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ROM SAF Report 37

6th ROM SAF User Workshop

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Issue/Revision	*Date*	*By*	*Description*
1.0	10/2 2020	SBH	First version of Report from the 6th ROM SAF User Workshop (UW6) held jointly as: ROM SAF – IROWG 2019. Input provided by IROWG Chairs.

ROM SAF

Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing centre under EUMETSAT which is responsible for operational processing of GRAS radio occultation (RO) data from the Metop 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, and iii) Met Office in Exeter, United Kingdom. To get access to our products or to read more about the ROM SAF please go to: http://www.romsaf.org

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Abstract

The ROM SAF took the opportunity of the international GNSS radio occultation (GNSS-RO) community meeting for the joint 6th ROM SAF User Workshop and the 7th IROWG Workshop (held jointly as ROM SAF – IROWG 2019) to formulate a set of recommendations to inform priorities for CDOP-4. The four IROWG working groups were provided with a set of questions and discussion points, and asked to return written recommendations to the ROM SAF. These working group recommendations are summarised in this report.

In general, there remains strong support for continuing the work of the ROM SAF. In the context of NWP, this includes continuing the near-real-time (NRT) provision of refractivity, further development of the ROPP software package, and maintaining the NRT monitoring system. The climate recommendations include more work on the retrieval of tropospheric humidity information, improving the retrieval of temperature information in the upper stratosphere, and the provision of robust uncertainty information with all climate data records. The Space Weather group support the ROM SAF developing ionospheric products from EPS-SG. They also support the development of 1D-Var retrieval techniques, if the ultimate aim is to include horizontal gradient information in order to reduce retrieval errors. The Receiver Technology and Innovative Occultation Techniques group recommend that the ROM SAF starts developing forward models appropriate for the assimilation of PAZ and new LEO-LEO observations. The latter is required for Observing System Simulation Experiments (OSSEs).

1. Background

The joint 6th ROM SAF User Workshop[1] and 7th IROWG Workshop[2] was held at Konventum, Helsingør (Elsinore), Denmark on 19 - 25 September, 2019. The workshop attracted 103 international scientists, and over 100 oral and poster presentations were given.

The topics discussed at the workshop included:

- Current status of "agency-led" GNSS-RO missions, including COSMIC-2, FY-3C,D and Metop-A,B,C
- Latest assessments of measurements from commercial missions
- Climate monitoring applications
- Climate model validation with GNSS-RO climatologies
- New results from the PAZ polarimetric RO mission
- Progress on the LEO-LEO measurement concept, and status of possible missions
- Improving the impact of GNSS-RO measurements in operational NWP and climate reanalyses
- Improving GNSS-RO retrievals in the lower troposphere and upper stratosphere
- Ionospheric retrievals and space weather applications
- New innovations and applications of GNSS-RO data

Presentations and abstracts are available at the ROM SAF – IROWG 2019 workshop website:

http://www.romsaf.org/romsaf-irowg-2019/

The workshop also provided the opportunity for a number of side meetings, perhaps the most significant being on the GNSS-RO contribution to the Sixth Assessment Report of the IPCC, which will include GNSS-RO data provided by the ROM SAF.

From an IROWG perspective, a key objective of the joint workshop was to formulate a set of user driven recommendations for the operational space agencies, to be presented at the Coordination Group for Meteorological Satellites (CGMS) in 2020.

The ROM SAF used the opportunity of the international community being together to have the four IROWG working groups discuss, inform and recommend possible future work for CDOP-4, covering the period 2022-2027.

The four IROWG working groups focus on the following areas:

- Numerical weather Prediction (NWP)
- Climate Applications
- Space Weather

[1] ROM SAF Workshops: http://www.romsaf.org/workshops/

[2] International Radio Occultation Working Group: http://www.irowg.org/

- Receiver Technology and Innovative Occultation Techniques

The procedure during the workshop was as follows. The ROM SAF project team formulated a set of questions and discussion points for each working group. These were provided to the working group chairs, who were asked to provide written recommendations back to the ROM SAF at the end of the meeting. The ROM SAF discussion points/questions are provided in Annex A. The full workshop program is included in Annex B.

The recommendations provided by the working groups are summarised in this document. The style of the response from each working group differs, but these differences have been preserved to avoid misinterpretation. Some minor editing of the recommendations has been performed, but these revisions have been subsequently checked and approved by the relevant working group chairs. The name and affiliation of the (co)chairs are given below.

The number of recommendations from each group is roughly in line with its size, with the NWP group providing most, followed by climate, space weather and then receiver technology/techniques. In general, resource requirements were not discussed by the working groups, but in some cases they have ranked priorities. Some NWP recommendations suggest possible visiting scientist activities. These could start during CDOP-3.

