ROM SAF Report 46
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EUMETSAT ROM SAF
RADIO OCCULTATION METEOROLOGY

ROM SAF Report 46

8th EUMETSAT ROM SAF user workshop on GNSS radio occultation measurements

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1.0	20/12 2014	KL	First version of Report from UW8 Workshop. Input provided by Chairs and Rapporteurs (K. Lonitz, H. Anlauf, H. Gleisner, J. K. Nielsen, S. Elvidge, R. Notarpietro)

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing centre under EUMETSAT which is responsible for operational processing of radio occultation (RO) data from the Metop, Metop-SG and Sentinel-6 satellites and radio occultation data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, humidity, and other geophysical variables in near real-time for NWP users, as well as reprocessed Climate Data Records (CDRs) and Interim Climate Data Records (ICDRs) for users requiring a higher degree of homogeneity of the RO data sets. The CDRs and ICDRs are further processed into globally gridded monthly-mean data for use in climate monitoring and climate science applications.

The ROM SAF also maintains the Radio Occultation Processing Package (ROPP) which contains software modules that aid users wishing to process, quality-control and assimilate radio occultation data from any radio occultation mission into NWP and other models.

The ROM SAF Leading Entity is the Danish Meteorological Institute (DMI), with Cooperating Entities: i) European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, ii) Institut D'Estudis Espacials de Catalunya (IEEC) in Barcelona, Spain, iii) Met Office in Exeter, United Kingdom, and iv) and Wegener Center, University of Graz, in Graz, Austria. To get access to our products or to read more about the ROM SAF please go to: https://rom-saf.eumetsat.int

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List of Contents

Abstract

GNSS radio occultation (GNSS-RO) measurements are an important and well-established component of the global observing system. With more than 10,000 occultations per day available, we are now starting a data-rich era and it is important to exploit the measurements in the best way possible.

This workshop, organized by ECMWF and the EUMETSAT Radio Occultation Meteorology Satellite Application Facility (ROM SAF), reviewed the use of the GNSS-RO data at the major NWP centres, and explored how the assimilation of the measurements can be improved using more sophisticated observation operators. The value of GNSS-RO as "anchor measurements" for estimating the bias correction of satellite radiances was emphasised. The workshop also covered new work on polarimetric RO (PRO), and reviewed the work on climate monitoring and space weather with GNSS-RO.

This workshop was co-sponsored by ECMWF and the EUMETSAT ROM SAF. The workshop helped to inform future research and development directions for the ROM SAF.

The workshop was attended by around 35 international scientists, with expertise in using GNSS radio occultations for NWP, climate applications and space weather. It followed the standard format of a series of presentations, followed by NWP, climate working and space weather working groups, and then a plenary session. The presentations from the 8th user workshop are available at the website: https://rom-saf.eumetsat.int/workshops/uw8/

The NWP working group highlighted that there is a strong need to exploit the data as much as possible, in terms of looking into improving observation uncertainty models, refining approaches in forward modelling and making use of new observations.

The climate working group emphasised the need for more actively engaging in using RO data as a tool for answering questions that are relevant for IPCC and also to continue developing and implementing rigorous uncertainty quantification for the full processing chain.

Overall, this was a useful and enjoyable workshop, which benefited greatly from the diversity of the participant's research interests.

1. Plenary session

The reports from the NWP, climate and space weather working groups were presented at the workshop plenary session. Nearly all the workshop participants and other observers from ECMWF attended this.

The following recommendations from the working groups were discussed during this session:

- Continue support for the ROM SAF NRT monitoring and products
- Understand the importance of spatial and temporal distribution and magnitude of impact especially in the lower troposphere
- Act to a fast changing environment, e.g., availability of commercial RO data
- Need for more actively engaging in using RO data as a tool for answering questions that are relevant for IPCC
- Provision of electron density profiles and associated uncertainty
- Provision of additional data (sTEC, pTEC, scintillation indexes) and of an observation operator through ROPP that allows users to assimilate ionospheric bending angle profiles

The detailed working group reports and recommendations are given in the following three sections. The workshop programme is included at the end of this report.

