Summary of the Sixth International Radio Occultation Workshop

Held in Estes Park, USA

From Thursday, 21st September to Wednesday, 27th September 2017

Starting at 09:00 hours on 21st September

Ending at 13:30 hours on 27th September

EXECUTIVE SUMMARY

This report summarizes the IROWG-6 meeting held on September 21-27, 2017 in Estes Park, USA. 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 providing good spatial and local time coverage, to be made freely 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) are encouraged 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 stresses the importance of long-term archiving of the Level0 data – and all the relevant meta data – from both the agency-led and "commercial" missions. These long term costs should be included in mission budgets. Researchers need access to this data, and to information about the GNSS-RO receiver performance, for climate reprocessing activities. Access to just the retrieved products is not considered sufficient for many research applications.

1 INTRODUCTION

This IROWG report presents the minutes / full recommendations of the combined-Tenth COSMIC Data User' Workshop and the sixth workshop of the International Radio Occultation Working Group (IROWG-6). The meeting was organized by University Corporation for Atmospheric Research (UCAR) and held in Estes Park, USA, from September 21-27, 2017.

The workshop was attended by more than 130 scientists, including representatives from all the major RO processing centers, space agencies, the weather prediction centers assimilating RO data, the research community, and representatives of commercial data providers. Overall, this was a very good workshop, with a particularly strong representation from the US research community. Approximately 70 talks and 50 posters were presented. Recommendations were developed in dedicated sub-working groups, and then presented and agreed upon in a plenary discussion on the last day. Additionally, IROWG-6 was used by several researchers for dedicated specialist/splinter meetings, such as SCOPE-CM for example. These meetings are not covered here.

As it was only one year since IROWG-5 (September 2016), many of the key discussion points throughout the IROWG-6 workshop remained the same, and in fact three of the four main IROWG-6 recommendations to CGMS are essentially carried forward from IROWG-5. However, this meeting was seen as an important opportunity for the IROWG community to hear the progress and plans for the NOAA Commercial Weather Data Pilot (CWDP) Study. The NOAA CWDP team was active throughout the meeting, in both the oral sessions and working groups. Furthermore, NOAA requested the IROWG community provide feedback on a forthcoming Commercial Weather Data Pilot Study Request for Proposals (RFP) expected in 2018. There remains strong support for the CWDP within IROWG because it is essential for *assessing the actual capabilities* of the various GNSS-RO mission options. We hope that we can maintain a good dialogue between the IROWG and the NOAA CWDP team in the coming years.

The meeting showed that the commercial GNSS-RO missions continue to make good progress. SPIRE, in particular, have moved from showing individual cases at the meeting in 2016 to now showing measurement departure statistics in 2017, which is encouraging. Nevertheless, there remains strong support for a fully funded COSMIC-2 mission within IROWG. Overall, the aim of the community is to ensure the long-term continuity of the GNSS-RO measurements, and to maximize the number of high-quality GNSS-RO observations, providing good spatial and local time coverage, which can be freely exchanged.

Members of the GNSS-RO research community are concerned that they will not be consulted sufficiently when assessing the various agency led and commercial GNSS-RO proposals, and they emphasize that their requirements may differ from those of operational NWP users. Specifically, the researchers need access to the raw data, not just retrieved Level2 or Level3 products. The provision and funding of long-term archiving of both the raw GNSS-RO data and all the meta-data is essential for climate reprocessing activities, for example. The researchers also need access to information about the instrument performance. Overall, it is important that multiple centers have all the information required for them to process and re-process GNSS-RO from both agency led and commercial missions.

There is also some concern within IROWG about how the NWP impact of future GNSS-RO missions are beings assessed in simulations. This concern is because of apparently contradictory results between OSSEs and the Ensemble of Data Assimilations (EDA) approach in some COSMIC-2 simulations. Collaboration in this area is encouraged.

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-6 SETUP

IROWG-6 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-6 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-46; these were endorsed by all participants.

