Summary of the 2nd International Radio Occultation Workshop

Held in Estes Park, Colorado, US

From Wednesday, 28th of March to Tuesday, 3rd of April 2012

Starting at 08:30 hours on 28th of March

Ending at 12:30 hours on 3rd of April

1 INTRODUCTION

This IROWG paper presents the minutes / full recommendations of the 2nd International Radio Occultation (RO) Working Group Workshop (IROWG-2). The workshop was organized by the University Corporation for Atmospheric Research (UCAR), the UCAR Joint Office for Science Support (JOSS), NOAA, and EUMETSAT. The meeting was held in Estes Park, Colorado, US, from 28th of March to 3rd of April 2012.

Background: The CGMS meeting 37 in October 2009 endorsed the establishment of the IROWG. Dave Ector (NOAA) and Axel von Engeln (EUMETSAT) were selected as co-chairs and Mitch Goldberg (NOAA) as rapporteur to CGMS. In order to have a first IROWG workshop in 2010, the co-chairs and the rapporteur decided to join with the already scheduled workshops of OPAC-4 and the GRAS-SAF Climate in September 2010. IROWG-1 was thus “only” providing a platform for discussions and recommendations, while the talks that were given were organized by OPAC-4 and the GRAS SAF.

Here we report on the 2nd workshop IROWG-2, which included a full conference agenda with many talks in addition to the platform for discussions and recommendations. It was attended by more than 70 scientists, including all the major centres providing and all major centres assimilating RO data. There were more than 60 talks given and about 20 posters presented. Recommendations were worked out in dedicated sub-working groups and presented in a panel discussion. Additionally, IROWG-2 was also used by several researchers for dedicated splinter meetings, which are not covered here.

The structure of this paper 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, Section 4 contains the proceedings of the sub-groups, and Section 5 concludes.

This IROWG document provides the full minutes / recommendations / discussions of the sub-working groups within IROWG. Note also that in total three CGMS working papers are provided to the CGMS meeting 40. These three CGMS working papers (a) summarize the workshop and give the main recommendations of the IROWG-2 meeting (thus a subset of this document); (b) discuss *Climate related Processing and Potential of Radio Occultation Data*, and (c) present the *Status of the global Radio Occultation Observing System* **[1,2,3]**.

2 IROWG-2 SETUP

IROWG-2 was a full workshop, including presentations, posters and sub-group discussions. Both, the presentations/posters and the sub-group discussions were focussed on specific topics, namely:

- Numerical Weather Prediction;
- Climate;
- Research to Operations;
- Payload Technology;
- Innovative Occultation Techniques;
- Space Weather.

IROWG-2 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.

One outcome of the IRWOG-2 was three CGMS-40 working papers:

1. Report from the 2nd International Radio Occultation Workshop **[1]**
2. Climate related Processing and Potential of Radio Occultation Data **[2]**
3. Status of the global Radio Occultation observing system **[3]**

which are available on our website www.irowg.org. The first document highlights the main recommendations of IROWG-2, where participants agreed to include three main recommendations for CGMS, which were endorsed by all participants, and additionally present one main recommendation per sub-group that is relevant at CGMS level. The second document presents contributions of IROWG to ECV (Essential Climate Variables) production and reprocessing activities, and other relevant climate work. The third document presents the current and future Radio Occultation (RO) observing system, focussing on the period up to the year 2027. Documents 2 and 3 were triggered by CGMS-39 actions.

The here presented document is an extension of the document **[1]** above, where all recommendations, discussions, and actions from IROWG-2 are presented. For completeness, it first lists the three main recommendations, as presented in working paper **[1]**.

3 IROWG-2 MAIN RECOMMENDATIONS

as presented in CGMS working paper [1]

IROWG-2 participants noted that the main IROWG-1 recommendations have made progress in the mean time; however, further work is required to fully address them. The urgency of the tasks requires re-stating several of them here in an updated form.

The following three main recommendations have been agreed upon by all participants at IROWG-2:

3.1 Operational Continuity Plan for RO – including Troposphere and Ionosphere

We recommend that CGMS devise a detailed **GNSS-RO Continuity Plan** with the operational agencies, outlining how we move towards a fully operational GNSS RO constellation providing **at least 10000 observations per day**.

GNSS RO has been demonstrated to be a critical element in the global data observing system for Numerical Weather Prediction (NWP), providing high positive impact to forecast skill in all the major national weather forecasting centres. GNSS RO also provides a very important data record for the global climate observing system, providing essential climate variables of benchmark quality. In addition, this data is critical for space weather observation and input to space weather prediction systems that are currently being developed.

The **continuity of GNSS RO observations in the future is not guaranteed by operational programs**. As of 2012, GRAS remains the only operational program for GNSS RO and this accounts for only about 25% of the occultations assimilated by operational NWP centres. Research programs may be able to supplement operational RO programs temporarily; as well as, exploring the potential of RO at higher spatial sampling, but they carry much higher risk.

Thus **research programs are not the answer for a fully operational GNSS RO constellation**. The amount of investment in GNSS RO and other satellite programs overall should be correlated to the positive impacts they have on NWP, climate, and chemistry, and GNSS RO impacts in NWP are comparable to that of the other major operational instruments. Proper GNSS RO continuity requires a constellation of properly spaced LEO satellites, providing a minimum of 10000 soundings per day. **It is of highest importance for NWP, climate, and space weather to assure the continuity of RO measurements**, especially following the COSMIC-1/FORMOSAT-3 constellation mission.

3.2 GNSS RO Data Gap Filling is Required

A concern shared by all attendees at the IROWG-2 is the impending GNSS RO data gap as coverage from COSMIC-1/FORMOSAT-3 is rapidly declining as it nears its end of life. The present plan for the next GNSS RO constellation is the first 6 satellites from the COSMIC-2/ FORMOSAT-7 mission that will nominally be operational in 2016. COSMIC-2/FORMOSAT-7 is a low inclination (24 degree) mission that will provide an unprecedented density of low latitude coverage critically needed for tropical storms and space weather monitoring and prediction. It will, however, not provide mid- and high-latitude coverage required for NWP, climate, and space weather at those latitudes. Thus, under the present plans, we are looking at a gap from about 2012 to 2016 in terms of low latitude coverage by a constellation and a substantially longer term gap of unknown duration at mid- and high-latitudes.

In light of the upcoming drop in the number of available radio occultations due to COSMIC-1/ FORMOSAT-3 nearing its end-of-life, **it is becoming critical to fill the impending data gap** with GNSS RO from any and all available mission data sources particularly in the 2012 – 2016 timeframe.