2. NWP Working Group Report

Chairs
Katrin Lonitz (ECMWF), Harald Anlauf (DWD)

Participants
Joe Turk (JPL), Ben Ruston (JCSDA), Mary Forsythe (UKMO), Sean Healy (ECMWF), Xuanli Li (NOAA), Estel Cardellach (IEEC), Ramon Padulles (ICE-CSIC), Neill Bowler (UKMO), Daisuke Hotta (JMA), Jennifer Haase (Scripps Institute of Oceanography), Dominique Raspaud (Meteo France), Mi Liao (CMA), Congliang Liu (National Space Science Center), Josep M. Aparicio (Environment Canada), Philip Jales (Spire), Stig Syndergaard (DMI)

Discussion

There was a good discussion on various topics. One recurring example was if we should attempt to quantify the additional benefit to NWP of observations from satellites with equator crossing times (ECT) away from the main cluster. That means to study, e.g., observations with ECT of around 3 am/3 pm. This could be done with an explicit study on timing. We could use FY3's and/or other data sources if available as work for a visiting scientist.

In terms of **observation impact studies** three areas were discussed:

1. To understand the data assimilation impact of observations in the troposphere and attempt to explain why this is relatively small.

   Here the following questions arose:
   - What is the key factor in instrument design for RO performance in the troposphere?
   - Is it the data or not making enough use of the data in assimilating the RO data "correctly"?
   - What can the ROM SAF do to improve the impact in the troposphere?
   - Explore influence of different choices of signal cut-off in data processing?
   - Explore multiple bending angles in data?
   - Are current approximations in forward operators limiting the usage in the troposphere?

2. Scientific studies needed to explore underused information in the data. For that one could think about using a "better" or more dynamic observation error model and quality control. Also to exploit ROMEX data to reassess the approaches we are taking.

3. Add more flexibility to react to sudden changes, e.g., evaluation of new (commercial) data and ROMEX data. This is important to a wider community. To undertake

individual studies should be possible, testing new data or different processing to improve data products. This can be modelled after AMV analysis reports in NWP SAF. **React to changing (satellite/obs) to create products w/o consultation of SG.**

For the **Forward Model** the group thinks it is necessary to do a state of the art review of what is currently used; i.e. strengths and weaknesses. Also, test the forward models, e.g., settings in ROPP-2D forward model, 1D vs. 2D, in high impact weather events (TCs, AR cases). One could use ROMEX 2 data for that.

For high resolution data **products** it is important to have software to do the processing (averaging/smoothing/sampling of profiles) so users are supported. Here, we could use test data (maybe different configurations). Furthermore, refractivity products shall continue in NRT. For 1D-Var products (temperature, specific humidity, surface pressure) the continuation as NRT in BUFR (e.g., as quality variables or as formal operational products) needs to be examined. For this, a user survey is needed. Recommendation pending on outcome.

In terms of **processing** a systematic assessment of uncertainties/ambiguities in the retrievals is needed. For example we could do a "ROtrends" for troposphere: comparing BA retrievals from a number of processing centres, e.g. by selecting a case, for what the different processing centres provide data.

For **polarimetric RO**, it will be important to develop an improved 2nd version of the forward operator for the next CDOP phase with a first version going to be implemented into ROPP by 2027. Details need to be discussed further pending on the outcome of possible impact studies funded outside of ROM SAF. We recommend evaluating the potential impact using existing PRO data comparing microphysical schemes on modelling deltaPhi. Does ROPP need to be adapted to work with PRO data?

For **airborne RO** the first version of ROPP forward operator is going to be implemented into ROPP by 2017. Can we identify areas of future research to improve version 2 of this operator for the next phase of CDOP?

Recommendations

The discussions led to the following set of recommendations for ROM SAF and the RO community:

REC-NWP-01: The NWP Group recommends that the ROM SAF should continue support for the ROM SAF NRT monitoring, alerts and provision of uncertainty estimates.

REC-NWP-02: The NWP Group recommends that the ROM SAF should undertake a study to analyse the importance of data with complementing equator crossing times.

REC-NWP-03: The NWP Group recommends that the ROM SAF should run studies to understand the magnitude of impact of RO data in the troposphere.

REC-NWP-04: The NWP Group recommends that the ROM SAF and RO community should assess sensitivity to using different observation error models for the assimilation of RO data.

REC-NWP-05: The NWP Group recommends that the ROM SAF should do similar study as done for NWP SAF AMV analysis reports to be able to react to sudden changes in RO data streams faster than previously.

REC-NWP-06: The NWP Group recommends that the ROM SAF should do sensitivity studies with current forward models for RO.

REC-NWP-07: The NWP Group recommends that the ROM SAF shall continue refractivity products as NRT.

REC-NWP-08: The NWP Group recommends that the ROM SAF should assess how far NRT is still necessary for 1D-Var products.

REC-NWP-09: The NWP Group recommends that the ROM SAF should do "ROtrends" for troposphere, to determine how sensitive the operational bending angles are to processing choices.

