NWP Working Group

Chair: Paul Poli, Rapporteur: Sean Healy, Participants: Lidia Cucurull, Estel Cardellach, Dick Dee, Ching-Yuang Huang, Mike Rennie, Chris Marquardt, Josep Aparicio, Detlef Pingel, Chuen-Teyr Terng, Stig Syndergaard, Ismail Mert, Ismail Yucel

1. What is the potential of GPSRO data for constraining humidity?

EC, NCEP, Met Office, MF, DWD and ECMWF have all found small positive impacts for lower tropospheric humidity in their NWP models as a result of assimilating GPSRO data. One possible reason why the impact may be limited in the tropics is the low GPSRO data density in that region. Another reason may be the difficulty to separate the humidity signal from the temperature signal when assimilating the refraction measurements.

Recommendation to space agencies: To consider the feasibility of orbital configurations that increase the number of GPSRO measurements in the tropical region.

In addition, further work is required on the assumed error and bias characteristics. The tropospheric errors used at the met services are probably too conservative. However, there are still biases in the measurements in the lower troposphere, so the errors have to be inflated to compensate for this.

Recommendation: To conduct a set of impact experiments looking at the sensitivity of the water-vapour results with respect to the assumed observation errors.

The group is not aware of any results that show that water vapour information derived from GPSRO analyses/retrieval improves the fit to radiosondes, and this may be an interesting research area. Comparisons with ground-based GPS total column measurements should be considered, but this will be complicated by the fact that GPSRO measurements do not in general reach the surface.

Recommendation: To conduct further validation studies of the GPSRO humidity retrievals with respect to Ground-based GPS (when the GPSRO measurement gets close to the surface), MW radiometers and lidar

Recommendation to data providers: To include data quality flags that could influence the usability of the data (e.g., in the lower troposphere: surface reflection and super refraction)

Recommendation: To pursue the experimental demonstration of the active LEO-LEO measurements, where the frequencies have been picked to observe water vapour absorption lines.

2. Potential of GPSRO data for specific applications: planetary boundary layer, extreme weather and surface pressure

Planetary boundary layer (PBL) information from GPSRO measurements is another example of how the GPSRO information content complements information provided by advanced passive infra-red sounders. NCEP and UCAR have just started a joint project, with the ultimate aim of assimilating the GPSRO PBL information in a mesoscale model.

Recommendation: To continue research in the very promising area of extracting and using PBL information from GPSRO data. This should include a detailed error analysis and a validation exercise with respect to other sensors (e.g., CALIPSO). One area that should be addressed is the error differences over land and sea.

Results for severe weather in the Taiwan region (e.g., hurricane track prediction) are encouraging. It is noted that 2D operators also appear to have a positive impact in this context. The impact of GPSRO measurements on extreme weather events has not been investigated in any detail at the met services.

Recommendation: To investigate the impact of GPSRO on forecasting extreme weather events at the met services.

It was noted that most centres report small improvements in surface pressure prediction.

3. Observation operators

As a general principle, an observation operator should be made as accurate as possible, within the time constraints of the operational system. In general, 2D operators are not a massive computational burden. However, it was noted that the implementation of the 3D operator at DWD ran into trouble in the Physical Space Assimilation System (PSAS), because of the cost of mapping the background matrix to all the required profiles. Most centres have plans to investigate the use of 2D operators at some stage.

Recommendation: To continue efforts on the development of more accurate and computationally affordable observation operators for data assimilation.

We note that it may be useful to exchange (o-b) departure information between the met services and ultimately perform a comparison of the various observation operators used at different centres.

Recommendations to NWP centres:

- To exchange (o-b) departure statistics for as many products as possible and display them on a single monitoring web-site (possibly on the GRAS SAF site).
- To exchange (o-b) departures to enable profile-by-profile comparisons.
- To plan for an observation operator inter-comparison exercise, based on experience gained from other communities (e.g., ITWG).

4. How can GPSRO measurement and representativeness error correlations be defined? Can we use simple models?

Simple correlation models are probably not adequate. More work needed to investigate the relative importance of forward model and processing error correlations. Recent work has demonstrated that the observation error correlations are influenced by the smoothing and filtering applied at the processing centres. It is clear that further research is required in this area.

Recommendation to GRAS SAF: This is a potentially interesting research area for the GRAS SAF (visiting scientist activity). Any project will require collaboration with the processing centres and the met services, in order to consider both the processing and forward model/representation error correlations.