While data from RO science missions will require extra effort to be incorporated into operations due to non-standard payloads and configurations, and data volume per satellite is expected to be 1/3rd to 1/5th the data volume expected from an operational mission, **it has been shown that this data can have significant positive impact in weather forecasting**. Science missions that are expected to have the capability to provide data to partially fill this gap include e.g., Oceansat-2, Megha-Tropiques, SAC-D-Aquarius, TanDEM-X, Kompsat-5, and PAZ. **Effort and funding should be set aside for these missions to make the data available for weather forecasting in near real-time.**

It is however also important to note that data from the 3 ROSA GPS RO instruments currently flying on Oceansat-2, Megha-Tropiques, SAC-D-Aquarius have not been made available to the community and early quality assessments demonstrated problems in tracking the GPS L2 frequency at least on Oceansat-2.

We also note that several data buy (commercial) missions are currently being discussed, and if any of these launches in the 2014-2016 time frame, these might be able to help fill the data gap. They would however still require government funding to purchase such data when it becomes available.

3.3 Potential of GNSS RO use for anchoring Climate Re-analysis

The climate community has been slow to adopt GNSS RO, even with its proven accuracies and extremely low measurement uncertainty. GNSS RO has the two properties necessary to make it a benchmark of the climate, specifically the atmosphere: (a) traceability to the international definition of the second (SI), and (b) adequate coverage in space and time.

These same properties suggest that it should also be of great advantage to anchoring climate re-analyses, which typically suffer from drift because of shortcomings in the removal of biases from observational data, inadequate physical processes in the core model, and temporal inhomogeneity of the assimilated data. RO data need not be bias-corrected - like strongly calibrated radiosondes - and thus should serve as an important anchor to reanalysis to prevent drift.

In order to take full advantage of RO data in reanalysis, though, it is necessary to model the RO observable (bending angle, Doppler delay) given state variables of the atmosphere (temperature, pressure, specific humidity) with an accuracy of 1 part in 10,000. Arguments based on theory and dated laboratory measurements of refractivity coefficients have been used to argue for a model with such accuracy, but it is incumbent that **modern laboratory studies on refractivity coefficients be undertaken to verify such a claim**.

This objective is urgent because the climate research community overwhelmingly defaults to use climate reanalyses for climate monitoring and trend research. Several numerical weather prediction centres are undertaking or have recently published second generation reanalyses with variational bias correction, but they do not agree in their trends over the past three decades. Incorporation of GNSS RO as an anchor is a necessary part of the solution to this problem.

4 ACTIONS FROM IROWG-1 MEETING

Action IROW1-1: D. Ector to try to locate any missing GPS/MET data.	**Closed**: no further data is available.
Action IROW1-2: S. Leroy to provide CLARREO science requirements.	**Closed**: Information is e.g. provided at http://clarreo.larc.nasa.gov/
Action IROW1-3: D. Ector to explore options for either NSPO or CWB to become more closely involved with CGMS activities.	**Closed**: Will be re-discussed at upcoming CGMS Working Group Meeting at EUMETSAT 2012 conference.
Action IROW1-4: J. Wickert to draft a letter of support for NRT operations of TerraSAR-X and Tandem-X from operational agencies.	**Closed**: Letter sent 22 Nov. 2010, TerraSAR-X data now available in NRT.

5 SUB-GROUP RECOMMENDATIONS / DISCUSSIONS

This section presents the recommendations, actions, and discussions from the different sub-groups. Note that sub-groups were asked for a few main recommendations, but were otherwise free to discuss and present all other relevant issues. Hence discussion form and presentation is not uniform throughout the different presentations. Actions were only allowed within the sub-groups or within IROWG with consent by the Actionee.

5.1 Numerical Weather Prediction (NWP) Sub-Group

Chair: S. Healy (ECMWF, UK)

Rapporteur: B. Ruston (NRL Monterey, US)

Participants: J. Haase, K. Boniface, N. Saint-Ramond, M. Schwaerz, F. Harnisch, C. Burrows, H. Owada, S.-Y. Chen, J.K. Nielsen, S. Macpherson, H. Anlauf, J. Aparicio.

Background

We note that many of our recommendations have been carried forward again and some progress is noted. However, **the failure of operational agencies to support GNSS constellations such as COSMIC-II is received as a disappointment**. Investment in GNSS and satellite programs overall should be correlated to the positive impacts they have on NWP, climate, and atmospheric chemistry, in order to optimize the impact of the global observing system. **We welcome the latest news that following a user consultation process, the EPS Second Generation is likely to contain two operational GNSS receivers**. We also express our support and thanks to Taiwan for their dedication and effort in the COSMIC missions, and to the United States Air Force for their support of the first six satellites in the COSMIC-II constellation.

Recommendation to CGMS

GNSS RO has been demonstrated to be a very important element in the global data observing system for NWP, despite the relatively low number of observations. The continuity of GNSS RO observations in the future is not guaranteed by operational programs, and this remains a major concern. As of April 2012, GRAS remains the only operational program for GNSS RO and it accounts for only 25 % of the occultations assimilated by operational NWP centres. Research programs may be able to supplement operational RO programs temporarily, but they can carry a higher risk and are not the answer to a fully operational GNSS constellation. We also note that the number of GNSS RO missions of opportunity is likely to fall in the coming years due to the current and past success. Consequently, GNSS RO is no longer likely to be considered a new or novel topic of research.

We recommend for the CGMS to encourage its member agencies to promote and support efforts for **operational** GNSS continuity programs in the future.

We note that the GOS 2025 vision from the WMO recommends at least 8 satellites, and the draft implementation plan (EGOS-IP, section 6.3.3.2) includes the action on "CGMS with WMO commissions, satellite agencies and data processing centres" to

> *"Ensure and maintain a radio-occultation constellation of at least 8 GNSS receivers onboard 8 platforms on different orbits, and organize the real-time delivery to processing centres."*

We welcome this action, and hope that it will be used in support of proposed GNSS RO constellations, but we note that the 8 platform requirement is ambiguous. This requirement does not state whether these are operational or research satellites, how many occultations each satellite provides per day, or how the measurements are distributed geographically. We recommend that GCMS revisit the GOS 2025 vision/implementation plan and can carry forward our recommendation – based on the latest research – if they agree.

The current 1 operational and 9 research satellites provide around 2000 occultations per day. There is no evidence of saturation with the current system, and it will not meet future demand. About 70% of the current data volume is obtained from research satellites that have already exceeded their design life and are showing significant signs of aging and downtime. Also, higher resolution NWP systems in the near future will require accrued volumes of data to deliver their full potential.