3 SUB-GROUP RECOMMENDATIONS / DISCUSSIONS

3.1 Numerical Weather Prediction (NWP) Sub-Group

Chair/Rapporteur: Josep M. Aparicio (EC)

Members: Hui Liu (UCAR/COSMIC), Ming-En Hsieh (TTFRI/NARLABS), Hiromi Owada (JMA), Jyh-Ching Juang (NCKU), Jennifer Haase (SIO/UCSD), Jae-Gwan Kim (KMA), Eun-Hee Kim (KMA) Stig Syndergaard (DMI), Hailing Zhang (UCAR/COSMIC), Dominique Raspaud (Météo-France), Benjamin Ruston (NRL-MRY), Ian Culverwell (UK Met Office), Christian Marquardt (EUMETSAT), Kent Lauritsen (DMI), Michael Gorbunov (IAP RAS & SPIRE), Sean Healy (ECMWF), Jan Weiss (UCAR), Bill Schreiner (UCAR), Richard Anthes (UCAR), Eric DeWeaver (NSF), Anthony LaRosa (NOAA), Doug Whiteley (NOAA).

Recommendations

1) IROWG **acknowledges and supports NOAA's effort** with the evaluation of commercially provided data. There will be a second round of the Commercial Weather Data Pilot (CWDP), and we understand that input from IROWG (technical, scientific, testing) will be welcome. The IROWG community will provide this input to NOAA, and also offers to later support NOAA in the monitoring of the data, and provide comments on data content.
2) IROWG expresses a need for a **long term continuity plan**, at the target of 20,000 occultations/day, globally well distributed, and covering **all local times**. IROWG sees the ensemble of COSMIC-2 A and B as the only project with demonstrated ability to implement the immediate part of this plan. The announcement that part B will not go ahead is seen by the IROWG as a **gap in this plan**, still with no alternative able to fill it in quantity, in quality, nor in free availability. Besides this immediate term, there will be also a need to maintain this continuity in the long term **after COSMIC 2**.
3) IROWG recommends the support of a GNSSRO **Backbone** (one or several reference data sources, using state of the art technology, openly and extensively documented, and freely available), regardless of the existence of supplementary sources of data (provided by either public or commercial groups). The IROWG recommends that the rest of the data (beyond the backbone) is also freely available.
4) **IROWG understands that there are differences** between approaches to evaluate simulated data assimilation studies. We recommend that the community participates in joint efforts to evaluate the relative **merit of the different approaches being used**, and their meaning, as well as in other inter-center activities (e.g., participation of researchers from outside a given center in a study, or to perform inter-center OSSE).

Other:

- We recommend that the IROWG community collects and develops a common set of options, abilities, expectations, and standards, to be a reference for future data provision, of either public or private initiative. A **collective document** will be much stronger and consolidated.
- IROWG considers GNSS data as **essential in the sense of WMO 40**. Intrinsic benefits from international sharing of these data accrue to all weather centers (exchange and comparison of final analyses and forecasts). In addition, global GNSS data support the provision of services for public safety and security (e.g. hurricane tracks). We recommend **investing some IROWG effort** into properly **documenting** this.
- IROWG recommends that **ground station support towards NRT** availability be given to PAZ mission.
- The community **acknowledges efforts** done by CMA to have provided FY data in GTS, and by ISRO to provide MT-ROSA, as well as efforts by KMA to provide KOMPSAT data into GTS (probably available in spring 2018).

3.2 Climate Sub-Group

Chair: Andrea Steiner (WEGC, Austria)

Rapporteur: Hans Gleisner (DMI, Denmark)

Members: Riccardo Biondi (CNR, Italy), Vicky Chu (NSPO, USA), Julia Danzer (WEGC, Austria), Ulrich Foelsche (WEGC, Austria), Hans Gleisner (DMI, Denmark), Shu-Peng Ho (UCAR, USA), Florian Ladstädter (WEGC, Austria), Hong Liang (UCSD, USA), Tie-Yue Liu (NSPO, Taiwan), Johannes Nielsen (DMI, Denmark), Liang Peng (UCAR, USA), Marc Schwärz (WEGC, Austria), Jeremiah Sjoberg (UCAR, USA), Andrea Steiner (WEGC, Austria), Bomin Sun (NOAA/NESDIS, USA), Jordis Tradowsky (Bodeker Scientific, New Zealand), Panagiotis Vergados (JPL, USA), Axel von Engeln (EUMETSAT, Germany), Hallgeir Wilhelmsen (WEGC, Austria). **Visitors**: Sean Healy (ECMWF, UK), Rob Kursinski (Space Sciences and Engineering, USA), Tony Mannucci (JPL, 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 and coverage of all local times. Operational GNSS RO missions for continuous global climate observation need to be established as a backbone to ensure continuity and high quality data**.

   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 with research/commercial missions, which is of main concern regarding the provision of continuous climate products.

   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., MSU/AMSU, 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.

