Summary of the Fifth International Radio Occultation Workshop

Held in Seggau Castle, Leibnitz near Graz, Austria

From Thursday, 8th September to Wednesday, 14th September 2016

Starting at 09:00 hours on 8th September

Ending at 12:30 hours on 14th September

EXECUTIVE SUMMARY

This report summarizes the IROWG-5 meeting held on September 8-14, 2016 near Graz in Austria. It provides the recommendations from the four IROWG sub-groups: NWP, Climate, Space Weather and Receiver Technology/Innovative Occultation Techniques. The four key recommendations for CGMS – endorsed by the IROWG community at the plenary session – are:

- **Ensure that both equatorial and polar components of COSMIC-2 are fully funded and launched; this is required for Numerical Weather Prediction, Climate, and Space Weather**

- IROWG recommends targeting at least 20,000 occultations/day, to be made available to the operational and research communities of Numerical Weather Prediction, Climate, and Space Weather

- International space agencies (in particular NASA, ESA and CNSA, 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 for the LEO-LEO observations.

- **IROWG recommends that CGMS should encourage GNSS providers and agencies to make ICDs of GLONASS and Beidou Open Service** signals available as soon as possible, in order to allow RO instrument providers to design and develop the future receivers without uncertainties due to missing information.

1 INTRODUCTION

This IROWG report presents the minutes / full recommendations of the combined OPAC-IROWG Workshop (OPAC-6 & IROWG-5) of the International Radio Occultation (RO) Working Group and Occultations for Probing Atmosphere and Climate. The workshop was organized by the Wegener Center for Climate and Global Change at the University of Graz, Austria. The meeting was held at Seggau Castle, Leibnitz near Graz, Austria from September 8-14, 2016.

The workshop was attended by more than 60 scientists, including representatives from all the major RO processing centres, space agencies, the weather prediction centres assimilating RO data and representatives of commercial data providers.

This was one of the best workshops on GNSS-RO for many years. Approximately 60 talks and 15 posters were presented. Recommendations were developed in dedicated sub-working groups and presented and agreed upon in a plenary discussion on the last day. Additionally, IROWG-5 was used by several researchers for dedicated specialist/splinter meetings, which are not covered here.

A key issue throughout the meeting was the relationship between the new agency-led GNSS-RO missions and the commercial GNSS-RO proposals. The latest results from SPIRE, demonstrating their ability to measure and process GNSS-RO measurements made with CubeSats, was one of the highlights of the meeting. This is an impressive first step. However, it was recognized that a detailed analysis of the SPIRE data, and data from other commercial options, is required. Therefore IROWG fully supports the aims of the NOAA Commercial Data Pilot Study, and will assist this process if required. Similarly, IROWG would like to support the NOAA OSSE activities related to the future provision of GNSS-RO measurements.

There remains strong support for a fully funded COSMIC-2 mission. Overall, the aim of the community is to maximize the number of high-quality GNSS-RO observations, which can be freely exchanged.

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 with the four main recommendations for CGMS.

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-5 SETUP

IROWG-5 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;
- Receiver technology and Innovative Occultation Techniques;
- Space Weather.

IROWG-5 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-45; 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/Rapporteur: Josep M. Aparicio (EC)

Members: Harald Anlauf (DWD), Dominique Raspaud (Météo-France), Doug Hunt (UCAR), Michael Gorbunov (IAP RAS), Pawel Hordyniec, (WUELS) Kent Lauritsen (DMI), Christian Marquardt (EUMETSAT), Sean Healy (ECMWF), Marc Schwärz (WegC), JaeGwan Kim (KMA), Hiromi Owada (JMA), Chris Burrows (Met Office), Mi Liao (NSMC, CMA), Yan Liu (NWPC, CMA), Stig Syndergaard (DMI), Lidia Cucurull (NOAA).