A simulation study is underway, which aims to quantify the number of occultations where the NWP forecast benefit of GNSS RO measurements will saturate. The latest results presented at the IROWG workshop suggest that the impact of an observing system of 10000 occultations per day is not saturated. Therefore, our recommendation is that 10000 operational profiles per day should be the **minimum** aim for the future **operational** GNSS constellation.

We recommend that CGMS devise a detailed "GNSS-RO Continuity Plan" with the operational agencies, outlining how we move towards a fully operational GNSS constellation providing at least 10000 observations per day.

Goal: A fully operational GNSS constellation which provides at least 10000 observations per day.

We restate the recommendation that CGMS coordinate efforts between operational data providers, NWP agencies, and research agencies to provide support for Near-Real-Time (NRT) infrastructure and fundamental research to extend the availability and use for these research GNSS satellite data. This support of fundamental research and NRT support is essential because these data provided by research GNSS receivers are being extensively relied upon operationally. An example is what is currently being done with COSMIC, and is being planned for COSMIC-II.

Recommendations within IROWG

Recommendation: A greater coordination between the ITWG and IROWG including joint studies such as OSSE or observation impact analysis. Further, a joint examination on methods used to maximize the contributions from radiances and GNSS and their interaction throughout the atmospheric column.

Recommendation: Figures showing the timeline of GNSS missions distributed by the IROWG shall clearly distinguish the difference between operational and research missions.

Recommendation: Investigate the issue of the uncertainty in the refractivity coefficients that impact NWP biases and have a potential impact on climate monitoring. There was interest in forming a sub-group within IROWG to study these uncertainties, with the aim of producing a recommendation about whether new laboratory measurements are required or not. Josep Aparicio volunteered to lead this sub-group.

Recommendation: We carry over the recommendation that error quantities are included in the BUFR files. The processing centres provide detailed documentation on data errors, correlations, and the processing chain. The documents should be linked to the IROWG web pages.

Recommendation to EUMETSAT: Prioritize improved processing of tropospheric GRAS measurements and make sample data available to NWP centres as soon as possible for parallel testing and feedback on data quality.

Tropospheric information from GRAS: The group acknowledges the great efforts by EUMETSAT scientists in getting the GRAS operational processing software (which was produced by industry) debugged and producing high quality stratospheric information. However, GRAS is still not producing tropospheric data that can be used in NWP applications, and this is particularly disappointing given the decline in COSMIC measurements which can be used in the troposphere.

Recommendation to ECMWF: Demonstrate the value of historical datasets used in climatological studies, and review the impact of these datasets in the ECMWF reanalysis system.

The ERA-interim reanalysis illustrated a discontinuity in the fields passing from a CHAMP data only system to the arrival of the full COSMIC. The GPS/MET "prime-time" data have been used in climate trend studies. The quality of these historical data sets could be investigated further using a reanalysis system.

Actions within IROWG

Action IROWG2-01: On IROWG co-chairs to contact the ITWG and survey the common interests between the groups.

Collaboration between IROWG and ITWG: The IROWG and ITWG NWP and climate sub-groups are likely to share many common interests and goals. A joint meeting between the respective co-chairs of these groups could be useful, and in the longer term it may be of interest to have IROWG and ITWG workshops that overlap.

Recommendation to IROWG co-chairs: Contact ITWG co-chairs to survey common interests, and canvas opinion on a meeting between the respective IROWG and ITWG NWP and climate sub-group co-chairs to discuss possible areas of collaboration.

Actions within IROWG NWP Sub-Group

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 and COSMIC-II; as there is a distinct possibility of no COSMIC data by 2014.

Action IROWG2-03: Chris Burrows and Ben Ruston will distribute a survey between operational centres showing use of GPS data, thinning methods, bending angle and/or refractivity use, observation error, and observation sensitivity plots.

Action IROWG2-04: NRL, ECMWF, JMA and EC; and if possible DWD, NCEP, Météo-France and UK Met Office will conduct a data denial experiment which uses only GRAS for a time period for a minimum of a month. Josep Aparicio, Sean Healy and Ben Ruston will coordinate the time of the case study (likely 2010) and coordinate the experiment with the other centres. We will include the observation sensitivities from each of the centres.

5.2 Climate Sub-Group

Chair: Stephen Leroy (Harvard University, US)

Rapporteur: Ian Culverwell (Met Office, UK)

Members: Andrea Steiner (Wegener Centre), Barbara Scherllin-Pirscher (Wegener Centre), Shu-peng "Ben" Ho (NCAR), Chi Ao (JPL), Feiqin Xie (JPL), Hans Gleisner (DMI), Joe Nielsen (DMI), Panagiotis "Peter" Vergados (JPL), Baijun Tian (JPL), Torsten Schmidt (GFZ), Rob Kursinski (Broad Reach Engineering), Gottfried Kirchengast (Wegener Centre), Tony Mannucci (JPL), Eric DeWeaver (NSF), Ying Li (RMT).

Recommendation to CGMS

1. 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. 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. **It is of highest importance to assure the continuity of RO measurements**, especially after COSMIC-1/FORMOSAT-3.

2. **Operational GNSS RO missions for continuous global climate observation within GCOS** need to be established.

3. **Future missions should consider covering 360° in ascending node**. The sampling need not be regular in ascending node, but it should definitely extend well beyond 180°. If all 360° is not covered, sinusoidal sampling biases poleward of 50° latitude with the period of constellation precession is present due to selected local time sampling. (Main recommendation #1 of the climate working group, 1st IROWG, 2010.)

4. **RO measurements from ROSA receivers** on current missions (e.g., OCEANSAT-2, MEGHA-Tropique) **need to be made available to the scientific community soon** in order to investigate the climate utility of ROSA data. These data could help to fill the gap after COSMIC-1 (see recommendation #1).

5. **Encourage software flexibility (especially upload) in future RO missions**, e.g., Metop-B GRAS. The RO measurement technique is unique in that it requires evaluation and update of the software operating on the orbiting RO GNSS receiver during the mission checkout period. We encourage future projects to assure this capability during mission checkout.

6. Recent studies found a signature in L1/L2/L5 signals from Block IIF satellites, which could affect the quality of the RO benchmark climate record. **This L1/L2/L5 drift in recent Block IIF satellites as well as possible L1/L2 drift on previous Block I, Block II satellites needs to be investigated**. There is a possibility that clock drifts such as these cause an otherwise undiagnosed systematic error in RO soundings.