2. NWP Recommendations to ROM SAF

IROWG Chairs: Neill Bowler (Met Office, UK), Hui Shao (JCSDA, Boulder, CO, USA)

Report:

UW6-NWP-01. IROWG recommends that ROM SAF continue to produce refractivity products in NRT. Meteo-France and Canada (at least currently) still use these data in their operational systems. In addition, refractivity is still used in non-local phase and refractivity operators.

UW6-NWP-02. IROWG recommends that ROM SAF continue to support ROPP, and to contact operational centres and research entities to inquire if they would be beta testers for new versions.

UW6-NWP-03. IROWG recommends that the ROM SAF consider a move towards an open-source model for ROPP. In particular, this may allow contributions from the research and the NWP community to be made better use of e.g. from the JEDI development.

UW6-NWP-04. While not many NWP centers are using the existing 2D operator available in the ROPP software package at present, plans for future use do exist. Thus, IROWG recommends to the ROM SAF to continue the development of the 2D operator, and to keep it aligned with the implementation used at ECMWF.

UW6-NWP-05. IROWG recommends the development of three new forward operators in ROPP. The order of priority should be:

- Airborne GNSS-RO – there is a current demand for this operator from researchers – top priority
- PAZ (H-V polarisation) – JPL is also pursuing this development, so try to leverage collaboration
- LEO-LEO – currently lowest priority, but in the plenary discussion it was noted that there is a need for OSSEs, and there is a possibility of future missions

UW6-NWP-06. IROWG supports the collaboration with the Joint Center for Satellite Data Assimilation (JCSDA) on the Joint Effort for Data assimilation Integration (JEDI) project (see, *https://www.jcsda.org/jcsda-project-jedi*), so that the ROPP_FM operators are available in the JEDI system.

UW6-NWP-07. IROWG considers the ROM SAF monitoring site a valuable resource, and recommend continued development.

UW6-NWP-08. The group considers that the current ROM SAF NRT monitoring of NWP data is adequate displaying just the ECMWF and Met Office information; no further NWP systems need to be included in the statistics provided on the ROM SAF website. However:

- IROWG recommends that the ROM SAF contact other operational NWP centres, and provide a listing of monitoring websites on the ROM SAF website. Further, encourage others centres to produce similar graphs, and provide monitoring software if requested.

UW6-NWP-09. IROWG recommends that the ROM SAF routinely provide new mission assessment reports and documents.

UW6-NWP-10. Given that data providers and users have diverse approaches to quality control, IROWG recommends two ROM SAF visiting scientist missions:

- A visiting scientist to compare QC procedures and quality metrics for evaluation of bending angle and refractivity profiles.
- A visiting scientist to compare methods for understanding observation uncertainties, such as the 3 Cornered Hat, Desroziers, and Local Spectral Width.

UW6-NWP-11. IROWG recommends making available the ECMWF and Met Office Desroziers diagnosed R matrix. Consider one diagnosed from a year of randomly sampled dates and update yearly.

UW6-NWP-12. There is a desire to provide RO data on an increased set of levels:

- IROWG recommends that the ROM SAF (co-ordinated with EUMETSAT and UCAR) conduct a study to consider vertical spacing and resolution of the data in the NRT BUFR files.

3. Climate recommendations to ROM SAF

IROWG Chair: Andrea Steiner (Wegener Center, University of Graz, Austria)

Report:

UW6-CLIM-01. IROWG recommends the continuation of current work on climate data records, and on improving the climate quality – long-term stability and homogeneity – of radio occultation data in the lower troposphere and upper stratosphere regions.

UW6-CLIM-02. IROWG recommends that the ROM SAF continues to provide RO gridded data products (e.g., bending angles, refractivity, temperature, humidity) including validated uncertainty estimates. ROM SAF should work on producing robust error estimates for all level 3 climatologies. Provide RO variables both on altitude and pressure levels for promoting the use in the climate model community, e.g., by providing tailored ROPP utilities.

UW6-CLIM-03. RO has a large impact on the bias correction in reanalysis, making trend estimates based on re-analysis difficult when the number of assimilated RO observations varies over time: .

- IROWG thus recommend to continue working on the impact of RO on reanalysis

UW6-CLIM-04. IROWG recommends to investigate and improve the RO water vapour products and providing uncertainty information to support a better understanding of the diurnal cycle, and allow their use in climate assessments as appropriate.

UW6-CLIM-05. IROWG recommends continuing to provide relevant data products to IPCC assessments, including MSU/AMSU brightness temperature equivalents.

UW6-CLIM-06. IROWG recommends that work on the ROPP package should continue, and include the computation of the uncertainties enrolled in the climate data records.

