2 are required for NWP**.
2. Recent studies show that substantial increases in NWP accuracy are obtained for increases in number of RO profiles to at least 20,000/day, and beyond, not approaching saturation. **We recommend targeting for at least 20,000 occultations/day to be available to the operational community**.
3. Existing programs (COSMIC-2, assuming both equatorial and polar components, and EUMESAT's EPS-SG) would provide 10,000-15,000 occultations/day. **We recommend that additional missions be considered to meet the desired target of at least 20,000 occ/day, which may include research missions, additional government programs, and commercial sources, provided they follow the WMO Res. 40 open data policy.**

Actions within IROWG NWP Sub-Group

1. Action 1: CDAAC and EUMETSAT/ROM SAF will provide 1 month of test data with different smoothing configurations, before Jul 31st 2015 to all NWP centers interested. They will allow NWP users for feedback until Oct 31st 2015. NWP users will coordinate an answer during Oct 2015.
2. Action group: BUFR specifications. By early may 2015 Harald will coordinate a teleconf:
    - The BUFR template for RO is generic, and this has led to different interpretations by the processing centers. NWP users to revise compliance and propose stricter guidelines (UW5-NWP16)?
    - Standard set of vertical levels?
    - Fixed definition of azimuth, occultation point, time of positions/velocities, etc.
    - L1/L2 bending angles
    - Any use for Ionospheric parameters? Excess phase?
    - Reflections: Should IROWG discuss recommendations to investigating and/or producing reflections products, i.e., 1) flagging of occultations, 2) BA parts for the reflected parts?
3. Recommend that GRAS provides wave optics data.
4. Recommend New Project to CGMS: to compare EDA approach with OSSE approach.

3.2 Climate Sub-Group

Chair: Ulrich Foelsche (IGAM/WEGC, Austria)

Rapporteur: Chi Ao (JPL, USA)

Members: Yago Andres (EUMETSAT, Germany), Chi Ao (JPL, USA), Birtukan Biadglgne (BOM, Australia), Ulrich Foelsche (WEGC, Austria), Gottfried Kirchengast (WEGC, Austria), Rob Kursinski (SS&E, USA), Anthony Mannucci (JPL, USA), Johannes Nielsen (DMI, Denmark)

Visitors: Harald Anlauf (DWD, Germany), Rick Anthes (UCAR, USA), Josep Aparicio (Environment Canada, Canada), Sung-Rae Chung (KMA, South Korea), Lidia Cucurull (NOAA, USA), John LeMarshall (BOM, Australia), Christian Marquardt (EUMETSAT, Germany), Hirome Owada (JMA, Japan), Bill Schreiner (UCAR, USA), Stig Syndergaard (DMI, Denmark), Axel von Engeln (EUMETSAT, Germany), Greg Bodeker (Bodeker Scientific, New Zealand)

Recommendations to CGMS

1. **It is of highest importance to ensure the continuity and long-term availability of RO measurements with global coverage.** GNSS RO has been demonstrated to be a very important data record for the global climate observing system providing essential climate variables of benchmark quality and stability. The continuity of GNSS RO observations in the future is not sufficiently guaranteed, which is of main concern regarding the provision of continuous climate products, especially after COSMIC-1, with long-term (decadal) commitments to resolve different the climate variabilities of different timescales. **Operational GNSS RO missions for continuous global climate observation need to be established**. While research missions are a valuable component, operational missions are required as a backbone to ensure continuity.

2. **Global coverage and coverage of all local times needs to be ensured for a climate observing system and GNSS RO should contribute at least 20,000 occultations per day.** For reference, a monthly mean record utilizing the effective horizontal resolution of about 300 km with a 6-hour resolution of the diurnal cycle requires at least 20,000 occultations per day.

