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Atmosphere and Climate

Studies by Occultation Methods

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Editors

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With 134 Figures, 21 in color

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Preface

Since the early use of the occultation measurement principle for sounding planetary atmospheres and ionospheres, its exploitation in atmospheric remote sensing has seen tremendous advances. In this book we focus on sensors on Low Earth Orbit (LEO) satellites, which exploit solar, lunar, stellar, GNSS (Global Navigation Satellite Systems), and LEO-crosslink signals for observing the Earth's atmosphere and climate.

The methods all share the key properties of self-calibration, high accuracy and vertical resolution, global coverage, and (if using radio signals) all-weather capability. The atmospheric parameters obtained extend from the fundamental variables temperature, density, pressure and water vapor via trace gases, aerosols and cloud liquid water to ionospheric electron density. Occultation data are therefore of high value in a wide range of fields including climate monitoring and research, atmospheric physics and chemistry, operational meteorology, and ionospheric physics.

The 2nd International Workshop on Occultations for Probing Atmosphere and Climate – OPAC-2 – was held September 13–17, 2004, in Graz, Austria. OPAC-2 aimed at providing a casual forum and stimulating atmosphere fertilizing scientific discourse, co-operation initiatives, and mutual learning and support amongst members of all different occultation communities. The workshop was attended by 40 participants from 12 different countries who actively contributed to a scientific programme of high quality and to an excellent workshop atmosphere, which was judged by the participants to have fully met the aims expressed.

The programme included 7 tutorial lectures and 15 invited presentations, complemented by about 30 contributed ones, including 11 posters, and an occultation software demonstration. It covered occultation science from occultation methodology in general via different occultation methods and new concepts to use and applications of occultation data in atmosphere and climate science. The detailed programme and all further workshop information will continue to be available online at the OPAC-2 website at http://www.uni-graz.at/opac2.

This book was compiled based on selected papers presented at OPAC-2 and well represents in its six chapters the broad scope of the workshop. Results from the radio occultation experiment onboard CHAMP, which is now over five years in orbit, are collected in chapter 1 while chapter 2 comprises results from the stellar occultation experiment GOMOS onboard ENVISAT. Wave optics algorithms turned out to be very useful for the processing of radio occultation data in the lower troposphere; they are covered in chapter 3. Chapter 4 deals with future occultation missions and with the novel LEO-LEO crosslink concept. Radio occultation data are now increasingly used in numerical weather prediction and atmospheric studies as well as in climate monitoring and change research. This is reflected by the significant amount of articles in chapter 5 and chapter 6, respectively.

We cordially thank all OPAC-2 colleagues, who contributed as authors and co-authors to the book, for the effort and diligent work invested into their papers and for largely observing the length target. All papers were subjected to a peer review process, involving two independent expert reviewers per paper from the community of OPAC-2 participants and beyond. We also very much thank these reviewers for their important service to coherently ensure scientific correctness and high quality of the book from first to last page.

The reviewers, in alphabetical order, were C. O. Ao, G. Beyerle, C. Boone, M. Borsche, F. Cuccoli, A. de la Torre, U. Foelsche, A. Gobiet, M. E. Gorbunov, K. Hocke, A. S. Jensen, G. Kirchengast, E. R. Kursinski, E. Kyrölä, K. B. Lauritsen, R. Leitinger, S. S. Leroy, J.-P. Luntama, A. Löscher, M. S. Lohmann, R. Notarpietro, A. G. Pavelyev, M. Petitta, P. Poli, C. Retscher, S. Schweitzer, V. F. Sofieva, A. K. Steiner, M. Stendel, S. Syndergaard, J. Tamminen, A. von Engeln, and J. Wickert.

Special thanks are, furthermore, due to M. Sc. Barbara Pirscher for her tireless support in the final copy editing and formatting of the book and to Dr. Wolfgang Engel, Mrs. Helen Rachner, and Mrs. Agata Oelschläger from Springer Verlag, Heidelberg, for the kind offer to issue this book as Springer publication and the related technical support. Many thanks also to all others who provided support in one or another way, in representation of which we thank the sponsors of OPAC-2 (see the OPAC-2 website noted above for details) and the sponsors of the START Program No. Y103-N03 (Federal Ministry for Education, Science, and Culture; Austrian Science Fund) for providing the material support enabling the realization of the book.

We hope that, in the spirit of the OPAC-2 aims, the book will become a useful reference for the members of the occultation-related community but also for members of the science community at large interested in the present status and future promises of the field of occultations for probing atmosphere and climate.

