RO-CLIM Project Description

Note: Format, main outline is based on the Letter of Intent

1. Project title:

"Radio occultation based gridded climate data sets - RO-CLIM"

2. Main applicant[1]:

Name: Hans Gleisner
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3. Composition of the project team for this project:

Name and title	Institute	Address
K. Lauritsen, S. Syndergaard	ROM SAF / DMI	Danish Meteorological Institute, Copenhagen, Denmark
S. Healy	ECMWF	European Centre for Medium Range Weather Forecasts, Reading, UK
C. Marquardt, R.A. Roebeling, A. von Engeln	EUMETSAT	EUMETSAT, Eumetsat Allee 1, Darmstadt, Germany
T. Schmidt, J. Wickert	GFZ	GeoForschungsZentrum, Helmholtz Centre Potsdam, Germany
C. Ao, T. Mannucci	JPL	Jet Propulsion Laboratory/NASA, Pasadena, California, US
M. Ringer	Met Office	Met Office, Exeter, UK
R. Kursinski	Moog	Moog Broad Reach, Boulder, USA
B. Schreiner, S.-P. Ho, D. Hunt	UCAR	COSMIC Program Office, University Corporation for Atmospheric Research, Boulder, Colorado, USA
A. Steiner, U. Foelsche, G. Kirchengast	WEGC	Wegener Center for Climate and Global Change, University of Graz, Graz, Austria

4. Satellite Climate Data Records capabilities

Radio occultation data uses the impact of the changing Earth refractivity field on GPS signals observed in a limb sounding geometry through the atmosphere. This geometry involves thus a GPS (and in future also e.g. GLONASS, Galileo) satellite, and a low earth orbiting one. For an overview, please refer to Anthes 2011. The measurement is time based, a phase delay, from which profiles of bending angle, refractivity, temperature, and water vapor can be derived. And since the measurement is time based, long term records for trend estimates can easily be produced from different satellites, requiring no inter-satellite calibration, only a consistent processing setup. The continuous data record starts

[1] The project lead of RO-CLIM was shifted from Axel von Engeln, EUMETSAT to Hans Gleisner, EUMETSAT ROM SAF / DMI on 24. March 2014. Document is otherwise unchanged.

in 2001 with the CHAMP instrument. The processing from bending angles to refractivity, to temperature (the water vapor observations are not yet suited as a climate record) involves different levels of a priori knowledge, but all processing levels are well suited for climate related investigations.

Radio occultation observations as a key component of the global climate observing system, providing benchmark observations capability to calibrate other measurements, is also indentified in GCOS 2011. It identifies several areas for “Immediate action, partnerships and international coordination”, listing beside others “Construction of an FCDR of bending angles from GPS-RO data” as a key point. One of the products of RO-CLIM particularly addresses this action. The bending angles are at the FCDR level, and the related ECV is the upper air temperature. RO-CLIM addresses also the following products identified in GCOS 2011:

- Product A.3.1 Upper-air temperature retrievals
- Product A.3.2 Temperature of deep atmospheric layers

a. Geophysical parameters

The data set will cover gridded products based on bending angles, refractivity, temperature, pressure, and geopotential height. The gridding is performed on a default height grid over monthly and latitude bins. Depending on the number of occultations available, the use of a more dense grid will be assessed, which might lead to the generation of data sets with shorter time spans, but higher resolution in latitude and longitude. The core resolution data set, which is tied to the early CHAMP data coverage, will however continue to be generated.

b. Satellite sensor / Atmospheric Model records

The following radio occultation instruments will at least be included: CHAMP, COSMIC, Metop/GRAS. In addition, ECMWF model data from re-analysis runs (e.g. ERA-Interim, ERA-CLIM) and from a climate model run at the Met Office is provided. The possibility to include other radio occultation instruments, such as GRACE, TerraSAR-X, or data of the ROSA instruments flying on Oceansat-2, SAC-D, and Megha Tropiques will be considered. An overview of past, current, and future mission is given in *Figure 1*. Further information on these missions is available in IROWG 2012a**.**

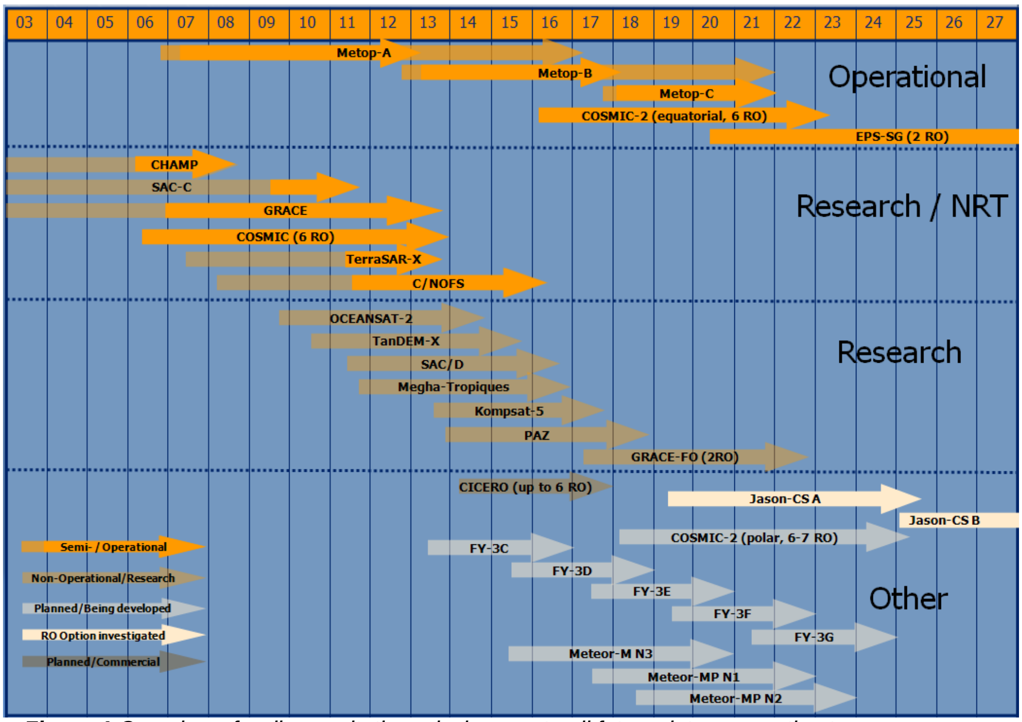

***Figure 1** Overview of radio occultation missions, note all future dates are estimates.*

c. Processing chains

Several processing chains operating on radio occultation data are used in RO-CLIM. Some of these start at the instrument measurement Level 0, others base their processing on an intermediate product, where the involved satellite positions, and the phase measurement is already available (Level 1A). Not all chains process the data up to temperature, but all chains are well validated against various other measurements and model data. Additionally, a co-located, ECMWF model based data set is also provided, where model temperature, pressure, water vapour, geopotential, and forward modelled bending angle and refractivity are available.