1. **We carry forward the previous recommendations to CGMS:**

    a. "Ensure that both, equatorial and polar components of COSMIC-2 are fully funded and launched; this is required for Numerical Weather Prediction, Climate, and Space Weather;"

    COSMIC-2 is a long term, reference mission. It is advanced and well-defined, and is based on extensive heritage in hardware, software and team experience, including a decade of COSMIC-1 in-orbit operations, research and development. There is no other project, public or private, with this level of definition and heritage. Consideration of future proposals, including commercial, should be based on **well demonstrated** levels of attained capability and operational readiness.

    b. We confirm that the following, already adopted by CGMS, still applies.

    "IROWG recommends targeting at least 20,000 occultations/day to be made available to the operational and research communities of Numerical Weather Prediction, Climate, and Space Weather"

2. **IROWG/NWP welcomes the ongoing NOAA Commercial Data Pilot Study**, which is requesting industry to demonstrate current and immediate capabilities. It is important to verify what the actual capabilities are.

3. Regardless of the future possibility of commercial provision of data, IROWG recommends provider agencies to **support a backbone of instruments**, technologically **state-of-the-art**, and **labelled** as **essential** (WMO Res 40), and that at least **match the current operational data**. This backbone should target to provide the highest level of performance, and become a reference asset. Observations from this backbone should be freely available.

4. Besides this backbone, IROWG recommends that

   a supplementary set of instruments provide further data, perhaps commercial, **not necessarily** labelled essential. **IROWG strongly recommends that this supplementary data are nevertheless as freely available as possible**.
   Regardless of the operational availability, it is important that there is a clear characterization of the properties (accuracy, error properties) of this dataset.

Other Points:

- KOMPSAT-5: Data are being collected and are being processed, but the downlink is insufficient for NRT.

  Given the fall in data numbers, this could be an important new source of data. IROWG recommends that other agencies offer to supplement downlink capability, addressing technical and IT security issues. IT security issues related to KOMPSAT-5 will be addressed by NOAA.

- Data from FY-3C exists and are most probably useful. CMA have confirmed that FY3C data will be made available in BUFR format and be on the GTS in 2017. IROWG participants offer to help with recoding & verification activities. We propose that a **SAMPLE Level 0** and either decoding software, or preferably a technical format specification, are made available for verification.
- We also encourage all new GNSS-RO projects, and restate the offer of the community to provide technical advice (best effort) to interested agencies.

3.2 Climate Sub-Group

Chair: Chi Ao (JPL, USA)

Rapporteur: Andrea Steiner (WEGC, Austria)

Members: Chi Ao (JPL, USA), Riccardo Biondi (CNR, Italy), Alejandro de la Torre (Universidad Austral, Argentina), Ulrich Foelsche (WEGC, Austria), Hans Gleisner (DMI, Denmark), Shu-Peng (Ben) Ho (UCAR, USA), Josef Innerkofler (WEGC, USA), Congliang Liu (NSCC, China), Johannes Nielsen (DMI, Denmark), Ben Santer (LLNL, USA), Torsten Schmidt (GFZ, Germany), Andrea Steiner (WEGC, Austria), Jördis Tradowsky (Bodeker Scientific, New Zeeland), Panagiotis Vergados (JPL, USA), Hallgeir Wilhelmsen (WEGC, Austria)

Visitors: Sean Healy (ECMWF, UK), Rob Kursinski (Space Sciences and Engineering, USA)

Recommendations to CGMS

1. **It is of highest importance to ensure the continuity and long-term availability of high quality 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 the climate variabilities at different timescales. **Operational GNSS RO missions for continuous global climate observation need to be established**. **While research missions are a valuable component, operational missions (like the planned COSMIC-2 equatorial and polar constellations) 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. GNSS RO is also valuable for checking the reliability of climate data records estimated from other satellite-based instruments (e.g., A/MSU, which requires correction of local time drifts).