2. **Require that satellite operators make all information available that is necessary for independent processing centers to process from raw level 0 data to climate data products. This should include long-term archiving.** The raw (level 0) data, metadata, and associated documentation should be available to the scientific community, and retrieval software should be open. This is of high importance since the raw data are necessary to achieve full traceability of the retrievals regardless of the source of the data. **Promote cross-collaboration and sharing of data and knowledge between the RO community and the satellite operators**.
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. 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.
4. **Promote funding of 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 of climate data records is important.

Recommendations to satellite operators and data providers

1. Documentation of 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 publically 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. We acknowledge JPL's ongoing efforts in this area. We believe that multi-center ensembles of independently processed RO datasets, rather than only multi-center averages, will be useful in quantifying the structural uncertainty. 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 data, amplitude data, and satellite orbit data in a well-documented netCDF file**. This would enable independent RO processing centers to cross-check their systems and to estimate the overall uncertainties in their retrievals (see also recommendation #4 to CGMS above).

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

6. Data providers should maintain parallel data streams of RO climate data 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 #2 to CGMS above).

Recommendations within IROWG

1. **The SCOPE-CM initiative, under WMO, should continue to contribute to the development of GNSS RO as a climate monitoring system by** a) assessing the structural uncertainty of RO retrieval data, including differences between processing centers and between different RO instruments and missions, and by b) supporting the generation of multi-center ensembles of RO climate data records (see also recommendation #3 to data providers above). Possible physical constraints to identify outliers should also 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). We acknowledge progress and ongoing efforts. We recommend**

continuous coordination among IROWG, bringing in metrology experts, and recommend status reporting from JPL.

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 these areas and recommend that these efforts should continue.**

4. **Assess the current status of RO water vapor products in terms of random and systematic uncertainties, guided by GEWEX and GCOS requirements.** RO data provide unique high vertical resolution information on tropospheric humidity that is much needed to improve our understanding of the coupling of thermodynamics and large-scale circulation in the lower troposphere, 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/AMSU 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.

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 from IROWG5, Recommendation IROWG-06: CLOSED:

Check if JPL has navigation bit data records dating back to 2005 (start of open-loop RO data). **Tony Mannucci reported that JPL only has records back to January 2006**.

3.3 Receiver Technology and Innovative RO Techniques

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

Rapporteur: J. Braun (UCAR, USA)

Members: Rob Kursinski (SS&E, USA), Estel Cardellach (ICE/CSIC-IEEC, Spain), Michel Tossaint (ESA, Netherlands), Anders Carlstrom (RUAG Space, Sweden), Jens Wickert (GFZ, Germany), Feiqin Xie (TAMUCC, USA), ChenYung Huang (NSPO, Taiwan), Kuo-Nung (Eric) Wang (JPL, USA), Jennifer Haase (UCSD, USA), Michael J Murphy (UCSD, USA), Teresa Van Hove (UCAR, USA), Tom Meehan (JPL, USA), Sun Yueqiang (NSSC, China), Liu Conglinang (NSSC,China), Josef Innerkofler (WEGC/UniGraz, Austria), Joe Fong (NSPO, Taiwan), Dave Kunkee (Aerospace, USA), Gottfried Kirchengast (WEGC/UniGraz, Austria), Sergey Sokolovskiy (UCAR, USA), Doug Hunt (UCAR, USA), Wei Xia-Serafino (NOAA,USA) , John Braun (UCAR, USA), Jonathan Fulford (NOAA, USA), Bill Schreiner (UCAR, USA).

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

1. International space agencies (in particular NASA, ESA and CAS, where LEO-LEO and GNSS-RO&-Reflectometry proposals are pending) to support **mission preparation and implementation projects towards LEO-LEO microwave occultation and GNSS-RO&-Reflectometry demonstration missions**. This should include recommending new OSSEs & EDAs for the LEO-LEO observations.

2. **Require that satellite operators, as part of their services as data providers, make all information available that is necessary for independent scientific processing centers to process from raw level 0 data to atmospheric and climate data products. This should include long-term archiving.** This means that the raw (level 0) data, metadata, and associated documentation should be available to the scientific community. This is of high importance since the raw data are necessary to achieve full traceability of the retrieved atmospheric profiles, regardless of the source of the data. **Promote cross-collaboration and sharing of data and knowledge between the RO R&D community and the satellite operators**.

3. Continuous collaboration and high quality data comparison are of great value for all parties. Accordingly, the IROWG recommends that requirements be incorporated into the Round 2 RFP of the NOAA CWDP to ensure full traceability to raw, Level 0 data, for any higher-level retrievals and that all documentation and/or software/constants/firmware, required to achieve this traceability, be made available to the international scientific community.