UW6-CLIM-07. IROWG recommends further investigation of single frequency/non-prime time retrievals for GPS/Met and Ørsted for climate data record continuation. The relevant processing algorithms should be included in the ROPP package, thus making them publicly available.

4. Space Weather recommendations to ROM SAF

IROWG Chair: Bill Schreiner (UCAR, Boulder, USA)

Report:

The space weather group answered the ROM SAF questions /discussion points more directly so they are included here to provide context.

UW6-SPACE-01. What importance does this group place on continuing the work on the retrieval of ionospheric parameters using 1DVar?

- High importance. We assume this is focused on enhanced Abel retrievals that utilize additional (horizontal gradient) information to help mitigate retrieval errors.

UW6-SPACE-02. What importance does this group place on further investigation of single frequency retrieval?

- Low. It is much simpler to use dual-frequency data to generate products.

UW6-SPACE-03. Should the ROM SAF develop ionospheric products from the EPS-SG higher profiles (up to ~500 km altitude)? Which products would be interesting for the users?

- Yes. Absolute TEC, relative TEC, topside TEC, electron density, scintillation indices.

UW6-SPACE-04. Would it be of interest for the ROM SAF develops forward operators for ionospheric products and introduce them in ROPP? Recommend?

- In general, it can be helpful to provide such forward operations to the community if they plan to use the ROPP codes in their space weather data assimilation system or their scientific studies.

UW6-SPACE-05. Should the ROM SAF develop ionospheric products from the EPS-SG GNSS POD measurements (above the LEO height)? Which of such products (vertical electron content, scintillation indices, etc) would be interesting for the users?

- Yes. TEC would be useful above LEO height and scintillation products would be useful above LEO height under strong geomagnetic storm conditions.

5. New Techniques recommendations to ROM SAF

IROWG Chair: Rob Kursinski (PlanetiQ, Golden, CO, USA)

Report:

The ROM SAF only asked the new techniques group to consider the following:

Should new forward models for PAZ, airborne RO and LEO-LEO applications be developed? Justified by operational mission plans?

- PAZ and LEO-LEO operator might require federated activities with the NWP SAF.
- LEO-LEO operator needed for OSSEs.

In response, the working group recommended that the ROM SAF develop these observation operators at the plenary session. (*The recommendation is captured by a similar recommendation from the NWP group*.)

6. Summary

This report summarises the main recommendations to the ROM SAF provided by the four IROWG working groups after the joint 6th ROM SAF User Workshop and the 7th IROWG Workshop (ROM SAF – IROWG 2019) held at Konventum, Helsingør (Elsinore), Denmark on 19 - 25 September 2019. The four working groups were given a set of questions/discussion points by the ROM SAF (See Annex A), and they provided the written recommendations at the end of the meeting. These recommendations will inform ROM SAF priorities during CDOP-4.

Acknowledgements

The ROM SAF would like to thank the financial support for the ROM SAF – IROWG 2019 workshop from the following agencies and companies: EUMETSAT, Darmstadt, Germany; GeoOptics, Pasadena, CA; PlanetiQ, Golden, CO; RUAG Space, Gothenburg, Sweden; Spire Global, Inc., Glasgow, UK and WMO, Geneva, Switzerland.

Annex A. ROM SAF questions/discussion points provided to the working groups

These questions/discussion points were provided by the ROM SAF team members.

NWP Group

ROM SAF produces NRT refractivity and 1D-Var derived temperature, humidity, pressure and surface pressure using ECMWF short-range forecasts.

- Should ROM SAF continue to produce these products in NRT for specific users groups (for global models, for regional models, other activities)?
- Refractivity: still needed in non-local phase?

ROPP

General: Continued support for the maintenance and development of ROPP by ROM SAF?

- ROPP_FM contains the assimilation software by many users
- ROPP_PP is the processing software used in computing climate data records, e.g., NRT processing of GNOS

ROPP_FM

New Ideas for improving existing ROPP 1D and 2D operators?

What CRAZY, expensive assimilation ideas need to be revisited? Assimilate phase/amplitude or Doppler, direct assimilation of L1, and L2 (L5).

Are users planning to move towards 2D operators? To date, not many NWP assimilation users but the code is used in OSSEs for simulating data. Recommend, continue develop these in ROPP? Try to keep ROPP aligned with the ECMWF operational 2D approach?

Should new forward models for PAZ, airborne RO and LEO-LEO applications be developed? Justified by operational mission plans?

- PAZ and LEO-LEO operator might require federated activities with the NWP SAF.
- LEO-LEO operator needed for OSSEs previously recommended by IROWG.