5. Can we assume GPSRO measurements are unbiased?

Different smoothing/filtering implementions at the phase-delay level are probably causing small biases between GPSRO data from different centres. This is an example of “structural uncertainty” in the processing.

Recommendation: To conduct an inter-comparison project for the processing centres, at an individual profile level, for bending angle and refractivity profiles. This can build upon the GRAS SAF ROPIC project. Investigate bending angle differences at the 0.1-0.2% level in the stratosphere. Coordination with the ROtrends project is recommended.

6. Specific issues for reanalysis

The value of GPSRO in the reanalysis context is partly dependent on it being unbiased. This means that it should be possible to introduce new GPSRO instruments into the reanalysis without introducing discontinuities in the time series. Clearly the outcome of the ROPIC comparison project (recommended above) and the ROtrends work will have relevance in the context of reanalysis.

Reanalyses need consistently reprocessed data, preferably produced at one centre, with all the reprocessed data available at a single site. QC information such as a "usable range" for the measurements should also be provided.

Recommendation: At least one processing centre should undertake the reprocessing of all GPSRO missions since GPS/MET, for use in reanalysis applications. The data should be accompanied by error estimates and QC/usable range information.

7. Community processing algorithms

The group felt that the Radio Occultation Processing Package (ROPP) would be improved by allowing non GRAS SAF members to contribute to ROPP.

Recommendation to the GRAS SAF: To consider how the ROPP development could be opened up to non GRAS SAF participants.

8. Are systematic differences in the processing of radiosonde and GPSRO measurements limiting the impact of GPSRO?

GPSRO is the first space based system that assimilates data on height levels.

One area of concern is the calculation of geopotential heights in GPSRO forward models and the calculation used in the verification packages. Are they consistent? The DMI Science report 00-05 by Henrik Vedel may be of interest in this context.

Recommendation to NWP centres: The group stresses the importance of considering consistent methods for height calculations when incorporating all measurements in data assimilation systems.

Climate Working Group

Chair: Stephen Leroy, Rapporteur: Andrew Collard; Participants: Gottfried Kirchengast, Huw Lewis, Marc Schroeder, Mark Ringer, Kent Lauritsen

9. Improving GPSRO visibility in the climate community

The formation of a GPSRO International Working Group was discussed. It was noted that international GPSRO working groups in the form of workshops sponsored by the Wegener Center of the University of Graz (G. Kirchengast) and the COSMIC project do exist but do not have status outside the immediate GPSRO development community. There was much discussion on exploring the possibility of appropriate affiliation outside this community.

One suggestion was a model based on that of the CERES team which has set up a climate monitoring advisory panel.

It was also noted that the climate monitoring and climate modelling communities have limited interaction and that it would be desirable to invite representatives of both the climate modelling and the climate detection communities to any GPSRO-based working group.

Recommendation: Set up a climate monitoring working group (with GPSRO as one focus) under auspices of WMO with climate modellers specifically part of the group.

Recommendation: PIs from large missions and research institutions to include climate applications of GPSRO in presentations, especially its unique properties for climate monitoring. PIs should anticipate getting feedback from the climate community on the form of products that is most desirable.

It was further suggested that in order to facilitate the education of the climate community on GPSRO methodology and resources, existing frequently used web pages for projects and data access should provide references and links to two or three of the important tutorial papers on GPSRO. The provision of links to data providers would also be useful.

Recommendation to research and data centres: Standard GPSRO web pages should have prominent links to tutorials on use of GPSRO data and links to data providers. These papers should include:

Fjeldbo, G., A.J. Kliore, and V.R. Eshleman, 1971: The neutral atmosphere of Venus as studies with the Mariner V radio occultation experiments. Astron. J., 76 (2), 123–140.

Kursinski, E.R., G.A. Hajj, J.T. Schofield, R.P. Linfield, and K.R. Hardy, 1997: Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System. J. Geophys. Res., 102 (D19), 23429–2346.

Eyre, J.R., 1994: Assimilation of radio occultation measurements into a numerical weather prediction system. ECMWF Tech. Memo. 199, European Centre for Medium-range Weather Forecasts, Geneva.

Recommendation to GPSRO experts: Produce an up-to-date review paper on the status of GPSRO science including climate applications.

10. Preferred Variables

For climate purposes, as a rule it is preferable to use variables that are as close as possible to the calibrated observable. It is important, however, to address directly the requirements of the customers in the climate community. The requirements of the user community of GPSRO can only be ascertained through verbal interaction. One simple way to bring that interaction about is to ensure that presentations from GPSRO mission teams include climate applications.