   While large-scale climate monitoring and research questions can be successfully tackled with less than 20,000 occultations, the study and improved understanding of many regional-scale and large-scale climate processes critically depends on diurnal-cycle and meso-scale resolution. Further needs for higher RO density include the analysis of atmospheric blocking situations with middle and upper troposphere data, and 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 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 there is an especially urgent need for a COSMIC-2 second satellite constellation in high inclination orbits to provide global and local time coverages. 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 has the opportunity to be an important data contributor in the future. **Making the raw (level 0) data, metadata, and associated documentation available to the scientific community as soon as possible is of high importance since the raw data are necessary to achieve full traceability of the retrievals regardless of the source of the data**. Continuous collaboration and data comparison are of great value for all parties.
5. **Fund regular reprocessing activities of RO climate data records** from different RO processing centers along the principles for reprocessing climate data records of the WCRP Observation and Assimilation Panel (WOAP; http://www.wcrp-climate.org/documents/WOAP_ReprocessingPrinciples.pdf) Documentation of the historical evolution of processing systems for the provision climate data records is important.

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/SCOPE-CM (http://www.scope-cm.org/projects/scm-08/).
2. 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 "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 and where the traceability chain may be broken (in accordance with the GCOS-143 Document).**

3. **Data providers should make available gridded data together with uncertainty and algorithm descriptions.** This will help to promote 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. JPL has provided obs4MIPs datasets consisting of monthly gridded temperature and geopotential heights from 10–400 hPa covering the period of 2002–2014. We recommend that a multi-center ensemble of independently processed RO datasets will be useful in quantifying the structural uncertainty rather than a multi-center average. Derived parameters such as tropopause heights may also be desirable. We recommend and acknowledge ongoing efforts on establishing a web portal for all centers (IROWG/SCOPE-CM) to put their data or links to their data there (http://www.scope-cm.org/projects/scm-08/). Continuity of funded efforts is desired.
4. All level 1 data providers should **make available excess phase and amplitude data, and orbit data in a standard format,** preferably NetCDF. This would enable independent RO processing centers to cross-check their systems and to estimate the overall uncertainties in their retrievals (see recommendation #4 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 #2 to CGMS above) as well as increase past coverage.
6. Data providers should maintain parallel data streams of RO climate products, one operational data version and one uniformly reprocessed version. The reprocessed version should always cover the full data time period until a new processing version takes over (see recommendation #5 to CGMS above).

Recommendations within IROWG

1. **The SCOPE-CM working group should continue to contribute to the development of GNSS RO as a climate monitoring system** by assessing the structural uncertainty of RO retrieval data including differences between processing centers and between different RO instruments and missions. Possible physical constraints to identify outliers should be considered.
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). Recommend continuous coordination and progress among IROWG and bringing in metrology experts. We acknowledge progress and ongoing efforts.**
3. **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 the iono-atmo coordination workshop in 2014 and a**

dedicated session during the IROWG-5 workshop 2016. 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 are 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, GRUAN, GSICS, obs4MIPs, MSU community) and collaboration for the promotion of RO data and the complementary use of different data sets. **We acknowledge ongoing activities and efforts.**
6. Ensure a complete archive of navigation data bits in a standard format. We recommend making this information available to the community. Action: check if JPL has record dating back to 2005 (start of open-loop RO data).
7. **Encourage research into the benefits of higher SNR and the 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. Subtle changes in the transmitted GNSS signals over time may affect the estimate of long-term trends from RO data. Such effects need to be assessed and quantified.

