

5th ROM SAF User Workshop on the Applications of GNSS-RO observations

Background

The 5th ROM SAF user workshop on the applications of GPS-RO measurements was hosted by ECMWF on June 16-18, 2014. The workshop was attended by around 30 international scientists, with expertise in both GPS radio occultation and climate applications. It followed the standard format of a series of presentations, followed by a day in NWP and climate working groups, and then a plenary session.

The workshop presentations are available at:

<http://www.ecmwf.int/en/rom-saf-workshop-presentations>

Plenary session

The reports from the NWP and climate working groups were presented at the workshop plenary session. This was attended by nearly all of the workshop participants, and other observers from ECMWF. The group emphasised that GNSS-RO is now clearly an important measurement technique for both NWP and reanalysis applications.

The following recommendations were made during this session:

- ***PLEN1: Recommendation to the ROM SAF. The ROM SAF GNSS-RO reanalysis should focus on the COSMIC period, from 2006-2014.***
- ***PLEN2: Recommendation to the EU Copernicus Programme, ESA and EUMETSAT. Consider adding GNSS-RO instruments on to the Sentinel 1,2,3 missions.***

The detailed working group reports and recommendations are given below. The full list of recommendations is at the end of this document.

NWP Working Group Report

Chair: Josep Aparicio; rappporteur: Sean Healy

Participants: Lidia Cucurull, John Derber, Nathalie Boullot, Harald Anlauf, Chris Burrows, Ian Culverwell, Nick Yen, Bill Kuo, Sergey Sokolovskiy, Hataek Kwon, Ji-Sun Kang, Thomas Grelier, Dave Offiler, Stig Syndergaard, Estel Cardelach, Carla Cardinali (part time) and Steve English

The working group considered a set of proposed discussion topics and questions. These are given in **bold face**, with supplementary information to the question given in *italics*. The main recommendations are written in **blue**.

Are most Global NWP centres are now assimilating bending angles? *Do we expect all global NWP users to move to bending angle soon? In 5 years time will we need the refractivity profile dissemination in near-real-time (NRT)? Should the ROM SAF plan to continue this product in NRT over the next 5-10 years?*

Environment Canada currently assimilates refractivity, and it is proving difficult to justify the move to bending angle in forecast impact experiments. The group noted that refractivity is used for quality control (QC) at some institutes. In addition, some non-local (2D) phase/refractivity observation operators require refractivity.

→ **NWP1: Recommendation for the ROM SAF and other data providers. Continue to provide refractivity in NRT for NWP users.**

It was noted that the 1D-Var level 2 products contained in the NRT BUFR files are useful for comparison and validation activities.

→ **NWP2: Recommendation for the ROM SAF and other data providers: Continue to provide 1D-Var level 2 products in NRT BUFR files.**

Assimilation of GNSS-RO into regional (limited area/mesoscale) models: *latest work/ any specific challenges?*

The group noted that observations close to the domain boundaries may be problematic. The impact of the broad horizontal scale-length of the observations needs also to be considered carefully. The best results may require non-local (2D) operators. Assimilation without the need for bias correction is clearly useful. Increasing the height of the model lid might be necessary for bending angle assimilation, and it was noted that this would also improve the assimilation of radiances. The limited number of observations available for assimilation was identified as a potential problem.

→ **NWP3: Recommendation to data providers. Improve the timeliness of the GNSS-RO data to improve numbers available for assimilation into regional model.**

There are existing studies with the ALADIN system, and NCEP have a demonstrated a positive impact in their regional model, but the group considered further studies are required in this area.

- ***NWP4: Recommendation for the ROM SAF. Consider a visiting scientist activity to investigate the impact of GNSS-RO in regional models. Consider, for example, the impact on precipitation scores and high impact events, if possible.***

At the plenary session, it was asked if the purpose of data assimilation in regional models was to provide large scale information. This should also be considered in the VS activity.

GNSS-RO impact on tropospheric humidity: *“impact smaller than expected?” Is this a problem with the assimilation approach, or is it reflection of the **actual** GNSS-RO information content, relative to other observing systems assimilated?*

The group believes that the impact on the humidity is primarily limited by model error/bias and the background error covariance. Therefore, improvements in these areas will have a beneficial impact on the GNSS-RO assimilation. However, the impact of GNSS-RO may be improved by better quality control (QC) and the use of situation dependent observation error statistic estimates.