To further facilitate the interaction between the climate community and the data providers, research centres should be encouraged to advertise their climate datasets and give detailed accounts of their utility.

Recommendation to research and data centres: Published GPSRO climate data must include error estimates.

Recommendation to Data Providers/GRAS-SAF: Provision of a GPSRO climate data set in the form of suitably gridded monthly means would be of particular use to the climate community. A range of variables should be provided: bending angle as a function of impact parameter/altitude; refractivity and dry pressure as a function of geopotential height. These data should be easily accessible online and in netCDF format.

11. IPCC

The importance of getting results from GPSRO into the next IPCC report was noted. It is expected that any paper that shows a statistically significant trend in GPSRO data will be included in the report. Such papers would probably need to be accepted by December 2011. It was further recommended that the attempt be made to get experts in GPSRO included as contributing authors to the relevant climate monitoring chapters of the next IPCC report. This can be accomplished by contacting the lead authors, who are yet to be identified by the IPCC, on the chapter pertaining to observed trends in the climate system.

Recommendation: If significant climate monitoring results are available, papers demonstrating these trends in GPSRO data should be accepted in peer reviewed journals by December 2011. Essential papers emphasising the unprecedented strengths of GPSRO for climate monitoring must be contributed.

Recommendation: Contact lead authors for relevant chapters of the IPCC Fifth Assessment Report, who themselves have yet to be selected by the IPCC, and get at least one GPSRO expert as a contributing author to these chapters.

12. Absolute accuracy of GPSRO and the need for re-processing

A systematic difference in bending angle between observations of COSMIC and the CHAMP, GRACE-A, and GRAS receivers after processing by different retrieval centres have been found. The magnitude of this error is less than 0.1% in bending angle in the 15–25 km region and is consistent with temperature errors of around 0.2 K immediately beneath that layer. It is not clear whether these differences arise from differing calibration and retrieval methods or from fundamental calibration complications inherent to one or many GPSRO missions.

We anticipate that these differences are related to different implementations of the calibration process (removal of clock error on the transmitter and receiver, precise determination of the transmitters' and receivers' positions and velocities) at the various centres. This can only be checked by calibration of a selected period of GPSRO missions' data through a single calibration chain. Doing so is essential if the claims of GPSRO being a climate benchmark are to be credible.

Recommendation to data providers: In order to understand and, if possible, eliminate systematic differences between GPSRO sensors (i.e., biases between CHAMP and COSMIC), the GPSRO data should be re-processed with consistent orbit calculations and clock corrections. The results should be published in a peer reviewed journal. The relevance of such work to climate monitoring and climate benchmarking in particular should be emphasised insofar as it will be a valuable tutorial regarding the handling of climate benchmark data types.

Explicit recommendation to data providers: In order to implement the recommendation immediately above, the centres that acquire GPSRO data from the various GPSRO missions should make available to the community the raw data, including phase delay, amplitude, and satellite orbital data (in netCDF or, if not, with reading software in Fortran) required to calibrate GPSRO data for a common pre-determined period. It is sufficient that each GPSRO mission provide that data through its web site but not necessarily for global distribution.

13. Is vertical resolution important for climate

Data with high vertical resolution is important in climate research particularly in resolving structures in the tropopause region. For most climate purposes, vertical resolution of 500–1000 m is sufficient. Such resolution is obtained with the current processing. In the case of studies of the planetary boundary layer, significantly higher vertical resolution is needed, probably about 100 m. Such vertical resolution can only be obtained with diffraction and atmospheric multipath correction algorithms, typically some appropriate combination of backpropagation, canonical transform (CT), and full spectral inversion (FSI). Studies of the planetary boundary layer require access to large archives of individual GPSRO profiles with 50–100 m vertical resolution in the lower atmosphere.

14. Are GPSRO Products of Climate Benchmark Quality?

Compared to passive microwave radiances and a variety of in situ sounding systems, GPSRO observations are in a strong position to establish climate benchmark quality.

