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CLIMATE RELATED PROCESSING AND POTENTIAL OF RADIO OCCULTATION DATA

In response to CGMS action 39.41: CGMS requests the Rapporteurs to discuss, at the upcoming Intern. Scientific Working Group meetings, the WG contributions to ECV production and reprocessing activities, and other relevant climate work.

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Radio occultation (RO) data offer a unique opportunity for climate studies and for "anchoring" analysis, re-analysis, and climate model runs since they require no calibration. Pre-requisite for such data use are (1) consistently processed long-term data sets from RO instruments; (2) assessment of the trends derived from RO data, including the impact of processing by different centres.

RO offers continuous data from 2001 onwards and first re-processing activities and trend estimates have been performed; results have already been / are about to be published in peer-review journals. The initial focus was on the CHAMP mission, which provided data from 2001 to 2008. Many more observations have been provided by COSMIC, from April 2006 onwards. RO instruments offer at the various processing levels (1) bending angles, (2) refractivity, (3) temperature and water vapour profiles. Recent studies show that although the derived variables including bending angle, refractivity, pressure, geopotential height, and temperature are not readily traceable to SI units of time, the high precision nature of the raw RO observables is preserved in the inversion chain. This demonstrates the usefulness of all these RO derived variables from bending angle to temperature for climate studies.

This working paper presents the activities in the RO community that are related to the generation and evaluation of climate data sets. Reprocessing activities from different worldwide centres are summarised first, and an evaluation of the trend consistency derived from the different data sets is shown afterwards (ROTrends Project). Note that RO re-processing is only required if the actual processing or input data has improved, e.g., due to better GNSS (Global Navigation Satellite System such as GPS) orbits and clocks being available or improved processing options.

Additionally we present the possibility of extending the GNSS RO technique by providing signal sources at other interesting frequencies, e.g., near and at water vapour and carbon dioxide lines, to also make use of absorption features (LEO-LEO occultations).

Data sets from the CHAMP re-processing and trend evaluation are available to the climate community. Future activities to include more recent data sets have already been agreed upon.

Climate related Processing and Potential of Radio Occultation Data

1 INTRODUCTION

Radio occultation (RO) observations of GNSS (Global Navigation Satellite System, e.g., the American Global Positioning System (GPS)) satellites offer a unique opportunity for studies of the climate system since they:

- require no calibration (they are essentially time measurements) and offer thus long-term stability;
- have by nature a high vertical resolution, and, depending on the orbits, a global distribution, and an appropriate diurnal sampling;
- have high accuracy and precision;
- are minimally affected by clouds and precipitation.

Please also refer to **[1]** for an excellent overview of the RO technique and its capabilities.

The first characteristic above allows for example to combine different sensors to generate a long term data set without requiring inter-calibration (see e.g.; **[2]**). It is however required to process the different sensors in a consistent manner to avoid the introduction of processing differences (called Structural Uncertainty - SU), since every processing centre uses slightly different processing assumptions, e.g. with respect to quality control. In analysis and re-analysis runs, RO does not only provide information on temperature and water vapour, but it also acts as an "anchor" for drifting radiance instruments **[3,4]**. More recently, RO data have also been used to correct other observation types, e.g., radio-sondes which show different bias structures depending on the manufacturer of the sonde. This "anchoring" feature and the very different measurement principle is also an excellent benefit for validation of other satellite observations such as radiance measurements, and could also be beneficial for constraining climate models. The high vertical resolution of RO also allows it to "distinguish" between stratospheric cooling and tropospheric warming **[5,6]**, unlike e.g., the MSU4/AMSU-9 channel which are used for stratospheric trend detection, but the channel straddles the tropopause in the tropics, essentially averaging out the stratospheric cooling and tropospheric warming **[7]**.