   While large-scale climate monitoring and research questions can be successfully tackled with less than 20000 occultations, the study and improved understanding of many regional-scale and large-scale climate processes critically depends on diurnal-cycle and meso-scale resolution. For example, as summarized by the findings and recommendations of the recent high-level climate symposium on “Climate Research and Earth Observations from Space – Climate Information for Decision Making” (http://www.theclimatesymposium2014.com), height-resolved water vapor observations in the lower troposphere are part of much needed data to understand and improve significant climate model discrepancies in representing the coupling of thermodynamics and large-scale circulation in the lower troposphere, critical to climate sensitivity and changes in the water cycle. GNSS RO with at least 20,000 occultations per day can substantially contribute to this thermodynamic information, in particular on water

vapor, and the climate symposium explicitly stressed the vital role of GNSS RO and emphasized that "it is important that the [GNSS RO] continuity is ensured with optimum global coverage." Further climate science needs for higher RO density include the analysis of atmospheric blocking situations with middle and upper troposphere data, and of their relation to extreme climate events such as heat waves, analysis of thermodynamic imprints of deep convective systems such as tropical cyclones, volcanic eruptions, and many others.
Regarding the status of RO coverage, the current and future MetOp satellite series only cover certain local times. The COSMIC-1 mission is past its design life, has already severely degraded, and we are facing an imminent observational gap. A COSMIC-1 follow-on mission is needed urgently. The first satellites of the planned COSMIC-2 mission will be in low inclination orbits and will cover low latitudes only. Thus, for the future there is an urgent need for COSMIC-2 second satellites in high inclination orbits to provide global coverage and local time coverage. Overall, the aim should be to take advantage of all available GNSS constellations to maximize coverage.

3. Encourage GNSS receiver software flexibility in future RO missions, while ensuring strict change control management. **IROWG recommends that the RO receiver design includes sufficient software/firmware flexibility to allow changes in the signal processing including processing of new signals/constellations as they become available.** All these updates shall be well documented.
    a. While some agencies are running long term programs (e.g. EPS/EPS-SG) lasting for two decades or more, GNSS signals structure have evolved in a shorter time scale (e.g. L2C, L5 introduction). Without this capability, otherwise healthy instruments may become obsolete and/or the availability of new constellations/signals might not be exploited.
    b. Receiver firmware changes should be carried out only with strict and well documented change control management. Full documentation of all software modifications and their potential impact on measurement quality is crucial so that a homogeneous dataset can be properly maintained.

4. **Promote cross-collaboration and sharing of data and knowledge between the RO community and the satellite operators**, e.g., the FY-3 satellite series with the GNOS receiver might be an important data contributor in the future. **Making the raw (level 0) data available to the scientific community as soon as possible is regarded of high importance since the raw data are necessary to achieve full traceability of the retrievals**. Continuous collaboration and data comparison are of great value for all parties.

5. **Promote and support regular reprocessing activities of RO climate data records** from different RO processing centers along the principles for re-processing climate data records of the WCRP Observation and Assimilation Panel (WOAP; http://www.wcrp-climate.org/documents/WOAP_ReprocessingPrinciples.pdf). This requires dedicated funding, since reprocessing activities are generally not covered within research proposals.

6. **Encourage NWP centers including ECMWF to engage in reanalysis activities based only on data types that are not bias-corrected, especially RO and high-quality radiosondes.**

Recommendations to satellite operators and data providers

1. Documentation on retrieval processing chains by all processing centers is essential to ensure traceability in climate data (e.g., 1DVar retrieval documentation). Documentation on LEO receiver firmware is also needed. IROWG recommends **fully documenting processing chains, keeping track of any introduced changes/updates to processing or instrument**. The data providers should provide such information on an official repository set up by the IROWG.

   Action: The IROWG shall establish an initial repository (e.g., wiki page) where such data can be deposited.