Support for the collaboration with JCSDA on the JEDI project so that the ROPP_FM operators are available in JEDI?

Monitoring

Is the ROM SAF monitoring/alerts site a valuable resource? Recommend continue?

NWP SAF provides written monitoring reports routinely, but ROM SAF does not. Should these be introduced by ROM SAF?

Should EUMETSAT ROM SAF enhance the current NRT monitoring with NWP data by adding comparisons from NWP centers than other ECMWF and Met Office (and which NWP centers would be willing to provide such NWP data)?

- If yes, do these multi centre comparisons need to be done daily, or would it be sufficient to have monthly or quarterly comparisons? What is the purpose of multi centre – checking the data or comparing the centres?

(This is a question which came up at the ROM SAF Operations Review in 2019 and which we agreed to raise at IROWG)

Given that data providers and users all have diverse approaches to quality control, does this group think it would be a good idea to attempt to establish best practice in this area?

Data-provider related questions:

- Does this group agree that all changes made by data suppliers should be documented, and that documentation circulated via a suitable mailing list in advance of the change?
- Does this group agree that some changes made by data suppliers (to formats or processing software) are sufficiently large that test data should be provided to users in advance of the change?
- If so, what criteria should be used to decide whether a change needs test data to be provided?

BUFR

We could have a general discussion of common definitions of the contents of BUFR files.

Value of making ECMWF/MetO Desrozier matrices available to NWP users as a ROM SAF product.

ECMWF talk on weak constraint 4d-var has used RO “dry” temperature retrievals for forecast verification on the stratosphere up to ~5 hPa. These are computed daily based on the bending angles in the BUFR files. Basis of a new ROM SAF temperature verification product?

Climate Group

At the 2014 meeting, it was recommended that the climate group write a short, focused publication outlining the strengths and weaknesses of RO for climate applications. This never happened. *Still of interest to this group?*

As the length of the RO data series becomes longer, they are increasingly useful for climate studies, climate monitoring, and climate-model related studies. Construction of long time series requires that we can take data from multiple RO missions/satellites, with different instrument and sampling characteristics, and combine them into single data series. The evolution of the global RO constellation

needs to be properly handled. Different missions and different geophysical variables may be more or less easy to combine, and there are limitations in altitude, latitude, and time. Systematic structural errors may prevent us from combining missions in the lower troposphere and middle/upper stratosphere.

Questions:

1. What are the main limitations for construction of long time series?

- Are the current processing methods well suited to construct long-term stable lower-tropospheric climate data series? Upper-stratospheric data series?

- How can we ensure, and validate, the stability of long time series?

- Can we identify any gaps in the validation of RO climate data records against other observational data records?

2. Use of RO climate data records within the scientific community and the climate-modelling community requires that they are fit for purpose. Exactly what this means depend on the application.

Questions:

- Which RO variables, and spatial and temporal resolutions of the RO gridded data are useful?

- The ROtrends collaboration led to a series of publications on structural uncertainty (related to the spread amongst the processing centers). Would it be useful to make RO climate data available as ensemble data, in its simplest form just by agreeing on common file formats and meta-data?

- Are better file formats or means of dissemination required? Is Obs4MIPs the preferred format for climate modellers?

- Can we identify any gaps in the range of RO data and tools for handling the data, that the data providers currently make available?

3. Tropospheric humidity in climate data records:

There is a demand for stable tropospheric RO climate data records. Especially tropospheric humidity is being requested from entities such as Copernicus and G-VAP. Humidity is measured with moderate accuracy by other instruments, such as IASI, CrIS or AIRS. The accuracy of RO humidity products is comparable to that of for instance IASI, but the stability of RO based humidity is questionable partly because of contamination from the necessary background data.

- How can we overcome trends and bias jumps in model background data?
- Is it feasible to construct de-trended model forecast to be used as background for 1D-Var in climate data records?
- Is it possible to remove transient model artefacts before running moist retrieval?
- Can IROWG recommend data RO data providers to explore possible use of climatology or modified model forecast as background for moist retrieval?

4. Uncertainty and error correlations are determining for moist retrieval:

An alternative to bottom up error propagation is emerging. By combining multiple data sets it is possible to disentangle errors and error correlations from the individual datasets, to some extent.

- What is the status of these error retrieval methods?
- Can IROWG recommend data providers to implement 1D-Var moist retrievals with observation based uncertainty and correlation estimates?