Recommendations to Satellite Operators and Data Providers

1. Documentation on retrieval processing chains by all processing centers is essential to assure traceability in climate data (e.g., 1DVar retrieval documentation, which serves to resolve the wet-dry ambiguity in RO data). 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**.
2. All level 1 data providers should make available calibrated excess phase, amplitude, 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.
3. Data providers should maintain parallel data streams of RO climate products, one operational and one uniformly reprocessed version. Uniform reprocessing, as in climate and atmospheric reanalysis, guarantees the removal of discontinuities in a timeseries of RO data due to changes in a retrieval system.
4. **Generate a working paper for CGMS-40 (November 2012) on status of ROTrends and reprocessing activities**. This activity was requested by CGMS.

Recommendations within IROWG

1. **The ROTrends working group should continue to contribute to the affirmation of GNSS RO as a climate monitoring system** by demonstrating the insensitivity of trends (1) to retrieval system and (2) to receiver provider. ROTrends has been very successful to date and the RO climate community endorses its continuation.
2. There is an uncertainty in the refractivity coefficients that might impact RO's ability to anchor atmospheric reanalysis systems. Recent work by Dr. Josep Aparicio presents a new formulation for the forward model for refractivity based on theory and indirect laboratory data. The RO climate community wishes to see this expression for refractivity and other candidate expressions tested in the laboratory. First, though, the RO community needs to decide what the accuracy requirements for the forward model for refractivity should be. **Requirements for the accuracy of the refractivity coefficients should be established**.
3. **Encourage research into the benefits of higher SNR**, which is likely to extend the benchmarking capability of GNSS RO higher into the stratosphere.
4. Systematically investigate the feasibility of a "climate-quality" water vapour product.
5. **We recommend that ECMWF engage in a reanalysis activity based only on data types that are not bias-corrected, especially RO**. Results should be compiled into MMC format and incorporated into ROTrends. (Recommendation #8 of the climate working group, 1st IROWG, 2010.)

5. Continue participation in the wider scientific community (e.g., CMIP and GEWEX).
6. Investigate the 2.0E-8 rad bending angle offset. Work presented by Dr. Bill Schreiner (UCAR) indicates this offset in bending angle between COSMIC-1/FORMOSAT-3 data and coincident data from other RO missions.

Action IROWG2-05: On IROWG co-chairs and B. Ho, A. Steiner: Provide the following ROTrends information on the IROWG homepage: (a) Links to processing descriptions of all data providers; (b) Published ROTrends intercomparison papers; (c) ROTrends PPC and MMC datasets (including sampling errors of the latter).

5.3 Research to Operations / Payload Technology Sub-Group

Chair: Kent Lauritsen (DMI, Denmark)

Rapporteur: Bill Schreiner (UCAR, US)

Participants: Lidia Cucurull (NOAA), Chen-Joe Fong (NSPO), Doug Hunt (UCAR), Byron Iijima (JPL), Tim Maclay (WeatherDyn), Christian Marquardt (EUMETSAT), Yoke Yoon (EUMETSAT), Florian Zus (GFZ)

Background

Since IROWG-1 there has been some progress related to making RO data from research missions available for NWP centres in NRT. There has also been some progress in making documentation and low level readers available. All this progress is detailed further below. There is however room for additional progress and accordingly several of the recommendations from IROWG-1 have been kept in similar form and updated (see below).

The main considerations for transitioning research missions into operations that have led to the recommendations below are as follows:

- Put RO on all available satellite systems;
- Operational agencies should support research missions for NRT applications;
- Improve and expand GNSS ground networks;
- Provide level0 data, data formats, software to read data, and receiver configuration information;
- Continue improvements to receiver tracking firmware;

Recommendation to CGMS

1. RO measurements are a valuable information source for NWP and climate. Within NWP, the number of RO instruments have not reached saturation level. Hence IROWG recommends that operational and research organizations consider adding Global Navigation Satellite System (GNSS) RO payloads on all suitable non-commercial and commercial satellite systems. For example, the operational centers should consider adding a GNSS RO payload to the Jason-CS and Sentinel missions.
2. In light of the upcoming drop in the number of available radio occultations due to COSMIC nearing its end-of-life, IROWG recommends that operational agencies

consider supporting research missions to provide their GNSS RO data and format information to research and operational communities in Near Real Time as early as possible after launch, e.g. by providing support or funding as needed for (1) downlink and dissemination capabilities; (2) processing capabilities; (3) consultation on best practices in processing and design.

3. Processing of RO data requires access to GNSS ground station networks to derive orbit, clock and navigation data modulation (NDM) bit data. IROWG recommends maintaining and improving these networks and making the data publicly available as required for the Near Real Time and research operation of RO missions. Special consideration should be given to ground network data from GLONASS and Galileo. It is also recommended that agencies should provide past GPS NDM data sets for merging into a combined archive.

Recommendations to Satellite Operators and Data Providers

1. IROWG acknowledges the release of a test ICD for BeiDou/Compass. IROWG recommends to China to make BeiDou/Compass ICDs with full required information 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 BeiDou/Compass signals 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) and GNSS system operators by, e.g., participation in its organizing bodies / governing board.

4. IROWG recommends that missions, instrument developers, and processing centers provide level0 data format documentation, and/or necessary software to read data, and payload firmware configuration information.

Mission Specific Recommendations

1. IGOR/FORMOSAT-3, COSMIC: IROWG acknowledges efforts by UCAR and JPL to provide low level data format documentation and readers to the RO community to ease cross-centre processing comparisons. IROWG recommends that additional data format modifications and payload firmware configuration information be made available to the community.

2. GRAS/Metop: IROWG acknowledges efforts by EUMETSAT to improve GRAS tracking performance. IROWG recommends that EUMETSAT continue to address issues caused by the tracking behaviour of the GRAS instrument and apply necessary software and configuration fixes to improve raw sampling data quality.

3. ROSA/Oceansat-2 and ROSA/SAC-D, Aquarius: IROWG acknowledges planning and validation efforts by EUMETSAT and ROM SAF to make ROSA/Oceansat-2 data available in NRT for operational forecasting. IROWG recommends to ASI to provide level0 data, format information and decoding software as early as possible to the RO

community. IROWG also recommends that ASI attempt to improve L2 receiver tracking to minimize ionospheric extrapolation in the troposphere.

4. ROSA/Megha-Tropiques: IROWG acknowledges planning efforts by EUMETSAT, CNES, and ISRO to make ROSA data available in NRT for operational forecasting. IROWG recommends to the Megha-Tropiques consortium to provide RO data in NRT. IROWG also recommends to ISRO to provide level0 data, format information and decoding software as early as possible to the RO community.

5. IGOR/TerraSAR-X, TanDEM-X: IROWG acknowledges efforts by GFZ to make TerraSAR-X data available in NRT for operational forecasting. IROWG recommends to GFZ to explore options to (1) enable forward occultations to increase the number of occultations; (2) provide TanDEM-X RO data in NRT (3) provide the full set of all available RO data to the RO community; (4) provide data format information and readers.