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, CAS 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 microwave and infrared-laser occultations, 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, as well as transferring the unique accuracy, precision and high resolution of the LEO-LEO observations into the NWP forecasts and reanalyses via assimilation. Initial mountaintop demonstrations have been made successfully at cm, mm and micrometer wavelengths.

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

IROWG recommends strengthening the scientific and technical activities related to the exploitation of the potential **to combine the application of the GNSS radio occultation technique with GNSS reflectometry (GNSS-R)** 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, and vegetation index). GNSS reflectometry measurements are potentially also appropriate for atmosphere/ionosphere sounding, in particular, those reflected signals in very slant geometries, such as collected unintentionally with standard RO receivers.

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 in a cost effective way.

A forerunner for these developments is the ESA **GEROS-ISS** mission, which was proposed in 2011 as a combined GNSS-RO and GNSS-R mission and completed Phase A in 2016. GEROS-ISS is intended to provide unique data especially for the sea surface height and wind speed determination, as well as for land surface monitoring and GNSS-RO with new aspects, as, e.g., precipitation measurements. It is anticipated that the GEROS-ISS data will enable fundamental investigations for the development of both the GNSS-R and GNSS-RO technique individually, as well as for their combined application. The same is expected for the G-TERN mission, which was proposed in response to ESA's recent Earth Explorer 9 call in mid-2017. G-TERN is based on the same observational concept of GEROS-ISS with extended scientific objectives, especially focussing on the cryosphere and related interactions with the hydrosphere and atmosphere.

IROWG focus on 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. These measurements are strongly synergetic with GNSS–RO measurements. **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 the FY3-E satellite, in 2018. It has been decided that the GNSS (GPS + BDS) reflectometry function will be added to the GNOS II receiver. A nadir LHCP antenna will be deployed with the goal of measuring 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.

The FORMOSAT-7 Reflectometry (FS-7R) satellite, targeted for launch in 2020, is a NSPO (National Space Organisation) technology demonstration platform for a GNSS-R instrument, developed by NSPO. It will serve as a demonstration mission for GNSS-R applications, as the determination of sea surface roughness/wind speed, soil moisture and sea ice. A feasibility study for a miniaturized satellite constellation with combined GNSS-RO/R payload is being carried out in addition by NSPO, based on its in-house technology. IROWG encourages interested colleagues to contact NSPO in support of GNSS-R's instrument design, data retrieval algorithms, and remote sensing applications.

IROWG recommends, that future international conferences/workshops specifically focus the synergies between GNSS-RO and GNSS-R and LEO-LEO occultation techniques. Good opportunities for this are upcoming meetings, as, e.g., the **ICGPSRO (International Conference on GPS Radio Occultation) to be held in Taipei in April 2018** and the IGL-1 workshop 2018 (Innovations in GNSS and LEO Occultations & Reflections Workshop - 1) in Beijing September 2018. The relevant organizations, as, e.g., NASA/ESA and others should be involved in the discussion of the related important developments and joint activities.

3) Lower troposphere/Boundary layer profiling

Information about the moist lower troposphere is crucial for tropical meteorology. A number of studies presented at the workshop have demonstrated improvement in forecasting tropical cyclones through the use of RO data. To obtain maximum information for data assimilation in the presence of strong moist convection in the tropics and strong capping inversion layers in the sub-tropics, it is recommended that RO receiver tracks signals in the fully open-loop mode (without feedback) down to the height of straight line of at least -300 km. It is recommended that the antenna should result in the 1-Hz SNR of about 2000 V/V for L1 CA (without de-focusing). To prevent the loss of the SNR, the receiver should maintain accurate open-loop aiding models in real time (the delay model errors should be much less than CA code chip length), or run multiple offset correlators and provide their outputs.

4) GNSS observations from airborne platforms

Rationale: GNSS observations from airborne platforms offer unique datasets with distinct advantages for weather forecasting and studies of regional weather and climate processes. The techniques include radio occultation, reflectometry/reflection, altimetry, and polarimetry, for sensing the atmosphere (moisture, temperature, hydrometeors), land surface (soil moisture and dielectric constant), and ocean surface (surface roughness, wind, sea ice) and ionosphere (total electron content).