Although RO observations may be processed with ancillary data to obtain temperature and water vapour profiles, NWP (Numerical Weather Prediction) centres generally prefer to assimilate the data at bending angle or refractivity level, since (a) this introduces the least additional processing and use of ancillary data; and (b) forward operators to "map" the model data (temperature, humidity, pressure, geopotential height) to measurement space are straight forward. Although bending angles or refractivity are not "standard" ECVs (Essential Climate Variables), analysis of this data - as well as temperature, pressure, geopotential height profiles derived from RO observations - have shown high potential for climate monitoring, see e.g. **[6,8,9,10,11]**. In particular, different variables can be complementary, e.g. refractivity can be unaffected if temperature and pressure changes compensate each other, but further processing to temperature allows separating the two, see e.g. **[12]**. Geopotential height of pressure levels and the ECV upper-air temperature are well suited for producing RO-based fundamental climate data records

(FCDR) in the upper troposphere and lower stratosphere region, see e.g. [**10]**. This includes also trend detection of tropopause heights, see e.g. **[13]**.

The GPS/MET experiment (1995-1997) produced the first RO profiles of Earth's atmosphere and demonstrated the value of RO observations for climate, weather prediction and space weather **[14]**. However, this proof of concept experiment produced only a limited number of high-quality profiles per month and lasted only for two years. The first long term RO data set is provided by the CHAMP mission, spanning from 2001 to 2008. It provided on average about 180 occultations per day, already sufficient to generate climate data sets, and showing a clear impact in NWP model assimilation. Several other missions provide additional coverage within this time frame, most notably from 2006 onwards by the COSMIC constellation with up to 3000 globally distributed occultations per day, and the GRAS instrument, the first operational RO mission. An overview of the past, current, and future RO missions is given in a separate CGMS-40 working paper **[15]**.

In particular the ROTrends project seeks to validate that RO, because of its traceability to the international definition of the second, yields climatological trends that are independent of retrieval centre. Pre-requisite for such an activity is a consistent, re-processed data set from each centre. Below, we first give an overview of the currently available re-processing activities / data sets, and then summarize the main findings of the ROTrends project based on CHAMP data. Future steps in the ROTrends project are also outlined. Finally prospects of LEO-LEO occultations, a potential future complement to GNSS RO with unique climate utility, are summarized.

2 REPROCESSING ACTIVITIES

There are currently 6 reprocessing centres that contribute e.g., to the ROTrends project, which are (in alphabetical order): (1) DMI / ROM SAF (Danish Meteorological Institute / Radio Occultation Meteorology Satellite Application Facility); (2) EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites); (3) GFZ (German Research Centre for Geosciences); (4) JPL (Jet Propulsion Laboratory); (5) UCAR (University Corporation for Atmospheric Research); (6) WEGC (Wegener Center for Climate and Global Change/University of Graz); Reprocessing activities at the different centres are given below.

2.1 DMI / ROM SAF

The ROM SAF (Radio Occultation Meteorology Satellite Application Facility) hosted by DMI (Danish Meteorological Institute) is one of EUMETSAT's decentralised SAF processing centres. The ROM SAF will be producing offline and reprocessed RO data sets based on operational Metop/GRAS data and RO data from other missions (COSMIC, CHAMP, TerraSAR-X, TanDEM-X, GPS/MET), including missions that are supported by EUMETSAT through the ERA-CLIM activity. Third party missions with the ROSA GPS receiver that are going to be supported by EUMETSAT will also be included (Oceansat-2, Megha Tropiques, SAC-D-Aquarius). All processed RO data will be made available to the public at: http://www.romsaf.org.

The RO data sets consist of bending angles and refractivity, temperature, pressure and specific humidity profiles, and gridded and monthly averaged bending angles, refractivity, temperature, pressure, specific humidity, and geopotential heights (see e.g. **[11,16]** for the DMI contribution to the ROTrends studies).

Since software for the processing of RO products is updated and improved over time it is planned to regularly do a complete reprocessing of all RO data using the most recent version of the processing software. Two such reprocessing activities are planned: one in 2014 and one in 2016. The reprocessing activities are coordinated with EUMETSAT through the EUMETSAT Working Group on data set generation through reprocessing.