6. BlackJack/SAC-C: IROWG acknowledges efforts by JPL, NOAA, UCAR, and GFZ to make SAC-C data available in NRT for operational forecasting. IROWG recommends to CONAE, NOAA, UCAR, and JPL to work together to re-initiate provision of SAC-C RO data in NRT as soon as possible.

7. CORISS/ C/NOFS: IROWG acknowledges efforts by USAF and UCAR to make C/NOFS data available in NRT for operational forecasting. IROWG recommends to USAF, NOAA, UCAR, and JPL to (1) extend data in RO BUFR profiles below 8 km altitude, (2) provide increase in number night-time RO profiles, (3) investigate possibilities to upgrade receiver firmware to track in open-loop mode.

8. IGOR+/KOMPSAT-5: IROWG acknowledges planning by KARI, KASI, NOAA, and UCAR to make KOMPSAT-5 data available in NRT for operational forecasting. IROWG recommends to NOAA, UCAR and JPL to work with KASI and KARI to provide highest quality RO data in NRT. IROWG also suggests that NOAA provides ground station resources and suggests that KOMPSAT-5 allow upgrades to receiver firmware.

9. IGOR+/PAZ: IROWG acknowledges planning efforts by NOAA, IEEC, and UCAR to make PAZ data available in NRT for operational forecasting. IROWG recommends to NOAA to work together with IEEC to implement RO data in NRT. IROWG also suggests that NOAA provides ground station and data processing resources. IROWG recommends to IEEC to provide level0 data, format information and decoding software as early as possible to the RO community.

Action IROWG2-06: F. Zus to check availability of level 0 data of TerraSAR-X in Near-Real-Time.

5.4 Payload Technology

Chair: Garth Franklin (NASA/JPL, US)

Rapporteur: Garth Franklin (NASA/JPL, US)

Participants: Larry Young (NASA/JPL), Tom Meehan (NASA/JPL), Magnus Bonnedal (RUAG), Sergey Sokolovskiy (UCAR), Josep Rosello (ESA), Staffan Backen (Colorado University)

Recommendation to CGMS

- Recommend 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.

- Recommend 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.

- Recommend 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.

- Recommend that the GNSS RO payload manufacturers publish / make available how the observations are formed.

- Recommend that the GNSS RO manufacturers and RO data users work together to identify sources of RFI that affect RO observations.

- Recommend that the GNSS constellation manufacturers provide availability plans (schedule, number or satellites) for the different GNSS signals.

  Note: The objective is that the GNSS receiver manufacturers and RO missions can plan when to use codeless processing, L1/L2 frequencies, L1/L5 frequencies, accordingly.

- Recommend 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.

5.5 Innovative Occultation Technique

Chair: R. Kursinski (U. Arizona, US)

Rapporteur: K. Zhang (RMIT, Australia)

Participants: Chi Ao (JPS/NASA), Josep M. Aparicio (Environmental Canada),

Estel Cardellach (IEEC), Jennifer Hasse (Purdue), Cheng-Yung Huang (National Central University, Taiwan), Kjartan Kinch (DMI), Gottfried Kirchengast (Wegener Centre), Paytsar Muradyan (Purdue), Sergey Sokolovskiy (UCAR), Stig Syndergaard (DMI), Feiqin Xie (JPL/NASA)

Recommendation to CGMS

Preamble: GNSS Radio Occultation (GNSS RO), which provides accurate vertical profiles of the atmosphere, has proven to be extremely useful and has shown considerable impact on operational weather forecasting, climate monitoring and scientific research. However, GNSS RO has certain limitations. Related next-generation technologies promise to complement GNSS RO with additional data of considerable operational and research value.

IROWG recommends that the development of these next-generation technologies is supported in order to bring them towards operational availability, in view of their promising potential.

Specifically the following priorities have been identified:

1) Moving LEO-LEO occultation development forward towards a space demonstration mission

Rationale: While GNSS RO proves to be increasingly successful and is strongly endorsed, e.g. in the US NRC Decadal Survey and within the EUMETSAT Polar System, it only measures refractivity which leaves a temperature-water vapour ambiguity in the troposphere and limits water vapour information to below the 240 K level in the troposphere (approximately 9 km in the tropics). LEO-LEO occultations measuring both refraction and absorption of coherent microwave and infrared signals would provide a much more complete set of atmospheric variables that includes thermodynamics (temperature, pressure, water vapour), dynamics (line-of-sight winds), climate/chemistry (ozone, carbon dioxide, methane, and other greenhouse gases and trace species) as well as cloud, aerosol and turbulence information. These “next-generation RO” data will have negligible ionospheric residual errors and provide the key upper air WMO/GCOS Essential Climate Variables (ECVs), independent of models, as a dataset of climate benchmark quality.

A LEO-LEO observing system complementing GNSS RO would thus provide an authoritative reference standard in the global free atmosphere (above the boundary layer) for these essential variables to which all other observing systems and weather and composition assimilation and forecasting systems could “anchor”. The climate community as well as the NWP and atmospheric chemistry communities can benefit strongly from this information, including the long-term operational use of such a reference observing system in the 21st century.

U.S. and European agencies (NSF, ESA, NASA) have undertaken technological and scientific preparatory activities for more than a decade, which should be continued with high priority towards a demonstration mission to begin such a benchmark climate record as soon as possible.

Recommendation: CGMS member space agencies are asked to **support research towards implementation of LEO-LEO occultation demonstration** to pave the way towards developing an authoritative metrologically-controlled reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs). Initial mountaintop demonstrations have been made at cm, mm and micrometer wavelengths. The next step within the next 2 years should be an **airborne occultation demonstration**. Specifically, CGMS is asked to encourage international space agencies (NASA-ESA-NSF-NOAA-EUMETSAT and others) to **hold an interagency workshop** as soon as possible to define how they can cooperate in implementing an the airborne demonstration and a LEO-LEO research and demonstration mission.

2) Transmitter system: Modulation on new GNSS signals, Desire for unmodulated pilot tones

Rationale: In the not too distant future there will be 4 international GNSS constellations: GPS, GLONASS, Galileo and BeiDou/Compass. With 12 orbiting 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 problem is this modulation makes it increasingly difficult to use these signals for open loop tracking in the lower troposphere and will likely degrade occultation performance there. The new navigation modulation such as binary offset carrier (BOC) has a more complex autocorrelation function that not only narrows the central peak of the autocorrelation function but also has anticorrelated response at certain time lags. This response makes acquisition of signals in the lower troposphere difficult and will at the very least degrade the occultation performance there and may render the new signals unusable for occultations in the lower troposphere.