REC-NWP-10: The NWP Group recommends that the ROM SAF should develop an enhanced forward operator for Polarimetric RO.

REC-NWP-11: The NWP Group recommends that the ROM SAF should identify areas of improvements for Airborne RO processing and assimilation.

3. Climate Working Group Report

Chair
Hans Gleisner (DMI)

Rapporteur
Johannes Nielsen (DMI)

Participants
Gottfried Kirchengast (Wegener Center), Hans Gleisner (DMI), Johannes Nielsen (DMI), Kent B. Lauritsen (DMI), Marc Schwärz (Wegener Center), Mi Liao (CMA), Ricko Yudistira (Univ. Reading), Sean Healy (ECMWF)

Discussion

The starting point for the discussions within the climate group was the information provided by Peter Thorne, Maynooth University (in his presentation at the workshop) and Mark Ringer, Met Office (in an email sent to the organizers before the workshop). In his presentation, Peter Thorne was very explicit on the developments he would like to see for the ROM SAF data to be of more relevance to climate science in general and the IPCC assessments in particular. In his email, Mark Ringer had a series of rather concrete suggestions of topics where ROM SAF data could have an impact central to climate science. In addition, Mi Liao (CMA) had some suggestions involving reprocessing of FY-3 GNOS RO data and possible collaboration with the ROM SAF.

The topics that the discussions touched upon were the following:

- RO data has helped to start to resolve the scientific questions related to the amplification of the tropical troposphere warming, as witnessed by the contribution to the IPCC AR6 report. However, it was noted that in AR6, RO data is not used for model validation or for detection and attribution (D&A), because of a lack of published studies.

- Important to identify science questions. Climate users prefer an effort to demonstrate application.

- Peter Thorne: If you want RO to be more used and visible in IPCC AR7, strengthen the link to the climate science community and the CMIP community.

- Need to continue to develop RO products, but Peter Thorne also suggested to rebalance efforts between dataset development and deployment to the use of RO data as a tool for answering questions that are relevant to science.

- Many open questions where RO could help, e.g., detection and attribution, tropopause height, diurnal cycle effects for long-term MSU data records.
- Mark Ringer suggested applications related to D&A where RO data could play a role: early warning system (rapid change, tipping points, higher than expected global climate sensitivity) and identification of signals of accelerating change in the UTLS.

- Specific topics where RO could be useful: Upper tropospheric temperatures in the tropics in particular over the equatorial Pacific in relation to SSTs (much less warming, even cooling, in the east compared to the west), the lapse rate feedback (differential warming between surface and UT), and associated circulation changes.

- RO data could potentially be used for identifying changes in boundary-layer depth, particularly in areas of low-level cloud in the tropics/sub-tropics to the west of South America, California, Southern Africa, etc.

- Wider role of RO to evaluate and help improve models used for climate projections and decadal prediction systems. Again, not just use of RO by itself, but rather as a complement to other observations used for this purpose.

- Useful with further progress on RO-based water vapour climate data records.

Recommendations

The discussions led to the following set of recommendations for ROM SAF and the RO community:

REC-CLIM-01: The Climate Group recommends that the ROM SAF more actively engage (besides data record development) in the use of RO data as a tool for answering questions that are relevant for IPCC.

REC-CLIM-02: The Climate Group recommends that the ROM SAF more actively engage in using RO also in detection and attribution studies, given the data record length of over 20 years already.

REC-CLIM-03: The Climate Group recommends that the ROM SAF should perform application demonstration studies (e.g. on detection and attribution) and publish the results in the peer-reviewed literature, noting that there will be a cut-off of the literature used as input to the IPCC process in early 2027.

REC-CLIM-04: The Climate Group recommends that the ROM SAF should continue development and implementation of rigorous uncertainty quantification for the full processing chain, following the principles of the GUM (and GAIA-CLIM and FIDUCIO, as applicable).

REC-CLIM-05: The Climate Group recommends that the ROM SAF should continue engaging in exploration of the diurnal cycle, with the goal that this can be used for recalibration of historical missions, and supporting a possible back extension towards old AMSU and MSU data records.

REC-CLIM-06: The Climate Group recommends that the ROM SAF should engage in the use of RO-based tropopause height (e.g., for formal model comparisons/validation, understanding causes, process understanding, e.g., changing statistics of double tropopause, TTL and implications).

REC-CLIM-07: The Climate Group recommends that the ROM SAF should engage in supporting climate sensitivity and feedback exploration studies (e.g., related to lapse rate feedback and circulation changes, heat content change and energy imbalance).