2. In the retrieval processing chains, uncertainty estimation and documentation needs to receive increased attention, as for example raised via Action G-3 on IROWG members by the "3Gs" community at the WMO-organized workshop in Geneva in May 2014. IROWG recommends that processing centers **increase efforts on uncertainty estimation, make uncertainty calculations publicly available through peer-reviewed publications, including where background information comes into the processing, where the traceability chain may be broken (in accordance with the GCOS-143 Document on climate monitoring principles).**

3. **Data providers should make available gridded data with prescribed uncertainty and algorithm descriptions.** This will help to promote the use of RO data by the climate community. It is recommended to establish a web portal for all centers, to put their data or links to their data, and to adhere to a common format (e.g., obs4MIPs). Continuity of funded efforts desired.

4. All level 1 data providers should **make available the raw data, excess phase and amplitude data, and orbit data in a standard format,** preferably NetCDF, as soon as possible. This would enable independent RO processing centers to cross-check their systems and to estimate the overall uncertainties in their retrievals (see recommendation #3 to CGMS above).

5. **RO measurements from past and current missions that have not yet been fully processed** (e.g., KOMPSAT-5, FY-3C, SAC-D, OceanSat-2, MEGHA-Tropiques) **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 (see recommendation #3 to CGMS above) as well as increase past coverage.

6. Data providers should maintain parallel data streams of RO climate products, one operational and one uniformly reprocessed version. The reprocessed version should always cover the full data time period until a new processing version takes over.

Recommendations within IROWG

1. **The SCOPE-CM working groups should continue to contribute to the development of GNSS RO as a climate monitoring system** by assessing the sensitivity of trends (1) to retrieval system and (2) to receiver provider.

2. There is an uncertainty in the refractivity coefficients that impacts the accuracy and traceability of RO climate time series and trends. We are encouraged by recent progress in **new measurements of the refractivity coefficients with higher accuracy (better**

than 1.E-4). We recommend continuous coordination and progress within IROWG and to bring in metrology experts.

3. **Issues of ionospheric correction and statistical optimization should be further investigated to optimize the climate utility in the entire stratosphere. We acknowledge progress by the iono-atmo coordination workshop in 2014 in Boulder and these efforts should continue.**
4. **Systematically investigate the feasibility of an RO "climate-quality" water vapor product.** RO provides 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, which are critical to climate sensitivity and changes in the water cycle.
5. **Continue participation in the wider scientific community** (e.g., CMIP, GEWEX, SPARC, ITWG, 3G, obs4MIPs) and collaboration for the promotion of RO data and the complementary use of different data sets. Use IPCC and similar web sites to promote RO products.
6. Ensure a complete archive of navigation data bits in a standard format.
   Action: check if JPL has a record dating back to 2005 (start of open-loop RO data).
7. **Encourage research into the benefits of higher SNR**, which is likely to extend the benchmarking capability of GNSS RO more robustly into the troposphere and higher into the stratosphere.
8. Recent studies found a signature in L1/L2/L5 signals from Block IIF satellites, which could affect the quality of the RO benchmark climate record. **This L1/L2/L5 drift in recent Block IIF satellites as well as possible L1/L2 drift on previous Block I, Block II satellites needs to be investigated.**
9. Investigate the consistency of data from different RO missions ($2.0 \cdot 10^{-8}$ rad bending angle offset).

3.3 Receiver Technology and Innovative RO Techniques

Chair: R. Kursinski (SS&E, US)

Rapporteur: S. Syndergaard (DMI, Denmark)

Participants: Dave Ector (UCAR, US), Gottfried Kirchengast (Wegener Center, Austria), Kefei Zhang (RMIT, Australia), Congliang Liu (NSSC/CAS, China), Yago Andres (EUMETSAT, Europe)

High priority recommendations

Ensuring adequate firmware settings of existing GNSS RO firmware

IROWG recommends to EUMETSAT to explore the feasibility of **modifying the firmware** in the GRAS RO instruments onboard Metop-A, B and C, so that the occultations are continued to at least an altitude of 120 km. This will permit better insights into ionospheric sporadic E-layer signatures, which may be responsible for loss of lock or other tracking errors

even at altitudes below 80 km (e.g., if/when E-layers are tilted). Tracking to higher altitudes than 80 km could also help investigations into ionospheric correction improvements at high altitudes as well as help to diagnose possible small mean bending angle biases, which could be important for climate monitoring. Finally, more data at high altitudes can help dynamic error estimation in the operational processing of occultations and ease the identification of bad data to scintillations/tracking errors in limited vertical intervals.

