# Summary of the 1st International Radio Occultation Workshop

**Held at Karl-Franzens University Graz, Austria**

**On Friday, 10 and Saturday, 11 September 2010**

**Starting at 14:00 hours on 10 September**
**Ending at 16:30 hours on 11 September**

## 1 INTRODUCTION

This document summarizes the outcome of the 1st International Radio Occultation (RO) Working Group Workshop (IROW1). The workshop was hosted by the Wegener Center / University of Graz, Austria. It took place together with the OPAC-4 and GRAS SAF Climate Workshops; these ran from the 6th of September 2010 to the 10th of September (mid day) and IROW1 was on the 10th and 11th. IROW1 focused on sub-group discussion and recommendation and finished with a panel discussion.

IROW1 was attended by more than 60 scientists, including all the major centres providing and all major centres assimilating RO data.

Members of the workshop's organizing/scientific committee were: A.K. Steiner, U. Foelsche, G. Kirchengast (Wegener Center / U. Graz, Austria), K.B. Lauritsen and H. Gleisner (DMI, Copenhagen, Denmark / GRAS-SAF), A. von Engeln and D.R. Ector (Co-Chairs IROWG), R. Anthes (UCAR, Boulder, USA), T. Tsuda (RISH, U. Kyoto, Japan).

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 all the main recommendations and discussions within the different sub-groups, and Section 4 concludes.

## 2 IROW1 Organization

CGMS meeting 37 in October 2009 endorsed the establishment of the IROWG. Dave Ector (NOAA) and Axel von Engeln (EUMETSAT) have been 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 is grateful in particular to the hosting Wegener Center at the University of Graz, Austria, and to the sponsors EUMETSAT, CGMS, WMO, and NOAA.

The aim of IROW1 was on focused sub-group discussions after the OPAC-4 and GRAS-SAF workshops. IROW1 participants were asked to summarize relevant activities within the scope of the sub-group and express recommendations which could either be relevant to CGMS, to the RO community, or to providers of RO data. The co-chairs suggested 6 sub-groups: (1) Numerical Weather Prediction; (2) Climate; (3) Research to Operations; (4) Payload Technology; (5) Innovative Occultation Techniques; (6) Space Weather, out of which 5 were selected and sub-group (4) was joined with sub-group (3) to Research to Operations / Payload Technology.

Each sub-group was asked to present their recommendations to the workshop participants for discussion.

# 3 Sub-Group Recommendations / Discussions

This section presents the recommendations and discussions from the different sub-groups. Note that sub-groups were asked for a few main recommendations, but were otherwise free to discuss / present all other relevant issues. Note also that the participant's lists are incomplete since some people only attended Friday, or moved around sub-groups without formally signing into one.

## 3.1 Numerical Weather Prediction (NWP) Sub-Group

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| Chair: | J. Aparicio (Environment Canada) |
| Rapporteur: | L. Cucurull (NOAA/NWS/NCEP/EMC, US) |
| Participants: | H. Anlauf (DWD, Germany), K. Boniface (EC, Canada), A. von Engeln (IROWG), M. Gorbunov (Inst. Atm. Phys., Russia), S. Healy (ECMWF), C.-Y. Huang (NCU, Taiwan), K. Lauritsen (GRAS SAF, Denmark), E. Ozawa (JMA, Japan), M. Rennie (Met Office, UK), C. Rocken (UCAR, US), H. Seko (MRI/JMA, Japan), S. Syndergaard (GRAS SAF, Denmark), F. Zus (GFZ, Germany) |