Recommendations: We ask CGMS to

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

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

Rationale: Current GNSS systems use L-band frequencies between 1 and 2 GHz. Additional use of one or more higher frequencies well separated from L-band would have substantial benefit to RO. For instance, for Galileo, ESA is considering a 5 GHz frequency in the C-band range. This would increase the useful altitude range of

GNSS radio occultation by about 15 km because sensitivity to the ionosphere is an order of magnitude less at 5 GHz than at L-band frequencies. Ionospheric scintillations induced by sporadic E-layers, which can influence the accuracy of retrieved profiles in the stratosphere, will be significantly reduced at 5 GHz. In addition, such signals would open the door to new applications of RO signals that exploit the better sensitivity to depolarization and reflection effects in C-band such as remote sensing of precipitation, capillary wave/gravity wave interactions and surface winds over oceans. Focus in this area should be given to signal modulation/coding schemes that reduce interference by other signals, improve range resolution and increase SNR,

Recommendation: We ask CGMS to **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, COMPASS, and IRNSS) to consider implementation of such higher frequencies for the benefit of operational weather and climate monitoring and prediction.

4) Improvement of spectroscopy

Rationale: As noted by a number of researchers, there is uncertainty in the refractivity "constants" that leads to subtle, systematic errors in the interpretation of the refractivity, especially for climate monitoring. Also spectroscopic constants recorded in different databases show differences which lead to uncertainties in derived products. Improved knowledge of these constants in the MW and IR spectral regions for targeted absorption lines would be beneficial for the design and assessment of LEO-LEO occultation missions.

Recommendation: IROWG recommends that funding agencies (e.g., ESA, NSF) and national and research metrology laboratories (e.g., NIST, NPL, NRCAN) **provide support in performing refractivity and spectroscopic laboratory and open air measurements** to improve the existing refractivity constants and spectroscopic databases for targeted absorption lines.

5) Improvement of high-altitude initialization

Rationale: All occultation methods need some type of initialization at the upper boundary of the data domain if geophysical variables are retrieved from the Level 1b data (bending angle profiles, transmission profiles). This is currently accomplished via a variety of different methods assuming different information about the variables above the data domain, generally termed statistical optimization or upper boundary initialization in the RO community. The influence of such initialization generally decays exponentially downwards from upper boundaries (or upper boundary domains).

Climate and other applications (e.g., atmospheric process studies such as on atmospheric waves/gravity waves) require that the initialization, which determines residual bias errors, fulfils very strict accuracy requirements (e.g., errors less than 0.1K or even stricter) in the height domain of core interest (e.g., below approximately 35 km for GNSS RO). In other words, climate benchmark data quality should be delivered.

Recommendations: GNSS RO processing centres and developers of advanced occultation techniques (e.g., LEO-LEO) are asked to 1) carefully quantify errors from initialization in height domains of interest in current retrieval algorithms, 2) put high priority in algorithm development to improve initialization, 3) quantitatively assess by intercomparison between processing centres residual structural uncertainty attributable to initialization in retrieved geophysical variables of interest. Space agencies and other funding agencies should support studies in the direction of implementing the above quantifications and intercomparisons with priority.

6) **Algorithm development and assessment:** Improved processing and products in the lower troposphere and boundary layer

Rationale: Planetary boundary layer (PBL) information from GPSRO measurements is another example of how the GPSRO information content complements information provided by advanced passive IR sounders.

Recommendation: We recommend continuing research in the very promising area of extracting and using PBL information from GNSS data. More specifically, it is recommended to explore methods that provide information about the PBL from GNSS such as new diffraction correction techniques and methods that deal with and take advantage of ducting and surface reflections. In addition, the information content of the observations and error estimates are needed to improve NWP via assimilation of GNSS PBL observations.

7) **LEO-LEO algorithm development and assessment**: Cloudy air algorithms

Rationale: For NWP and climate, in particular, it is critical that observations provide a complete and unbiased determination of the atmospheric state. Given that clouds cover 70% of the Earth, doing so requires the ability to determine the atmospheric state in the presence of clouds. Unlike IR and passive microwave radiometry, LEO-LEO occultations at microwave wavelengths offer the potential of providing high vertical resolution profiles of the atmosphere above, within and below clouds unambiguously at least under the assumption of spherical symmetry. Also LEO-LEO infrared signals, with the individual laser pulses penetrating intermittent cloudiness or below clouds being of clear-air quality, provide profiling potential in cloudy air.

Recommendation: We recommend that agencies consider supporting the research community to develop and evaluate algorithms for retrieval of the atmospheric state from LEO-LEO occultation measurements in cloudy air. This includes both theoretical development and the acquisition and use of experimental data sets to evaluate the success and effectiveness of these retrievals.

8) **GNSS observations from airborne platforms**

Rationale: GNSS observations from airborne platforms offer a new data set for NWP in particular. The applications include radio occultation, reflectometry/reflection, altimetry, soil moisture, and emission.

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 NWP. We recommend pursuing opportunities to exploit GNSS and communications signals of opportunity on these platforms for reflectometry/reflection, altimetry, soil moisture, emission, where collaboration benefits both communities by sharing technology and expertise, speeding development, and reducing logistical constraints.

Action IROWG2-07: Gottfried Kirchengast to provide response to CGMS-40 request, documenting the LEO-LEO Essential Climate Variables (ECVs) capabilities.

Background/Notes

- **LEO-LEO**

  The sub-group meeting began with a discussion about the scope of topics that fall within this working group. There was general agreement that this sub-group should focus on inter-satellite occultations with innovative GNSS-like satellite signals at microwave and infrared wavelengths as well as on innovations of GNSS RO itself that advance the current status of GNSS RO techniques and algorithms.

- **Other Occultation sources**

  We also discussed use of **signals of opportunity** such as telecom signals. For a LEO-LEO point of view this is challenging. Difficulties include POD, very high frequency stability, demodulation of whatever modulation is being used and calibration tones to remove common mode noise.

- **Surface reflections**

  We spent a lot of time discussing surface reflections and their utility and whether they belong in this group. The glancing surface reflections are of limited utility for characterizing surface properties. Higher incidence angles are definitely useful but it is not clear they belong in this group. There are other groups pursuing these issues. This is unresolved whether surface reflections for characterizing the surface properties should be included here in this group.

  Rick Anthes suggested that we recommend the Taiwan ocean reflections mission.