Moving LEO-LEO occultation development forward towards a demonstration mission

IROWG recommends that CGMS adopt an action asking international space agencies (NASA-ESA-NSF-NOAA-EUMETSAT and others) to **hold an interagency workshop** as soon as possible to define how they can cooperate in the next steps towards a LEO-LEO research and demonstration mission such as, for example, and airborne demonstration. IROWG also recommends that CGMS encourage space agencies to support research towards implementation of LEO-LEO occultation demonstration to pave the way towards developing an authoritative reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs). Initial mountaintop demonstrations have been made at cm, mm and micrometer wavelengths. The next step within the next 2 years might be an airborne occultation demonstration.

GNSS system recommendations

Transmitter system: General recommendations

1. IROWG acknowledges the release of the B1 Open Service ICD for BeiDou. IROWG recommends to China to make BeiDou/Compass ICDs with full required information (i.e., including B2 and B3 signals) available so that future missions can make use of the signals from this Navigation System, increasing the number and usefulness of RO measurements for both NWP and climate.
2. IROWG recommends to the Indian Space Research Organization to make a comprehensive IRNSS signal ICD available so that future missions can make use of the signals from this Navigation System, increasing the number and usefulness of RO measurements for both NWP and climate.
3. IROWG recommends to operational agencies and instrument developers to also consider the use of GLONASS FDMA as well as the new and emerging constellations (BeiDou, Galileo, IRNSS, QZSS) in future receivers, in order to increase the number of available RO measurements.
4. IROWG recommends closer cooperation between the RO community and organizations such as IGS (International GNSS Service) and GNSS system operators by, e.g., participation in its organizing bodies / governing board.
5. IROWG recommends that the GNSS constellation operators provide Equivalent Isotropically Radiated Power (EIRP) as a function of the on-board antenna angles (elevation and azimuth) on a satellite per satellite basis, formed from post-launch power measurements combined with transmit antenna gain patterns.
6. IROWG recommends that the GNSS satellites transmit significant power levels beyond the limb of the earth, in order to allow radio occultation applications from LEO meteorological satellites.

Transmitter system: Modulation on new GNSS signals, desire for un-modulated pilot tones

Rationale: In the not too distant future there will be 6 international GNSS constellations: GPS, GLONASS, Galileo, BeiDou, QZSS, and IRNSS. With 12 orbiting LEO satellites, these will produce more than 30,000 daily occultations.

The navigation modulation of new GNSS signals and systems is yielding increasing precise ranging data. Unfortunately this modulation makes it increasingly difficult to use these signals for open loop tracking in the lower troposphere and will likely degrade occultation performance there. 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 difficult and will at the very least degrade the occultation performance there and may render the new signals unusable for occultations in the lower troposphere.

Recommendations: We recommend that CGMS

- **Make GNSS developers aware of the important NWP and climate applications of their GNSS systems and how the GNSS signals and systems are being used**
- **Encourage space agencies to maintain course resolution (BPSK) modulation signals**
- **Consider transmitting un-modulated pilot carrier tones for occultations for NWP and climate.**

Transmitter system: Additional signals on GNSS (e.g. 5 GHz on Galileo)

Rationale: Current GNSS systems use L-band frequencies between 1 and 2 GHz. Additional use of one or more higher frequencies well separated from L-band would have substantial benefit to RO. For instance, for Galileo, ESA is considering a 5 GHz frequency in the C-band range. This would increase the useful altitude range of GNSS radio occultation by about 15 km because sensitivity to the ionosphere is an order of magnitude less at 5 GHz than at L-band frequencies. Ionospheric scintillations induced by sporadic E-layers, which can influence the accuracy of retrieved profiles in the stratosphere, will be significantly reduced at 5 GHz. In addition, such signals would open the door to new applications of RO signals that exploit the better sensitivity to depolarization and reflection effects in C-band such as remote sensing of precipitation, capillary wave/gravity wave interactions and surface winds over oceans. Focus in this area should be given to signal modulation/coding schemes that reduce interference by other signals, improve range resolution and increase SNR.