Graz, January 2006

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Mission Status, Retrieval, Validation, and Error Analysis

GPS Radio Occultation with CHAMP and GRACE: Recent Results

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Abstract. The German CHAMP (CHAllenging Minisatellite Payload) satellite provides continuously GPS radio occultation data since February 2001. The measurements are analyzed by an operational orbit and occultation processing system at GFZ. In total ~170 000 high quality globally distributed vertical profiles of refractivity, temperature and water vapor are provided as of October 2004. The ground infrastructure from GFZ allows for the demonstration of a rapid data analysis since February 2003. The average delay between each measurement and provision of atmospheric excess phase data was reduced to ~4 hours by mid April 2004 and is continuously reached. The complete set of the available refractivity profiles is compared with corresponding analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) between 0 km and 30 km altitude. The comparison shows nearly bias-free refractivity between ~7 km and 30 km, the standard deviation is ~1 %. The known negative refractivity bias of the CHAMP data in relation to ECMWF is significantly reduced in comparison to earlier product versions by applying the Full Spectrum Inversion (FSI) method for the data analysis in the lower troposphere. First radio occultation measurements from the GRACE-B (Gravity Recovery And Climate Experiment) satellite are available for a 25 h period on July 28/29, 2004. The stability of the satellite clock from GRACE-B is significantly improved in relation to CHAMP. This allows for precise occultation analysis using 30 s clock solutions applying a zero difference technique. Thus the disadvantageous use of a reference GPS satellite link to eliminate the clock error from GRACE-B can be avoided.

1 Introduction

Atmospheric profiling aboard the German CHAMP (Reigber et al. 2005) satellite was activated on February 11, 2001 (Wickert et al. 2001b). The experiment brought significant progress (Hajj et al. 2004; Kuo et al. 2004; Wickert et al. 2005c) for the innovative GPS (Global Positioning System) radio occultation (RO) technique (e.g., Kursinski et al. 1997) in relation to

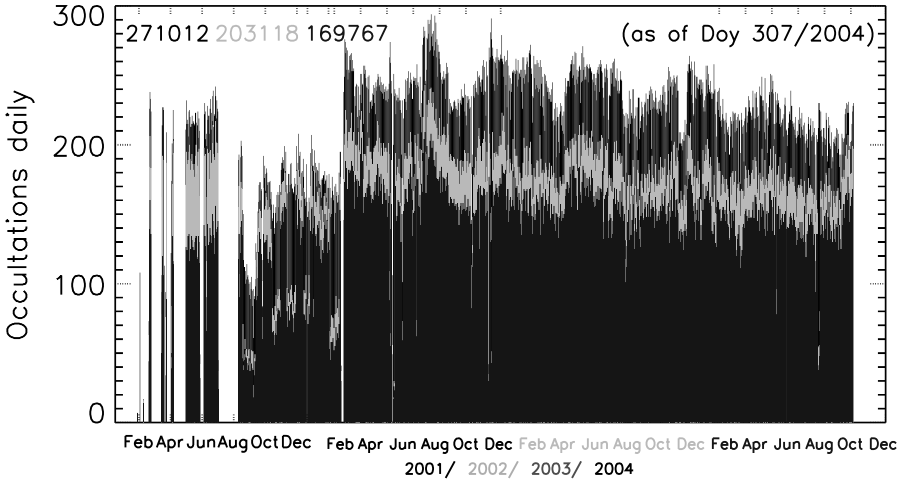

Fig. 1. Number of daily CHAMP occultations (duration >20 s) as of November 2, 2004. The total height of the columns corresponds to the number of daily measurements. The height of the light gray color indicates the number of atmospheric excess phases. The height of the dark gray columns corresponds to the number of vertical atmospheric profiles provided to the CHAMP data center (ISDC, Information System and Data Center) at GFZ.

the pioneering GPS/MET (GPS/METeorology) mission (Ware et al. 1996; Rocken et al. 1997). Main advantages of the calibration-free RO method are global coverage, high vertical resolution and all-weather capability combined with high accuracy. These properties allow for various applications in atmospheric/ionospheric research (e.g., Hajj et al. 2000; Ratnam et al. 2004; Wickert et al. 2004b; Wang et al. 2004; Wickert 2004; Kuo et al. 2005), weather forecast (e.g., Kuo et al. 2000; Healy et al. 2005; Healy and Thepaut 2005) and climate change detection (e.g., Randel et al. 2003; Schmidt et al. 2004, 2005a; Foelsche et al. 2005). Together with CHAMP, several upcoming RO missions will provide thousands of occultations daily and will extend the prospects of this promising technique (e.g., EQUARS (EQUatorial Atmosphere Research Satellite, Takahashi et al. (2004)); COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate, Rocken et al. (2000)) or Metop (e.g., Loiselet et al. 2000; Larsen et al. 2005)). We review recent results from the CHAMP RO experiment and present first results from the activation of GPS RO aboard the U.S. American/German GRACE mission (Dunn et al. 2003; Tapley and Reigber 2004).