REC-CLIM-08: The Climate Group recommends that the ROM SAF should continue engaging in evaluation of climate models, with the goal to help improve them for climate projections and use in decadal prediction systems.

REC-CLIM-09: The Climate Group recommends that the ROM SAF should continue developing and improve water vapour climate data records from RO, in particular trying to optimize their long-term stability.

REC-CLIM-10: The Climate Group recommends that CMA should perform a reprocessing of FY-3 GNOS data, with the goal to generate climate data records.

REC-CLIM-11: The Climate Group recommends that the ROM SAF should support CMA in reprocessing of the FY-3 GNOS data.

4. Space Weather Working Group Report

Chairs
Sean Elvidge (University of Birmingham), Riccardo Notarpietro (EUMETSAT)

Participants
Manuel Hernandez Pajares (UPC, Barcelona), Gemma Halloran (Met Office), Ishita Gulati (Met Office), Francisco Sancho (EUMETSAT)

Discussion

The working group convened to discuss the important role of RO in the space weather community, emphasizing its significance in monitoring and modelling the ionosphere. Acknowledging that the broader space weather community has not always routinely taken advantage of RO observations, the group's discussion was focused on how to change this. A critical aspect highlighted was the necessity for rigorous verification and validation of RO data to ensure its reliability. Additionally, the group underscored the importance of making RO data easily accessible and user-friendly to foster broader adoption among scientists and operational users.

Continuation of Electron Density Retrievals

While recent techniques have proposed the direct assimilation of bending angles from RO data, the working group firmly believes that electron density retrievals should continue to be provided. These retrievals are deemed broadly useful to the scientific community, particularly for newcomers integrating RO data into their products, services, and research. The availability of electron density profiles facilitates a more comprehensive understanding of the ionospheric conditions, which is essential for both academic studies and operational applications. In particular the group believes that output from all of AVHIIROv2, 1D-Var (a VaryChap variational assimilation approach) and the traditional Abel transformation [when using non-truncated RO observations] should be provided within the Level2 product. It was discussed that AVHIIROv2 provides a high vertical resolution but may have potential discontinuities, the 1D-Var has lower vertical resolution, but is double differentiable (i.e. continuous and smooth) and the Abel transform can be used as a reference retrieval. The user may want to use different retrievals in different scenarios, however each should have its uncertainty as fully quantified as possible, and quality control processes should be in place.

Enhancing Retrieval Methods and Quality Assurance

The group identified a pressing need to improve the methodologies used in retrieving profiles from RO data. This involves advancing the algorithms and techniques to enhance accuracy and reliability. It was highlighted the need to define the optimum number of layers for the 1D-Var approach, eventually increasing the vertical resolution of the final product. We also discussed the possibility to investigate the possibility to combine the 1D-Var with the AVHIIROv2

results, and eventually to advance the AVHIIRO algorithm incorporating horizontal gradients as derived from Global Ionospheric Maps (GIMs).

Integral to this improvement is the incorporation of uncertainty quantification and robust quality control measures in all proposed methods. Embedding these practices ensures that the data products meet high standards of scientific rigor and can be confidently used in various applications.

Production of Additional Data Products

Beyond electron density profiles and bending angles, the working group advocates for the continued production of other valuable data products. These include:

- Provide forward operators in ROPP to help users in assimilating bending angles.
- Slant Total Electron Content (STEC): Provides critical information on the total number of electrons along the path between the satellite and receiver in the occultation path, essential for correcting signal delays in satellite communications and navigation. The group suggested to introduce uncalibrated and calibrated sTEC in Level1 and Level 2 products respectively. Plasmasphere TEC (pTEC): Derived from the Precise Orbit Determination (POD) antenna, pTEC data is valuable for understanding the plasmasphere's contribution to the overall electron content, which has implications for high-frequency radio wave propagation. As for the STEC along the occultation paths, uncalibrated and calibrated pTEC should be routinely included in Level1 and Level 2 products respectively.
- Scintillation Indices (S4 and Sigma_phi [σ_ϕ]): These indices measure the amplitude and phase fluctuations of the received signals caused by irregularities in the ionosphere, which are crucial for assessing the reliability of satellite communication and navigation systems.

Geolocating and forecasting ionospheric irregularities: A further topic to be investigated relates the development of algorithms and strategies to geolocate scintillations and ionospheric irregularities. Eventually identifying methods for their effective forecast. Considerations for Future Satellite Missions

The group recommended that future satellite mission designs should carefully consider the orientation of the RO and POD antennas. Aligning these antennas optimally can enable a combined and continuous solution, enhancing the quality and continuity of the collected data. Such design considerations would facilitate more seamless data integration and improve the overall effectiveness of RO measurements for space weather monitoring.