The phase delay is tied to the international definition of the second, its SI traceability, and therefore has the single most fundamental property of a climate benchmark data type. Also fundamental to space based SI traceability is that multiple paths of traceability be established, each involving different physics, so that the uncertainty of the measurement can be evaluated by direct measurement on-board. For GPSRO, these multiple traceability pathways can be established with those GPSRO missions that have implemented ultra-stable oscillators (USOs) on-board the GPS receiving satellite, namely the GRACE-A and GRAS radio occultation instruments. A study should be undertaken that compares the bending angle and refractivity that result from calibration of GPSRO by (1) double differencing, in which all clocks are referenced to a clock on the ground; (2) single differencing, in which clocks are tied to multiple GPS satellite clocks; and (3) zero differencing, in which the transmitting GPS clock and a USO on-board the receiving satellite are the references. We note local multipath, the error induced by reflection of an occultation signal from some part of the receiver's spacecraft, cannot be resolved by such a study.

Recommendation: A comparison of bending angles or refractivity as determined after calibration using the on-board, the GPS and the ground clocks (double-differencing, single-differencing, and zero-differencing) should be used as standards to determine uncertainty in calibration of phase-delay, therefore establishing it as a climate benchmark.

The L1 and L2 bending angles are derived directly from the derivative of phase delay (although correlated noise is introduced) and these are of benchmark quality. However, the influence of the ionospheric is still included in these measurements and must be completely removed before the occultation data can be interpreted as a strictly atmospheric data set.

There was a suggestion to use L5, a third GPS carrier signal, to provide an independent check of the ionospheric calibration. L5 (115×10.23 MHz carrier frequency) is in its experimental phase on GPS Block IIM-R, and because it is not far separated from L2 in carrier frequency (120×10.23 MHz), we are not certain that it can be used as an independent check of ionospheric calibration using L2.

After ionospheric calibration, wherein the ionospheric influence on bending angle is removed by simple linear combination of L1 and L2 bending as a function of impact parameter, the resulting ionosphere-corrected bending angle is no-longer of benchmark quality because of loss of SI traceability. No independent calibration is possible and hence it is impossible to determine overall uncertainty by direct measurement on-board. It is possible, however, to estimate the error associated with the ionospheric correction in the ionosphere-corrected bending angle by computer simulation. Such simulations have been performed and published. The conclusion is that tropospheric trends of GPSRO data are little impacted by ionospheric residual, and stratospheric trends, while more greatly impacted, have a characteristic error envelope that is inversely proportional to atmospheric density.

Refractivity is not SI traceable either, but the error associated with ionospheric residual and initialization of the Abel integral transform that converts ionosphere-corrected bending angle to refractivity also follows an envelope that is inversely proportional to density. The error envelope is sufficiently small in the troposphere and lower stratosphere so that refractivity is of high enough quality to be useful for climate monitoring.

15. LEO-LEO Occultations

The derivation of water vapour and other key fields through the absorption of electromagnetic signals between low Earth orbiting spacecraft is encouraged. These data are particularly interesting as they require no ionospheric correction and are potentially of climate benchmark quality. Climate modellers remain extremely interested in the evolution of water vapor concentration in the upper air (troposphere and stratosphere).

Recommendation: Continued development and demonstration of the LEO-LEO concept is recommended.

16. The Contribution of NWP to GPSRO Climate Studies

Tools used in NWP, particularly observation operators (simulating bending angle and refractivity profiles), data type converters, have application in climate research. These tools are well tested with well-defined error characteristics. The Radio Occultation Processing Package (ROPP) offered by the GRAS-SAF is an example of this and could be advertised more widely.

Recommendation to data providers: Tools to calculate relevant GPSRO observed quantities from climate models should be provided with the data.

GPSRO sampling patterns are inhomogeneous is space and time, so NWP analysis products are useful for evaluating sampling error. It is not necessary for the NWP analysis to be absolutely accurate because it is the variations associated with synoptic variability that dominantly contribute to sampling error. NCEP analyses are widely used because of their availability. ECMWF analyses are highly desired for estimation of sampling errors but are less used due to access constraints.

Recommendation to ECMWF: ECMWF analysis products should be made available to members of the GPSRO Climate Working Group. [It is still possible to use ECMWF Reanalysis products, but they are difficult to locate.]

The use of GPSRO-derived water vapour and temperature via 1DVar as independent climate products was discussed, particularly issue of the wet-dry ambiguity inherent to GPSRO. The retrievals can be provided with estimated full error covariance matrices which characterise the correlation between the humidity and temperature fields. The influence of the background fields on the final retrievals would need to be quantified. It would be useful if these error covariance matrices can be verified with independent observations (e.g., radiosondes, IASI retrievals) particularly in challenging atmospheric scenarios (e.g., convective regions, regions with strong horizontal gradients). While climate modellers are well accustomed to working in the space of the data (i.e., the channels of the MSU), water vapour derived from GPSRO may be of interest to climate modellers especially if it can demonstrate validated utility for climate studies beyond that of the operational sounders (AIRS, IASI, CrIS).