Recommendation: We recommend that CGMS **encourage space agencies to assess the utility of higher frequencies on next generation GNSS systems** (e.g., 5 GHz on a next generation Galileo) for radio occultation and related applications. In this context, CGMS is also invited to encourage GNSS providers (Galileo, GPS, GLONASS, BeiDou, and IRNSS) to consider implementation of such higher frequencies for the benefit of operational weather and climate monitoring and prediction.

Payload recommendations

Receiver system: General recommendations

1. IROWG recommends that missions, instrument developers, and RO data processing centres provide level0 data format documentation, and/or necessary software to read data, and payload firmware configuration information.
2. IROWG recommends that an investigation of the GNSS transmitter frequency variations over temperature for durations of a few minutes that can affect un-differenced or single- differenced occultation observations is performed.
3. IROWG recommends that the GNSS RO payload manufacturers publish / make available how the observations are formed.
4. IROWG recommends that the GNSS RO manufacturers and RO data users work together to identify sources of RFI that affect RO observations.
5. IROWG recommends that JPL and GFZ determine the feasibility of modifying the firmware in the IGOR RO instruments on TDX and TSX. Firmware modifications should include at least the following three features:
    1) If not already in place; load the most up to date and capable firmware version on both instruments.
    2) Test L2C setting occultations on both with the expectation that L2C occultations will be permanently enabled on both TDX and TSX.
    3) Add capability to output 100 Hz RO phase and SNR on one unit and compare TDX with TSX running at both 50 Hz and 100 Hz rates.
6. Given the large uncertainty in the time of availability of the future signals, IROWG recommends maintaining a proper flexibility in the design of future GNSS-RO receivers. Joint support of L1/E1, L2 (P(Y) and L2C), and L5/E5a is recommended to enable dual-frequency tracking of GPS, QZSS and Galileo.
7. IROWG recommends EUMETSAT to explore the feasibility of modifying the firmware in the GRAS RO instruments onboard Metop-A, B and C, so that the occultations are continued to at least an altitude of 120 km, to permit insights into the E layer signatures.

3.4 Space Weather Sub-Group

Chair: A. J. Mannucci (JPL, US)

Rapporteur: B. A. Carter (RMIT University/Boston College)

Members: F. Menk (Newcastle University), M. Terkildsen (Space Weather Services, Bureau of Meteorology, SWS/BoM), M. Francis, (SWS/BoM), R. Norman (RMIT University), A. Seif (RMIT University)

Recommendation to CGMS

1. **The Space Weather sub-group of IROWG recommends that all reasonable effort be expended to launch the FORMOSAT-7/COSMIC-2 (FS7/C2) Polar mission** in the 2018 time frame as originally planned. With the decline of FORMOSAT-3/COSMIC-1 and other research satellites, lack of FS7/C2 Polar will result in the

absence of any ionospheric radio occultation measurements above approximately 40° latitude. We note that FS7/C2 first launch is planned for a low inclination orbit that will not provide data at middle and higher latitudes, where significant space weather impacts are present, which need to be monitored.