**Main Recommendations:**

1. GPSRO has been demonstrated to be a very important element in the global data observing system for NWP. The continuity of GPSRO observations in the future is not sufficiently guaranteed. IROWG recommends that **CGMS coordinate efforts between operational data providers and NWP agencies to establish long term continuity plans**.
2. Operational NWP centers should be aware of a substantial reduction of available GPSRO data in real time, that has already begun, and will continue (CHAMP no longer functioning, COSMIC degrading, COSMIC II planned to be operational only by 2015). Processing of research data could fill the gap (TERRASAR-X, TANDEM-X, OCEANSAT-2, SAC-D, PAZ, etc, where the first 3 have already been launched). IROWG recommends that **CGMS coordinate efforts between operational data providers, NWP agencies, and research agencies, to investigate and potentially support NRT (Near-Real-Time) infrastructure for these data** (downlink, processing, dissemination and archiving).
3. The saturation level of GPSRO data might depend on the application (e.g. global -, regional forecasting, climate) and is not known today. IROWG recommends **to encourage observing system simulation experiments (OSSE) to determine the optimal number of observations for different applications.**

4. There is an uncertainty in the refractivity coefficients that impact NWP biases, also with potential implications in climate monitoring. IROWG recommends that CGMS **coordinate efforts to determine the refractive coefficients at the GPS wavelengths**.

**Recommendations within IROWG:**

1. BUFR file contents, and all processing leading to them, should be driven by NWP user requirements only. Fulfilling the requirements of all other users should be done through other files.
2. IROWG recommends efforts investigating the properties of extracted PBL height, errors and characteristics of the different algorithms. It should be considered to allow the insertion of PBL height in the BUFR files.
3. Processing errors/correlations: The processing centers should consider providing detailed documentation, with information on data errors, correlations, and the processing chain. We recommend that data providers include error estimates in the profiles.
4. IROWG recommends processing centers report/investigate if NWP should expect a degradation of the quality of the data due to an increase of geomagnetic/ionospheric activity in the coming years.
5. IROWG should investigate if GPSRO is suitable for radiance calibration (GSICS), and coordinate with ITWG if further action needs to be taken.
6. Processing harmonization: we recommend the processing centers to monitor and investigate their differences – including the QC, filtering, cutoff, initialization, final vertical grid – by processing common data in a systematic manner.

**Recommendations within Sub-Group:**

1. Investigate if more positive impact in the moisture field could be obtained.
2. More investigation of the negative bias distribution and identification of the conditions that lead to it.
3. Research on non-standard operators (2D, 3D, bending, freq, phase): NWP users to report how feasible it would be to implement operationally any of these. Researchers investigating 2D or 3D to consider under which conditions these operators would justify the CPU cost and complexity.

## 3.2 Climate Sub-Group

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| Chair: | U. Foelsche (Wegener Center, Austria) |
| Rapporteur: | S. Leroy (Harvard University, US) |
| Members: | B. Biadglgne (NCC, Australia), R. Biondi (DTU, Denmark), H. Gleisner (GRAS SAF, Denmark), B. Ho (UCAR, US), B. Lackner (Wegener Center, Austria), T. Mannucci (JPL, US), A. Steiner (Wegener Center, Austria), J. Taylor (NCAR, US) |
| Visitors: | R. Anthes (UCAR, US), A. von Engeln (IROWG), S. Healy (ECMWF), R. Kursinski (U. Arizona, US) |

**Main Recommendations:**

1. **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 pole wards of 50° latitude

with the period of constellation precession is present due to selected local time sampling.

2. Documentation on retrieval processing chains by all processing centers (UCAR, GFZ, Wegener Center, JPL, GRAS-SAF, EUMETSAT) is essential to assure traceability in climate data. Documentation on LEO receiver firmware is also needed. IROWG recommends to **fully document processing chains, keeping track of any introduced changes/updates to processing or instrument**.
3. Clarify that there **is a difference between Climate Data Records and Climate Benchmarks**. RO does not require inter-calibration, overlapping records, assumptions of stability, and as such should not be considered in the same category as Climate Data Records as spoken of in GSICS and defined in a NAS Press white paper. RO has already demonstrated that different centers produce the same trends and that calibrated RO observations are the same across platforms. Moreover, RO data can be used to diagnose calibration of other data types (re: MSU).
4. For climate monitoring and future RO missions, the sampling focus is primarily the extra-tropics. The tropics are fairly quiet synoptically and so do not require the high density that NWP might for typhoon/hurricane forecasting. The **mid-latitudes are far more synoptically active, giving rise to greater sampling error and requiring greater sampling density**.
5. Climate process requirements are currently not adequately discussed in IROWG. Nevertheless, we recommend that **NWP centers strongly consider changes to physical parameterizations and data assimilation to assure better agreement with climatologies of water vapor and temperature, UTLS and below, established by GPS RO**.

