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FFG-ALR study:

EOPSCLIM – End-to-end Occultation Processing System and Climate Monitoring Service
[Contract No: ALR-OEWP-CO-414/07]

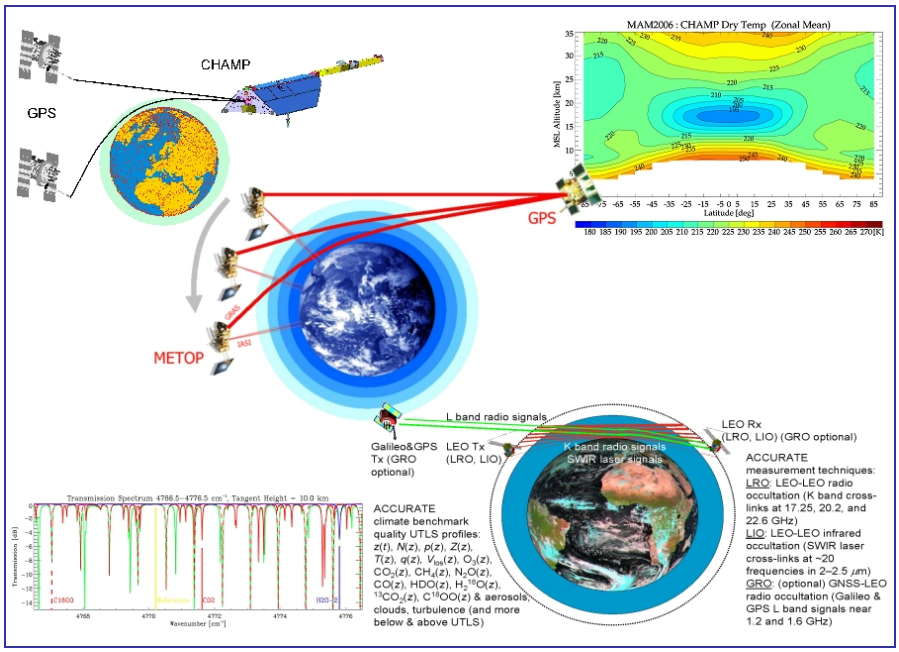
FINAL REPORT - Executive Summary

EOPSCLIM

End-to-end Occultation Processing System and Climate Monitoring Service: MetOp GRAS and ACCURATE Integration

Project Leader: G. Kirchengast
Project Manager: S. Schweitzer
Project Team: S. Schweitzer, B. Pirscher, M. Pock, F. Ladstädter, B.C. Lackner, I. Thaler, M. Borsche, U. Foelsche, A.K. Steiner, J. Fritzer, G. Kirchengast

Wegener Center for Climate and Global Change (WegCenter)
University of Graz, Graz, Austria



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Executive Summary

Deutschsprachige Kurzzusammenfassung

Die Bereitstellung sorgfältig validierter Klimatologien auf Basis von Radiookkultations-(RO)-Messungen der neuen europäischen MetOp Wettersatelliten (Start MetOp-A im Oktober 2006) ist ein Schlüsselinteresse der Klimaforschung. Dies deswegen, da diese RO-Messungen basierend auf Navigationssignalen des Globalen Positionierungssystems GPS die Bestimmung fundamentaler Klimaparameter der Atmosphäre (wie Temperatur, Druck und Feuchte) mit einer bisher nicht erreichten Genauigkeit und Konsistenz ermöglichen. Ergänzend ist die Satellitenmission ACCURATE (Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer), die am Wegener Zentrum erdacht wurde, von besonderem Interesse: ein geplantes Okkultations-Messkonzept der nächsten Generation mit dem in Zukunft zusätzlich auch Treibhausgas-Konzentrationen und Wind gemessen werden können. Dies kann weitere Schlüsselinformationen bezüglich Zunahme von Treibhausgasen und Klimaänderungen in bisher nicht verfügbarer Genauigkeit und Zuverlässigkeit liefern.

In diesem Kontext trug das EOPSCLIM Projekt in drei Bereichen bei: 1) Validierung von RO-Daten des MetOp RO-Instruments GRAS (GNSS Receiver for Atmospheric Sounding), wobei Vergleichsdaten anderer RO-Satellitenmissionen und von Analysen des Europäischen Zentrums für Mittelfrist-Wettervorhersage (ECMWF) verwendet wurden, 2) Weiterentwicklungen zur ACCURATE Infrarot-Laserokkultation im end-to-end occultation simulator system “EGOPS” des Wegener Zentrums im Bereich Aerosolmodellierung und Windbestimmung, 3) Beitrag zur Integration der Prozessierung von aktuellen RO-Echtdaten im EGOPS System, mit Fokus auf den Datenstrom vom neuen MetOp GRAS Instrument.