Current offline RO data:

CHAMP 2002-2008: profiles and gridded data
COSMIC 2011: profiles and gridded data
GRAS 2012: profiles (generated continuously)

Planned RO offline data:

End 2012: COSMIC 2006-2012: profiles and gridded data
2014: Reprocessed RO profiles and gridded data from CHAMP, COSMIC, GRAS, GRACE (and possible others)
2016: Reprocessed RO profiles and gridded data from CHAMP, COSMIC, GRAS, GRACE (and possible others)

2.2 EUMETSAT (CAF)

EUMETSAT hosts a large set of data from its geostationary and low-Earth-orbit satellites. Dedicated reprocessing environments have been set up at the Central Application Facility (CAF) at EUMETSAT. In addition, the SAFs (Satellite Application Facility) are involved in the generation of climate data sets (e.g. at the Climate Monitoring, the Ocean Sea Ice, and the ROM SAF). EUMETSAT is also strongly involved in the GSICS and SCOPE-CM (Global Space-Based Inter-Satellite Calibration System, Sustained Coordinated Processing of Environmental Satellite Data for Climate Monitoring), as well as the European Union Framework 7 project ERA-CLIM (European Re-Analysis of Global Climate Observations) led by ECMWF. Please refer to **[17]** for a full list of EUMETSAT climate related activities and to e.g. **[11,16]** for first CHAMP comparison results.

The EUMETSAT RO data is generally processed to level 1b (bending angle over impact parameter) at the CAF, while processing to level 2 (refractivity, temperature, pressure, water vapour, geopotential profiles) is performed at the ROM SAF. The ROM SAF and the CAF in addition generate climate data sets from their re-processed data. Within the ERA-CLIM project EUMETSAT will generate consistent bending angle data sets through re-processing of GRAS, CHAMP, COSMIC and GRACE RO missions. This might be extended in the future with other available RO mission data. Periodic reprocessing activities are planned afterwards in order to have processing system and/or auxiliary data updates included in the reprocessed data sets. All data will be made available through the EUMETSAT Data Centre at http://www.eumetsat.int.

EUMETSAT generated a validation data set from CHAMP level 1a data, provided by UCAR, for use by several institutes looking into RO trends.

Current offline RO data:

CHAMP Sep 2001 - Sep 2008: bending angle profiles and gridded data

Planned RO offline data:

2013: Reprocessed RO bending angle profiles from CHAMP, COSMIC, GRAS, GRACE
2016: Reprocessed RO bending angle profiles from CHAMP, COSMIC, GRAS, GRACE (and possible others)

2.3 GFZ

GFZ has many years of experience with the installation, operation and advanced data analysis of ground and satellite based GPS receivers. One of these receivers, aboard the German CHAMP satellite, provided measurements for the first long-term RO data set between 2001 and 2008. The data from CHAMP and current (GRACE, TerraSAR-X, and TanDEM-X) GFZ RO missions are processed from raw data level including the generation of precise satellite orbits in near-real time with an average delay of less than 2 hours between measurement aboard the satellite and provision of corresponding atmospheric analysis results to international weather service centers **[18]**.

A main focus of the GFZ RO research is the improvement and extension of GPS RO data analysis techniques. These activities include the first application of the space-based zero and single differencing techniques **[19]** as well as advanced investigations to improve the data analysis in the lower troposphere **[20]**, but also investigations of GPS signals reflected from water and ice surfaces **[21]**. This work includes also the re-processing of RO data sets for climatological investigations **[9,11,13,16,22]** with continuously improved analysis software.

The RO data are available as single profiles containing bending angle, refractivity, temperature, pressure, and geopotential height in the altitude range up to 40 km (100 m vertical grid) for all RO missions processed at GFZ: CHAMP (2001-2008), GRACE (since 2006), and TerraSAR-X (since 2009). TanDEM-X data will be available during 2012. The data sets for each mission are provided as daily archives (tar.gz) via the GFZ data centre (http://isdc.gfz-potsdam.de).

2.4 JPL

JPL currently processes all RO data from CHAMP, SAC-C, COSMIC/FORMOSAT-3, GRACE, and TerraSAR-X starting with the raw measurements (Level 0 data) and retrieving bending angle, refractivity, temperature, pressure, geopotential height, and water vapour profiles (Level 2 data). Both the “quick” and the higher-accuracy “post-processed” versions of these products are available to the public via http://genesis.jpl.nasa.gov. The post-processed data are recommended for climate analysis and are currently available for CHAMP, SAC-C, and COSMIC/FORMOSAT-3.