Action IROWG4 Recommendation CGMS-06: **CLOSED**:

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. **Sean Healy reported that ROMSAF has set up such reanalysis runs and that results would be available in 2017.**

3.3 Receiver Technology and Innovative RO Techniques

Chairs: R. Kursinski (SS&E, USA)

Rapporteur: R. Notarpietro (EUMETSAT, Germany)

Members: Weihua Bai (NSSC/CAS, China), Anders Carlstr□m (RUAG Space, Sweden), Dave Ector (Spire Global Inc., UK), Gottfried Kirchengast (WEGC/UniGraz, Austria), Rob Kursinski (SS&E, USA), Andang Hu (RMIT University, Australia), Ying Li (IGG/CAS, China), Congliang Liu (NSSC/CAS, China), Riccardo Notarpietro (EUMETSAT, Germany), Stig Syndergaard (DMI, Denmark), Sergey Sokolovskiy (UCAR, USA), Jens Wickert (GFZ, Germany), Nick L. Yen (NSPO, China).

Top recommendations from the subgroup, suggested towards CGMS level at front-page:

1. International space agencies (in particular NASA, ESA and CNSA, 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 for the LEO-LEO observations.

2. **IROWG recommends CGMS to encourage GNSS providers and agencies to make ICDs of GLONASS and Beidou Open Service** signals available as soon as possible, in order to allow RO instrument providers to design and develop the future receivers without uncertainties due to missing information.

High priority recommendations

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

IROWG recommends that CGMS adopt an action asking international space agencies (in particular NASA, CNSA and ESA, where proposals towards initial LEO-LEO demonstration missions are pending) to **support mission preparation projects** that implement the next steps towards a LEO-LEO microwave occultation (LMO) demonstration mission. Such next steps within the next two to three years include LMO instrument developments towards flight instrumentation, microsat platform design and preparation, and dedicated Phase A/B studies towards mission implementation. IROWG also recommends that CGMS encourage space agencies to support R&D towards implementation of LEO-LEO demonstration in a broader sense, including on infrared-laser occultation in addition to microwave occultation, in order to pave the way towards developing an authoritative reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs) on composition (greenhouse gases) and climate. Initial mountaintop demonstrations have been successfully made at cm, mm and micrometer wavelengths.

2. Requesting the release of GLONASS and BeiDou Open Service signals Interface Control Documents.

IROWG recommends CGMS to encourage GNSS providers and agencies to make ICDs of GLONASS and Beidou Open Service signals available as soon as possible, in order to allow RO instrument providers to design and develop the future receivers without uncertainties due to missing information.

3. Exploiting the synergy of GNSS radio occultation with GNSS reflectometry, pushing forward the next development phases of the GEROS-ISS mission and to support GNOS II instruments, which involves both GNSS RO and GNSS–R functions for the subsequent FengYung 3 series of Chinese satellites

IROWG recommends to strengthen the scientific and technical activities for the exploitation of the potential **to combine the application of the GNSS radio occultation technique with GNSS reflectometry (GNSS-R)** for global monitoring of several geophysical Earth Surface parameters (e.g., altimetric height of water and ice surfaces, wave heights and wind speed/direction over the oceans, soil moisture, vegetation index). GNSS reflectometry measurements are also appropriate for atmosphere/ionosphere sounding.

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

A forerunner for these developments is the **GEROS-ISS** mission from ESA, which was proposed in 2011 as a combined GNSS-RO and GNSS-R mission and recently finished Phase A. GEROS-ISS is intended to provide unique data especially for the sea surface height and wind speed determination, but also for land surface monitoring and GNSS-RO with new aspects, as, e.g., precipitation measurements. It is expected that the GEROS-ISS data will allow fundamental investigations for the development of both, the GNSS-R and GNSS-RO technique individually, but also for their combined application.

IROWG focus to recent Observation System Simulation Experiments (OSSE) within the GEROS-ISS Phase A, where a high potential of the relatively new coherent GNSS-R altimetry measurements at low elevations with high precision and high observation density was indicated. **IROWG recommends and stimulates the scientific investigation of the dependency of the coherent GNSS-R technique on the roughness of the reflecting surface** and of potential additional geophysical applications of this method.