Generally, we use the following level definitions within this document, note however that these definitions are not necessarily used at the different centres in this way:

> *Level 0*: Raw sounding, tracking and ancillary data, and other GNSS data before clock correction and reconstruction;
>
> *Level 1a*: Reconstructed full resolution excess phases, Signal-to-Noise Ratios, amplitudes, orbit information, I, Q, and NCO values of the tracking loop, and navigation bits;
>
> *Level 1b*: Bending angles and impact parameters, Earth location, metadata and quality information;
>
> *Level 2*: Refractivity profiles, and pressure, temperature, and specific humidity profiles, Earth location, metadata, and quality information;
>
> *Level 3*: Gridded Level 1 and 2 offline profile products in the form of, e.g., monthly and seasonal zonal means, metadata, and quality information; Gridding of Level 1 and 2 offline profile products into e.g. monthly and seasonal zonal means, metadata, and quality information.

A generic processing flow is depicted in Figure 2, where the processing starts from Level 0 mission data (raw instrument data). This is pre-processed with mission specific auxiliary data (e.g. instrument characteristics) to generate the required input data for the Precise Orbit Determination (POD) of the Low Earth Orbit (LEO) satellite. The POD of the LEO satellite requires further auxiliary information on e.g. GPS orbits and clocks, Earth Orientation Parameters. The Level 1A processing ingests the generated LEO and auxiliary GPS orbits and clocks and calculates total and excess phases, which characterize the impact of the atmosphere onto the GPS signal. The Mission Level 1A data is further processed to Level 1B (including primary assimilation products such as bending angles over impact parameter) and Level 2 (e.g. refractivity, temperature, pressure) in dedicated processing steps. The last step in the generation of gridded products of RO-CLIM is the ingestion of the Level 1B and 2 data into a binning and averaging routine, which includes a correction of the sampling error, usually based on ECMWF/NWP global data.

As noted above, the blue coloured Mission Level 0 and 1A data are the possible starting points from where the Level 1B, 2 data, and the gridded data is generated.

The current setup foresees the following starting points for the different partners:

Institute	**Starting Point for Level 1B, 2 Generation**
DMI	Level 1A generated at UCAR or EUMETSAT
ECMWF	not applicable
EUMETSAT	Level 0 or Level 1A generated at UCAR
GFZ	Level 0 or Level 1A generated at UCAR, EUMETSAT
JPL	Level 0 or Level 1A generated at EUMETSAT
Met Office	not applicable
Moog	not applicable
UCAR	Level 0 if possible
WEGC	Level 1A generated at UCAR or EUMETSAT

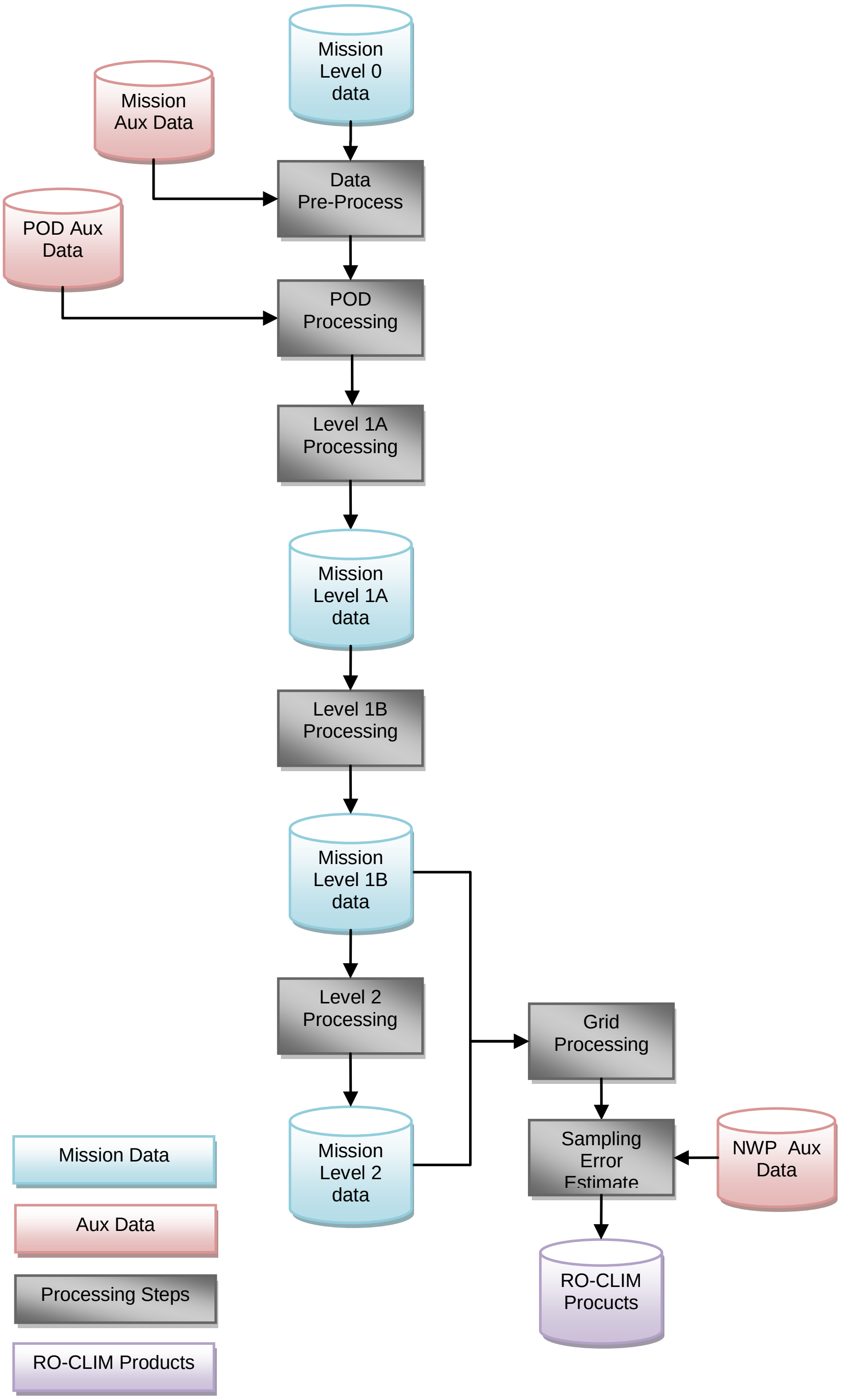

Figure 2 Generic processing flow to generate gridded RO-CLIM products.

d. Algorithms

All instrument processing chains follow the "standard" radio occultation processing. Depending on whether starting from Level 0, this includes orbit and clock estimates of the involved satellites, bending angle calculation from phase and amplitude measurements, ionospheric correction of bending angles, initialization of the bending angles at high altitudes to derive refractivity, followed by a dry air retrieval. Please refer to Kursinski et al. 1997 and Ho et al. 2009, 2012 for further details. The forward modelling of ECMWF data relies on the standard assimilation algorithms for this kind of data [Healy and Thépaut, 2006].