We plan to reprocess all data from 2001 onwards in a consistent manner with improved high-altitude initializations. An emphasis will be made on providing full documentation of our processing and error characterizations. We also plan to reprocess all available GPS/MET data (1995-1997) using a new single-frequency retrieval method.

2.5 UCAR

UCAR has been processing radio occultation data since the pioneering GPS/Met mission in 1995. The core team has remained largely stable since then resulting in many decades of combined radio occultation processing experience in our group. The UCAR COSMIC Data Analysis and Archive Center (CDAAC) currently processes raw RO data into atmospheric profiles in a): near real-time for COSMIC and other missions (C/NOFS, SAC-C) for use by operational weather centers b) ~3 months after real-time with currently developed algorithms for all available missions (i.e. post-processed solution) and c) and reprocesses data for all available missions every ~2 years with up-to-date and consistent software. Details of the orbit position and velocity estimation and atmospheric excess phase processing performed at CDAAC are detailed in **[23]**. The calculations of bending angles and higher level products using closed-loop and open-loop data are outlined in **[24,25,26]**. In addition to profile-based occultation data, UCAR is now producing gridded monthly mean climatologies as detailed in **[11,16]**.

Since the state of the art of radio occultation processing is being periodically improved, we have undertaken many reprocessings of each mission with consistent software and algorithms to provide a stable RO dataset suitable for climate studies. All input and output data have been archived including the CDAAC source code and binaries, CDAAC configuration parameters, and also the operating system used. This was done to understand and duplicate the same processing years in the future. Our latest reprocessings include data from each mission as follows:

GPSMET (1995-1997), CHAMP (2001-2008), SAC-C (2006-2009), GRACE-A (2007-2010), COSMIC (2006-2010), and Metop-A/GRAS (2007-2011). Planned reprocessings include a 2012 COSMIC reprocessing, and further reprocessings for all other missions. Processing of ROSA missions is planned pending availability of data and documentation. All data is/will be made available through our data center, please refer for further information to http://www.cosmic.ucar.edu/.

2.6 WEGC

WEGC (Wegner Center for Climate and Global Change, Graz) focuses on applications of RO for climate monitoring, diagnostics, and process studies and on the processing, provision and use of RO-derived profiles and gridded fields for such applications. WEGC's Occultation Processing System (OPS) and Climatology Processing System (CLIPS), for retrieving atmospheric profiles and deriving gridded fields, respectively, embody its experience in RO since the mid-1990ties. The most recent re-processing used the version OPSv5.4/CLIPSv1.3. Overview descriptions of OPSv5.4 are contained in **[5,11,27]**, a detailed description of OPSv5.4 and CLIPSv1.3 is given in **[28]**, and analysis and modeling of errors in the profiles and fields are described in **[29,30]**. WEGC's recent review on RO for climate monitoring and change detection **[6]** surveys the various climate science studies performed, including first climate change signal detection studies **[5,10]**.

Current data. The OPSv5.4/CLIPSv1.3 re-processing, which started with excess phase and orbit data from UCAR, provided profiles and gridded data for GPS/MET (1995-1997 primetimes), CHAMP (2001-2008), SAC-C (2001, 2002), COSMIC (2006-2010), and GRACE-A (2007-2010). The data are online at WEGC's RO data portal (http://www.wegcenter.at/globclim). The RO Trends project was supported by the CHAMP dataset from this database.

Planned data. A re-processing with the version OPSv5.5/CLIPSv1.4, which will start with the most recent UCAR-reprocessed excess phase and orbit data from GPS/MET, CHAMP, SAC-C, COSMIC, MetOp-A/GRAS, and GRACE-A, is scheduled to be completed in early 2013. OPS/CLIPS is phased out thereafter and WEGC's new RO processing system, a fresh development over 2011-2013, is scheduled to complete its first re-processing of the multi-satellite data in 2014. This is the first re-processing planned to provide integrated uncertainty estimation for all profiles and fields, traced from the SI universal time standard.