2. **IROWG recommends that CGMS encourage international support of the FORMOSAT-7/COSMIC-2 program through the fielding of FS7/C2 ground stations in countries at low latitudes to augment ground stations planned by the USA and Taiwan, including the planned stations in Northern Australia and Brazil.** This action will significantly reduce the data latency from FS7/C2 in the important low latitude and equatorial regions, which will benefit space weather monitoring and forecast capabilities around the world. Of particular interest is the development of three latitudinal chains of three ground stations each in the Asian, Middle Eastern/African, and American longitude sectors. It is recognized that a first step is to obtain configuration and access information for FS7/C2 ground stations distributed globally. (See Action IROWG3-02).
3. IROWG recommends CGMS to encourage missions flying GNSS RO sensors to incorporate a complete set of ionospheric measurements including measurements of ionospheric scintillation (high-rate scintillation measurements on all available lines of sight where TEC data are obtained, if possible). Further, **IROWG recommends that future RO missions plan to overcome potential hardware and software limitations in recording TEC across all elevation angles (particularly from "zenith to negative elevations")**. The ionosphere and plasmasphere above the satellite orbit altitude contains a significant contribution to the total electron content, and should be measured for operational and research purposes.
4. **IROWG recommends that CGMS coordinate efforts to collect requirements from the atmospheric and climate communities regarding ionospheric products that serve their needs, including potentially forecasting ionospheric weather.** Efforts should continue to standardize an ionospheric data format for operational use of RO, create a real-time data accessing service available for space weather assimilation models with latencies below 30 min, and archive historical data for ionospheric climate and scientific research purposes. **The issue of the specific parameters, data format and method of data exchange should be investigated in coordination with parallel efforts in WMO ICTSW**.
5. The Space Weather sub-group of IROWG recommends that International Ionosphere-Atmosphere Coordination Workshops continue to be held. In particular, **the issue of increasing the upper altitude of the lower atmospheric profiles by better characterizing ionospheric effects needs to be addressed at a future workshop.**

Recommendations within IROWG

1. In its response to action 39.03 received from CGMS regarding development of an inventory of radio occultation missions, **IROWG should document the abilities of each mission to obtain ionospheric data so as to highlight the compliance, or lack thereof, of each mission with the Main Recommendation #3 above.** The information in the inventory for each RO mission should include the extent to which the mission collects ionospheric profile data, the data latency associated with the mission, and the

extent to which ionospheric scintillation data are collected. The WMO OSCAR database is particularly useful for this purpose.

2. The coupling between stratosphere/mesosphere/lower thermosphere and the ionosphere through gravity waves, planetary waves, and tides has shown significant and unexpected contributions to ionospheric variability. GNSS RO provides unique observations to conduct related scientific research by simultaneously sampling both the lower atmosphere and ionosphere. However, the currently processed RO data has a gap between ~40 and 90 km due to the difficulty of completely removing the ionospheric effects on the ray bending caused in the neutral atmosphere. **IROWG recommends efforts to develop improved analysis methods and instrumentation to extend the upper altitudes of current RO retrieval capability, in line with CGMS recommendation #5.**

Recommendations within Sub-Group

1. It is desirable to continue to **expand the sub-group membership in the areas of personnel associated with operational space weather support centers 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 centers that will enable scientists to support future IROWG meetings.
2. **Space Weather sub-group team members should continue to advocate for and support greater incorporation of ionospheric radio occultation science topics** (such as those described in CGMS Recommendations #4 and #5) within existing ionospheric science venues such as CEDAR 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.
3. Advancement of ionospheric model science depends on the collection of both ionospheric and thermospheric information (e.g., densities, drifts/winds etc.). GNSS RO observations alone are not sufficient to address this issue, so **the members of the Space Weather sub-group should engage with the COSMIC-2 program to advocate for incorporation of space weather secondary payloads on the high inclination portion of that mission**. **Therefore, the status of secondary payloads for COSMIC-2 need to be determined.** Further, the value of Ionospheric Connection Explorer (ICON) and Global-scale Observations of Limb and Disk (GOLD) missions needs to be investigated.
4. The sub-group should coordinate with space weather activities throughout WMO. **Efforts should be ongoing to invite members of the WMO ICTSW to attend future IROWG Space Weather sub-group meetings.**

Action IROWG3-03: J. Y. Liu and Tony Mannucci will each provide a report on the activities at CEDAR that were initiated by Gary Bust and Geoff Crowley as part of Action IROWG2-08. J. Y. Liu will report RO related activities at the IRI conference in Olsztyn, Poland (June 2013). Due: IROWG-4. Completed by Mannucci. Dr. Mannucci reported that RO is fully accepted as a valid and useful measurement for space weather modeling and data assimilation

activities. There are several examples of CEDAR sessions where RO was discussed. Dr. Liu did not attend IROWG-4, so the IRI related action is still open.