Recommendation to providers of retrieval products: A validation paper for GPSRO 1DVar retrievals should be written. Validation should demonstrate utility of GPSRO-derived water vapour beyond that of water vapour derived by operational sounders. The influence of the a priori data can be determined by doing two retrievals with separate NWP model fields. Full error covariance matrices should be produced and validated versus independent measurements.

Future Systems Working Group

Chair: John Eyre, Rapporteur: Peter Bauer; Participants: Rob Kursinski, Jens Wickert, Bill Kuo, Dave Offiler, Axel von Engeln, Chi Ao

1. Can we give a recommendation that a GPSRO constellation should be part of the global observing system? What is CGMS involvement and is the space agencies' commitment sufficient?

A radio occultation (RO) constellation is already a part of WMO's implementation plan for the evolution of the global observing system (GOS) which has been presented to the Coordination Group for Meteorological Satellites (CGMS). It also has a prominent position in the new "Vision for the GOS in 2025" that is under development within WMO. CGMS have requested the user community to provide guidance on the optimal number of RO-soundings per day and hence the number of satellites required in a RO-constellation.

The NWP-impact has been well demonstrated but the optimal number of satellites depends on the application:

- at least 1 for stratospheric bias,
- a constellation for global NWP (the current number of 6-8 receivers is very beneficial, and should be regarded as a minimum, assuming that we have GPS transmitters only),
- number for regional NWP is unknown but the horizontal spatial scale mismatch may be an issue,
- for climate applications, the lower threshold is 3-6 for resolving the diurnal cycle.

The data is not being fully exploited yet (e.g. assimilation with 1D operators). **Important**: by the end of the nominal COSMIC lifetime (2011+), the GPSRO coverage will definitely become insufficient unless a follow-on mission has been launched.

2. Are new scientific studies needed for the definition of mission requirements (OSEs, OSSEs, EnDA, etc.)? Studies in late 1990's (MPI) suggested the optimal constellation should be ~24 satellites.

The MPI study does not represent the current status of observing system and data assimilation systems.

The WG strongly supports further studies:

- OSEs should be performed with various scenarios of constellations up to the maximum available number of satellites right now; the background observing system should reflect observing system expected for 2010+.
- OSSEs should simulate similar scenarios and their credibility will depend on how well they match results from OSEs.
- The degree of saturation of NWP impact from the OSEs will determine the relevance of OSSEs for larger constellations.
- The WG encourages trade-off studies (e.g. GRAS vs COSMIC-type) to evaluate the advantage of high-gain antennas with better sensitivity for lower tropospheric (in the Tropics) sensing against the additional cost.

The WG recommends that OSE/OSSE studies shall be undertaken to evaluate the number of GNSS transmitters-receivers required for optimizing global NWP impact. The WG encourages the extension of these studies to also address issues like: vertical resolution, lower tropospheric sounding, impact on tropical cyclone prediction. The WG encourages ECMWF to perform OSEs of the above type and further support the envisaged OSSEs hosted by JCSDA.

3. Dedicated GPSRO constellation vs a constellation of opportunity, e.g. by putting GPS-type receivers on all new Met-satellites. Will the latter meet user requirements?

The decision is affected by cost (e.g. accommodating GRAS on Metop has been costly). The GPS receiver cost alone is not the cost-driver. Being hosted by a meteorological mission may restrict the observation capabilities and the performance (scanning, RFI) that can be driven by other instruments.

Other factors such as implementing high-gain antennas or accommodating the instrument on a satellite may increase cost. However, CHAMP, GRACE, Terrasar are examples for cost-effective opportunity missions with small occultation antennas. Specific mission requirements may be better covered by a dedicated constellation, e.g. diurnal cycle. Dedicated constellations will allow the relaxation of the requirements for operational robustness, with respect to individual components. Satellite attitude control/monitoring seems to be less of an issue. NWP usage is driven by data timeliness - it may therefore be problematic with missions of opportunity unless GPSRO is hosted by operational meteorological satellites.

It was noted that geodesy has contributed greatly to the development of GPSRO science, in particular by helping to improve the near-real time precise orbit determination of GPS receivers and GPS transmitting satellites. Geodesy missions have also contributed to the actual deployment of current GPSRO receivers (e.g. CHAMP and GRACE) that now benefit the meteorological community. The deployment of future GPSRO receivers for meteorology missions may further benefit from a synergy with the planning of geodesy mission carrying GPS receivers.

