GPS BASED ATMOSPHERIC SOUNDING WITH CHAMP:
RESULTS ACHIEVED AFTER FOUR YEARS

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ABSTRACT

The German geoscience satellite CHAMP (CHAllenging Minisatellite Payload) was launched mid 2000. Equipped with a GPS (Global Positioning System) receiver “BlackJack” provided by the Jet Propulsion Laboratory, CHAMP exploits the signals of the GPS satellites for remote sensing of temperature and humidity in the atmosphere. The innovative GPS occultation technique provides globally distributed, calibration-free and weather independent measurements with high vertical resolution. In comparison to the earlier US-American proof-of-concept mission GPS/MET, the CHAMP occultation experiment exhibits improved instrument characteristics and demonstrates quasi-continuous provision of atmospheric data. An unique long-term set of GPS radio occultation measurements is currently generated, since the CHAMP mission is expected to last until 2008. More than 350,000 occultations were recorded as of September 2005.

Data and analysis results are provided to the international scientific community and stimulated several activities to apply CHAMP’s data in meteorology. The data are currently in use by more than 40 research groups to prepare and improve analysis centers for future operational occultation missions (e.g. COSMIC or Metop), to demonstrate positive impact to numerical weather prediction, to show ability to detect climate trends, and to compare with other satellite and ground based atmosphere sounders. We briefly summarize the scientific results after more than four years of GPS radio occultation with CHAMP. The work with the CHAMP data brought significant improvements for the GPS radio occultation technique itself, but also for its application in atmospheric research. Highlights were, e.g., demonstration of continuously near real time data provision and analysis, improvements of the GPS occultation data analysis, progress in the improvement of the occultation data quality in the lower troposphere, and also first successful impact studies using the CHAMP data for Numerical Weather Prediction (NWP). We focus to these selected and other highlights and include initial occultation results from the U.S.-German gravity mission GRACE (Gravity Recovery And Climate Experiment) in our discussion.

1. INTRODUCTION

GPS radio occultation (RO) is considered as an innovative global sounding technique for providing atmospheric data as refractivity, temperature and water vapour with high information content for numerical weather prediction and climate change studies [e.g., Anthes et al., 2000; Kursinski et al., 1997]. The practical feasibility of this method and its potential in various applications in atmospheric research were first demonstrated by the pioneering proof-of-concept GPS/Meteorology (GPS/MET) experiment [e.g., Rocken et al., 1997].

The GPS occultation technique is based on precise dual-frequency phase measurements (L-band) of a GPS receiver in a Low-Earth-Orbit (e.g., CHAMP) tracking the signals of setting or rising GPS satellites. Combining these measurements with the satellites’ position and velocity information, a series (e.g. 50 Hz in case of CHAMP) of small atmospheric induced excess phases (up to ~ 1 km in the vicinity of the Earth’s surface) during the occultation event can be derived with very high accuracy. The temporal variation of this series (atmospheric induced Doppler shift) together with the signal’s amplitude can be converted to a vertical profile of bending angles (see also Fig. 1). Assuming spherical symmetric distribution of the atmospheric refractive index, vertical profiles of the refractivity can be derived and then converted to vertical profiles of atmospheric parameters as pressure, temperature and, using independent knowledge of temperature, also of water vapor partial pressure. Main advantages of the calibration-free sounding technique are global coverage, high vertical resolution and all-weather-capability combined with high accuracy.
CHAMP, in the footsteps of GPS/MET, fills the measurement gap between GPS/MET and the upcoming operational occultation missions, as COSMIC [e.g., Rocken et al., 2000] or Metop [e.g., Loiselet et al., 2000] and, in addition, brought significant progress for the GPS occultation technique.

Fig. 1: Schematic overview of the CHAMP GPS radio occultation experiment and the related operational infrastructure. A sequence of bending angles $\alpha$ can be derived from the precise phase and amplitude measurements of the GPS receiver aboard CHAMP. A double differencing technique using simultaneous ground and space based GPS observations of occulting and reference GPS satellites allows for the correction of the significant GPS and CHAMP clock errors with high accuracy. Using the CHAMP and also GRACE data the application of alternative differencing techniques using less satellite links was demonstrated for the first time (single and zero differencing, see text).

2. STATUS OF CHAMP AND THE OCCULTATION EXPERIMENT

CHAMP was launched on a Russian COSMOS rocket on July 15, 2000 during maximum solar activity. The nearly circular orbit (eccentricity=0.004) had an initial altitude of 454 km and an inclination of 87.2°. Two manoeuvres with orbit lifting of ~20 km have been successfully carried out on June 9 and December 10, 2002, respectively. As of September 2005 the altitude is about 360 km, the instruments aboard the satellite are in excellent condition. A lifetime (mean altitude ~300 km) until early 2008 is currently predicted.