Necessity of Routine External Validation

Recognizing that the uptake of RO data within the space weather community is contingent upon the credibility of the outputs, the working group stressed the need for routine external validation. They propose conducting these validations approximately every six months

(potentially aligning with CDOP 4 work package 4420). The validation processes should include:

- For Retrievals: Comparison against manually-scaled ionosondes to validate bottom-side electron density profiles and against incoherent scatter radar measurements for comprehensive electron density validation.
- For TEC Products: Validation against differential STEC (dSTEC) measurements from closely-located missions to ensure accuracy in total electron content estimations.
- For Scintillation Products: Further work is needed to validate geolocated scintillation products, potentially utilizing the Rate of TEC Index (ROTI) as a validation metric.

Data Latency and Accessibility

The current data latency, within 90 minutes, is deemed sufficient for existing users of RO data. However, the working group acknowledges that operational space weather users may require a higher volume of RO data than what is currently provided by EUMETSAT alone. To meet this demand, these users might need to supplement their data sources with offerings from commercial providers.

Engagement with Operational Space Weather Centers

The group recommends proactive efforts to engage operational space weather centers, encouraging them to utilize the existing near real-time RO data, which many are currently not leveraging. Targeted organizations include:

- International GNSS Service (IGS) Rapid Product Users
- UK Met Office
- NOAA Space Weather Prediction Center (SWPC)
- German Aerospace Center (DLR)
- Australian Bureau of Meteorology (BoM)
- South African National Space Agency (SANSA)
- Relevant agencies in Korea

By fostering collaborations and providing support, these centers can integrate RO data into their operations, enhancing their space weather monitoring and forecasting capabilities.

Ensuring Long-Term Data Security and Accessibility

The group emphasized the importance of securing RO data for the long term to ensure resilience and continuity. Easy access to this data by the broader community could likely support the wider use of the data within the community. Potential collaborations to facilitate this include:

- International GNSS Service (IGS): Leveraging their infrastructure for data distribution.
- Madrigal Database (MIT): Utilizing this established platform for data sharing.

- European Project PITHIA-NRF: Engaging with the Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services: a Network of Research Facilities (PITHIA-NRF) initiative to enhance data accessibility and integration within European networks.

Inclusion of permanent space weather expertise into the next phases of the Continuous Development and Operation Phase (CDOP)

In line with these discussions, the working group highlighted also the importance to include permanent expertise dedicated to operational space weather RO in the future CDOP phases. This role would be akin to the contributions of ECMWF and the UK Met Office concerning RO applications in the troposphere. Such expertise would provide ongoing support, development, and coordination efforts necessary to advance RO applications in space weather.

Improving the ROPP Software

Lastly, the group addressed the usability of the Radio Occultation Processing Package (ROPP). While ROPP is recognized as a powerful tool for processing RO data, its user-friendliness poses challenges. Key issues identified include:

- Programming Language Choice: The current language (FORTRAN) may not be accessible or familiar to all potential users, limiting its adoption.
- User Guides: There is a need for more comprehensive and user-friendly documentation to assist users in navigating the software.
- Dependencies: The software requires numerous dependencies for installation, which can be a barrier for users, especially those interested in only specific functionalities.

The group suggests that ROPP should be modularized to allow users to access and install only the components relevant to their needs, such as the electron density retrieval module. Streamlining the installation process and improving documentation would significantly enhance the software's usability and encourage more widespread use of RO data.

Conclusion

The working group's discussions highlight the critical importance of RO ionospheric data in advancing space weather research and operational capabilities. By addressing the challenges in data retrieval methods, validation processes, data accessibility, and software usability, the community can enhance the utility and adoption of RO ionospheric data. Collaborative efforts, both in engaging operational centres and in securing long-term data accessibility, are essential steps forward. Implementing these recommendations will strengthen the integration of RO data into space weather monitoring and forecasting, ultimately benefiting a wide range of scientific and operational stakeholders.

Recommendations

The discussions described above led to the following set of recommendations for ROM SAF and the RO community:

REC-SPWX-01: The Space Weather Group recommends that electron density retrievals should continue to be provided, including both AVHIROv2, 1D-Var and a 'standard' Abel inversion. Incorporate Uncertainty Quantification (UQ) and robust Quality Control (QC) measures in all methods.