Specific questions about ROM SAF work:

- Should EUMETSAT ROM SAF generate data products for regular climate assessment, e.g., products similar to the data/plots produced as suggestions for the IPCC AR6 Report?
- Should EUMETSAT ROM SAF generate a time series of mean tropical temperatures in 300-100 hPa layer (e.g. plotted versus surface temperature)?
- EUMETSAT ROM SAF regularly performs a reprocessing of RO data from several RO missions and generates a set of homogeneous CDR data records. The next such reprocessing is planned for the 2020-21 timeframe. Should ROM SAF supplement the reprocessed RO CDR data records with ERA5/5.1 data, and for these reanalysis fields also generate different quantities characterizing temperature trends and quantities corresponding to AMSU/MSU brightness temperatures?

Additional questions from meeting:

How do we validate the kappa correction, or more sophisticated residual ionospheric error approaches? Reference datasets?

How do we compute and validate uncertainty estimates for monthly mean quantities? The 1/root N scaling does not apply to systematic errors. Do we have a good estimate of systematic errors in RO retrievals? EG, refractivity coefficients.

What importance does this group place on further investigation of single frequency retrieval? Eg, GPS/MET reprocessing by JPL?

Space Weather Group

Sean Burns (EUMETSAT) provided questions for the space weather group.

- Who are the end users? – the users of the space weather products
- Who are the generators of the products? Which organisations/companies
- Which applications are being used to derive products?
- What data is required? Instruments/measurement parameters
- What sampling frequency is required?

- What is the timeliness requirement from measurement to product generator to product production? 15 minutes or less?
- What is the overall timeliness for the end user?
- What are the availability (timeliness, completeness and quality) requirements? 95% or higher?

Other:

What importance does this group place on continuing the work on the retrieval of ionospheric parameters using 1DVar?

What importance does this group place on further investigation of single frequency retrieval?

Should the ROM SAF develop ionospheric products from the EPS-SG higher profiles (up to ~500 km altitude)? Which products would be interesting for the users?

Would it be of interest for the ROM SAF develops forward operators for ionospheric products and introduce them in ROPP? Recommend?

Should the ROM SAF develop ionospheric products from the EPS-SG GNSS POD measurements (above the LEO height)? Which of such products (vertical electron content, scintillation indices,...) would be interesting for the users?

New Techniques Group

This text is also in the NWP section.

Should new forward models for PAZ, airborne RO and LEO-LEO applications be developed? Justified by operational mission plans?

- PAZ and LEO-LEO operator might require federated activities with the NWP SAF.
- LEO-LEO operator needed for OSSEs.

Annex B. Workshop program

Wednesday, 18 September 2019	
16:00-18:00	**Registration**
19:00-20:00	**Dinner (paid separately as part of the registration)**

Thursday, 19 September 2019		
07:00-09:00	**Breakfast and Registration**	
Session 1: Missions – Introduction and Welcome **Chair: Sean Healy**		
09:00-09:30	Introduction to EUMETSAT ROM SAF - IROWG 2019 and welcome address: - Welcome and practical information - Marianne Thyrring (Director, DMI) - Lothar Schueller (SAF Network Manager, EUMETSAT)	
09:30-10:00	Richard A. Anthes	Advances in Atmospheric Science Using Radio Occultation* Observations (*Still the world's most accurate and precise thermometer from space!) **(Keynote)**
10:00-10:20	Kent B. Lauritsen	Overview of ROM SAF activities
10:20-10:40	Christian Marquardt	EUMETSAT: RO Present status and Future Plans **(Invited)**
10:40-11:00	**Coffee Break**	
Session 2: Missions **Chair: Kent B. Lauritsen**		
11:00-11:30	Chen-Joe Fong	From FORMOSAT-3/COSMIC to FORMOSAT-7/COSMIC-2 Mission: A New Era of Operational GNSS Radio Occultation Constellation Observing System **(Invited)**

Thursday, 19 September 2019		
11:30-12:00	Jan P. Weiss	COSMIC-2 Status and Initial Results **(Invited)**
12:00-13:00	**Lunch Break and Group Photo**	
Session 3: Missions **Chair: Stig Syndergaard**		
13:00-13:20	Bill Schreiner	Performance Assessment and Requirement Verification of COSMIC-2 Neutral Atmospheric Radio Occultation Data
13:20-13:40	T. K. Meehan	The TriG Radio Occultation System on COSMIC-2. Early Performance Assessment
13:40-14:00	Anders Carlström	The RO Instrument for MetOp-SG – Engineering Model Test Results
14:00-14:20	Dallas Masters	Status and Plans for Spire's Growing Commercial Constellation of GNSS Science CubeSats
14:20-14:40	Neill Bowler	Initial assessment of GNSS-RO data from Spire
14:40-15:00	Christian Marquardt	Assessment of Spire Commercial RO Data
15:00-15:20	**Coffee Break**	
Session 4: Missions **Chair: Bill Schreiner**		
15:20-15:40	Alex Saltman	The CICERO constellation: Characteristics, status and data
15:40-16:00	Torsten Schmidt	An overview of radio occultation activities at GFZ Potsdam: data processing and applications
16:00-16:20	Chad Galley	Jason-CS/Sentinel-6 GNSS Radio Occultation Instrument overview and Performance
16:20-16:40	E. Robert Kursinski	PlanetiQ GNSS RO Update
16:40-17:00	Weihua Bai	The FengYun-3 radio occultation sounder GNOS: a review of the missions and early results
17:30-18:30	**Early Dinner**	
18:30-21:00	**Ice Breaker** **(Bus departure at 18:30)**	