- **Airborne Observations**

  Airborne observations were discussed and are being added

- **Update on Scope of Group**

  The current areas of innovation include (underlined are those areas where a recommendation was deemed needed and formulated):

  - **LEO-LEO occultations:** use of coherent microwave signals and infrared signals
  - **Surface reflections:** using reflected signals from RO to study the

bottom portion of the troposphere in particular the possible use of reflected signals to characterize the vertical structure in the presence of super-refraction requires further research. This potentially also includes *reflectometry/reflection, altimetry, soil moisture, and emission*.

- **Precipitation:** Sensitivity to heavy precipitation at GNSS wavelengths, drizzle to heavy rain at shorter wavelengths
- **Clouds:** liquid, ice, supercooled liquid water
- **Polarization:** Surface**,** liquid and ice clouds**,** liquid and solid forms of precipitation**,** multipath
- **Instability index**: Lapse rates, equivalent potential temperature, CAT
- **Scintillations:** Detection, intensity, temporal-spatial scales, climatology, short term weather forecasting for aviation and momentum exchange within the atmosphere
- **Atmosphere related Products**
  - gravity waves and temporal and spatial scale and climatology
- **Internal boundaries within the atmosphere:** Top of PBL, Freezing level**,** Tropopause(s)**,** Stratopause(s)
- **Algorithm development and assessment**
  - Innovation in GNSS processing and products
    - ionospheric corrections
    - boundary layer
    - diffraction corrections
    - correction of turbulence-induced scintillation
  - Improvement of high-altitude initialization
  - Quality control
  - LEO-LEO algorithm development and assessment
    - cloudy air algorithms
    - correction of turbulence-induced scintillation
  - Joint retrieval development
- **Transmitter system**
  - Additional higher frequencies for GNSS (e.g. 5 GHz on Galileo)
  - Use of new GNSS signal features, e.g. **pilot signals**
  - GNSS clock performance
- **Improvement of spectroscopy**
  - Refractivity "constants"
  - Laboratory measurements
  - Open air instrument measurements
- **Calibration**
- **Water vapour retrieval algorithms and assessment of their accuracy**
- **QC in lower troposphere**

5.6 Space Weather Sub-Group

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

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

Members: J. Y. Liu (NCU, Taiwan), S. Y. Su (NCU, Taiwan), X. Yue (UCAR, USA), R. Bishop (The Aerospace Cooperation, USA), G. Crowley (ASTRA, USA), M. Cordrescu (NOAA/SWPC, USA), R. Viereck (NOAA/SWPC, USA), G. Bust (ASTRA, USA), R. Wilder (ASTRA, USA)

Visitors: T. Meehan (JPL, USA)

Recommendation to CGMS

1. **The Space Weather Group of IROWG recommends that an International Workshop be held to discuss three aspects of RO analysis involving the ionosphere,** probably to be funded by government agencies. The workshop shall include a cross-section of ionospheric space weather experts and scientists concerned with removing ionospheric effects from RO for neutral atmospheric parameters. The workshop will include the following three sessions: (A) removing ionospheric effects from RO for neutral atmospheric parameters; discussion of various ionospheric corrections currently being used; (B) discussion of various ionospheric data assimilation methods; (C) ionospheric effects, especially scintillation, on Radio Occultation using the extensive RO databases. (See Notes section for additional information).

2. **IROWG recommends that CGMS encourage international support of the COSMIC-2 program through the fielding of COSMIC-2 ground stations in countries at low latitudes to augment ground stations planned by the USA and Taiwan.** This action will significantly reduce the data latency from COSMIC-2 in the important low latitude and equatorial regions. Of particular interest is the development of three latitudinal chains of three ground stations each in the Asian, Middle Eastern/African, and American longitude sectors.

3. The lack of ionospheric RO data is becoming a limiting factor in the inversion of RO data from the lower atmosphere. In addition, the value of GNSSRO data to ionospheric modeling is expected to grow as the amount of available data increases over time. A variety of science and operational missions are in the planning stages, and it seems likely that more may be planned in the near future. While GNSSRO sensors that are able to observe lower atmospheric profiles can also generally measure ionospheric RO signals, there have been times in the past (e.g., GRAS on METOP) when the focus on terrestrial retrievals has resulted in unnecessary exclusion or reduction of ionospheric capability. Furthermore, GNSSRO sensor capabilities for observing ionospheric scintillation are not yet common to all missions. In addition, low data latency needs associated with operational space weather applications are not always met. **IROWG recommends CGMS to encourage missions flying GNSSRO sensors to incorporate a complete set of ionospheric measurements including measurements of ionospheric scintillation (high rate data scintillation measurements on all available line of sight TEC measurements) and, wherever possible, to reduce data latencies to less than 30**

minutes. It should be noted that antenna designs similar to COSMIC-1 (wherein canted zenith antennas with broad fields of view are used for tracking ionospheric occultations) provide one means of maximizing ionospheric data collection.

4. GNSS RO has been demonstrated to show great value in the global ionospheric climate, weather, variability monitoring and related scientific research. This value is expected to be greatly increased with more available data over time. However, the RO data format, a system for real time data access, and a historical data archive for ionospheric data is not yet established. **IROWG recommends that CGMS coordinate efforts to standardize an ionospheric data format for operational use of RO (similar to the BUFR format in the neutral atmosphere), create a real-time data accessing service available for space weather assimilation models, and archive historical data for ionospheric climate and scientific research purposes.** This will especially benefit operational nowcast and short term forecast space weather capabilities.

Recommendations within IROWG

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

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

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 advocate for and support greater incorporation of ionospheric radio occultation science topics (such as those described in Main Recommendation #1) within existing ionospheric science venues such as CEDAR (leads: Geoff Crowley & Gary Bust) and IRI workshops (leads: Tiger Liu and S. Y. Su). Collaborations within the sub-group membership involving evaluations

of ionospheric models using GNSSRO data, or development/refinement of ionospheric or scintillation specification models using GNSSRO data sets, are also encouraged.

3. Advancement of ionospheric model science depends on collection of both ionospheric electron density information, such as is obtained from GNSSRO sensors, and coincident observations of thermospheric parameters such as neutral composition and winds, and ionospheric plasma drifts. Since it is unlikely that the ultimate solution to ionospheric specification problems can be accomplished with GNSSRO observations alone, the members of the Space Weather sub-group should engage with the COSMIC-2 program to advocate for incorporation of space weather secondary payloads on the high inclination portion of that mission.

4. The sub-group should coordinate with space weather activities throughout WMO. Sub-group members will distribute space weather related documents among the sub-group that are part of WMO future planning (Evolution of the Global Observing System). These include documents obtained from Terry Onsager of NOAA's Space Weather Prediction Center (ET-EGOS-7 Document 8.3.2, 04-Apr-2012, "Statement of Guidance for Space Weather Observations") and a document obtained from Sean Healy of ECMWF (EGOS-IP V10 "Implementation Plan for the Evolution of Global Observing Systems").