Zusätzlich zu seinen essenziellen Beiträgen zur MetOp GRAS Validierung und zur Weiterentwicklung des ACCURATE Konzepts hat EOPSCLIM dabei erstmalig im Rahmen der RO-Datenprozessierung auch regionale Klimatologien über den offiziellen Regionen des IPCC geliefert (mehr als zwei Dutzend Landregionen weltweit in Afrika, Europa, Asien, Nordamerika, Mittel- und Südamerika, Australien und Neuseeland; ergänzt durch polare und ozeanische Regionen). Damit hat EOPSCLIM auch eine neue Schiene der Verwertung von RO-Daten für Monitoring und Diagnose von regionalen Klimaänderungen eröffnet.

English Summary (with short summaries of project reports enclosed)

The provision of carefully validated radio occultation (RO) climatologies from the new European MetOp satellites (MetOp-A launched in October 2006) is of key interest to climate research, since these RO observations derived from navigation signals of the Global Positioning System (GPS) allow to retrieve fundamental variables of the Earth’s atmosphere (temperature, pressure, humidity) with unprecedented accuracy and consistency. Complementarily, preparing for future occultation systems, the ACCURATE (Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer) mission conceived at the Wegener Center is a next-generation climate mission concept adding greenhouse gas and wind measurement information. Further developing this concept is another key interest for enabling future occultation systems to provide unprecedented benchmark observations of greenhouse gas increases and related climate change.

In this context, the EOPSCLIM project contributed along three main lines: 1) validation of MetOp GRAS data with data from other research RO missions as well as ECMWF analyses, and set up of regional climate monitoring based on RO data for IPCC regions, 2) advancement of the new ACCURATE infrared laser occultation functionality within the WegCenter's end-to-end occultation simulator system ("EGOPS") by aerosol modeling and by a first version of wind profile retrieval processing, 3) contribution to the integration of real RO data processing within the EGOPS system, focusing on the new MetOp GRAS data stream.

In addition to its vital contributions to further development of the ACCURATE concept and to MetOp GRAS validation in the framework of the ESA/EUMETSAT MetOp Research Announcement of Opportunity, EOPSCLIM made available, for the first time, RO based regional climate monitoring over the official IPCC regions (about two dozen worldwide land regions in Africa, Europe, Asia, North America, Central and South America, Australia and New Zealand, complemented by polar and oceanic regions). This opens a new avenue of exploiting RO data for regional climate change diagnosis.

Attached to the Executive Summary, this "Final Report" comprises two reports, describing the results of the EOPSCLIM work in detail. Below the main results of these two reports are briefly summarized, first for the *MetOp GRAS Validation and Regional Climate Monitoring Setup Report* then for the *EGOPS Enhancement Report*.

MetOp GRAS Validation and Regional Climate Monitoring Setup Report
Initial Validation of GRAS Occultation Data from MetOp and Setup of Regional Climate Monitoring including the IPCC Land and Ocean Regions

This report describes the results of two main parts of work: an initial validation of MetOp GRAS (GNSS Receiver for Atmospheric Sounding, the GPS RO instrument of MetOp) data was conducted and, in view of RO climate data being available for several years now, the use of RO for regional-scale climate monitoring (in addition to global-scale) was prepared.

In the first work part, the quality of the different RO receivers on the three missions MetOp, COSMIC (U.S.-Taiwan RO mission), and CHAMP (German RO mission), was assessed based on bending angle data quality at high altitudes; atmospheric profiles of retrieved refractivity and dry temperature were statistically validated against ECMWF (European Centre for Medium-Range Weather Forecasts) analysis profiles. The second part of the report deals with the CHAMP data and ECHAM5 (European Centre Hamburg Model) climate model data. CHAMP data constitute the first long-term RO data set which was used for the first time to create regional RO climatologies in more than two dozen world regions that were also used by the IPCC (Intergovernmental Panel on Climate Change) in its recent 4th Assessment Report (AR4) to discuss regional climate change results. Since six years of CHAMP data are still too short to investigate trends, the longer-term ECHAM5 data were used for regional-scale climate trend studies. The results from the two parts, Metop GRAS validation and regional climate monitoring setup, can be summarized as follows.

Validation of MetOp GRAS data

The MetOp mission will provide operational GRAS RO data until 2020. Here a first day of GRAS RO data ("test day of data") was validated against COSMIC and CHAMP RO data as well as ECMWF analysis data. In view of the expected higher quality of MetOp data, an alternative retrieval approach has been applied in addition to the standard approach used for CHAMP and COSMIC so far: in this alternative, termed noBEC ("no Bending angle Error

Corrections"), we did not apply error corrections. The investigated MetOp bending angle data were found to show superior basic quality compared to CHAMP and COSMIC data. The median value of the standard deviations of MetOp bending angle data (0.66 µrad) is somewhat more than a factor of two smaller than for COSMIC and somewhat more than a factor of four smaller than for CHAMP. Even accounting for the different clock differencing schemes in the processing of these satellites, creating least noise contribution for MetOp with its zero-differencing given its precise ultra-stable oscillator, these results indicate the high quality of MetOp data. As a consequence, the height range where MetOp RO profiles are observation-dominated extends considerably higher than for COSMIC and CHAMP. Using MetOp data, the range of high quality climatologies can likely be extended, relative to CHAMP, by about 10 km upwards to ~40 km height, although this could not yet be demonstrated for refractivity and dry temperature in this initial validation, where the processing of MetOp data needs further improvements. The results, if confirmed over a longer period, underpin the expected potential of MetOp GRAS data for climate monitoring.