Recommendation: We recommend facilitating radio occultation observations from airborne platforms, such as high altitude aircraft, balloons, and UAVs, that allow testing of new instrumentation, algorithms, and assimilation methods that can benefit operations and research. The higher spatial and temporal density of targeted observations over phenomena of interest (i.e., severe thunderstorms and tropical cyclones) can benefit NWP and provide validation for spaceborne missions (future RO missions / RohPAZ / CYGNSS). We recommend pursuing opportunities to exploit GNSS and communication signals of opportunity on these platforms where collaboration benefits the community by sharing technology and expertise, speeding development, and reducing logistical constraints.

5) 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. Studies based on synthetic data have shown the feasibility of a statistical inversion approach which provides the standard RO profiles together with profiles of rain probability. 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 relative to a single-polarization RO system. The Radio Occultation and Heavy Rain with PAZ (ROHP-PAZ) experiment will be orbiting by 2018, providing the first spaceborne GNSS polarimetric RO for demonstration of the concept. In particular, **we encourage the analysis of the polarimetric data sets to be provided by PAZ, and further investigations on potential uses of these new thermodynamic and hydrometeor products. IROWG also recommends that future RO missions should include the capability to track GNSS signals in two orthogonal polarizations.**

6) 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 would 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 challenging 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**

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**
d. the provision that the IGS community begin collecting high rate (5Hz) observation data to support monitoring of GNSS transmitter clock stability.

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.
6. IROWG recommends that the GNSS constellation operators provide Allan deviation and/or equivalent phase noise spectra information for transmitter satellites at rates that are significant for RO (100 to 0.01 Hz or equivalently 0.01 to 100 seconds).

General recommendations for instrument providers

1. IROWG recommends that missions, instrument developers, and RO data processing centres **provide level 0 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 to or even better than that of 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**. This includes terrestrial sources such as DME/TACAN and LightSquared. In particular, IROWG recommends initiating a request to agencies and/or ITU **to better protect against known ground based transmissions (i.e. DME/TACAN and LightSquared)** which strongly impact RO receivers and could also impact GNSS receivers on board aircraft.
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 extend 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 existing missions including TDX, TSX, and KOMPSAT-5 have firmware updates to include the following features:
   1) If not already in place, load the most up to date and capable firmware version on all instruments.
   2) Test L2C setting occultations on these 3 with the expectation that L2C occultations will be permanently enabled on TDX, TSC and KOMPSAT-5.
   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.

Progress regarding previous recommendations.

1. 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.

Updated GLONASS and BeiDou ICD documents have been publicly released. The Russian ICDs can be found at http://gpsworld.com/new-glonass-interface-control-documents-released/ December 14, 2016. New English versions of ICDs for BeiDou open service signals B1C and B2a were released in December 2017.

This recommendation can now be closed.

1. 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 **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. 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.

3.4 Space Weather Sub-Group

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

Rapporteur: W. Schreiner (UCAR)

Members: T. Kurino (WMO), T. Mannucci, (JPL), Tiger JY Liu (NCU), C. Lin (NCKU), K. Kabo-bah (UENR), J. Currie (RMIT), A. Hu (RMIT), I. Cherniak (UCAR), B. Cao (UCSD), J. Fulford (NOAA/NESDIS, Tech. Adven. LLC), N. Pedatella (UCAR/NCAR), K. Groves (BC), R. Caton (AFRL), Ann Werkley (AFRL), D. Fuller-Rowell (NOAA/SWPC), T. Fuller-Rowell (NOAA/SWPC), G. Crowley (Astra), T. Duly (Spire), V. Nguyen (Spire), T. Winning (TAMUCC), L. Gelinas (Aerospace), Q. Wu (NCAR), C. Watson (UCAR), B. Breitsch (CU)

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 2020-2021 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 space weather RO data from research and operational missions, including commercial missions, be available to the community in near real-time, in standard formats with needed metadata and documentation.** Efforts should also be made, in coordination with WMO IPT-SWeISS, to facilitate data access to raw data, products, metadata and documentation, and to define standard data exchange formats for RO sensor ionospheric products.
3. **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, including both its large-scale properties such as the F-layer and bottomside, and small-scale properties related to ionospheric scintillation effects.** FS7/C2 Equatorial will provide RO data coverage in this region that is an order of magnitude denser than any prior RO system, together with ionospheric electric field and *in-situ* density data from the secondary Ion Velocity Meter (IVM) instrument. Coincident data from of the Ionospheric Connection Explorer (ICON) and Global-scale Observations of Limb and Disk (GOLD) missions will also be available to benefit modeling efforts. Electric fields are the most critical driving force for low latitude ionospheric dynamics 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 operational space weather systems, if model development efforts are adequately funded.