Recommendation:

To <u>operational</u> agencies: Given the above considerations, dedicated constellations appear to be the most cost-effective option to fulfil user requirements for future operational missions.

To <u>research</u> agencies: The WG also encourages research agencies to implement additional receivers on experimental satellites.

4. Summary of the status of proposed constellations (COSMIC-2, CICERO, Iridium, others). What are the user requirements that drive the choice for a constellation?

- Ensure strong interaction between data users and data providers on definition of data content (including raw data, information on detailed instrument specifications, characterization and processing) and data quality.
- Future systems should conform to WMO requirements for systems to be part of the GOS, including free and timely data distribution to all users as well as optimal global coverage, including the diurnal cycle (climate).

Given the option of commercial data acquisition, it will be important that data/metadata are provided in sufficiently raw form to serve the diverse needs of the user community and to allow for future developments given the early stage of the exploitation of GNSS observations at this time.

The WG was aware of the following mission concepts:

- COSMIC-2: 6+1 from Taiwan + 6 from US, GPS/GALILEO/GLONASS with governmental funding.
- CICERO: 12-24 satellites, GPS/GALILEO/GLONASS.
- Iridium-2: 66 satellites, many or all of which could have RO-receivers. The status of Iridium-2 and possible NOAA involvement is unclear. EUMETSAT and the EU are not likely to consider cooperation in the near future.
- National initiatives: German constellation of nano-satellites subject to funding - but this not planned as an operational mission.
- Decadal survey recommendation: CLARREO (3 satellites) in NASA study-phase. Note that all 9 recommended missions are supposed to carry GNSS receivers.

Timeliness: Final cost/design is also a function of the timeliness requirements. E.g. the stated space weather warning requirements is 5-minute access, but some benefits may still be obtained with a longer delay. Whether a 5-minute requirement is realistic for the combined measurement time, down-link and processing/distribution is unclear.

5. Multiple-GNSS receivers (GPS/GALILEO/GLONASS and others): Should any new mission have multiple-GNSS receivers (Metop-C)? What is the cost impact?

Yes, receiver upgrade will be cheaper than launching separate satellites. Specifically, upgrading Metop-C's GRAS to receive GALILEO transmission should be considered. Accurate orbit determination is required for any new transmitter system to ensure optimal data usage. A fiducial ground network is required to provide support for precise orbit/clock determination.

6. What is the value of LEO-LEO measurements and the information content compared to existing satellite measurements?

The primary purpose of LEO-LEO measurements is UT/LS humidity for climate variability monitoring.

The NWP application is difficult to estimate due to uncertain moisture distributions near UT/LS in models (also manifested in lack of moisture radiance data assimilation). LEO-LEO promises to better distinguish between temperature and moisture and therefore provide additional capabilities to profile frontal zones at high vertical resolution, PBL identification and more accurate surface pressure information.

The WG encourages more simulation (e.g. cloud impact) and airborne demonstrator studies, potentially followed by a LEO-LEO proof-of-concept demonstration using 22 and 183 GHz channels (183-channels have more sensitivity where moisture contents are low). The active observation principle will provide better bias characteristics than existing limb MW radiometers.

7. What is the potential of exploiting reflected GNSS data?

Grazing reflections can be exploited now using the given occultation geometry:

- Improvement of atmospheric applications.
- Ocean altimetry: coverage better than altimeters, accuracy about 20 cm or better.
- Ice depth/coverage: Depth more relevant than coverage, accuracy?

Additionally, nadir (possibly with large antennas) observations can provide:

- Soil moisture: accuracy open, more studies should be undertaken to demonstrate sensitivity. Observation geometry and antennas may not be sufficient.
- Wind speed/direction (nadir-view) over oceans: Accuracy may be sufficient at low wind speeds with current systems. Large antennas required.
- Ocean topography resolving smaller-scale eddies.

The WG encourages more detailed studies on the exploitation of existing grazing reflection signals and in those areas requiring different observational capabilities.

8. Do we need an international GNSS RO Working Group, similar to ITWG, IWWG, IPWG?

The WG supports the idea of a new WMO-endorsed working group (also to not distract from focus of others by integrating group in, e.g., ITWG). An interface to the WMO space programme is expected to have a beneficial impact on future mission support (COSMIC-2).The group could report to CGMS.