Setup of regional climate monitoring

Starting from the heritage of previous work on global-scale climatologies, the Wegener Center's Climotology Processing System (CLIPS) was advanced to produce user defined regional-scale climatologies. The CLIPS products are data files and graphics of RO-based climatologies of refractivity, pressure, geopotential height, dry temperature, and further products. Reference climatologies (from the European weather centre ECMWF) and corresponding error characteristics are provided along with the climatologies to enable a full interpretation of the data sets. In order to demonstrate the regional-scale setup we compared time series of CHAMP RO climatologies with corresponding climatologies constructed from ECMWF analyses and global climate model data (ECHAM5/MPI-M model). CHAMP data show slightly warmer stratospheric temperatures and slightly colder upper tropospheric temperatures than ECMWF analyses; the two data sets agree well in general. The temperatures of ECHAM5 deviate systematically from the observations, showing a stronger temperature gradient in the troposphere. Furthermore, the potential of RO-accessible climate trend indicators was studied by means of IPCC AR4 model data. These model simulations until 2060 show clear signals of a temperature decrease in the stratosphere and of a temperature increase in the troposphere. Different RO atmospheric parameters are found sensitive at different height levels and thus allow covering the upper troposphere/lower stratosphere (UTLS) region as a whole with good climate trend indicators.

In summary it is evident that RO measurements can serve the need of climate monitoring for long-term stable, intrinsically calibrated and highly resolved global data for the UTLS region. Due to their high quality in this region, RO data are highly qualified to investigate upper tropospheric warming and lower stratospheric cooling in a changing climate.

EGOPS Enhancement Report

End-to-end Generic Occultation Performance Simulation and Processing System EGOPS: Enhancement of GPS RO Data Processing and IR Laser Occultation Capabilities

This report describes the results of the advancement work under the EOPSCLIM project on the WegCenter's EGOPS software. For setting the scene and providing basic EGOPS context, the report first introduces the EGOPS software and in particular its on-going developments towards the new EGOPS6 system. It then describes the EGOPS enhancements that were implemented under EOPSCLIM along two main lines: 1) contribution to the integration of

real RO data processing in EGOPS, focusing on the new MetOp GRAS data stream, and 2) advancement of the new ACCURATE infrared laser occultation functionality in EGOPS by aerosol modeling and by a first version of wind profile retrieval processing. Results from RO data processing and ACCURATE-related simulations with the enhanced software are also discussed, underpinning the utility of the new advancements.

Summarizing the results, the integration of real GPS RO data processing into EGOPS and the subsequent enhancements from CCRv2.3 version (before EOPSCLIM project) to OPSv5.4 version (by end of EOPSCLIM) were successful. The integration also will greatly facilitate further planned enhancements, where in particular advancement towards climate-quality moist air retrieval in the troposphere (including humidity retrieval) from real GPS RO data is an essential next step.

The inclusion of the new latitude-height-frequency-dependent aerosol extinction coefficient model based on SAGE II (U.S. solar occultation instrument) data turned out to be very useful. It enabled seamless integration of modeling aerosol effects on shortwave-infrared signal propagation, and the results under different aerosol loading conditions ("background", "medium", "volcanic") look reasonable. Also the inclusion of an initial wind retrieval capability was found useful and it could be demonstrated that this simplified approach already delivers quantitatively useful wind profiles in smooth wind conditions. The initial performance analysis also provided valuable pointers to next steps for improvement.

Looking to the immediate future, the enhancement of EGOPS for both real GPS RO data processing as well as ACCURATE end-to-end simulations is scheduled to be continued in the on-going FWF-CLIMROCC project and the new ESA-ACTLIMB study (performance of active limb sounding; ESA/ESTEC study) starting by May 2008 as well as the new ESA-MMValRO study (multi-mission validation by RO; ESA/ESRIN study) starting by July 2008. In addition, the on-going ESA-Prodex project on EGOPS6 System Development (until mid 2009) will provide important continued support at EGOPS S/W system engineering level also to these future enhancements. It is one major aim of these follow-on projects to further advance the EGOPS retrieval system so that both real GPS RO and simulated ACCURATE data can be processed with further improved quality, e.g., in the latter case for studying trace gas and wind retrieval performances in detail.

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