Another mission to combine the application of the GNSS radio occultation technique with GNSS reflectometry (GNSS-R) is **FY3 GNOS II**, which will be onboard FY3-E satellite, in 2018. It has been determined to add the GNSS (GPS + BDS) reflectometry function to the GNOS II receiver. A nadir LHCP antenna will be deployed, and the goal is to measure the roughness of the sea surface and the sea surface wind field. IROWG recommends GNOS designers, manufacturers and agencies **to support GNOS II instruments**, which involve both GNSS RO and –R functions, for the subsequent FY3 series satellites, i.e., FY3 E to G satellites.
IROWG recommends to **organize a dedicated workshop** for the GNSS-RO and GNSS-R communities including relevant organizations as, e.g., NASA/ESA as soon as possible to discuss this important developments and the related joint activities in detail.

4. Additional signals on GNSS (e.g. 5 GHz on Galileo)

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 i**ncrease 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. It would also:

- **Reduce the effects of ionospheric scintillations from F and sporadic E layers**, which introduce large random inversion layers in the stratosphere
- **Reduce any large-scale higher-order ionospheric effects**, which introduces errors for climate applications in the stratosphere

- **Reduce the effects of horizontal electron density gradients** on the retrieved heights of inversion layers in the troposphere

Thus, a C-band frequency would **improve accuracy and increase reliability** of retrieved profiles in many different ways, and be beneficial to both climate and weather applications. 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.

IROWG recommends 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.

5. Modulation on new GNSS signals

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. The new navigation modulation such as binary offset carrier (BOC) has a more complex autocorrelation function that not only narrows the central peak of the autocorrelation function but also has anti-correlated response at certain time lags. This response makes acquisition of signals in the lower troposphere more difficult and could potentially impact the occultation performances there.

IROWG 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 GNSS developers to maintain course resolution C/A (BPSK) like signals**

6. Polarimetric RO observations

Recent theoretical analysis and ground observations have indicated that **dual polarization GNSS signals are sensitive to heavy precipitation** due to the non-spherical shapes of the hydrometeors. Thus, polarimetric RO observations give unique coincident information on precipitation and moist thermodynamics of the atmosphere, with only a small increase in cost and complexity from single-polarization RO system. In particular, **we encourage the timely deployment of the PAZ satellite**, which is designed to provide the first spaceborne demonstration of the concept.

IROWG recommends that future RO missions should include the capability to track GNSS signals in two orthogonal polarizations.

General recommendations for service providers

1. 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.
2. IROWG recommends to operational agencies and instrument developers to also consider the use of **GLONASS FDMA and CDMA signals, 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.
3. IROWG recommends closer cooperation between the RO community and organizations such as IGS (International GNSS Service), IERS (International Earth Rotation and Reference Systems Service), GNSS system operators and others by, e.g., participation in its organizing bodies / governing board for
    a. **the provision, if necessary, of clock biases at higher sampling rate** compatible with RO applications
    b. the **standardisation and eventually the provision of a common GNSS time reference GNSS system**
    c. the **provision of Ultra Rapid Orbits and Clock bias data for Beidou system**
4. 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. This will provide a better understanding about SNR, allowing more accurate link budget estimations, useful for climate control.
5. 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.

General recommendations for instrument providers

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 the GNSS RO payload manufacturers **publish / make available how the observations are formed**.
3. IROWG recommends that the **new generations of RO receivers will provide measurements with a quality comparable or even better than the one characterizing the receivers currently operated**, especially in view of the attempts to miniaturize receivers for deploying constellations of small satellites.

4. IROWG recommends that the GNSS RO manufacturers and RO data users work together to **identify sources of RFI that affect RO observations**. In particular, IROWG recommends to initiate a request to agencies and/or ITU **to better protect the L5 band against ground based known transmissions** (i.e. DME/TACAN) which strongly impact RO receivers collecting new signals in the L5 band and might impact also GNSS receivers on board aircrafts.
5. IROWG recommends to EUMETSAT to continue 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.
6. 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.
7. 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.
8. 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.