5. Justification of the proposed project

a. Introduction

Radio occultation is a satellite observation technique that does not require any calibration. It is thus very well suited for the generation of climate data sets [IROWG 2012, GCOS 2011] and to validate other satellite based long term trend estimates of temperature in the upper troposphere and the stratosphere. The vertical extent is from 0 km to a maximum of about 50 km, vertical resolution of a few hundred meters in the troposphere to 1.5 km in the stratosphere. Horizontally, the measurement averages over about 300 km, owing to the limb sounding technique. The vertical extent depends on the instrument, since modern instruments have much lower instrument noise. For the early instruments, the vertical range extends up to about 40 km for bending angles, and is reduced to about 30 km for refractivity and temperature, pressure profiles.

Radio occultation has shown to provide very valuable information to modern Numerical Weather Prediction models [Healy and Thépaut, 2006], since it (a) has information at high vertical resolution; (b) provides an anchor point to the assimilation of bias affected radiances; and (c) has global coverage. The calibration free nature of radio occultation data very much simplifies the generation of long term data sets from different instruments, since no inter-satellite or inter-instrument calibration is required. Such inter-calibration required for radiance based instruments can cause large uncertainties in the trend estimates, as shown in the MSU based data sets, and more recently in the SSU one [D. Thompson et al., 2012].

A recent drawback of radio occultation data for climate trend assessments data has been the rather short time span covered. Radio occultation measurements are continuously available from 2001 onwards, starting with the CHAMP instrument. More recently, several other instruments have been launched, most notably the COSMIC constellation of 6 satellites (launch 2006), the first operational instrument Metop/GRAS (launch 2006), and GRACE-A (radio occultation data since 2006), TerraSAR-X (data since 2008). COSMIC and Metop/GRAS provide overlap with the CHAMP instruments between 2006 and 2008. The number of occultations available per day has also increased significantly, from around 180 during the CHAMP period, to > 2000 for recent periods. With coverage of more than 10 years, decadal trend estimates can be derived from radio occultation data.

First evaluations of trends based on radio occultation measurements have been made within the ROTrends project. ROTrends is a collaborative effort by different radio occultations processing centres to compare their respective processing streams.

b. Historical overview of related activities

Radio occultation data have been extensively validated since they became routinely available. This included validation against other radio occultation measurements, to determine the noise floor, as well as validation against radio sonde, numerical weather models, and other satellite observations. Very often these validation exercises reveal problems in the used validation data, e.g. such as the slightly different statistics found for various radio sonde manufacturers, or detected bias structures in weather prediction models. These validations look however very similar against different radio occultation instruments or against different processing streams of the same radio occultation instrument.

The best method to evaluate the different processing is thus a direct comparison of processing tools that use the same input data. Several of such comparisons have been performed over the last years, with the ROTrends project, using CHAMP data, being the most rigorous and advanced study. ROTrends focussed mainly on the structural uncertainty in the data and in the derived trends, which is introduced in the processing. Several peer reviewed articles are available on the ROTrends results [S.-P. Ho et al., 2009; 2012; A.K. Steiner et al. 2013]. All of them show the excellent agreement among the different processing centres, with mean trend differences of the centres of e.g. ±0.02%/5years for bending angles [S.-P. Ho et al., 2012].

Since ROTrends focussed on the CHAMP data set, it only covers the years 2001 to 2008, thus excluding the more recent measurements. An extension to include more recent instruments was agreed at the last ROTrends meeting in 2012, at the IROWG-2 workshop.

c. Summary of proposed project

While ROTrends provided a very valuable data set over the CHAMP period, an extension of that initial period to include the most recent radio occultation observations and build up a long term climate data record is one focus of this project. It will in addition also make use of the more dense coverage of recent satellites, to provide a shorter duration, higher resolution data set. By including model data from both ECMWF and the Met Office Hadley Centre an assessment of the model performance against radio occultation data is also possible. The SCOPE-CM used maturity matrix provides a very valuable reference for the currently available ROTrends data set, this set will be evaluated and “matured” against that matrix.

d. Assessment of the feasibility of the proposed project

The data sets are well suited for the proposed project [IROWG 2012]. The RO-CLIM consortium has also already shown the capacity to process and compare such long term radio occultation data sets within the ROTrends project. This has mostly relied on a best-effort basis at the various institutes.

e. References

R.A. Anthes (2011), Exploring Earth's atmosphere with radio occultation: contributions to weather, climate and space weather, Atmos. Meas. Tech., 4, 1077-1103, doi:10.5194/amt-4-1077-2011.

GCOS (2011), Systematic Observation Requirements For Satellite-Based Data Products For Climate Update, GCOS-154

S.B. Healy, J.-N. Thépaut (2006), Assimilation experiments with CHAMP GPS radio occultation measurements, Quarterly Journal of the Royal Meteorological Society, 12/2006; 132(615):605-623. doi:10.1256/qj.04.182

IROWG (2012), Climate related processing and potential of radio occultation data, CGMS-40 EUM-WP-03 2012, available at: http://www.irowg.org

IROWG (2012a), Status of the global Radio Occultation Observing System, CGMS-40 EUM-WP-02, 2012, available at: http://www.irowg.org

E.R. Kursinski et al. (1997), Observing Earth’s atmosphere with radio occultation measurements using the Global Positioning System, J. Geophys. Res., 102, 23,429–23,465, doi:10.1029/97JD01569.

S.-P. Ho et al. (2009), Estimating the Uncertainty of using GPS Radio Occultation Data for Climate Monitoring: Inter-comparison of CHAMP Refractivity Climate Records 2002-2006 from Different Data Centers, J. Geophys. Res., 114(D23), D23107, doi:10.1029/2009JD011969

S.-P. Ho et al. (2012), Reproducibility of GPS radio occultation data for climate monitoring: Profile-to-profile inter-comparison of CHAMP climate records 2002 to 2008 from six data centers, J. Geophys. Res., 117, D18111, doi:10.1029/2012JD017665

A.K. Steiner et al. (2013), Quantification of structural uncertainty in climate data records from GPS radio occultation, Atmos. Chem. Phys., 13, 1469-1484, doi:10.5194/acp-13-1469-2013

D. Thompson et al. (2012), The mystery of recent stratospheric temperature trends, Nature 29 November 2012, 491: 692–697, DOI:10.1038/nature11579

6. Current and targeted Maturity Level (see Maturity Matrix Model);

Two data sets with different maturity levels are generated within this project. One starts from the data generated within the ROTrends project, the second one is an extension of the ROTrends data to include more recent radio occultation observations:

1. based on the existing CHAMP ROTrends data set, higher maturity will be achieved by:
    a. Software Readiness: the underlying code at the different centers is well tested, however smaller improvements or minor bug fixes are expected to be found within the project, furthermore an estimate of the structural uncertainty will be derived;
    b. Meta Data: data is already available in netCDF 3 format, however further increments to get this data set to maturity level 6 are required;
    c. Documentation: the primary documentation is through peer-reviewed articles, e.g. [S.-P. Ho et al. (2009), S.-P. Ho et al. (2012), A.K. Steiner et al. (2013)], but the available data formats are not fully documented. There is also no operational algorithm description for each center;
    d. Validation: extensive validation and publication in peer reviewed journals is already available, further maturity is expected when cross-checking the early CHAMP data set against the more recent missions as processed in the extended ROTrends data set; further validation is also performed by cross-checking the data set against re-analysis or climate model data;
    e. Public Access: currently, all data is on an ftp site, the documentation and accessibility will be enhanced by a web based dedicated project page;
    f. Societal Impacts: better accessibility, and the extended data set will also benefit the maturity of the CHAMP based data.
2. an extended ROTrends data set with at least COSMIC, Metop/GRAS data included, starting from lower maturity. The generation of this data set will first require building up expertise at the different centers to process the different instruments, and will include at least 2 centers that start the processing at Level 0 and provide Level 1A data for other centers. The different instrument data at Level 1A can be processed fairly similarly, thus there are no major code developments expected for centers starting at Level 1A. More development work is however expected in order to start processing from Level 0. In addition, re-analysis and climate model based simulated occultations will be generated and processed / gridded in the same manner as the instrument data set.

	Software Readiness	Meta Data	Docu-mentation	Validation	Public Access	Societal Impacts
1. ROTrends Maturity level	5	4	3	5	3	3
Targeted 1 Maturity level	6	6	5	6	6	5
2. Extended ROTrends Maturity level	2	3	3	4	2	3
Targeted 2 Maturity level	5	6	5	5	6	5

7. Give the expected results, challenges and potential contributions of the project;

The project aims to (1) increase the maturity level of already existing data sets that were produced within ROTrends; (2) extend these data sets with more recent satellite data; (3) provide a direct link to modern climate, re-analysis runs; (4) make these data sets more easily available to the global climate community. This includes crossvalidation exercises, building up of capacity to process data from more recent satellites.

Challenges are not foreseen regarding the processing, this capability has already been proven, but more on the work load and the funding at the various institutes. The duration of the project was in response to these challenges set to 5 years.

Contributions to trend assessments of the atmosphere and other satellite instruments measuring upper troposphere and lower stratosphere temperatures are expected.

8. Duration of the project: 5 years
Proposed starting date: January 2014

9. Give the expected breakdown of the tasks to be performed in this project;

The following major milestones are foreseen:

- bring already existing ROTrends data set to higher maturity;
- generate co-located ECMWF re-analysis data set;
- generate co-located climate model data set;
- generate a common Level 1A format that can be processed at all centres;
- build up capacity at the various institutes to process COSMIC data;
- build up capacity at the various institutes to process Metop/GRAS data;
- extend original ROTrends data sets;
- provide higher resolution data sets of more recent observations.

10. Indication of the funding situation

SCOPE-CM does not support specific projects financially, instead providing coordination and interaction into the participating agencies' own programmes and activities. The current funding situation at the project partners is thus briefly presented here.

- DMI: ROM SAF Funding (Radio Occultation Meteorology Satellite Application Facility). Validation and processing activities will be incorporated in updated reprocessing plan for ROM SAF.
- ECMWF: ROM SAF Funding (Radio Occultation Meteorology Satellite Application Facility).
- EUMETSAT: activities are covered within the ERA-CLIM project, and within the normal re-processing and validation work.
- GFZ: activities are covered by GFZ funding.
- JPL: activities will be supported by expected NASA grants under the GPS Earth Observatory project and ROSES funding opportunities.
- Met Office: ROM-SAF funding for forward model to simulate Bas.
- UCAR: Current funding from the U.S. National Science Foundation under Cooperative Agreement No. AGS-1033112 - The Continued Operation of COSMIC in Support of Operational and Research Applications.
- WEGC: National and international research projects with funds from the European Space Agency (ESA), the Austrian Space Applications Programme (FFG-ALR), and the Austrian Science Fund (FWF) are ongoing and scheduled to be continued over the SCOPE-CM period.

11. Available processing capacities;

- DMI: ROM SAF GNSS Processing and Archiving Center (GPAC)
- ECMWF: Integrated Forecast System
- EUMETSAT: reprocessing facility
- GFZ: reprocessing facility for CHAMP, GRACE-A, TerraSAR-X from Level0 funded by GFZ
- JPL: existing computation hardware and software will be utilized for this work
- Met Office: not applicable/use of standard environment
- UCAR: Near real-time and reprocessing of RO data by the COSMIC Data Analysis and Archive Center (CDAAC)
- WEGC: 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) are currently used as (re-)processing tools.

DMI is willing to host the end products generated within RO-CLIM. This will be a data service website and dedicated project page on behalf of the RO-CLIM project team, accessible via the SCOPE-CM website http://www.scope-cm.org and prominently linked also via the IROWG website http://www.irowg.org.

12. Curriculum vitae of the key investigators

EUMETSAT

Dr. Axel von Engeln, *Born:*25/10/1965, German

1996	University of Bremen, Germany / M.Sc. degree in Physics (Dipl. Phys.)
2000	University of Bremen, Germany / Ph.D. Degree in Physics (Dr. rer. nat)
2001–2003	Naval Research Laboratory, Washington DC, Monterey CA, US / Postdoctoral scientist
2003–2004	University of Bremen, Germany / Senior Scientist
2004–2006	Met Office, Exeter, United Kingdom / Radio Occultation Scientist
2006-now	EUMETSAT, Germany / Remote Sensing Scientist

Experience and Expertise: Dr. von Engeln did his master thesis on the impact of Zeeman splitting on microwave observations in the upper atmosphere. His PhD thesis investigated the retrieval capabilities of (a) microwave observations; (b) radio occultation observation; (c) the potential synergy of these 2 observation techniques. He also participated in several ESA studies on the capabilities of microwave and sub-millimetre observations of the atmosphere. As a post-doctoral researcher, Dr. von Engeln mainly focussed on the capabilities of radio occultation observations, e.g. investigating the possibility to study the planetary boundary layer from this kind of observations. At EUMETSAT, he is one of the researchers responsible for the GRAS radio occultation instrument, which is the first operationally flying instrument of this type. He is also a co-convener of the GRAS Science Advisory Group, an expert group that meets annually to discuss and investigate options for GRAS data processing. In addition, Dr. von Engeln is co-chair of the International Radio Occultation Working Group.