Friday, 20 September 2019		
07:00-09:00	**Breakfast**	
Session 1: Climate **Chair: Axel von Engeln**		
09:00-09:20	Peter Thorne	The Potential role of GNSS-RO data in the IPCC AR6 report **(Invited)**
09:20-09:40	Hans Hersbach	The Importance of GNSS Radio Occultation data in the ERA5 global reanalysis **(Invited)**
09:40-10:00	Hans Gleisner	The ROM SAF RO climate data record: validation and intermission consistency
10:00-10:20	Panagiotis Vergados	Quantifying the lapse rate feedback using GNSS radio occultation
10:20-10:40	Jeremiah P. Sjoberg	Estimates of errors in radio occultation and multiple reanalyses
10:40-11:00	**Coffee Break**	
Session 2: Climate **Chair: Julia Danzer**		
11:00-11:20	Andrea K. Steiner	Atmospheric temperature trends from observations – an update on recent advances
11:20-11:40	Anthony J. Mannucci	An Assessment of Reprocessed GPS/MET Observations Spanning 1995-1997
11:40-12:00	Mayra Oyola	GNSS/RO data Processing for Climate Applications at JPL: Assessing the performance of the next-generation OBS4MIPS atmospheric products retrievals
12:00-13:00	**Lunch Break**	
Session 3: Climate **Chair: Christian Marquardt**		
13:00-13:20	Gottfried Kirchengast	Climate Monitoring of Atmospheric Heat Content and Heat Exchange with the Oceans: A new Key Role for Radio Occultation
13:20-13:40	Axel von Engeln	Latest Reprocessing and Occultation Prediction Activities at EUMETSAT
13:40-14:00	Marc Schwärz	Radio occultation processing at the Wegener Center: Validation results and first long-term time series of rOPS

Friday, 20 September 2019		
14:00-14:20	Florian Ladstädter	Climatological trends from RO
14:20-14:40	Jordis Tradowsky	The ongoing collaboration between GRUAN and the radio occultation community
14:40-15:00	Johannes K. Nielsen	Uncertainty of temperature, humidity and pressure profiles from the first ROM SAF Climate Data Record
15:00-15:20	**Coffee Break**	
Session 4: Climate **Chair: Congliang Liu**		
15:20-15:40	Julia Danzer	Sensitivity and impact of the ionospheric kappa-correction on RO climatologies
15:40-16:00	Stig Syndergaard	Implementation and results of the kappa residual ionospheric correction in ROM SAF processing
16:00-16:30	Presentation of IROWG Working Group and ROM SAF User Workshop objectives	
16:30-16:45	Heikki Pohjola	WMO Space Programme Update
16:45-18:45	Poster session	**Please refer to the Poster List at the end of these tables**
19:00-20:00	**Dinner**	

Saturday, 21 September 2019	
07:00-09:00	**Breakfast**
Session 1	
09:00-10:40	Working groups
10:40-11:00	**Coffee Break**
Session 2	
11:00-12:00	Working Groups
Excursion	
12:00-22:30	**Excursion and Conference Dinner (with lunch sandwich to-go)** **(Bus departure at 12:00)**

Sunday, 22 September 2019	
07:00-09:00	**Breakfast**
Session 1	
09:00-10:40	Working groups
10:40-11:00	**Coffee Break**
Session 2	
11:00-12:00	Working groups
Free	
12:00-	Free part