3.4 Space Weather Sub-Group

Chair: P. R. Straus (The Aerospace Corporation, US)

Rapporteur: W. Schreiner (UCAR)

Members: T. Kurino (WMO), T. Meehan (JPL), T. Mannucci, (JPL), S. Healy (ECMWF), B. Weihua (NSSC)

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 2019-2020 time frame. With the decline of FORMOSAT-3/COSMIC-1, lack of FS7/C2 Polar will result in a dearth of ionospheric radio occultation measurements above approximately 40° latitude. We note that FS7/C2 Equatorial launch will not provide data at middle and higher latitudes, where significant space weather impacts are present, which need to be monitored.

2. **The Space Weather sub-group of IROWG recommends that CGMS encourage the development of space weather data assimilation models to take full advantage of the FS7/C2 Equatorial data for specification and prediction of the low latitude ionosphere – to include both its large and small scale properties (the latter being related to ionospheric scintillation effects).** FS7/C2 Equatorial will provide RO data densities in this region that are an order of magnitude higher than any prior RO system together with ionospheric electric field and *in-situ* density data from the secondary Ion Velocity Meter (IVM) instrument. Electric fields are the most critical driving force for low latitude ionospheric physics and the *in-situ* density measurements can be used together with the RO data to clearly identify and track the turbulent "bubble regions" associated with scintillation. These new data sets from FS7/C2 Equatorial can be expected to lead to significant advances in the state of the art of ionospheric assimilative modeling, and associated improvements to operation space weather systems, if model development efforts are adequately funded.

3. Per CGMS priority HLPP 1.1.4 (optimized system for atmospheric and ionospheric RO observations), **the Space Weather sub-group of IROWG recommends CGMS encourage future GNSS RO missions, including potential commercial providers of RO observations, to incorporate a complete set of ionospheric measurements (including 50+ Hz ionospheric scintillation data collection on all available occulting lines of sight where TEC data are obtained).** Future RO missions should strive to overcome antenna field-of-view, hardware and/or software limitations to provide sensors that measure TEC across all elevation angles (particularly from "zenith to negative elevations"). It should be noted that measurements of ionospheric/plasmaspheric TEC above satellite orbit altitudes can provide significant benefit for operational and research purposes. For this reason future RO missions should make "overhead TEC" measurements as well as ionospheric occultation measurements. Additionally, non-RO missions that fly GNSS receivers for precise orbit determination should be encouraged to make available to the operational and research communities all necessary level-0 data (level-0 GNSS data, antenna phase center variations, spacecraft attitude orientation, and solar array motion) required to produce accurate overhead TEC data.

4. **In response to CGMS action A44.13 ("IROWG to define requirements on timeliness for RO observations"), we recommend that future RO missions include communications infrastructure that will enable 95% of the measurements to be available for use in operational models within 30 minutes or less.** Data older than 30 minutes is of lower value for current models. Near-real time data latency would be optimal, but is not always practical, and should be considered to be a useful goal for future missions when possible. **In the specific case of FS7/C2 Polar, south polar ground stations (e.g., McMurdo, Troll) should be deployed to reduce data latency.**

5. The Space Weather sub-group of IROWG recommends that efforts be made to standardize access to near real-time ionospheric RO data. As a starting point, **we**

recommend that WMO request that GNOS ionospheric data from the FY3 series of satellites (starting with archived FY3C data and continuing to data from future satellites FY3D-G) be made available to the international operations/research community. Efforts should also be made, in coordination with WMO ICTSW, to define standard data exchange formats for RO sensor ionospheric products.