Dr. Christian Marquardt, *Born:* 9/4/1964, German

1989	University of Düsseldorf, Germany / M.Sc. degree in Theoretical Physics (Dipl. Phys.)
1997	Free University of Berlin, Germany / Ph.D. Degree in Meteorology (Dr. rer. nat)
1997–1999	Free University of Berlin, Germany / Postdoctoral scientist
2000–2002	GFZ Potsdam, Germany / Scientist
2002–2005	Met Office, Exeter, United Kingdom / Radio Occultation Scientist
2005-now	EUMETSAT, Germany / Remote Sensing Scientist

Experience and Expertise: Dr. Marquardt did his PhD thesis on aspects of the long term variability of the global stratospheric dynamics, in particular the tropical Quasi-Biennial Oscillation (QBO). Over several years, he contributed to the German Ozone Research Programme (OFP) by analysing natural sources of ozone variability in the stratosphere using NWP and remote sensing data. At GFZ Potsdam, he was responsible for the retrieval of humidity from radio occultation soundings with both direct and variational methods, and lead validation activities for data from the CHAMP satellite. After joining the Met Office, he contributed to the variational assimilation of radio occultation data in operational NWP and implemented the initial version of the ROPP software. He has also served on the GRAS Science Advisory Group. At EUMETSAT, he is the other researcher responsible for the GRAS radio occultation instrument, which is the first operationally flying instrument of this type. He is responsible for the operational processing of GRAS and other RO data at EUMETSAT, and leads the activities for the further development and evolution of radio occultation processing algorithms.

Dr. Ir. R.A. (Rob) Roebeling, *Born:* 16/12/1965, Dutch

1991	Wageningen University, The Netherlands / M.S.c. degree in hydrology
1991-93	Winand Staring Centre, Wageningen, the Netherlands / junior scientist
1994-99	EARS Ltd, Delft, The Netherlands / project leader
2000-07	KNMI, De Bilt, the Netherlands / scientist
2007-11	KNMI, De Bilt, the Netherlands / senior scientist
2008	Wageningen University, The Netherlands / Ph.D in Environmental Sciences
2011-present	EUMETSAT, Darmstadt, Germany / Climate product expert

Experience and Expertise: Dr. Roebeling did his PhD thesis on Cloud Properties Retrievals from Satellite Observations. He has more than 20 years experience in the field of boundary layer meteorology, crop growth modelling, radiative transfer of the cloud atmosphere and multi-sensor remote sensing. From 2000 till 2011 Dr. Roebeling was employed at KNMI as Senior Scientist, where he was leading a research group on cloud physics and head of the three Observations Sections within the Weather Research Division. In 2011, he started working for EUMETSAT as Climate Product Expert, where he leads projects related to the generation of climate data records, and coordinates international efforts to better serve the climate research community with these records. He is co-chair of the Cloud Retrieval Evaluation Working Group (CRE-WG). He publishes actively, and serves as editor for Meteorology and Atmospheric Physics and as reviewer for several journals.

DMI

Dr. Kent Bækgaard Lauritsen, *Born:* 07/08/1965, Danish

1991	M.Sc., Aarhus University, Denmark
1995	Ph.D. in Theoretical Physics, Aarhus University, Denmark
1992	Research Fellow, Aarhus University, Denmark
1992/93	Research Fellow, HLRZ, Forschungszentrum Juelich, Germany
1994	Research Fellow, Boston University, Boston, Massachusetts, USA
1995	Post doc, Boston University, Boston, Massachusetts, USA
1996 – 97	Assistant Research Professor, Niels Bohr Institute, Denmark
1998 – 99	Associate Research Professor, Niels Bohr Institute, Denmark
1999 – present	Research Scientist, DMI, Denmark
2004 – present	Project Leader, DMI, Denmark

Experience and Expertise:

Dr. Lauritsen's M.Sc. work was concerned with Monte Carlo simulation studies of phase transitions in non-equilibrium systems. The Ph.D. work focused on theoretical studies of scaling and dynamics of Laplacian growth, random lattices, Ising models and interfaces.

Until 1999, Dr. Lauritsen's work covered various areas in non-equilibrium statistical physics and he initiated the investigations of boundary scaling in directed percolation and related models. He also contributed to the understanding of universality classes for self-organized critical models and their relation to interface depinning.

Since 1999 Dr. Lauritsen has worked on topics related to radio occultations, mainly advanced retrieval methods. Together with Dr. Michael Gorbunov, they carried out a detailed investigation of Fourier integral operator applications to radio occultation data and introduced the CT2 wave optics inversion method.

Since 2004 he has been the Project Manager of the Radio Occultation Meteorology Satellite Application Facility (ROM SAF, formerly GRAS SAF) under EUMETSAT which is a SAF responsible for the operational processing of radio occultation data from Metop and other satellites.

Dr. Lauritsen has published about 30 scientific articles in refereed, international journals (including 2 invited review papers), participated in over 100 conferences and workshops with many contributed talks, posters, and proceedings papers, and has about 10 invited talks and seminars at conferences and universities.

Research interests include: GNSS radio occultation processing, atmospheric multipath propagation, canonical transform inversion methods, and wave optics simulations.

Dr. Hans Gleisner, *Born:* 24/9/1964, Swedish

1989	Lund Univ. of Technology, Sweden / M.Sc. degree in Engineering Physics
2000	Lund University, Sweden / Ph.D. degree in Astronomy & Astrophysics
1990-92	Alfa-Laval Thermal AB, Sweden / Research Engineer, structural dynamics
1992-95	Alfa-Laval Thermal AB, Sweden / Research Engineer, computational fluid dynamics
1995-2000	Lund University, Sweden / Ph.D studies, graduate Teaching Assistant
2001-03	Danish Met. Institute, Denmark / ESA Research Fellow
2003-05	Danish Met. Institute, Denmark / Postdoctoral Scientist
2005-present	Danish Met. Institute, Denmark / Scientist

Experience and Expertise: Dr. Gleisner did his Ph.D. thesis on the relations between solar activity, solar-wind variations, and geomagnetic and ionospheric disturbances. This included work on non-linear regressive techniques, e.g. artificial neural networks. As an ESA Research Fellow during 2001-2003 (hosted by the Danish Met. Institute in Copenhagen) he developed methods for short-term forecasting of geomagnetic disturbances using real-time data from space-based solar and solar-wind observations, and ground-based geomagnetic and ionospheric observations. During 2003-2004, the forecasting methods were implemented as a real-time semi-operational system as a part of ESA's Space Weather Pilot Project. During this period dr. Gleisner also collaborated with DMI researchers on the detection of climate variability related to the 11-year solar cycle. Since 2006, he has worked as a member of the ROM SAF science team on topics related to GNSS radio occultation (RO) sounding, mainly on the generation and use of RO data in climate research. This work includes, e.g., studies of atmospheric sampling effects, 1D variational retrieval of temperature and humidity from RO soundings, and alternative methods for upper-level initialization of bending-angle inversion. He is currently active with the implementation of software for generation of RO-based climate data, and as the ROM SAF Climate Coordinator he is responsible for the operational generation and dissemination of the ROM SAF climate data products.