3 ROTRENDS PROJECT

The RO Trends Intercomparison Working Group was established in 2006. It is an international collaboration of RO processing centres focused on intercomparisons of RO multi-year data records for a systematic assessment of accuracy and data quality. The aim is to validate RO as a climate benchmark by demonstrating that trends in RO products are essentially independent of retrieval centre. A first step to reach this aim is the quantification of structural uncertainty (SU) in RO products arising from different processing schemes. Quantification of SU as one property of a climate benchmark data type is regarded an essential advance towards a multi-year RO climate record with complete error description.

A first intercomparison study was performed for refractivity data provided by four different processing centres, GFZ, JPL, UCAR, and WEGC, for the CHAMP record 2002 to 2006 **[16]**. SU was found <0.03% per 5 years for refractivity trends in large-scale monthly and zonal-mean refractivity fields.

In a second intercomparison six processing centres, DMI/ROM SAF, EUMETSAT, GFZ, JPL, UCAR, and WEGC, contributed re-processed data products for the common CHAMP period 09/2001 to 09/2008. SU was quantified for the full set of atmospheric RO variables including bending angle, refractivity, dry pressure, dry geopotential height, and dry temperature. Since RO products are available as individual profiles and as gridded fields we carried out two studies each focusing on one product.

In a profile-to-profile intercomparison (PPC) **[27]** we used exactly the same set of profiles from each data centre, i.e., a subset of profiles from each centre's profile products (Data centres basically use the same raw measurements as input but they provide a different number of output profiles due to different quality control procedures in their processing). A detailed description of the processing schemes of the different centres is provided to motivate further study of SU and how it varies for the different processing steps, from bending angle to temperature profile retrievals.

In the intercomparison study of RO gridded climate records, the full set of profiles provided by each centre was used and then averaged to monthly and zonal-mean climatological fields (MMC) **[11]**. The sampling error due to discrete sampling in space and time was estimated and subtracted from the climatologies. SU was quantified for the fields at full altitude resolution (200m vertical grid) as well as for altitude layer averages.

SU was found lowest within 50°S to 50°N at 8 km to 25 km for all inspected RO variables. In this region, the SU in trends over 7 years is <0.03% for bending angle, refractivity, and pressure, <3 m for geopotential height of pressure levels, and <0.06 K for temperature. SU increases above 25 km and at high latitudes, mainly due to different bending angle initialisation (which is required for further processing to refractivity, temperature, geopotential height, pressure) in the centres' processing schemes. The more retrieval steps are required for the RO variables, the lower is the altitude where larger differences occur. At high latitudes larger residual sampling error due to higher atmospheric variability is also a factor in the analysis.

The results for gridded climate records **[11]** are consistent with those for individual profiles **[27]** and with former results **[16]**, indicating that residual sampling error is small to negligible over the regions with a lower atmospheric variability. The consistency of findings from the different studies, based on different data versions and methodological approaches, underpins the quality of RO data and their utility for climate studies.

Currently GPS RO can be used for climate trend assessments within the region from 50°S to 50°N and below 25 km altitude, where SU meets stability requirements for air temperature as defined by the Global Climate Observing System (GCOS) program **[31]** as well as corresponding estimated requirements for the other RO variables. Since RO processing systems undergo continuous development, further improvements and reductions in SU are expected. The RO Trends project accepts as its goal a reduction of SU based on improved understanding of the different contributing error sources. Reduction of SU *per se* is not the goal of RO Trends.

The status of paper **[27]** is in press and the status of paper **[11]** is submitted. The data records used in **[27]** and **[11]** will be made available to the broader science community, including:

- profile data, gridded climatologies and sampling error estimates (netCDF files);
- bending angle, refractivity, dry pressure, dry geopotential height, dry temperature;
- of the centres DMI, EUM (only bending angle), GFZ, JPL, UCAR, WEGC.