Recommendations within IROWG

1. **IROWG should continue to explore approaches for reducing ionospheric residual errors in neutral atmospheric retrievals.** Success in this challenging area of work would both improve the upper altitude limit and errors of useful neutral atmospheric products. This would potentially benefit climate studies, numerical weather prediction (NWP) and research into upper atmospheric gravity waves, planetary waves, and tides, which have been shown to have significant space weather effects via lower-to-upper atmospheric coupling. A discussion of ionospheric-atmospheric coordination was held in the plenary venue of this IROWG meeting, as a follow-on to the coordination meeting at IROWG-4. It was decided that the climate application is currently best suited to benefit from such coordination. Next steps forward should include (1) 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) (2) Further assessment of recently proposed approaches to reduce residual small-scale ionospheric errors (based on back propagation techniques, or other); (3) development and use of new ionospheric re-analyses in neutral retrievals to assess possible benefits; (4) determination of ionospheric model accuracy requirements that, if met, would likely lead to a reduction in ionospheric residuals; (5) evaluation of existing datasets to determine the degree to which current ionospheric residuals conform to known aspects of ionospheric climatology.
2. **IROWG should verify that the WMO OSCAR database properly documents the abilities of current and future missions to obtain ionospheric data per Recommendation #3 above.** Capabilities of both RO missions and missions flying dual frequency GNSS receivers should be documented. 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.

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 Recommendation #2) 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 do not fully address these needs. **Members of the Space Weather sub-group should engage with the FS7/C2 program to advocate for incorporation of space weather secondary payloads on the Polar portion of that mission**. 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, particularly ICTSW. Whenever possible, members of WMO ICTSW and the Space Weather sub-group of IROWG should attend these organizations' respective meetings.

Action IROWG5-01: Dr. Straus will discuss possible future collaborations between IROWG and WMO ICTSW with Dr. Onsager of NOAA/SWPC and report back to the sub-group. Due: IROWG-6.

4 CONCLUSIONS

The workshop presentations are available at:

https://wegcwww.uni-graz.at/opacirowg2016/

This CGMS working paper from IROWG-5 will be available at http://www.irowg.org.

In summary, there remains strong support for a fully funded COSMIC-2 mission, for NWP, climate and space weather applications. More generally, the aim of the community is to maximize the number of high-quality GNSS-RO observations, which can be freely exchanged. The impressive progress made by SPIRE should be noted. However, a detailed analysis of all the commercially available data is required, and therefore IROWG fully supports the NOAA Commercial Data Pilot Study. IROWG would like to support the ongoing OSSE activities related to the future provision of GNSS-RO measurements.

Suggested high-priority recommendations for CGMS are:

- **Ensure that both equatorial and polar components of COSMIC-2 are fully funded and launched; this is required for Numerical Weather Prediction, Climate, and Space Weather.**

- IROWG recommends targeting at least 20,000 occultations/day, to be made available to the operational and research communities of Numerical Weather Prediction, Climate, and Space Weather.

- International space agencies (in particular NASA, ESA and CNSA, 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 for the LEO-LEO observations.

- **IROWG recommends that CGMS should encourage GNSS providers and agencies to make ICDs of GLONASS and Beidou Open Service** signals available as soon as possible, in order to allow RO instrument providers to design and develop the future receivers without uncertainties due to missing information.

ACKNOWLEGEMENTS

IROWG notes and thanks for financial support to this fifth workshop the following organisations: EUMETSAT, CGMS, ESA, FFG-ALR and WMO.

ACTIONS

The actions from the IROWG-5 workshop, including their status, are collected below.

Action IROWG5-01: Dr. Straus will discuss possible future collaborations between IROWG and WMO ICTSW with Dr. Onsager of NOAA/SWPC and report back to the sub-group. Due: IROWG-6.

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.	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: Discussed with Niels Bormann (ITWG) Closed**
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	An ROTrends website has been created

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).	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).	Status: Open.
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 activities at the IRI conference in Olsztyn, Poland (June 2013). Due: IROWG-4.	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 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: Closed**
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: Closed**
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.**

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.	Preprint available on request from J. Aparicio. **Status: Closed**. New experiments ongoing at Georgia Tech. USA.