**Recommendations within IROWG:**

1. Documentation on retrieval processing chains is essential. Recommend full documentation from UCAR, GFZ, Wegener Center, JPL, GRAS-SAF (DMI/EUMETSAT). Documentation on LEO receiver firmware is also very important.. Paper contributions to a peer-review technical journal should be considered - nominally JTECH. These should include information on smoothing, statistical optimization, parameters of retrieval and wave optics parameters.
2. Distribute the MMC’s of ROTrends together with uncertainty estimates to the world, subject to the consent of the contributing centers. Distribution could take place through the IROWG website through a simple anonymous FTP interface and thereby circumvent a need for a login/password. An announcement to EOS (AGU) could accompany the distribution. Multiple variables, from bending angles through higher level geophysical variables and their descriptions could be included in the EOS article and in the NetCDF and README files.
3. It is recommended to the RO community to draft a community-wide accepted version of climate monitoring science requirements for referral to future RO missions. CLARREO should circulate among this group its science requirements as a basis for discussion. Other groups (e.g., NOAA/UCAR) will be sought out for its draft requirements. Both baseline and threshold requirements should be prescribed.
4. Recommend to the RO community/ROTrends to complete the uncertainty study (PPC and MMC studies), sampling error, and submit findings to a peer-reviewed journal.

5. Publication and distributions of RO retrievals should include a quantitative description of influence of background in statistical optimization.
6. Continuing provision of climatologies by multiple retrieval centers is encouraged. In fact, it is not in our interest to assemble a single, universal product inasmuch as it would not reveal structural error in retrieval.
7. It is recommended to provide a series of follow-up reports on changes/versioning through links in IROWG web page which should also be archived by IROWG. The idea is to avoid the political difficulties experienced by Phil Jones (HadCRU) in providing documentation on the establishment of surface air temperature analysis.
8. Recommend ECMWF to engage in a re-analysis activity based on unbiased-corrected data types - especially RO. Results should be compiled into MMC format and incorporated into ROTrends.
9. GPS RO data should continue to be presented at climate modeling workshops, such as CLIVAR and CMIP, SPARC.

**Notes:** Sub-Group provided notes, available in the Appendix.

**Actions:**

Action IROW1-1: D. Ector to try to locate any missing GPS/MET data.

Action IROW1-2: S. Leroy to provide CLARREO science requirements.

### 3.3 Research to Operations / Payload Technology Sub-Group

Chair: B. Schreiner (UCAR, US)
Rapporteur: C. Marquardt (EUMETSAT)
Members: R. Anthes (UCAR, US), D. Ector (NOAA, US), E. Fu (RMIT, Australia), D. Hunt (UCAR, US). T. Liu (NSPO, Taiwan), A. Loescher (ESA), J. Wickert (GFZ, Germany), N. Yen (NSPO, Taiwan)

**Main Recommendations:**

1. RO measurements are a valuable information source for NWP and climate. Within NWP, the number of RO instruments has not reached saturation level. Hence IROWG recommends that **operational and research organizations consider adding Global Navigation Satellite System (GNSS) RO payloads on all suitable satellite systems**.
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 or funding as needed (1) downlink and dissemination capabilities; (2) processing capabilities; (3) consultation on best practices in processing and design. It should also be considered to maintain the COSMIC constellation beyond its current lift time (April 2011), as long as a valuable number (~500) of high-quality soundings per day are being obtained.
3. Processing of RO data requires access to GNSS ground station networks to derive orbit and clock data. IROWG recommends to **maintain and improve these networks as required for the Near Real Time and research operation of RO missions**. Products

and data obtained from these networks should be publicly available like other meteorological data.