4. 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 TEC across all elevation angles and 50+ Hz ionospheric scintillation data on all available occulting lines of sight where the TEC data are obtained and for which the level of ionospheric scintillation is significant).** 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 near the Earth's limb"). 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.

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.

Progress updates on these research topics should be revisited at the next IROWG meeting.

Recommendations within Sub-Group

1. The sub-group should coordinate with space weather activities throughout WMO, particularly IPT-SWeISS. Whenever possible, members of WMO IPT-SWeISS and the Space Weather sub-group of IROWG should attend these organizations' respective meetings. It was agreed that Bill Schreiner of UCAR will be the IROWG Space Weather subgroup representative to the IPT-SWeISS until the next IROWG meeting.
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 in sufficient detail to understand the ionospheric products. The information in the database for each mission should include the extent to which the mission collects ionospheric profile and overhead TEC data, the mission data latency, and the extent to which ionospheric scintillation data are collected. Bill Schreiner, representative to WMO IPT-SWeISS, should solicit input from the IPT-SWeISS on verification of the OSCAR database.
3. 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.
4. **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 #3) within existing ionospheric science venues such as AGU, AMS, 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.

Action Items from IROWG-5

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

Dr. Straus met with Dr. Onsager and discussed potential collaborations. Action IROWG5-01 **CLOSED**.

Action Items from IROWG-6

<u>Action IROWG6-01:</u>
IROWG SWSG should verify that the WMO OSCAR database properly documents the abilities of current and future missions to obtain ionospheric data per Recommendation Within Subgroup #2 above.
Due Oct 31, 2017.

Action IROWG6-02:
NOAA/SWPC should provide description of Commercial data pilot plans to IROWG SWSG.
Due Dec 31, 2017

Action IROWG6-03:
IROWG SWSG members should review and provide comments to NOAA on their draft RFP for round #2 of the Commercial Weather Data Pilot (CWDP).
See:
https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=6e53dc8fbffe3873c4c81c05e15ebcbc
Due Oct 31, 2017

Action IROWG6-04:
Tony Mannucci should provide IROWG SWSG a summary of GRACE Follow-On plans to collect ionospheric data.
Due Oct 31, 2017

Action IROWG6-05:
IROWG SWSG members should review COSMIC-2 ionosphere TEC and scintillation data formats and provide comments back to SWSG. See:
TEC:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=podTc2
On-board S4:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scn1c2
HR phase/amp:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scnPhs
Ground-computed S4/SigmaPhi:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scnLv2
Spectrograms of HR phase/amp:
http://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=scnSpc
Due Oct 31, 2017

Action IROWG6-06:
Bill Schreiner to determine if GTS-distributed space weather products must be BUFR.
Due Dec 31, 2017

Action IROWG6-07:
Bill Schreiner to determine accessibility of COSMIC-2 space weather products in near real-time. Near real-time COSMIC-2 space weather products will be available at the COSMIC-2 CDAAC website (http://cdaac-www.cosmic.ucar.edu/cdaac/products.html).
CLOSED

4 CONCLUSIONS

The workshop presentations are available at:

https://cpaess.ucar.edu/cosmic-10th-data-users-workshop-irowg-6-about

This CGMS working paper from IROWG-6 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 with good spatial and local time coverage, which can be freely exchanged. SPIRE continues to make progress. However, a detailed analysis of all the commercially available data is still required, and therefore IROWG fully supports the ongoing NOAA Commercial Weather Data Pilot Study. The research community are emphasizing the need for the provision and funding of long-term archiving of the raw GNSS-RO data and all relevant meta-data, and that access to just Level2 or Level3 products is not sufficient for their needs.

The 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 providing good spatial and local time coverage, to be made freely 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) are encouraged 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 stresses the importance of long-term archiving of the Level0 data – and all the relevant meta data – from both the agency-led and "commercial" missions. These long-term costs should be included in mission budgets. Researchers need access to these data, and to information about the GNSS-RO receiver performance, for climate reprocessing activities. Access to just the retrieved products is not considered sufficient for many research applications.

ACKNOWLEGEMENTS

IROWG notes and thanks for financial support to this sixth workshop the following organisations: NSF, NASA, EUMETSAT, ESA, SPIRE, IHI, Planet-IQ, GeoOptics and WMO.

ACTIONS

The actions from the IROWG-6 workshop are given in the working group reports.

The open actions from previous the workshops are collected below.

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 IROWG3-06: 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.**