REC-SPWX-02: The Space Weather Group recommends to continue the production of additional ionospheric data products, including uncalibrated and calibrated Slant Total Electron Content (STEC), Plasmasphere TEC (pTEC), and Scintillation Indices (S4 and σ_ϕ). Provide also a forward operator in a future ROPP release to help users in assimilating bending angles.

REC-SPWX-03: The Space Weather Group recommends to develop algorithms for effectively geolocating and forecasting scintillations and plasma irregularities.

REC-SPWX-04: The Space Weather Group recommends to improve retrieval methodologies from RO data by advancing algorithms and techniques to enhance accuracy and reliability.

REC-SPWX-05: The Space Weather Group recommends that future satellite missions should consider the optimal orientation of RO and POD antennas to enable a combined and continuous solution, enhancing data quality and continuity.

REC-SPWX-06: The Space Weather Group recommends to implement routine external validation approximately every six months in space weather products.

REC-SPWX-07: The Space Weather Group recommends to proactively engage operational space weather centers to encourage the utilization of existing near real-time RO data.

REC-SPWX-08: The Space Weather Group recommends to ensure the long-term security and accessibility of RO data and help to facilitate easy access for the broader community.

REC-SPWX-09: The Space Weather Group recommends to include permanent expertise dedicated to operational space weather RO in the future phases of CDOP.

REC-SPWX-10: The Space Weather Group recommends to improve the usability and installability of the ROPP software for the space weather community.

5. Workshop programme

Tuesday, 11 June 2024

09:15 to 09:55	**Registration and welcome**	
09:15 to 09:45	**Registration**	
09:45 to 09:50	**Welcome**	**Speaker:** Andy Brown (ECMWF)
09:50 to 09:55	**Welcome to SAF**	**Speaker:** Lothar Schüller (EUMETSAT)
09:55 to 10:00	**Welcome to ROM SAF User Workshop 8**	**Speaker:** Kent Lauritsen (DMI)
10:00 to 14:00	**Numerical Weather Prediction - 1** Chair: Katrin Lonitz	
10:00 to 10:30	**On the assimilation of GNSS radio occultation data at DWD** Presentation slides	**Speaker:** Harald Anlauf (DWD)
10:35 to 11:05	**Pathways for Integrating GNSS-RO in JCSDA JEDI** Presentation slides	**Speaker:** Ben Ruston (UCAR/JCSDA)
11:05 to 11:25	**Coffee break**	
11:25 to 11:55	**Recent developments on the assimilation of GNSS-RO in the METEO-FRANCE global and regional NWP models** Presentation slides	**Speaker:** Dominique Raspaud (Meteo France)
12:00 to 12:30	**Met Office highlights using GNSS-RO for NWP** Presentation slides	**Speaker:** Neill Bowler (Met Office)
12:30 to 13:30	**Lunch break**	
13:30 to 14:00	**Lessons learned from the assimilation of RO data at high volume at ECCC** Presentation slides	**Speaker:** Josep Aparicio (Environment Canada)
14:05 to 17:20	**Climate applications** Chair: Kent Lauritsen	
14:05 to 14:35	**Current and potential future applications of RO measurements in climate applications** Presentation slides	**Speaker:** Peter Thorne (Maynooth University)

14:40 to 15:10	**Stratospheric Temperature Biases in the ERA5 reanalysis & plans for ERA6** Presentation slides	**Speaker:** Bill Bell (ECMWF)
15:10 to 15:40	**Group photo and coffee break**	
15:40 to 16:10	**Wegener Center RO processing and climate studies: recent results and ROM SAF perspectives** Presentation slides	**Speaker:** Gottfried Kirchengast (Wegener Center)
16:15 to 16:45	**ROM SAF climate data records: applications and plans** Presentation slides	**Speaker:** Hans Gleisner (DMI)
17:30 to 19:30		
17:00 to 19:00	**Ice breaker and posters**	