**Further Recommendations:**

1. Recommendation to China to make formal Beidou/Compass ICDs available so that future missions can make use of signals from this Navigation System, increasing the number and usefulness of RO measurements for both NWP and climate.
2. Recommendation to instrument developers to also consider the use of GLONASS FDMA signals in future receivers, in order to increase the number of available RO measurements.
3. Recommendation to IGS to also place representatives from the RO community in its organizing bodies / governing board.
4. Recommendation to GNSS system operators to include representatives of the RO community in their scientific advisory bodies.
5. An improved number of occultations could be obtained by use of the Chinese Beidou/Compass system as well as the GLONASS FDMA signals in future receivers. IROWG recommends looking into these options.
6. 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.
7. COSMIC: Recommendation to UCAR/JPL to provide low level data format documentation and readers to the RO community to ease cross-center processing comparisons
8. GRAS: Recommendation to EUMETSAT to address issues caused by the tracking behavior of the GRAS instrument and apply necessary software and configuration fixes to improve raw sampling data quality.
9. ROSA/Oceansat-2 (~200 occs/day): Recommendation to ASI to provide data, format information and decoding software as early as possible to the RO community.
10. TerraSAR-X, Tandem-X (~200 occs/day/satellite): Recommendation to GFZ, together with operational centers, to explore options to (1) enable forward occultation to increase the number of occultations to 400/day/satellite; (2) provide RO data in NRT from at least one of the satellites; (3) provide the full set of all available RO data to the RO community; (4) provide data format information and readers.
11. SAC-C (~200 occs/day): Recommendation to NOAA, GFZ, CONAE and JPL to work together to provide SAC-C RO data in NRT as soon as possible.
12. C/NOFS (~200 occs/day): Recommendation to NOAA to work with US Air Force to provide RO data in NRT.
13. KompSAT-5 (~300 occs/day, planned for 2011): Recommendation to NOAA to work with KASI and KARI to provide RO data in NRT; suggest NOAA to provide ground station resources.
14. Megha-Tropiques (~400 occs/day, planned for 20??): Recommendation to EUMETSAT to work with CNES/ISRO to provide RO data in NRT.

15. PAZ (~200 occs/day, planned for 2012): Recommendation to NOAA to work together with IEEC to implement RO data in NRT; suggest NOAA to provide ground station and data processing resources.

**Actions:**

Action IROW1-3: D. Ector to explore options for either NSPO or CWB to become more closely involved with CGMS activities.

Action IROW1-4: J. Wickert to draft a letter of support for NRT operations of TerraSAR-X and Tandem-X from operational agencies.

### 3.4 Innovative Occultation Technique

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| Chair: | R. Kursinski (U. Arizona, US) |
| Rapporteur: | V. Proschek / K. Zhang (Wegener Center, Austria / RMIT, Australia) |
| Members: | K. Cook (C2 International, Taiwan), L. Cornman (NCAR, US), M. Cucca (Polito, Italy), C.-Y. Huang (NCU, Taiwan), G. Kirchengast (Wegener Center, Austria), R. Notarpietro (Polito, Italy), S. Schweitzer (Wegener Center/U. York, UK/Austria), S. Syndergaard (GRAS SAF, Denmark) |

**Main Recommendations**

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 8.5 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) 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 (ESA, NSF, 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 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). Specifically, as a first step, CGMS is asked to encourage European and US space agencies (ESA-NASA-NSF-NOAA-EUMETSAT) to hold an interagency workshop as soon as possible to define how they can cooperate in implementing a LEO-LEO research and demonstration mission and related preparatory activities (joint precursor demonstration experiments, scientific retrieval and impact studies, instrument development and mission design).