Action IROWG3-04: Obtain information regarding access to COSMIC-2 data downlinks globally to decrease data latency (objective is 30 minutes or less). Tony Mannucci will contact Paul Straus of Aerospace Corp to obtain information from the USAF. J. Y. Liu will contact NSPO to obtain information from that organization. Due: IROWG-4. Mannucci is attempting to close the loop with Dr. Straus of Aerospace Corporation.

Action IROWG3-05: Sun Yue-Qiang of the Space Weather Sub-group will provide information on the planned use of FY-3C ionospheric data, including its use in space weather models. Due: IROWG-4. Dr. Yue-Qiang did not attend IROWG-4. Her students reported on the successful use of ionospheric measurements from the GNOS sensor onboard FY-3C. No modeling information was provided. CLOSED.

Action IROWG3-06: All IROWG members to check and to provide feedback on the information given in the WMO Observing Systems Capability Analysis and Review Tool OSCAR: http://www.wmo-sat.info/oscar/. Due: ongoing (several updates have already been provided by the Co-Chairs).

4 CONCLUSIONS

The main recommendations of the fourth IROWG meeting were briefly summarised above - only a short and concise working paper could be provided to CGMS-43 since IROWG-4 and CGMS-43 occur within about one month. The full set of recommendations, relevant at CGMS, at satellite operator, and at IROWG level will be made available at http://www.irowg.org.

For work in the immediate future CGMS-43 is invited to emphasise the following four main IROWG-4 recommendations:

- Ensure that both, **equatorial and polar components of COSMIC-2 are fully funded and launched**; this is required for NWP, Climate, and Space Weather;
- IROWG recommends **targeting at least 20,000 occultations/day to be made available to the operational and research communities** of NWP, Climate, and Space Weather;
- IROWG recommends that the **RO receiver design includes sufficient software/firmware flexibility to allow changes in the signal processing including processing of new GNSS signals/constellations as they become available; all receiver measurements should cover the ionosphere** as well**;**
- International space/research agencies (e.g., NASA, ESA, CMA, CSA, NSF, NOAA, EUMETSAT and others) to hold an **interagency workshop to define cooperation options for implementing the next steps towards a LEO-LEO research and demonstration mission**.

All given presentations, as well as minutes, this CGMS working paper from IROWG-4 are/will be made available at http://www.irowg.org.

ACKNOWLEGEMENTS

IROWG notes and thanks for financial support to this fourth workshop the following organisations: EUMETSAT, CGMS, and WMO.

ACTIONS

The actions from the IROWG-3 workshop, including their status, are collected below.