- ***NWP5: Recommendation to data providers. Include situation dependent QC parameters for scaling observation error statistics. In addition, provide documentation of method used to aid interpretation at the NWP centres.***

- ***NWP6: Recommendation to ECMWF/other NWP centres. Continue to investigate the impact of 2D observation operators on humidity analyses and forecasts.***

Assimilation below a ducting layer/in presence of sharp refractivity gradients: *ROPP bending angle code includes a maximum refractivity gradient when computing the bending angle and does not assimilate below a ducting layer. This is very conservative but it circumvents problems with the 4D-Var linear assumption. Can we really extract information below these sharp layers?*

The group noted that retrieving information below a sharp structure/ ducting layer is currently a research problem, and NCEP are already pursuing this. It was noted that the high resolution GNSS-RO data may be of use in this context.

Latest work on GNSS-RO refractivity (bending angle) bias

It was noted that the ECMWF negative bending angle bias was reduced after the inclusion of the maximum refractivity gradient in the bending angle computation. The measurement technique struggles most with very sharp vertical gradients and the largest measurable bending angle was estimated at ~0.03 microradians. It was suggested that sources of bias included convection and insufficient signal to noise ratio (SNR). New results on this will be presented at UCAR meeting (October 2014).

GNSS-RO Forward model development

A number of proposed scientific modifications to the forward models were discussed.

The inclusion of liquid water/ice in the expression for refractivity. *A recent paper (Zou et al 2012, J. Atmos. Sci., 69, 3670–3682) has suggested that this is necessary to reduce a refractivity bias.*

This proposal has not been tested by operational NWP users.

- **NWP7: Recommendation to ECMWF. Test this result before proposing any changes to the ROPP operators.**

Assimilation of reflected signals

Environment Canada and IEEC have a joint study to investigate the assimilation and impact of reflected measurements. It was suggested that this should be completed before adapting the existing observation operators.

Assimilation with 2D bending angle operators: *Are most NWP centres planning to develop/implement 2D operators?*

In general, the group expressed the wish to move to 2D operators, or perhaps a 2D/1D hybrid approach for the 4D-Var inner and outer -loops. The problems associated with occultation planes crossing PE boundaries might be solved in different ways to the ECMWF approach, for example using larger halo regions.

- **NWP8: Recommendation to the ROM SAF/ECMWF. Continue to develop the 2D bending angle operator.**
- **NWP9: Recommendation to other NWP centres. Other centres encouraged to develop their own 2D implementations/approaches.**

New ideas after assimilating with GNSS-RO 2D operators?

The purpose of more complex operators is to reduce representation error, but this has to be balanced with computational efficiency and cost. The forward modelling of Doppler/phase is challenging, because of the need of the ray path to fit the satellite locations. It was noted that this also requires some ionospheric information. Furthermore, in 10 years combined ionospheric/NWP models will be available at some centres. Therefore, the capability of assimilating L1/L2/... will be required. It was noted that 1D L1/L2 operators will be available in the ROM SAF ROPP 8.

- **NWP10: Recommendation to the ROM SAF. Continue to develop the L1/L2 operators for direct assimilation into combined NWP/ionospheric models.**

The Spanish satellite PAZ will be launched this year.

One of the aims is to demonstrate the feasibility of polarimetric RO, potentially retrieving information about heavy precipitation and clouds. The group considered this as a research topic, and a 2D retrieval scheme is required to demonstrate the information content of the observations. Furthermore, the assimilation of cloud and rain is a challenging problem. However, if the value of the observations can be demonstrated, the observation operators will need to be modified accordingly.

Is continuity of refractivity gradients important in bending angle forward models? *It is not enforced in the ROM SAF codes.*

Two issues were identified. 1) Does it improve the forward model accuracy? 2) Are there minimization/adjoint issues? The group felt that technical issues like this could only be investigated in

a dedicated forward model comparison exercise. A 55 profile dataset of model N(z) is available for such a study.

→ ***NWP11: Recommendation to the ROM SAF. Co-ordinate a forward model comparison study.***

Observation error statistics estimates

The group discussed possible joint studies comparing the “Desroziers” observation error statistic estimates from different NWP systems. It was recognised that this could be difficult to interpret because of the different representation errors in the NWP systems. The importance of including error correlations was discussed.

→ ***NWP12: Recommendation to ECMWF. Investigate the impact of correlations produced by the Desroziers approach in a 1D-Var information content study. Investigate the impact of a more sophisticated observation error statistic model in 4D-Var. EG, variation with latitude, correlations, rising/setting differences.***

GNSS-RO as a tool for verification

When verifying against radiosonde observations in the Southern Hemisphere, we are comparing against around 35 sites. GNSS-RO could be a useful verification tool, particularly for stratospheric temperature information. NCEP are well placed to investigate this, having a system that routinely computes verification statistics against aircraft, ships, buoys, etc. The inclusion of GNSS-RO is a purely technical issue, adding the GNSS-RO forward operator to the verification code.