2 Status of the CHAMP RO Experiment

Occultation measurements were performed during 1 238 days since February 2001 as of November 2, 2004; giving a total of 271 012 recorded events (∼219 daily). For ~74.9 % of the occultations (203 118) atmospheric excess phases are available (see Fig. 1). Vertical profiles of atmospheric parameters were derived for 169 767 occultations (~62.6 %). The yield of the profiles in relation to the number of measurements is currently investigated in more detail within the framework of the Radio Occultation Sensor Evaluation activity (ROSE), jointly initiated by GFZ, Jet Propulsion Laboratory (JPL) and University Corporation for Atmospheric Research (UCAR) (Ao et al. 2003b; Wickert et al. 2005a). ROSE is aimed to evaluate and optimize the quality of CHAMP's analysis results and to improve the involved occultation processing systems.

3 Operational Data Analysis

The occultation data aboard CHAMP are recorded by the "BlackJack" GPS flight receiver provided by JPL. The ground infrastructure of GFZ is used for a fully automated data analysis. Details on the infrastructure and on the orbit and occultation processing system can be found in Wickert et al. (2004a,c); König et al. (2005); Schmidt et al. (2005b). A Near-Real-Time (NRT) provision of atmospheric excess phases is continuously demonstrated since February 2003. An average delay of ~5 hours between each measurement and provision of corresponding analysis results was reached. Optimized GPS ground station data handling for the precise orbit determination reduced this delay to ~4 hours since mid April 2004. For some measurements per day the delay is ~2.5 h (see Fig. 2). Further reduction is possible due to the use of a polar satellite receiving antenna at Ny Aalesund, Spitsbergen, (access to the satellite data every ~1.5 h) and a global low latency GPS ground network (access to the ground data every ~15 min), but requires further optimization concerning precise satellite orbit generation and occultation processing. The demonstration of NRT data analysis is an important milestone for the future assimilation of GPS RO data in numerical weather models. A positive impact of CHAMP data on global weather forecasts was already shown by Healy et al. (2005) and Healy and Thepaut (2005).

CHAMP data are analyzed using the standard double difference method to eliminate satellite clock errors (Wickert et al. 2001a). Atmospheric bending angles are derived from the time derivative of the excess phase after appropriate filtering. The ionospheric correction is performed by linear combination of the L1 and L2 bending angle profiles (Vorob'ev and Krasil'nikova 1994). The Full Spectrum Inversion (FSI) technique (Jensen et al. 2003), a wave optics based analysis method, is applied below 15 km to correct for the effect of lower troposphere multipath.

Vertical profiles of atmospheric refractivity are derived from the ionosphere corrected bending angle profiles by Abel inversion. For dry air, the density profiles are obtained from the relationship between density and refractivity. Pressure and temperature ("dry temperature") are obtained applying the hydrostatic equation and the equation of state for an ideal gas. More details