2. **Transmitter system:** Additional higher frequencies 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 which 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. A C-band frequency would also reduce higher order ionospheric systematic residuals via triple-frequency combinations using both L-band and C-band frequencies. 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, as well as to un-modulated signals (pilot tones) that allow for long integration times.

   **Recommendation:** CGMS is asked 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.

3. **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**: It is recommended that agencies **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.

4. **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 done by a variety of different methods assuming different information on 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 0.1 K 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.

5. **Algorithm development and assessment:** Improved processing and products in the 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.

6. **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.

**Notes:** Sub-Group provided notes, available in the Appendix.

## 3.5 Space Weather Sub-Group

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| Chair: | P.R. Straus (Aerospace Cooperation, US) |
| Rapporteur: | P.R. Straus (Aerospace Cooperation, US) |
| Members: | J. Y. Liu (NCU, Taiwan), D. Offiler (Met Office, UK), C.-S. Wang (RMIT, Australia), F. Wu (BUAA, China), B. Nava (ICTP, Italy), T. Meehan (JPL, USA), |
| Visitors: | T. Mannucci (JPL, USA) |

**Main Recommendations:**

1. While GPSRO has demonstrated an effective capability to measure ionospheric total electron content and electron density profiles, it impact on ionospheric specification accuracy when used in assimilative ionospheric models is yet to be quantified.
   IROWG recommends CGMS to encourage **the development of uniform metrics for evaluating assimilative ionospheric models together with forums wherein comparisons between assimilative models in terms of these metrics can be made** with and without GPSRO data incorporation.

2. The value of GPSRO 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 ionospheric measurement capabilities are generally a subset of the attributes of a GPSRO sensor which able to observe lower atmospheric profiles, 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, GPSRO sensor capabilities for observing ionospheric scintillation are not yet common to all missions.
   IROWG recommends CGMS to **encourage missions flying GPSRO sensors to incorporate antenna designs similar to COSMIC-1 (wherein canted zenith antennas with broad fields of view are used for tracking ionospheric occultations)**, and to employ GPSRO sensor software that maximizes the collection of ionospheric data. IROWG also recommends that CGMS encourage the development of a standardized ionospheric scintillation measurement capability for GPSRO sensors.

3. Advancement of ionospheric model science depends on collection of both ionospheric density information, such as is obtained from GPSRO sensors, and coincident observations of other thermospheric parameters such as neutral composition and winds and ionospheric plasma drifts. It is unlikely that the ultimate solution to ionospheric specification problems rests can be accomplished with GPSRO observations alone.

IROWG recommends CGMS to **encourage missions flying GPSRO sensors to also fly secondary payloads supporting thermosphere/ionospheric studies**, as was done by the COSMIC-1 and CHAMP satellite programs.

**Recommendations within IROWG:**

1. The coupling between the stratosphere/mesosphere and the lower thermosphere and E- and F-region ionosphere is currently a strong area of scientific study. The GPSRO technique is unique in that in provides a means of assessing lower atmospheric forcing (gravity wave activity) coincident with ionospheric densities. However, there is a gap in the GPSRO observations between 40 and 80-90 km due to the very small bending angles at this altitudes and incomplete removal of ionospheric effects. IROWG recommends efforts investigating the development of improved analysis or instrumentation leading to extension to the upper altitude limit of current GPSRO capability.
2. The name of this subgroup – “Space Weather” – is somewhat misleading because Space Weather encompasses a wide range of phenomenology, some of which cannot be supported significantly by GPSRO observations. We suggest changing the name of this subgroup to “Ionosphere”.

**Recommendations within Sub-Group:**

1. Expand the subgroup membership to include (1) NOAA Space Weather Prediction Center personnel, and (2) members of the international science community involved in the development and evaluation of assimilative ionospheric models.
2. Collaborations within the subgroup membership of involving evaluations of ionospheric models (e.g., NeQuick) using GPSRO data, or development of ionospheric or scintillation specification models based on COSMIC-1 and other GPSRO data sets is encouraged.