Dr. Stig Syndergaard, *Born:* 29/12/1962, Danish

1995	University of Copenhagen, Denmark / M.Sc. degree in Geophysics
1999	University of Copenhagen, Denmark / Ph.D. degree in Natural Sciences
1996/97	University of Arizona, Tucson, Arizona, USA / Visiting Scholar
1995-2000	Danish Meteorological Institute, Copenhagen, Denmark / Scientist
2000-2003	University of Arizona, Tucson, Arizona, USA / Research Associate
2002	University of Graz, Austria / Visiting Scientist
2003-2004	University of Arizona, Tucson, Arizona, USA / Research Scientist
2004-2007	UCAR, Boulder, Colorado, USA / Visiting Scientist
2007-present	Danish Meteorological Institute, Copenhagen, Denmark / Scientist

Experience and Expertise: Dr. Syndergaard did his Ph.D. thesis in the retrieval and analysis of radio occultation (RO) data. within mainly ESA funded projects, he developed computer programs to model and analyze some of the first RO data from the US GPS/MET experiment in 1995. He was responsible for the processing and analysis of the RO data measured by the Danish Ørsted satellite in 1999. At the University of Arizona he contributed to the understanding and development of the emerging microwave cross-link occultation technique, and developed an advanced method for assimilation of occultation data into NWP models. At the University Corporation for Atmospheric Research (UCAR), Dr. Syndergaard was responsible for the processing and analysis of the ionospheric data from the Formosat-3/COSMIC satellite mission. This included developing software for the calibration of GPS receiver differential code biases and cycle-slip detection and correction algorithms for the estimation of satellite-to-satellite total electron content (TEC). Most recent research project focuses on the potentials for RO with future Galileo frequencies (under ESA/EGEP). He is a member of the ROM SAF science team and involved with the processing and validation of ROM SAF products from the Metop satellite. He has authored or co-authored more than 30 scientific publications in a variety of international journals and conference proceedings.

ECMWF

Dr. Sean Healy, *Born:* 21/2/1969, British

1990	University of Leeds, UK / B.Sc. degree in Physics
1994	University of York, UK / Ph.D. degree in Computational Physics
1993-1996	University of York, UK/ Post-doctoral Research Fellow
1996-2003	Met Office, UK/ Research scientist in Satellite Section
2003-2006	ECMWF, UK/ EUMETSAT Fellow
2006-present	ECMWF, UK/ Research scientist in Satellite section

Experience and Expertise: . Dr Sean Healy has worked on the applications of GNSS radio occultation (GNSS-RO) measurements since 1996, starting with the validation of GPS-MET temperataure retrievals. He subsequently co-developed the first "1D-Var" retrieval codes for GNSS-RO measurements and performed early information content studies. Dr Healy designed and implemented the GNSS-RO refractivity assimilation system used operationally for NWP at the Met Office until 2010, and the bending angle assimilation system used operationally at ECMWF. He organised the ECMWF/GRAS SAF workshop on "Applications of GPS radio occultation measurements" in 2008, and is a member of EUMETSAT/ESA's GRAS Scientific Advisory Group (SAG). He has worked on assimilating GNSS-RO measurements in the ERA-Interim Reanalysis, climate applications of GNSS-RO measurements, the sensitivity to the empirical refractivity coefficients, and the retreival of surface pressure information from GNSS-RO. He has contributed to numerous successful projects for ESA and EUMETSAT, the most recent being a study to investigate the optimal number of GNSS-RO measurements for NWP based on an "Ensemble of Data Assimilations" as approach. He has authored/co-authored 31 journal papers in this area since 2000.

GFZ

Dr. Torsten Schmidt, *Born:* 5/4/1965, German

1989	Humboldt University of Berlin, Germany / M.Sc. degree in Meteorology (Dipl.-Met.)
1999	University of Bremen, Germany / Ph.D. degree in Atmospheric Sciences (Dr. rer. nat)
1991–1996	Alfred Wegener Institute Bremerhaven, Germany / Project scientist
1996–1998	University of Leipzig, Germany / Project scientist (starting Ph.D.)
1998–1999	University of Bremen, Germany / Project scientist (finishing Ph.D.)
since 1999	GFZ Potsdam, Germany / Remote Sensing Scientist

Experience and Expertise: Dr. Schmidt did his PhD thesis on the validation of aerosol models using sun photometer measurements. In 1999 he entered the GFZ Potsdam and developed the automatic and operational data processing system for radio occultations of the CHAMP mission (since 2001). Today he is responsible for the operational processing system of the GRACE and TerraSAR-X data. Dr. Schmidt has experience in the application of RO data in the upper troposphere and lower stratosphere region to study atmospheric gravity waves, tropopause dynamics and temperature variability (trends). He is author and reviewer of several scientific papers on the application of GPS based remote sensing (www.researcherid.com/rid/A-7142-2013).

Dr. Jens Wickert, *Born: 4/4/1963,* German

1989	Diploma physics, Technical University Dresden
2002	PhD Geophysics/Meteorology, University Graz/Austria
1989–1991	Academy of Sciences of the former GDR, Berlin, Scientist
1991–1993	German Weather Service, Scientist
1993–1995	AWI Bremerhaven, Scientist
1995	German Weather Service, Scientist
1996-1999	DLR Neustrelitz, CHAMP, GPS radio occultation
since 1999	GFZ, GNSS Earth Observation

Experience and Expertise: Dr. Wickert is currently deputy section head for GNSS Earth observation at GFZ and was the PI of the CHAMP radio occultation experiment. He accomplished fundamental contributions for the development of the GPS occultation technique and has extended expertise in atmospheric remote sensing and geodesy. He is author and co-author of more than 200 scientific papers in reviewed journals and books. Dr. Wickert is involved in numerous national and international research projects related to GNSS Earth observation mainly in a leading position. More detailed information is available via www.jenswickert.de.

JPL

Dr. Chi Ao

2001	Massachusetts Institute of Technology, U.S.A./ Ph.D. Degree in Physics
2001-now	Jet Propulsion Laboratory, U.S.A. / Technologist

Experience and Expertise: Dr. Ao did his Ph.D. thesis on theoretical and computational microwave remote sensing, specializing in electromagnetic wave scattering of random media. He joined the Tracking System and Applications Section at JPL in 2001 and has worked on various aspects of GPS RO since then. He has extensive experience in GPS RO inversion techniques and simulation methods. He has an in-depth knowledge of the JPL data processing system and has a strong interest in the climate applications of RO data. He is the principle investigator and co-investigator of several NASA grants and is currently a member of the NASA GNSS Science Team and the CLARREO Science Definition Team.