Wednesday, 12 June 2024

09:15 to 11:15	**Numerical Weather Prediction - 2** Chair: Harald Anlauf	
09:15 to 09:45	**Status on the operational assimilation of GNSS-RO data at ECMWF** Presentation slides	**Speaker:** Katrin Lonitz (ECMWF)
09:50 to 10:20	**Recent Progress in GNSS RO Data Assimilation in NCEP GFS** Presentation slides	**Speaker:** Xuanli Li (SAIC@NOAA/NCEP/EMC)
10:25 to 10:55	**Current status of GNOS data processing at CMA** Presentation slides	**Speaker:** Mi Liao (CMA)
10:55 to 11:15	**Coffee break**	
11:15 to 11:45	**RO data processing - recent trends and open points** Presentation slides	**Speaker:** Christian Marquardt (EUMETSAT)
11:15 to 14:00	**Polarimetric and Airborne RO** Chair: Sean Healy	
11:50 to 12:20	**Advances in GNSS PRO forward model and sensitivity to NWP microphysics schemes** Presentation slides	**Speaker:** Estel Cardellach (ICE-CSIC, IEEC) **Speaker:** Ramon Padullés Rulló (ICE-CSIC, IEEC)
12:30 to 13:30	**Lunch break**	
13:30 to 14:00	**Moisture in the Lower Free Troposphere and Radio Occultation Strategies for Obtaining Vertical**	**Speaker:** Joe Turk (JPL, California Institute of Technology)

	Profiles In and Near Convection Presentation slides	
14:05 to 14:35	**Assimilation of Airborne Radio Occultation data** Presentation slides	**Speaker:** Jennifer Haase (Scripps Institution of Oceanography, UCSD)
14:05 to 15:45	**Space weather** Chair: Stig Syndergaard	
14:40 to 15:10	**Assimilation of Radio Occultation Bending Angles in a Global Ionospheric Model** Presentation slides	**Speaker:** Sean Elvidge (University of Birmingham)
15:15 to 15:45	**1D Var Ionospheric Electron Density Retrieval – Analysis and Challenging Cases** Presentation slides	**Speaker:** Ishita Gulati (Met Office)
15:45 to 16:00	**Coffee break**	
16:00 to 16:30	**High resolution Abel-Vary Chap Hybrid modeling from topside incomplete ionospheric GNSS RO data: Present and future improvements** Presentation slides	**Speaker:** Manuel Hernández-Pajares (UPC-IonSAT)
16:30 to 18:30	**Working groups**	
16:30 to 16:40	**Working group introductions**	
16:45 to 18:30	**Working group discussions** Proposed topics: • NWP assimilation with PRO/ARO (including New processing and technologies) [co-chairs: Harald Anlauf, Katrin Lonitz] • Climate applications [co-chair: Hans Gleisner] • Space Weather [co-chairs: Sean Elvidge, Riccardo Notarpietro]	
18:30 to 20:30	**Dinner at ECMWF restaurant**	

Thursday, 13 June 2024

09:30 to 15:00	**Working group discussions and plenary**	
09:30 to 12:30	**Working group discussions and drafting of recommendations**	
12:30 to 13:30	**Lunch break**	
13:30 to 15:00	**Plenary session**	

Acknowledgements

The ROM SAF acknowledges ECMWF for hosting the 8th User Workshop.

List of ROM SAF (and GRAS SAF) User Workshops

UW1 1st User Workshop: GRAS SAF and CLIMAP User Workshop, Copenhagen, Denmark, 7 September 1999

UW2 2nd User Workshop: 2nd GRAS SAF User Workshop, Helsingør, Denmark, 11-13 June 2003

UW3 3rd User Workshop: GRAS SAF Workshop on Assimilation of GPS Radio Occultation Measurements, ECMWF, Reading, UK, 16-18 June 2008

UW4 4th User Workshop: GRAS SAF Climate Workshop, as part of OPAC-2010, Graz, Austria, 6-11 September 2010

UW5 5th ROM SAF User Workshop on Applications of GPS radio occultation measurements, ECMWF, Reading, UK, 16-18 June 2014

UW6 6th User Workshop: ROM SAF - IROWG 2019, Konventum, Helsingør (Elsinore), Denmark, 19-25 September 2019

UW7 7th User Workshop: EUMETSAT - ROM SAF - C3S Workshop 2020, virtual workshop, 8-10 December 2020

UW8 8th EUMETSAT ROM SAF User Workshop on GNSS radio occultation measurements, ECMWF, Reading, UK, 11-13 June 2024

In addition, a workshop related to a discussion of the GRAS instrument was held in 2005: GRAS SAF Open Loop Workshop, Helsingør, Denmark, 6-8 June 2005