→ ***NWP13: Recommendation to NCEP. Investigate the use GNSS-RO for forecast verification, and consider the added value. Report back to other NWP centres by making web-based verification statistics available.***

How to transfer GRUAN quality to other radiosondes?

The possibility of using GNSS-RO data to diagnose problems with radiosondes was discussed. GNSS-RO is already being used to revise radiosonde radiation corrections. The GRUAN network has high quality radiosondes. A new idea is to compare GNSS-RO departure statistics obtained at the GRUAN sites with other radiosonde sites.

→ ***NWP14: Recommendation to the ROM SAF. Consider a VS activity to investigate the use of GNSS-RO to compare quality of GRUAN radiosondes with other radiosonde data. Build on the existing NCEP work on radiosonde bias correction.***

Data issues

Resolution/sampling required between 10-20 km for NWP? UCAR have asked for consideration of an upgrade to their NRT output. These include

- *change in observation location*
- *change in geometrical optics/wave optics transition height*
- *changes in filtering of data*
- *Bending angles on fixed impact heights.*

The group found it difficult to give clear recommendations on these changes, but it was noted that the contents of the NRT BUFR files should be determined by NWP users.

A “significant change” of the data processing usually requires 3 months of trial data to be made available to the NWP centres.

UCAR are planning to make a trial dataset available in September 2014.

EUMETSAT GRAS L2 transition height for rising occultations?

There is a clear difference in the GRAS departure statistics for rising and setting measurements. This appears to be caused by the need to extrapolate the (L1-L2) bending angles below 20 km with the current instrument configuration, which was chosen to minimize problems with data gaps. The rising and setting data are assimilated assuming the same error statistics, and there is a question whether EUMETSAT should revert to a previous instrument configuration.

→ ***NWP15: Recommendation to ECMWF/Met Office. Investigate the impact of rising Metop occultations and report to EUMETSAT to inform their strategy.***

Meta data in BUFR files: Position/velocity/azimuthal angles. The need for precise, consistent definitions.

There are inconsistencies in contents of the NRT BUFR files provided by different processing centres. These seem to arise from a lack of precision in the original definition of some variables. For example, the locations of the observations will depend on the processing centre. This issue has been discussed previously at IROWG, but there is a question about who should be responsible for providing the precise definitions.

→ ***NWP16: Recommendation to IROWG. Set up an IROWG working group to unify the content of the BUFR files.***

COSMIC-2

There will be no change in format. The data will be available “immediately”. NWP centres should aim to feedback within 3 months of release.

ROM-SAF Climate Working Group Report

Chair: Axel von Engel; Rapporteur: Andras Horanyi

Participants: Bill Randel (part-time), Dian Seidel, Hans Gleisner, Mark Ringer, Gottfried Kirchengast, John Eyre, Tony McNally (part-time), Joe Nielsen, Torsten Schmidt, Kent Lauritsen, Rob Kursinski, Feiqin Xie, Irina Sandu (part-time)

THE MAIN DISCUSSION POINTS AND CONCLUSIONS

Main Themes discussed:

- Climate monitoring
- Climate model evaluation
- Process studies
- (ROM-SAF/ECMWF) products and outreach

Although re-analysis activities are also relevant for this group, it was left for Plenary Discussion since the group composition did not cover re-analysis experts.

General Points:

- GNSS-RO has been adopted quickly in the NWP community since they have a clear objective to improve forecast and a clear evaluation of the impact by measuring improvements in forecast skill – GNSS-RO use in NWP is a success story.
- GNSS-RO use in the climate community needs to be promoted through a different process; work needs to be done towards the user, e.g., show applications and potential (OBS4MIPS: Observations for Climate Model Intercomparison is a good example to follow where data sets are specifically generated for climate models). This should be addressed by:
 - A refocusing of RO groups toward climate products, including full uncertainty estimates.
 - Providing short, focussed publication to discuss climate capabilities and limitations.
 - Build closer relationships with the broader climate community, treat them as partners and not just data users

The most important recommendations:

- ***Focus efforts on product improvements, including accurate uncertainty estimates [CLIM02]***
- ***Keep the maximum reasonable resolution, along with the impact on uncertainties [CLIM07]***
- ***Engage with the wider climate community through:***
 - ***Provision of peer-reviewed paper on pros and cons of GNSS-RO [CLIM16]***
 - ***Pilot studies on generating RO-type products from climate model runs (tools to simulate RO observations from model have recently been made available). The ROM SAF is ideally positioned to start this activity through closer interaction between the Met Office NWP and Hadley Centre sections. [CLIM19]***
 - ***Engagement with the wider modelling community in a broader inter-comparison study of climate model runs, e.g. within CMIP7 [CLIM20]***

- *Potential involvement in IPCC report generation through CMIP7 discussions and evaluations [CLIM21]*

THE DETAILS OF THE DISCUSSION AND RECOMMENDATIONS

CLIMATE MONITORING

Question: What is the minimum duration of the GPS-RO time-series required, before the data are routinely used in climate monitoring activities? Where do we expect GPS-RO to have the biggest impact? How would the GNSS-RO be used? Variables? Bending angle, refractivity or (P,T, Z)?

Discussion:

- Longer the time series are the better
- Can RO data help in understanding the SSU data?
- Potentially include GPS/MET data in this activity (as a reference point in re-analysis), although the GPS/MET period falls into the NOAA 11 data gap?
- More research required to process GPS/MET data during A/S (Anti-Spoofing) on phase, using single frequency processing. JPL/UCAR/Moog working on this. Although 4 weeks with A/S off should be sufficient to provide an anchor point in re-analysis. Time series duration/usefulness depend on application.

Recommendations:

- ***CLIM01: Include GPS/MET A/S off data in re-processing of RO data sets.***
- ***CLIM02: Regular re-processing should be done by different centres (ROTrends/SCOPE-CM RO-CLIM).***

Question: Impact of residual ionospheric errors, and variation with solar cycle? Mannuci et al (AMT 2011, 2837-2850) suggest this is a significant problem based on a case study. “ ... even at 20 km altitude, ionospheric residual remains too large for climate monitoring applications during daytime solar maximum conditions.” (page 2848). Residual ionospheric errors would seem to be more problematic when using the temperature retrievals than - say - bending angles, because of noise amplification in the retrieval process. Are the residual errors more problematic for CHAMP because of altitude? Implications for the combined time-series from (CHAMP + COSMIC)? New ideas on modelling the residual ionospheric errors. Recommend further studies?

Recommendations:

- ***CLIM03: Initiate further investigation into residual ionospheric errors by RO community (partly ongoing), findings will feed into the uncertainty estimation.***
- ***CLIM04: EUMETSAT to re-assess the impact of extended L2 extrapolation in their Metop/GRAS processing and potentially revert to the old configuration (in order to avoid a possible degradation of climate quality)***

CLIMATE MODEL EVALUATION

Question: How is satellite data currently used to test/validate climate models? Forward modelling to raw measurements, or using retrievals? What new information could GPS-RO contribute to this

activity? How are reanalyses used for testing climate models? What additional information would the GPS-RO climatologies contribute? Is the GPS-RO data easy to use in this context? (Format etc)

Discussion:

- Lead people towards bending angle, start with known variables, e. g. temperature or refractivity.
- All RO data types actually have strengths and weaknesses.
- Model evaluations will likely be limited to just one variable.
- There is no “ideal” RO climate variable, thus activities should address all available ones with respect to particular applications.

Recommendations:

- ***CLIM05: Explore different RO variables and their characteristics with respect to the given climate application (e.g. model evaluation)***
- ***CLIM06: Provide a short and focussed publication discussing the climate capabilities and limitations of RO (e.g. to be done through the RO-CLIM SCOPE-CM activity)***

PROCESS STUDIES

Question: Would GNSS-RO gravity wave and tropopause height products be useful for climate model developers?

Discussion:

- No strong links exist with the climate community so far
- The need for such products depends on the users (e.g. Met Office would be interested in)
- Effort should go more to the temperature profile (vertical resolution is important and should be specified), including its uncertainties
- What is the best useful vertical resolution?
- Close collaboration is needed with the various climate user communities
- Profiles with extra derived parameters should be provided and the algorithm how the derived products are computed
- Short documentation is essential to prevent mis-use of data
- Different requirements for expert and non-expert users (short fact sheet with caveats and potential)
- Only reliable products should be provided
- See the way how the data can be published, for instance:
<https://www.earthsystemcog.org/projects/obs4mips/tech-notes>

Recommendations:

- ***CLIM07: Preferably vertical profiles should be given with maximum reasonable resolution together with uncertainty estimation. If derived quantities are provided, then the algorithm how the quantity is computed should be also given.***
- ***CLIM08: Investigate the OBS4MIPS dataset requirements and create similar ones based on GNSS-RO data.***

→ ***CLIM09: Initiate investigations into Gravity Wave parameters from GNSS-RO at ROM SAF***

Question: Suggested collaboration with GRUAN; “Look into tropopause and planetary boundary layer comparisons between GRUAN and GNSSRO”.