Future plans of the RO Trends working group include studies on:

- multi-satellite consistency, to analyse SU across different instruments and missions as revealed by different processing centres;
- upper stratosphere retrievals, by analyzing intermediate processing products, to determine how SU may be introduced in this critical initialization region;
- quality control, to understand why there are significant differences (~15%) in the number of quality controlled profiles generated at the different processing centres, providing further information on processing differences and SU.

4 LEO-LEO OCCULTATIONS

As summarized above GNSS RO provides vital and unique contributions to applications like NWP and climate monitoring. Building on this success, further advanced techniques emerge in form of occultations between Low Earth Orbit satellites (LEO-LEO), which do not only measure refractivity that leaves a temperature-water vapour ambiguity in the troposphere.

LEO-LEO occultations **[32,33]** can complement GNSS RO by measuring both refraction and absorption of coherent microwave and infrared-laser signals. This enables to vastly expand from the GNSS RO refractivity-based sounding of the thermodynamic structure to a complete set of weather and climate variables, including thermodynamic ones (temperature, pressure, water vapour), greenhouse gases (carbon dioxide, methane, etc.), wind speed, and others like cloud, aerosol and turbulence variables. An introduction of LEO-LEO microwave occultation is found in **[32]**, and of combined microwave and infrared-laser occultation in **[33]**. Recent descriptions of the advanced processing approaches and their scopes are given in **[34,35,36]** and first ground-based demonstration experiments are described in **[37,38]**.

The LEO-LEO data will contain negligible ionospheric residual errors and can provide almost all upper air Essential Climate Variables (ECVs) defined by WMO/GCOS **[31]** as a consistent dataset of climate benchmark quality. A LEO-LEO system complementing GNSS RO would thus provide an authoritative reference standard in the global free atmosphere (above the boundary layer) for large-scale monitoring of these ECVs. All other observing systems and weather and composition assimilation and forecasting systems could “anchor” to this standard. The climate community as well as the NWP and atmospheric chemistry communities can thus benefit strongly from these data, most so by long-term operational use as reference climate observing system for the atmosphere over the 21st century.

U.S. and European agencies (ESA, NSF, NASA) have supported scientific and technological preparatory activities for more than a decade meanwhile, see e.g. **[32,33,37,38]**. A continuation of these activities towards a LEO-LEO demonstration mission could offer a unique benchmark climate record for global monitoring of greenhouse gases and climate change in Earth’s atmosphere.

5 CONCLUSIONS

Radio occultation (RO) data offer a unique opportunity for climate studies and for “anchoring” analysis, re-analysis, and climate model runs since they require no calibration. Pre-requisite for such data use are (1) consistently processed long-term data sets from RO instruments; (2) assessment of the trends derived from RO data, including the impact of processing by different centres.

RO offers continuous data from 2001 onwards and first re-processing activities and trend estimates have been performed; results have already been / are about to be published in peer-review journals. The initial focus was on the CHAMP mission, which provided data from 2001 to 2008. Many more observations have been provided by COSMIC, from April 2006 onwards. RO instruments offer at the various processing levels (1) bending angles, (2) refractivity, (3) temperature and water vapour profiles. Recent studies show that although the derived variables including bending angle, refractivity, pressure, geopotential height, and temperature are not readily traceable to SI units of time, the high precision nature of the raw RO observables is preserved in the inversion chain. This demonstrates the usefulness of all these RO derived variables from bending angle to temperature for climate studies.

This working paper presented the activities in the RO community that are related to the generation and evaluation of climate data sets. Reprocessing activities from different worldwide centres were summarised first, and an evaluation of the trend consistency derived from the different data sets was shown afterwards (ROTrends Project). Note that RO re-processing is only required if the actual processing or input data has improved, e.g., due to better GNSS (Global Navigation Satellite System such as GPS) orbits and clocks being available or improved processing options.

Additionally we presented the possibility of extending the GNSS RO technique by providing signal sources at other interesting frequencies, e.g., near and at water vapour and carbon dioxide lines, to also make use of absorption features (LEO-LEO occultations).

Data sets from the initial CHAMP re-processing and trend evaluation are available to the climate community. Future activities to include more recent data sets have already been agreed upon.

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