Dr. Anthony Mannucci

1989	University of California, Berkeley, CA/ Ph.D. Degree in Physics
1989-now	Jet Propulsion Laboratory, U.S.A. / Research Manager

Experience and Expertise: Dr. Mannucci has been managing the GPS Earth Observatory project at JPL since 1999. The GEO project is responsible for delivering science data from NASA radio occultation instruments using JPL's science data processing system. He is Principal Investigator of several NASA Research Awards, including a project to create climate data records using radio occultation measurements. Dr. Mannucci has extensive experience with remote sensing of atmospheric and ionospheric parameters using Global Navigation Satellite Systems and developed methods to map ionospheric total electron content globally using GPS ground-based networks.

Met Office Hadley Centre

Dr. Mark A. Ringer, *Born:*23/6/1966, British

1988	University of Newcastle-upon-Tyne, U.K. / M.Sc. degree in Applied Mathematics
1994	University of Reading, U.K. / Ph.D. Degree in Meteorology
1994-1996	LMD, Ecole Polytechnique, Palaiseau, France / Postdoctoral Scientist
1997-2000	Met Office, Exeter, United Kingdom / Satellite Applications Scientist
2000–present	Met Office Hadley Centre, Exeter, United Kingdom / Climate Research Scientist

Experience and Expertise: Dr Mark Ringer leads the Climate Sensitivity and Feedbacks group at the Met Office Hadley Centre. The work of his group focuses on two main areas: process-based understanding of the most important feedbacks operating in the climate system; the evaluation and development of climate models using satellite observations. His personal research interests encompass both of these areas, concentrating mainly on the radiative impact of clouds in the present-day and in response to climate change. He is currently a member of the GEWEX Data and Assessments Panel, the GRAS Science Review Group, the CM-SAF Steering Group and the CERES Climate Model and Analysis Advisory Group, and has been a member of the EUMETSAT working group on climate monitoring and the GERB project steering group. He is also part of the Climate Modelling User Group of the ESA Climate Change Initiative.

UCAR

Dr. William S. Schreiner, *Born:* 24/09/1965, U.S.A.

1988	Ohio State University, Col., Ohio, U.S.A./ B.S. degree in Aeronautical and Astronautical Engineering
1993	University of Colorado, Boulder, CO, U.S.A./ Ph.D., Aerospace Engineering Sciences
1994 - present	Project Scientist I-III, University Corporation for Atmospheric Research (UCAR)

Experience and Expertise: Dr. Bill Schreiner is the manager of the COSMIC (Constellation Observing Systems for Meteorology, Ionosphere, and Climate) Data Analysis and Archive Center (CDAAC) at UCAR. He possesses experience and knowledge of the algorithms and geodetic modeling used for precise orbit and clock determination of low Earth orbiting (LEO) receivers, ground-based position and zenith tropospheric delay estimation, GPS clock offset estimation, derivation of atmospheric excess phase (the fundamental observable of radio occultation), and computation of absolute total electron content (TEC). He also has detailed understanding of algorithms used for both neutral atmospheric and ionospheric inversions, and experience in RO payload and mission design for the GPS/MET, COSMIC, and COSMIC-2 missions.

Dr. Shu-peng Ho, Born: 2/2/1965, R.O.C

1992	Rutgers-the State University of New Jersey, U.S.A./M.S. in Meteorology
1995	University of Wisconsin-Madison, U.S.A. /M.S. in Atmospheric Science
1998	University of Wisconsin-Madison, U.S.A. /Ph. D., in Atmospheric Science
1998-2001	NASA Langley Center, U.S.A. / Scientist
2001–2005	ACD/NCAR/ Project Scientist
2005-now	COSMIC/UCAR/Project Scientist

Experience and Expertise: Dr. Shu-peng Ho is currently a Research Scientist in the UCAR COSMIC program and Atmospheric Chemistry Division of the National Center for Atmospheric Research. He is an expert in satellite remote sensing. Dr. Shu-peng Ho has more than 12 years of experience in developing and testing retrieval algorithms and radiative transfer models for high spectral resolution instruments including AIRS, HIS, AMSR-E, and TES. Dr. Ho is a remote sensing expert and is a member of GEWEX water vapor assessment group, and a member of the Stratospheric Processes and their Role in Climate (SPARC). He is also a contributing author to the IPCC 5th assessment report. His recent works include the development of the combined AIRS, AMSU, and GPS RO retrieval algorithm for global temperature and water vapor profiles for data assimilation system. Dr. Ho received his Ph. D. in Department of Atmospheric and Oceanic Science from University of Wisconsin-Madison in 1998. At that time, Dr. Shu-peng Ho has developed an extensive familiarity with thermal profiles retrievals by using high spectral resolution instruments during his development, testing, and validation of the temperature and water vapor retrieval algorithm by using the combined HIS and AERI radiances. Dr. Ho published over 37 refereed journal papers and many conference articles and reports. He is a regular reviewer for several remote sensing related Journals.

Mr. Douglas Hunt, *Born: 07/12/1965, Nationality: U.S.A.*

1988	University of Colorado at Boulder, Colorado, USA. Applied Math B.S. with Special Honors
1988	University of Colorado at Boulder, Colorado, USA. French Literature B.A. Magna Cum Laude
1988-1993	Software Engineer, IBM corporation
1995-present	Software Engineer II, III, IV, University Corporation for Atmospheric Research (UCAR)

Experience and Expertise: Doug Hunt has been a software engineer for 25 years, working first at IBM on satellite data processing systems for the US Air Force and later at UCAR on radio occultation ground data processing. He is currently a senior software engineer at UCAR and the software architect of the CDAAC radio occultation processing system. His interests include satellite data formats, signal processing, web programming, database systems and perl programming. He has co-authored over 20 papers on radio occultation data processing.