Monday, 23 September 2019		
07:00-09:00	**Breakfast**	
Session 1: Space Weather **Chair: Weihua Bai**		
09:00-09:20	Riccardo Notarpietro	A multi-mission topside Total Electron Content product from GNSS-POD receivers on-board the EUMESTAT satellites
09:20-09:40	Irina Zakharenkova	Underutilized space-borne GPS observations for Space Weather monitoring
09:40-10:00	Haixia Lyu	Two methods of electron density retrieval from truncated ionospheric radio occultation data
10:00-10:20	Dong L. Wu	Understanding solar cycle variations of D/E-region electron density and sporadic-E (Es) with new GPSRO data
10:20-10:40	Vu Nguyen	Space weather observations from Spire's Growing CubeSat Constellation
10:40-11:00	**Coffee Break**	
Session 2: Space Weather **Chair: Riccardo Notarpietro**		
11:00-11:20	John Braun	COSMIC-2 Early Orbit Space Weather Data Assessment and Validation Activity
11:20-11:40	Iurii Cherniak	3D geolocation of ionospheric plasma irregularities by combination of RO and ground-based GNSS measurement
11:40-12:00	Mengjie Wu	An Abel inversion method assisted by an improved IRI model for GPS ionospheric radio occultation data
12:00-13:00	**Lunch Break**	
Session 3: New Techniques **Chair: Ben Ho**		
13:00-13:30	Estel Cardellach	Polarimetric GNSS RO aboard the PAZ satellite: status of the ROHP-PAZ experiment **(Invited)**
13:30-13:50	Ramon Padullés	Calibration and Validation of the Polarimetric Radio Occultation and Heavy Precipitation onboard PAZ experiment and potential scientific applications
13:50-14:10	Douglas Hunt	PAZ Neutral Atmosphere Radio Occultation Retrieval Processing

Monday, 23 September 2019		
14:10-14:30	Gottfried Kirchengast	ISSI-BJ Forum on Exploring Greenhouse Gases, Water and Climate Changes by LEO-LEO Occultation: Main Results and Next Steps
14:30-14:50	Congliang Liu	Introduction of Atmosphere and Climate Explorers LABoratory (ACELAB) mission concept
14:50-15:10	Jennifer S. Haase	Impact of Airborne Radio Occultation Observations on Atmospheric River Precipitation Forecasts on the US West Coast
15:10-15:30	**Coffee Break**	
Session 4: Science Applications **Chair: Estel Cardellach**		
15:30-15:50	Riley Fitzgerald	Formation-Flying CubeSat Constellations for Internal Gravity Wave Topography
15:50-16:10	Hallgeir Wilhelmsen	Double tropopause characteristics from the full radio occultation record
16:10-16:30	Patrick Laloyaux	Towards an unbiased stratospheric analysis
16:30-16:50	E. Robert Kursinski	ERA5, MERRA2 and GNSS RO Water Vapor Comparisons and Implications
16:50-17:10	Ulrich Foelsche	Observing Water Vapor with GNSS Radio Occultation Data
17:10-17.30	Bomin Sun	Utilization of GPSRO in the NOAA Products Validation Systems (NPROVS)
17:30-19:00	**SCOPE-CM RO-CLIM side-meeting**	
19:00-20:00	**Dinner**	

Tuesday, 24 September 2019	
07:00-09:00	**Breakfast**
Session 1: NWP	

Tuesday, 24 September 2019		
Chair: Harald Anlauf		
09:00-09:20	Hui Shao	GNSS-RO data assimilation advancement and implementation at JCSDA and NCEP
09:20-09:40	Francois Vandenberghe	Recent and New GNSS-RO missions: Quality Assessment and Comparative Data Assimilation Study
09:40-10:00	Benjamin Ruston	Present status and future directions of GNSS assimilation at NRL
10:00-10:20	Neill Bowler	Revised observation uncertainties for bending angle assimilation
10:20-10:40	Mitsuhiro Shimada	Effect of GNSS Radio Occultation Data Assimilation in JMA's Global NWP System
10:40-11:00	**Coffee Break**	
Session 2: NWP **Chair: Neill Bowler**		
11:00-11:20	Dominique Raspaud	Recent developments on the assimilation of GNSS-RO bending angles in the Météo-France 4D-Var system
11:20-11:40	Sean Healy	The use of GPS-RO at ECMWF
11:40-12:00	Liu Yan	Assimilation of FengYun GNOS Radio Occultation Data in GRAPES
12:00-13:00	**Lunch Break**	
Session 3: NWP and Science Applications **Chair: Ben Ruston and Andrea Steiner**		
13:00-13:20	Mi Liao	Processing and quality control of FY-3C/GNOS data used in numerical weather prediction applications
13:20-13:40	Chad Galley	Near-real-time radio occultation processing operations for weather forecasting applications
13:40-14:10	M. E Gorbunov	Generalized Canonical Transform Method **(Invited)**
14:10-14:30	Chi Ao	Characterizing the Vertical Stratification of the Earth's Planetary Boundary Layer with GNSS Radio Occultation
14:30-14:50	Sergey Sokolovskiy	Initial Assessment of the First Results of Sensing the Lower Troposphere with COSMIC-2