# 4 CONCLUSIONS

The first workshop of the IROWG (IROW1) was hosted by the Wegener Center / University of Graz and was organized together with the OPAC-4 and GRAS SAF Climate workshops in Graz, Austria. IROW1 was held on Friday, 10th of September 2010 and Saturday, 11th of September 2010, it was attended by more than 60 scientists, including all the major centres providing and all major centres assimilating RO data. IROWG has just been endorsed by CGMS and this was the first workshop of this group. Generally, all participants considered it a big honour to have been selected as the fourth working group under CGMS.

After a general introduction on the work of CGMS and IROWG, IROW1 participants were asked to work in sub-groups, covering the main fields of radio occultation observations: (1) Numerical Weather Prediction; (2) Climate; (3) Research to Operations / Payload Technology; (4) Innovative Occultation Techniques; (5) Space Weather; discuss activities within their field and express recommendations.

Each sub-group was asked to come up with recommendations and possibly actions. Recommendations were either relevant at CGMS level, within the sub-group, or to providers of RO data. The recommendations were later presented and discussed with all participants.

A summary of these recommendations / actions is given above. Concerning main recommendations for work in the immediate future the following ones are emphasized:

- Encourage long term continuity of RO observations e.g. by considering RO instruments for upcoming missions
- Encourage mitigation of possible data gaps in operational RO observations by bringing research missions into the Near Real Time stream
- Support unbiased local time sampling through appropriate orbits for climate application, as also expressed in the GCOS Climate Monitoring Principles
- Encourage the development of uniform metrics for evaluating assimilative ionospheric model
- Encourage to explore other occultation techniques such as LEO-LEO

Workshop proceedings of the OPAC-4 and GRAS SAF Climate workshops are planned to be published in a peer-review journal. All given presentations will be made available at http://www.uni-graz.at/opac2010/, this summary, along with the working paper to CGMS will be made available at http://www.irowg.org.

# APPENDIX

## 1 NOTES FROM CLIMATE SUB-GROUP

10 September 2010:

Re-analysis and anchor data types: Not all upper air measurements currently treated as bias-free should be treated as such. Sean suggested re-analysis based only on data that is bias-free.
Andrea: Documentation standards. EUMETSAT and CDAAC have different "level" terminology for processing stages. There needs to be better documentation of the contents of data files. Start with calibrated "excess phase" files. Difficult to figure out what goes into all of the variables in a file. What are the uncertainties? How were they derived? Identify a publisher for technical documents on retrieval systems. How to relay information on minor changes to a calibration/retrieval system? It must be in a digital archive. DOI? Each retrieval provider should keep running documentation of version history. Make it available to DOI. Where is the raw data? Who is archiving it?
Consider something like an ISO standard…
User-friendly formats: NetCDF and HDF. Climate modelers were invited to OPAC, but no one came. Few in-roads into the climate modeling community to date. Insufficient motivation for climate modelers now. Make use of the data easier. (What is refractivity? Dry pressure? Dry temperature? Bending angle?) Executive summary!! Lack of communication between scientific communities. WMO is aware of the capability of RO. The climate community would love to see a binned climate product. Consider publishing MMCs from ROTrends. Consider an EOS/AGU article to accompany the release. How to relay error/uncertainty? OK to be honest. IROWG can host the data distribution, or at least provide hyperlinks to the data. It should be clear which data centers generated the MMCs. Keep the MMCs at the individual centers? WegCenter already doing something like this… Any feedback? IROWG to host links… Need to get permission from the ROTrends contributors. MMCs are almost uniformly compliant and could be improved. To account for information content by data in statistical optimization, provide monthly mean O/(O+B). In that case, centers should provide the background climatology. Recommendation to retrieval centers: publish both raw bending angles and statistically optimized bending angles. Centers should give some idea of relative weighting of background/climatology and data, but work out the details later.
Tony: Climate impact of radioholographic processing. KBL talk showed change in bias from different wave optics processing techniques. Does it affect trends? Is there an issue of bugs?
Sean: ECMWF could produce a re-analysis based on RO data only. While it would contain physical biases, so do retrievals. It would serve as an independent "retrieval" and contribute its own MMC to accompany the MMCs of ROTrends. ECMWF has already shown that RO data constrains surface pressure and is in fact sensitive to stratospheric error on the order of 0.1%.
Climate sub-group should consider both "climate monitoring" and "climate processes". Perhaps a separate sub-group? A sub-sub-group?
For tomorrow, discuss sampling requirements for climate monitoring. How many satellites? What orbits, etc.?
Any GPS/MET data from 1997 onwards? 1-second ground data from GPS/MET era? JPL needs to find the person who possesses that data. Tony will search for him.