WEGC

Ass.-Prof. Andrea K. Steiner, *Born:* 08/05/1965, Austrian

since 09/2012	Wegener Center for Climate and Global Change, Univ. of Graz, Austria Assistant Professor Vice-Director for Quality Assurance & Inform. Management, IT & Technics Vice-Head of Atmospheric Remote Sensing and Climate System (ARSCliSys) Research Group
07–06/2012	Inst. of Rem. Sensing & Photogrammetry, Graz Univ. of Technol., Austria Project Leader
2010–06/2012 2005–06/2012	Wegener Center for Climate and Global Change, Univ. of Graz, Austria Vice-Director for Quality Assurance & Inform. Management, IT & Technics Vice-Head of (ARSCliSys) Research Group Research to Senior Scientist and Project Leader, Visiting Sci. UCAR (Aug 2010)
since 2003 1999–2005	Inst. for Geophysics, Astrophysics and Meteorol., Univ. of Graz, Austria Lecturer Post-Doc Scientist, GRAS SAF visiting scientist (Aug 2003)
1991–1998	Ph.D. degree Natural Sciences/Meteorology and Geophysics (1998) M.Sc. degree Meteorol. and Geophysics (1995), B.Sc. degree Environ. Sci.(1993)

Experience and Expertise:
Dr. Steiner did her Ph.D. thesis on the retrieval and validation of radio occultation (RO) data from the GPS/Met mission with first investigations of RO for studying stratospheric gravity wave activity.
As Post-Doc Scientist she focused on error analysis and characterization of RO data from observations and simulations, and on the investigation of the climate monitoring and atmospheric change detection capability of a GNSS occultation observing system (OSSE).
Her recent projects included the comparison of upper-air temperatures from atmospheric observations of RO, radiosonde and (Advanced) Microwave Sounding Unit ((A)MSU) data, the intercomparison of RO products from different data processing centers and the coordination of the International ROTrends working group.
Her current main research interests are the analysis, detection, and attribution of climate trends in atmospheric data records with focus on RO observations, the use of RO for climate change monitoring and for the analysis of climate variability and atmospheric processes, as well as for the evaluation of global climate models.
Dr. Steiner is team member of the stratospheric temperature trends group of WRCP/SPARC, of the Climate Subgroup of IROWG/CGMS, co-leader of the ROTrends working group, organizer and chair of workshops, and reviewer for international journals. (more at: www.uni-graz.at/andi.steiner)

Prof. Ulrich Foelsche, *Born:* 10/05/1968, Austrian

2011 – present	Head of the Institute for Geophysics, Astrophysics, and Meteorology, Inst. of Physics (IGAM/IP), University of Graz (UoG)
2011 – present	Associate Professor at IGAM/IP
2003 – present	Vice-head of the “Atmospheric Remote Sensing and Climate System” (ARSCliSys) research group at the Wegener Center for Climate and Global Change (WEGC), UoG.
from 1998	Visiting Scientist/Professor at MPI for Meteorology Hamburg, RMIT Univ. Melbourne, DMI Copenhagen, Denmark, UCAR Boulder, CO, USA, etc.
1999-2011	Post-Doc and Assist. Professor (as of 2004), UoG
2007-2008	Max Kade Fellow at UCAR Boulder, CO, USA
1999	PhD degree Natural Sciences Meteorology and Geophysics, UoG
1995	MSc degree in Geophysics, UoG

Experience and Expertise: Prof. Foelsche did his master thesis on causes and mechanisms of abrupt temperature changes during the last ice age. In his PhD thesis he investigated the retrieval of tropospheric water vapor from ground-based GPS (Global Positioning System) measurements and developed an algorithm for water vapor tomography by combination of spaceborne radio occultation (RO) data and ground-based GPS measurements.
As Post-Doc Scientist he focused on the climate monitoring capability of a RO data, performing observing system simulation experiments and error analyses of actual RO climatologies, with attention to the errors caused by undersampling of the “true” spatial and temporal variability.
From 2005 to 2009 he was National Representative of the COST (Cooperation in the Field of Scientific and Technical Research) action 296 “Mitigation of Ionospheric Effects on Radio Systems (MIERS)” and Work Package (WP) Co-leader of WP3.2 “Special mitigation techniques”.
His current main research interest is on global climate monitoring based on RO data from multiple satellites with focus on the establishment of accurate RO climatologies and the mitigation and characterization of remaining (small) systematic errors.

As Head of the Meteorological Station in Graz (since 2010) he also focused on the delivery of high-quality long-term climate data from meteorological stations (with a recent emphasis on accurate monitoring of solar radiation), and the analysis of current climate change based on data from meteorological stations with local and regional focus (Graz, Styria, Austria).

Prof. Gottfried Kirchengast, *Born:* 14/07/1965, Austrian

since 2012 also	Adjunct Professor, Geospatial Sciences School, RMIT Univ. Melbourne
2005 – present	Director, Wegener Center for Climate and Global Change, Univ. of Graz
2003 – present	Professor of Geophysics (Alfred Wegener's Chair), Univ. of Graz
from 1998	Visiting Scientist/Professor at UCAR Boulder, MPI for Meteorology Hamburg, Univ. of Arizona Tucson, GFZ Potsdam, Univ. of Hawai'i Manoa/Honolulu, RMIT Univ. Melbourne, etc.
1992-2002	Assist. Professor – Assoc. Professor (as of 1997), Univ. of Graz
1992-1994	Max-Planck Postdoc Fellow at MPI for Aeronomy Lindau/Göttingen
1988-1995	M.Sc. degree Geophysics (1988), Ph.D. degree Natural Sciences/Physics (1992), M.Sc. Physics (1995) (all graduations with highest honors)

Experience and Expertise: Since 1996 Prof. Kirchengast's research focuses on atmospheric remote sensing from space and exploitation for climate research. Foundation (1996) and direction of the Atmospheric Remote Sensing and Climate System (ARSCliSys) Research Group (about 12 scientists), later foundation (2003-2004) and direction (since 2005) of the Wegener Center for Climate and Global Change (WEGC) including ARSCliSys and other partner research groups (about 40 scientists).

Atmospheric remote sensing expertise includes occultation methods (like GNSS radio occultation and LEO-LEO occultation) and other coherent-signal and spectroradiometric methods (in infrared and microwave), with the main aim to conceive and advance methods and algorithms, and to provide optimal climate utility of such data. Since 2005 also complementary work on ground-based methods with very high resolution for climate applications (e.g., realization of the WegenerNet climate station network).

Climate expertise includes analysis of atmospheric change, validation and improvement of climate modeling by accurate observational constraints (climate benchmark data), climate change detection and attribution, and integrated climate analysis from global to local scale.

Methodological expertise behind includes advanced physical and statistical modeling, including forward, adjoint, and inverse modeling, as well as data assimilation, for simulations and optimal estimation in complex systems (e.g., parts of the climate-socio-economic system).

Prof. Kirchengast has conceived and pioneer-explored the LMIO and NIDAR techniques, stands also among the European pioneers in GPS radio occultation science, and is leader of many international and national research projects or of the University of Graz participation in them (with funds from ESA, Austrian Space Appl. Programme, Austrian Science Fund, etc.).

He is author/co-author of more than 85 peer-reviewed articles (ISI) and more than 170 further scientific articles and reports, and of several books. Furthermore, more than 25 Ph.D. students and more than 30 M.Sc. students have been supervised and given guidance to successful completion since 1992. In recognition of his merits so far he has been elected lifetime member of the Austrian Academy of Sciences in 2011.
(more information: www.uni-graz.at/gottfried.kirchengast)