Tuesday, 24 September 2019		
14:50-15:10	**Coffee Break**	
Session 4: Science Applications **Chair: Ulrich Foelsche**		
15:10-15:30	Erin Lynch	Inter-comparison between GNSS RO and hyperspectral infrared sounder observations
15:30-15:50	Michelle Feltz	Investigating the Comparisons of Hyperspectral IR Sounders, Radio Occultation, and Radiosondes in Radiance Space
15:50-16:10	Shu-peng Ho	NESDIS RO Science Studies and Quality Assurance through the STAR Integrated Cal/Val System
16:10-16:30	Changyong Cao	The Significant Roles of COSMIC2 GNSS RO in NOAA Integrated Calibration/Validation System for NWP
16:30-16:50	Valeria Cigala	GNSS RO technique pushes forward the detection of volcanic clouds
16:50-17:10	Pawel Hordyniec	The Southern Hemisphere jets and tropopause parameters derived from radio occultation monthly means
17:10-17:30	Josef Innerkofler	Multi-Mission Multi-Center Level 1 Data Inter-Validation towards Wegener Center Reference Occultation System Reprocessing
19:00-20:00	**Dinner**	

Wednesday, 25 September 2019	
07:00-09:00	**Breakfast**
Session 1: Working Groups	
09:00-10:10	Working Groups
10:10-10:30	**Coffee Break**
Session 2: Plenary and closing	
10:30-12:00	Plenary Session: Reporting from Working Groups
12:00-13:00	Closing Session (with lunch sandwich)
13:00	End of Workshop

List of Posters		
1	Richard A. Anthes	The Three-Cornered Hat Method for Estimating Random Error Variances in Multiple Data Sets
2	M. E. Gorbunov	Kirkwood Distribution Function and its Application for the Analysis of Radio Occultation Observations
3	Stanislav Kireev	NOAA STAR 1D-var Retrieval Algorithm to Process Radio Occultation Data
4	Stephen S. Leroy	Analysis of the Diurnal Cycle in RO Data using Bayesian Interpolation
5	Pawel Hordyniec	The Southern Hemisphere jets and tropopause parameters derived from radio occultation monthly means
6	Bin Zhang	Using Radio Occultation observations to detect ATMS brightness temperature bias
7	Kuo-Nung Wang	A study of the effects of heavy precipitation on Polarimetric Radio Occultation (PRO) bending angle observations
8	Evans A. Y. Adom	FORMOSAT-7/COSMIC-2 GNSS Radio Occultation Mission: The role of University of Energy and Natural Re-

List of Posters		
		sources and Capacity Building on RO data in Africa
9	Thomas Sievert	Simulating reflected GNSS-RO signals with wave-optics propagation
10	JaeGwan Kim	GNSS Radio Occultation Techniques and Applications at KMA
11	Matthias Stocker	Stratospheric temperature signals from post-2000 volcanic eruptions
12	Eun-Hee Kim	Assimilation of KOMPSAT-5 GNSS-RO data in KMA global NWP model
13	Xinjia Zhou	Construction of Temperature Climate Data Records from June 2006 to December 2018 using Multiple RO Missions
14	Jeremiah P. Sjoberg	The N-Concerned Hat method for estimating error variances between multiple data sets: theoretical considerations and comparisons with the two-cornered hat method
15	Vladimir Irisov	Radio Occultation Observations and Processing from Spire's CubeSat Constellation
16	Christian Marquardt	Empirical RO Uncertainty Estimates Based on Signal Spectra
18	Veronika Proschek	Analyzing structural uncertainty in rOPS and GPAC/ROPP processing: the chain from bending angle to dry-air atmospheric profiles
19	Ying Li	A new method to detect and monitor Sudden Stratospheric Warming events based on radio occultation: demonstration using the Jan-Feb 2009 event
20	Kent B. Lauritsen	The 17-year ROM SAF radio occultation climate data record
21	Vinícius Ludwig Barbosa	MPS simulations of ionospheric irregularities in E and F-region on GNSS-RO signals
22	Riccardo Biondi	How the recent Anak Krakatau eruption affected the atmospheric structure?
23	Stig Syndergaard	A bi-local estimation approach for residual ionospheric correction of radio occultation bending angles
24	Sean Healy	The ROM SAF reanalyses
25	Sean Healy	Estimates of forward model and instrument error statistics in the troposphere
26	Tom Yunck	To Everything A Season: RO Coming Of Age

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 ROM SAF User Workshop, as part of ROM SAF - IROWG 2019, Konventum, Helsingør (Elsinore), Denmark, 19-25 September 2019

ROM SAF User Workshops are accessible via the website: https://www.romsaf.org/workshops/

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

ROM SAF Reports are accessible via the ROM SAF website: http://www.romsaf.org