11 September 2010:

Attendees: Andrea, Ben, Hans, Birtukan
Stephen: Consider a more universally accepted version of "science requirements" for GNSS RO climate monitoring than that for CLARREO.
Qualify sampling requirements according to climate phenomenon to be resolved. "Climate processes" are subject to different sampling requirements than "climate monitoring." Sampling density should account for reliability of RO missions, especially opportunity missions.
Climate monitoring: For 2012-2017, only have Metop missions, which are sun-synchronous (9:30am descending). Expected to introduce large (semi)diurnal cycle bias. For sun-synch, bias is approximately 0.04K, annual averages, roughly at all heights, simulated from ECMWF analysis output, which is 4xdaily. If exactly sun-synch, we can always state that we're monitoring only that specific local time; however, if there is a slight drift in the orbit, then a sampling error trend is introduced, a potentially much bigger problem. COSMIC, while it covers local time well in low and mid-latitudes, leaves a ~6hr gap in polar latitudes, and consequently bias that is sinusoidal in the constellation precession period.
From Pirscher's work, even with precessing orbits (COSMIC), a diurnal cycle bias is introduced at high latitudes, especially above 50degrees latitude. Possibly ameliorate the problem with analysis of diurnal cycle and its harmonics, but we have a distinct preference for not leaving gaps in diurnal cycle coverage.
This subgroup acknowledges that improved knowledge of the refractivity coefficients/model is desirable; nevertheless, we don't believe that such improved knowledge is urgent. While poor knowledge of the refractivity coefficients does hinder an absolutely accurate reanalysis product, it is likely to contribute little to the overall uncertainty in estimated climate trends. If, on the other hand, accurate data assimilation becomes a higher priority in the NWP community and gains broad acceptance in the climate research community, the consequences of improved knowledge of refractivity coefficients would greatly benefit the RO climate subgroup's interests.

## 2 NOTES FROM INNOVATIVE OCCULTATION SUB-GROUP

The subgroup meeting began with a discussion about the scope of topics that fall within this working group. There was general agreement that Subgroup 5 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.
We discussed whether natural-source solar, stellar and lunar occultations belong under this group as well. These types of observations are somewhat limited in sampling density and characteristics, with a solar occultation satellite providing for instance about 30 occultations per day, but they offer some unique measurement features and potential for calibration. While no representatives from these areas were present at this first IROWG, there was general agreement that these observations might be included within the scope of this working group, so room for them was kept open for now.
We also discussed the fact that certain process-related or phenomenological areas such as gravity waves were not well represented in any of the existing subgroups. RO offers a wealth of unique observational constraints on atmospheric processes and phenomena and it may be a good idea to create a separate "processes" subgroup.

We considered areas where innovations will be useful; such 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:** Altimetry, soil moisture, surface roughness/winds, ice topography
- **Precipitation:** Sensitivity to heavy precipitation at GNSS wavelengths, moderate rain at shorter wavelengths
- **Clouds:** liquid, ice, supercooled liquid water
- **Polarization:** Surface, clouds, precipitation, multipath
- **Instability index**: Lapse rates, equivalent potential temperature, CAT
- **Scintillation:** 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**