Action IROWG2-08: Geoff Crowley and Gary Bust will lead workshops at CEDAR relevant to radio occultation. Tiger Liu and S. Y. Su will initiate radio occultation topics at upcoming IRI workshops.

Action IROWG2-09: Anthony Mannucci will distribute WMO information to the Space Weather sub-group according to sub-group recommendation 4.

Notes

Additional information regarding the first IROWG recommendation #1 for workshops is as follows:

Session A) Space weather (ionosphere) has a potentially significant impact on the operational use of radio occultation by introducing biases in the neutral atmospheric retrieval products that are routinely assimilated. Considerable ionospheric space weather expertise exists that could benefit the neutral atmosphere community to mitigate these impacts. Yet, this expertise is not integrated into the research and operations communities that assimilate RO data. **We recommend that a working group (WG) be formed over the next 18 months to organize and conduct a workshop supported by the WMO and other operational agencies that brings together a cross-section of ionospheric space weather experts and the neutral atmosphere community.** The WG will discuss the various ionospheric corrections currently being applied and possible improvements. Areas to be discussed include solar cycle, diurnal and seasonal variability, and sporadic-E climatologies. The extensive RO databases that currently exist are a valuable resource.

Session B) RO is not yet fully utilized by the operational space weather communities that are focused on ionospheric specification and nowcast. **We further recommend the formation of a focus group with support from operational agencies to develop uniform metrics for evaluating assimilative ionospheric models that ingest RO data, and to advance modeling approaches for assimilating RO data for space weather nowcasts and forecasts.**

Session C) An emerging use of RO is to measure L-band scintillation caused by ionospheric irregularities, from space. There is currently insufficient knowledge of how L-band scintillation measurements acquired in an occultation geometry translate to other geometries and frequencies of interest. **We recommend the formation of a focus group with support from operational agencies to address how space-based scintillation measurements can be used operationally.** A goal of the group is to understand how measurements from space can be compared to the extensive databases and models of scintillation developed from ground-based measurements. This should include a discussion of recommended flight receiver designs, acquisition approaches, algorithms for flight and ground processing of scintillation parameters, and the use of RO data for scintillation products.

Feedback was obtained during the rapporteur presentation to the wider IROWG of the sub-group recommendations, recorded here:

- The concept of an "Ionospheric reanalysis" was brought up. That means creating a long-term (several years), consistently processed 3D grid of electron density versus time similar to an NCEP or ERA-Interim reanalysis. For example, GAIM or IDA4D models could be used, assimilating RO and other data. The NWP centers are familiar with this concept and might use such re-analyses in their processing to mitigate ionospheric impacts.
- The NWP centers regularly use short-term forecasts in their processing, for example as an initial atmospheric state for processing. Rapporteur mentioned that the only operational forecasts of the ionosphere are from AFWA. However, these forecasts are not regularly evaluated by the science community. We might consider the next steps to make available short-term ionospheric forecasts widely available.
- Sean Healy will send us a WMO document that specifically recommends scrutiny by space weather community. (Referenced under sub-group recommendation #4).
- Per Hoeg suggested to include the term "Space Situational Awareness" (SSA) in our recommendations to connect with the operational agencies (Department of Defense in particular).

6 CONCLUSIONS

The full set of recommendations, relevant at CGMS, at satellite operator, and at IROWG level of the second IROWG were summarised above, including further discussion / background material.

Concerning recommendations for work in the immediate future the following recommendations are emphasised:

- A need for an operational continuity plan for RO – including troposphere and ionosphere – to provide a daily availability of at least 10000 occultations;
- An urgent need for data gap filling using research satellites or commercial sources (if available) is required for the near term, but this is not a replacement for a long-term continuity plan to provide operational GNSS RO data;
- The potential of GNSS RO for anchoring climate re-analysis needs to be further addressed, this also requires updated laboratory measurements of refractivity coefficients;
- Options to fly RO instruments on opportunity missions should be further pursued;
- Assure that GNSS operators are aware of the needs of RO applications, providing sufficient signal strength on the Earth limb;
- Support research towards implementing a LEO-LEO mission to fully explore the climate capabilities of RO;
- Engage CGMS agencies to organize a workshop to foster closer collaboration between the ionospheric and neutral atmospheric researchers.

All given presentations, as well as the CGMS working papers from IROWG-2 are available at http://www.irowg.org.

REFERENCES

[1] Report from the 2nd International Radio Occultation Workshop, CGMS-40 EUM-WP-01
[2] Climate related Processing and Potential of Radio Occultation Data, CGMS-40 EUM-WP-03
[3] Status of the global Radio Occultation Observing System, CGMS-40 EUM-WP-02

ACKNOWLEGEMENTS

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

ACTIONS

The actions from this workshop are collected below.

Action IROWG2-01: On IROWG co-chairs to contact the ITWG and survey the common interests between the groups.
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 and COSMIC-II; as there is a distinct possibility of no COSMIC data by 2014.
Action IROWG2-03: Chris Burrows and Ben Ruston will distribute a survey between operational centres showing use of GPS data, thinning methods, bending angle and/or refractivity use, observation error, and observation sensitivity plots.
Action IROWG2-04: NRL, ECMWF, JMA and EC; and if possible DWD, NCEP, Météo-France and UK Met Office will conduct a data denial experiment which uses only GRAS for a time period for a minimum of a month. Josep Aparicio, Sean Healy and Ben Ruston will coordinate the time of the case study (likely 2010) and coordinate the experiment with the other centres. We will include the observation sensitivities from each of the centres.
Action IROWG2-05: On IROWG co-chairs and B. Ho, A. Steiner: Provide the following ROTrends information on the IROWG homepage: (a) Links to processing descriptions of all data providers; (b) Published ROTrends intercomparison papers; (c) ROTrends PPC and MMC datasets (including sampling errors of the latter).
Action IROWG2-06: F. Zus to check availability of level 0 data of TerraSAR-X in Near-Real-Time.
Action IROWG2-07: Gottfried Kirchengast to provide response to CGMS-40 request, documenting the LEO-LEO Essential Climate Variables (ECVs) capabilities.
Action IROWG2-08: Geoff Crowley and Gary Bust will lead workshops at CEDAR relevant to radio occultation. Tiger Liu and S. Y. Su will initiate radio occultation topics at upcoming IRI workshops.
Action IROWG2-09: Anthony Mannucci will distribute WMO information to the Space Weather sub-group according to sub-group recommendation 4.