ROM SAF (and GRAS SAF) Reports

SAF/GRAS/METO/REP/GSR/001	Mono-dimensional thinning for GPS Radio Occultation
SAF/GRAS/METO/REP/GSR/002	Geodesy calculations in ROPP
SAF/GRAS/METO/REP/GSR/003	ROPP minimiser – minROPP
SAF/GRAS/METO/REP/GSR/004	Error function calculation in ROPP
SAF/GRAS/METO/REP/GSR/005	Refractivity calculations in ROPP
SAF/GRAS/METO/REP/GSR/006	Levenberg-Marquardt minimisation in ROPP
SAF/GRAS/METO/REP/GSR/007	Abel integral calculations in ROPP
SAF/GRAS/METO/REP/GSR/008	ROPP thinner algorithm
SAF/GRAS/METO/REP/GSR/009	Refractivity coefficients used in the assimilation of GPS radio occultation measurements
SAF/GRAS/METO/REP/GSR/010	Latitudinal binning and area-weighted averaging of irregularly distributed radio occultation data
SAF/GRAS/METO/REP/GSR/011	ROPP 1D-Var validation
SAF/GRAS/METO/REP/GSR/012	Assimilation of Global Positioning System Radio Occultation data in the ECMWF ERA-Interim re-analysis
SAF/GRAS/METO/REP/GSR/013	ROPP PP validation
SAF/ROM/METO/REP/RSR/014	A review of the geodesy calculations in ROPP
SAF/ROM/METO/REP/RSR/015	Improvements to the ROPP refractivity and bending angle operators
SAF/ROM/METO/REP/RSR/016	Simplifying EGM96 undulation calculations in ROPP
SAF/ROM/METO/REP/RSR/017	Simulation of L1 and L2 bending angles with a model ionosphere
SAF/ROM/METO/REP/RSR/018	Single frequency radio occultation retrievals: impact on numerical weather prediction
SAF/ROM/METO/REP/RSR/019	Implementation of the ROPP two-dimensional bending angle observation operator in an NWP system
SAF/ROM/METO/REP/RSR/020	Interpolation artefact in ECMWF monthly standard deviation plots
SAF/ROM/METO/REP/RSR/021	5th ROM SAF User Workshop on Applications of GPS radio occultation measurements
SAF/ROM/METO/REP/RSR/022	The use of the GPS radio occultation reflection flag for NWP applications
SAF/ROM/METO/REP/RSR/023	Assessment of a potential reflection flag product
SAF/ROM/METO/REP/RSR/024	The calculation of planetary boundary layer heights in ROPP
SAF/ROM/METO/REP/RSR/025	Survey on user requirements for potential ionospheric products from EPS-SG radio occultation measurements
SAF/ROM/METO/REP/RSR/026	Estimates of GNSS radio occultation bending angle and refractivity error statistics
SAF/ROM/METO/REP/RSR/027	Recent forecast impact experiments with GPS radio occultation measurements
SAF/ROM/METO/REP/RSR/028	Description of wave optics modelling in ROPP-9 and suggested improvements for ROPP-9.1

SAF/ROM/METO/REP/RSR/029	Testing reprocessed GPS radio occultation datasets in a reanalysis system
SAF/ROM/METO/REP/RSR/030	A first look at the feasibility of assimilating single and dual frequency bending angles
SAF/ROM/METO/REP/RSR/031	
SAF/ROM/METO/REP/RSR/032	An initial assessment of the quality of RO data from KOMPSAT-5
SAF/ROM/METO/REP/RSR/033	Some science changes in ROPP-9.1
SAF/ROM/METO/REP/RSR/034	An initial assessment of the quality of RO data from Metop-C
SAF/ROM/METO/REP/RSR/035	An initial assessment of the quality of RO data from FY-3D
SAF/ROM/METO/REP/RSR/036	An initial assessment of the quality of RO data from PAZ
SAF/ROM/METO/REP/RSR/037	6th ROM SAF User Workshop
SAF/ROM/METO/REP/RSR/038	An initial assessment of the quality of RO data from COSMIC-2
SAF/ROM/METO/REP/RSR/039	Impacts of RO mission differences on trends in multi-mission data records
SAF/ROM/METO/REP/RSR/040	Anomalous GRAS radio occultations
SAF/ROM/METO/REP/RSR/041	Assessment of sensitivity of the ROM SAF 1D-Var solutions to various error covariance choices
SAF/ROM/METO/REP/RSR/042	A one-dimensional variational ionospheric retrieval for truncated GNSS Radio Occultation measurements
SAF/ROM/METO/REP/RSR/043	Applying the ROPP ionospheric 1D-Var retrieval to Metop extension data
SAF/ROM/METO/REP/RSR/044	TBA
SAF/ROM/METO/REP/RSR/045	TBA
SAF/ROM/METO/REP/RSR/046	8th EUMETSAT ROM SAF user workshop on GNSS radio occultation measurements

ROM SAF Reports are accessible via the ROM SAF website: https://rom-saf.eumetsat.int/