Action IROWG2-01: On IROWG co-chairs to contact the ITWG and survey the common interests between the groups.	Mutual invitation to the respective workshops of ITWG/IROWG were expressed, the most recent workshops were however in Asia and Australia. The travel burden was considered too high. **Status: Open**
Action IROWG2-02: Josep Aparicio will undertake a review to estimate both the total number of radio occultation measurements and the number of operational measurements available per day, based upon the current timeline of GNSS. This will allow us to foresee problems in data coverage in the coming years. An example is the data gap between COSMIC-1 and COSMIC-2; as there is a distinct possibility of no COSMIC-1 data by 2014.	J. Aparicio provided a report on this during the NWP sub-working group discussions. **Status: Closed.**
Action IROWG2-05: On IROWG co-chairs and B. Ho, A. Steiner: Provide the following ROTrends information on the IROWG homepage: (a) Links to processing descriptions of all data providers; (b) Published ROTrends intercomparison papers; (c) ROTrends PPC and MMC datasets (including sampling errors of the latter).	An ROTrends website has been created at irowg.org, relevant information has been included, access to the website is given to A. Steiner, B. Hoe. It was agreed to close this action, further updates are normal work. **Status: Closed**
Action IROWG3-01: NWP sub-group will compile a table of current Metop-B standard latencies (50 and 90% latencies, after processing, ready for delivery). Future operational missions should take that table as standard requirement (incl. COSMIC-2).	In the process of being closed.
Action IROWG3-02: IROWG co-chairs to check progress towards updated laboratory measurements of the refractivity coefficients.	Co-Chairs have contacted several institutes that could provide such measurements. ESA and NASA are investigating possible activities. It was agreed to compile further information in a dedicated report that identifies area of uncertainty. New action on J. Aparicio. **Status: Closed**
Action IROWG3-03: J. Y. Liu and Tony Mannucci will each provide a report on the activities at CEDAR that were initiated by Gary Bust and Geoff Crowley as part of Action IROWG2-08. J. Y. Liu will report RO related	Part 1 completed by T Mannucci. Dr. Mannucci reported that RO is fully accepted as a valid and useful measurement for space weather modeling and data assimilation activities. There are

activities at the IRI conference in Olsztyn, Poland (June 2013). Due: IROWG-4.	several examples of CEDAR sessions where RO was discussed. Dr. Liu did not attend IROWG-4, so the IRI related action is still open. **Status: Partly Open**
Action IROWG3-04: Obtain information regarding access to COSMIC-2 data downlinks globally to decrease data latency (objective is 30 minutes or less). Tony Mannucci will contact Paul Straus of Aerospace Corp to obtain information from the USAF. J. Y. Liu will contact NSPO to obtain information from that organization. Due: IROWG-4.	T. Mannucci is attempting to close the loop with Dr. Straus of Aerospace Corporation. **Status: Open**
Action IROWG3-05: Sun Yue-Qiang of the Space Weather Sub-group will provide information on the planned use of FY-3C ionospheric data, including its use in space weather models. Due: IROWG-4.	Dr. Yue-Qiang did not attend IROWG-4. Her students reported on the successful use of ionospheric measurements from the GNOS sensor onboard FY-3C. No modeling information was provided. **Status: Closed**
Action IROWG3-06: All IROWG members to check and to provide feedback on the information given in the WMO Observing Systems Capability Analysis and Review Tool OSCAR: http://www.wmo-sat.info/oscar/. Due: ongoing.	Several updates have already been provided by the Co-Chairs. **Status: Ongoing.**

The open actions from all the workshops are collected below.

Action IROWG2-01: On IROWG co-chairs to contact the ITWG and survey the common interests between the groups. Determine potential IROWG participation in the 2015 ITWG meeting (October 2015). Due: IROWG-5.
Action IROWG3-03: J. Y. Liu will report RO related activities at the IRI conference in Olsztyn, Poland (June 2013). Due: IROWG-5.
Action IROWG3-04: Obtain information regarding access to COSMIC-2 data downlinks globally to decrease data latency (objective is 30 minutes or less). Tony Mannucci will contact Paul Straus of Aerospace Corp to obtain information from the USAF. J. Y. Liu will contact NSPO to obtain information from that organization. Due: IROWG-5.
Action IROWG3-06: All IROWG members to check and to provide feedback on the information given in the WMO Observing Systems Capability Analysis and Review Tool OSCAR: http://www.wmo-sat.info/oscar/. Due: ongoing.
Action IROWG4-01: J. Aparicio (with the help U. Foelsche) to compile a report, identifying areas of uncertainty in the refractivity parameters that could be addressed by updated laboratory measurements. Due: end of 2015 (date moved forward from mid 2015).