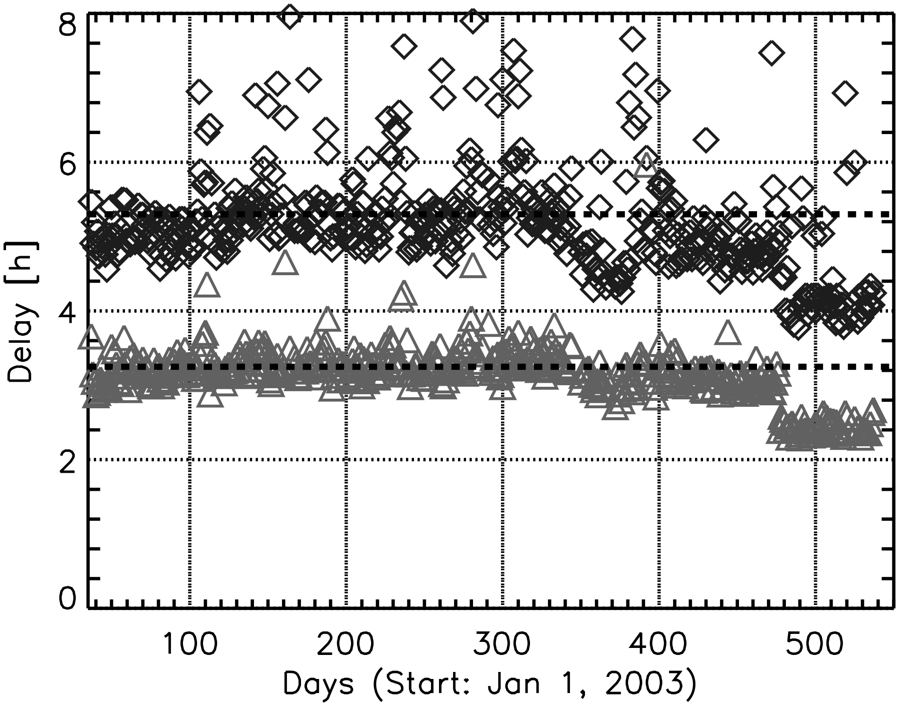

Fig. 2. Time delay between CHAMP occultation measurements and availability of analysis results at GFZ from February 2003 until mid May 2004. Black diamonds indicate the daily mean of the time delay between each measurement and the availability of the corresponding calibrated atmospheric excess phases. An average of ∼5 hours for nearly the entire period is reached. The minimum time delays are marked by gray triangles. Due to improvements in the satellite orbit provision the mean delay was reduced to ∼4 hours since end of April 2004.

on the retrieval are given by Wickert et al. (2004c). Basics of the GPS radio occultation technique and the derivation of atmospheric parameters are described, e.g., by Kursinski et al. (1997). The refractivity and dry temperature profiles (Product:CH-AI-3-ATM) are provided via the CHAMP data center at GFZ (http://isdc.gfz-potsdam.de/champ/).

Background information from ECMWF is used to derive vertical humidity profiles from the CHAMP refractivities. Two methods for the water vapor derivation were implemented to the operational data analysis. In addition to a standard 1Dvar retrieval (Healy and Eyre 2000) a new direct method (DWVP), introduced by Heise et al. (2005), is implemented. Here the background temperature and pressure information are used to calculate water vapor pressure p_{w} directly from the refractivity measurements using the Smith-Weintraub formula (Smith and Weintraub 1953). Both methods come to statistically comparable results and reveal a bias of less than 0.2 g/kg and a

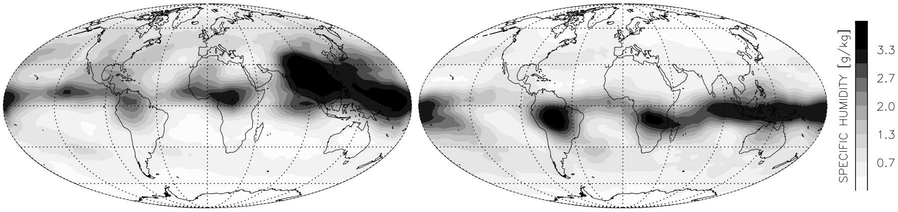

Fig. 3. Mean global distribution of specific humidity at 500 hPa derived from CHAMP occultation data. Left: Northern summer 2002, Right: Northern winter 2002/2003 (for details see Heise et al. (2005)).

standard deviation of less than 1 g/kg specific humidity in relation to radiosonde measurements in the mid troposphere. As an application example for the operational water vapor retrieval with CHAMP data, Fig. 3 shows the seasonal mean of the global water vapor distribution for northern summer (2002) and winter (2002/2003) at 500 hPa. The specific humidity data are derived using the DWVP method.

4 Recent Validation Results for CHAMP

The complete set of CHAMP measurements was reprocessed using the recent version (005) of GFZ occultation analyses software. The resulting set of refractivity profiles (∼170 000) is compared with corresponding analysis data from ECMWF (Gaussian grid with 0.5° × 0.5° resolution at the Equator, 60 altitude levels) between 0 km and 30 km.

The comparison shows nearly bias-free refractivity between 10 km and 30 km (see Fig. 4). The standard deviation is ∼1 %. The deviations show different characteristics in latitude (e.g., wave-like vertical structures of the bias above the south polar region with a period of ∼6 km). This fact suggests weaknesses of the analyzed data, introduced by the ECMWF assimilation scheme (e.g., Gobiet et al. 2005). Our validation results are, as expected, in good agreement with earlier validation studies (ECMWF and radiosonde data) using the previous product version 004 (Schmidt et al. 2004; Wickert et al. 2004c), since FSI is applied only below 15 km.

The major advantage of the recent version (in relation to earlier ones) of GFZ analysis software is the implementation of the FSI method (Jensen et al. 2003) to eliminate the effect of atmospheric multipath to the occultation data. The resulting bias and rms of the comparison with ECMWF is depicted in Fig. 5. The negative refractivity bias of the CHAMP data depends on latitude and is most pronounced in the tropics, where it reaches a value of 5 % at 1 km. However in mid latitude and polar regions the CHAMP data are nearly bias free throughout the entire troposphere. The rms also depends on the latitude. In the tropics values of ∼3 % are observed. In mid latitudes and