Discussion:

- The link to the application, e.g. climate, needs to be present in order to provide valuable information/products

Recommendations:

- ***CLIM10: consult with application experts on products, such as AMSU like brightness temperatures, preferably team up for collaborative projects.***
- ***CLIM11: 3G (GRUAN, GSICS, GNSS-RO) like meeting to be followed up and to extend collaboration to include application experts***

Question: PBL from GPS-RO: Error characteristics well understood/quantified? E.g., horizontal gradient errors?

Discussion:

- The issue needs further investigation.
- PBL height in NWP and climate model has high uncertainty, RO could provide valuable information.
- Different PBL height estimates give us different information on the PBL, such as cloud layer depth.
- Over ocean: marine Sc; very relevant for climate feedback.

Recommendation:

- ***CLIM12: Continue PBL investigations, establish link to other PBL height estimates and investigate combination of PBL height parameters to infer further information, engage with PBL parameterization (CFMIP-Cloud Feedback Model Intercomparison Project) community.***

(ROM-SAF/ECMWF) PRODUCTS AND OUTREACH

Discussions: Initial phase of COSMIC-2 deployment allows focused gravity wave investigation since profile observations are close together.

Recommendations:

- ***CLIM13: Geopotential height of dry pressure surfaces products to be produced***
- ***CLIM14: Work on ROM SAF products such as PBL height, tropopause height should continue***
- ***CLIM15: Consider focussing resources on early phase of COSMIC-2 constellation deployment for gravity wave studies***

Question: WMO 3G workshop, May 6-8, 2014. What is the value of this activity?

Also from 3G workshop: “Bring up at ROM SAF workshop interest in a potential RO community-based climatological dataset for the broader climate community for model validation and variability studies.” It was very clear that the non GNSS-RO attendees expressed a wish to see a single, recommended dataset so they do not have to choose one.

- Having multiple processing centres is clearly a positive in general, but non experts want a recommendation of which one to use.
- Does the GNSS-RO community think this is a good idea?
- How would we determine the single GNSS-RO community dataset? E.g., take a simple average of the RoTrends climatologies, or choose a specific provider?

Discussion:

- No detailed conclusion was reached on the issue of single or multiple datasets, however it was felt that in practise there would be always various datasets available. The existence of different datasets can help in the uncertainty estimation. It was however also pointed out that the different data sets can best be assessed within the GNSS-RO community, although with several data sets available an outsider would need clear guidance on advantages / disadvantages of a particular set.
- OBS4MIPS is considered as an example for data provision. Discussion on having data provision and/or collaboration. The importance of collaboration was emphasised.
- Resources are needed to be allocated for such collaborative activities
- Documentation is essential and should be provided for the users
- Uncertainties in the data should be expressed and documented.
- ROM-SAF activities are gradually moving towards climate needs. So additional pro-active efforts are required to engage the climate community

Recommendations:

- ***CLIM16: Provide a peer-reviewed paper on pros and cons of GNSS-RO data***
- ***CLIM17: Provide literature data base that lists RO publications by theme***
- ***CLIM18: Evaluate literature with respect to study focuses (bibliometric analysis)***
- ***CLIM19: ROM-SAF pilot study on generating RO products from climate model runs (model to RO tool; e.g. through activities within Met Office between NWP and Hadley Centre sections)***
- ***CLIM20: Engage wider modelling community in a broader inter-comparison study of climate model runs, e.g. within CMIP7.***
- ***CLIM21: Potential engagement in CMIP7 as potentially entry point to IPCC***

LIST OF RECOMMENDATIONS

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- NWP1: Recommendation for the ROM SAF and other data providers. Continue to provide refractivity in NRT for NWP users.
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- NWP6: Recommendation to ECMWF/other NWP centres. Continue to investigate the impact of 2D observation operators on humidity analyses and forecasts.
- NWP7: Recommendation to ECMWF. Test this result before proposing any changes to the ROPP operators.
- NWP8: Recommendation to the ROM SAF/ECMWF. Continue to develop the 2D bending angle operator.
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