First radio occultation measurements aboard CHAMP were recorded on February 11, 2001 [Wickert et al., 2001a]. Occultation measurements were performed during 1553 days since February 2001 as of September 13, 2005; giving a total of 341,187 recorded events (~220 per day). For ~75 % of the occultations (258,374) atmospheric excess phases are available (see Fig. 2). Vertical profiles of atmospheric parameters were derived for 214,609 occultations (~63 %) and are available via CHAMP’s data center (http://isdc.gfz-potsdam.de/champ). A corresponding histogram of the CHAMP’s radio occultation measurements is shown in Fig. 2. In parallel to occultation measurements of the electric neutral atmosphere also globally distributed vertical profiles of electron density between ~60 km and the orbit altitude are provided [see, e.g. Jakowski et al., 2002]. First occultation measurements from the GRACE mission were available on July 28, 2004 [Beyerle et al., 2005; Wickert et al. 2004]. A longer set of GRACE occultations (8 days) was recorded in late September 2005.
Fig 2: Number of daily CHAMP occultations (duration > 20 s) as of September 13, 2005. The total height of the columns corresponds to the number of daily measurements. The black (blue) and light grey (red) colors indicate numbers of occultations with less quality atmospheric excess phase and vertical atmospheric profiles, respectively. The height of the dark grey (green) columns corresponds to the number of vertical atmospheric profiles provided to the CHAMP data center (ISDC, Information System and Data Center) at GFZ.

3. OCCULTATION DATA ANALYSIS AND NEAR REAL TIME ACTIVITIES

CHAMP’s GPS navigation and occultation data are transferred to the ground via receiving antennas at Neustrelitz (Germany) and Ny-Ålesund (Spitsbergen) as part of the science data stream and transmitted to the Information System and Data Center (ISDC) at GFZ Potsdam. Together with GPS ground data from the operational global network (operated jointly by GFZ and JPL) these satellite data form the main input of the automated processing systems for the satellite orbit and occultation data analysis [König et al., 2005, Schmidt et al., 2005b, Wickert et al., 2004]. Hereby the operational occultation data processing software is based on a configurable and extendable system [Wehrenpfennig et al., 2000] for data analysis and product generation. The individual processing steps are initiated as soon as all required input data are available from the ISDC; the output data files are generated and transferred back to the ISDC.

The briefly described operational ground infrastructure of GFZ (for overview see also Fig. 1 and for details Wickert et al. (2004)) is used to demonstrate a continuous provision of atmospheric sounding data from CHAMP since February 2003. An average delay of ~5 hours between each measurement aboard the satellite and provision of corresponding analysis results (atmospheric excess phases) was reached when the activity was started. Optimized GPS ground station data handling for the precise orbit determination reduced this delay to ~4 hours since mid April 2004. The average minimum delay has been reduced from 3.5 to 2.5 hours accordingly (see Fig. 3). A further reduction of the average delay is currently planned within a joint research project of GFZ, ECMWF, and the German Weather Service with the MetOffice (U.K.) as external partner. The challenging goal of this project is, to reach ~2 hrs delay in average. This is feasible due to the use of the polar satellite receiving antenna (access to CHAMP’s data every ~1.5 h), and the low latency of the GPS data from the ground station network (access to these data every ~15 min), but requires further optimization concerning precise satellite orbit generation and the occultation processing. The demonstration of NRT (Near Real Time) data analysis will be the precondition for a continuous assimilation of the occultation data to global numerical weather forecast models.

Details on the operational GFZ retrieval and the used algorithms for the derivation of atmospheric parameters as well as summaries of related references are given by, e.g., Wickert et al. (2005a,b, 2004). A more detailed description of the GPS RO technique is given, e.g., by Kursinski et al. (1997). The atmospheric data products (refractivity and dry temperature profiles: CH-AI-3-ATM) are provided via the CHAMP data center. Vertical profiles of specific humidity can be made available on demand. Background information (here from ECMWF) is used to derive the humidity profiles from the CHAMP refractivities.
Results from two different water vapor retrieval techniques are available, the standard 1Dvar retrieval [Healy and Eyre, 2000] and a direct method (DWVP), introduced, applied and validated by Heise et al. [2005]. Both methods come to statistically comparable results and reveal a bias of less than 0.1 g/kg and a standard deviation of less than 1 g/kg specific humidity in relation to radiosonde measurements in the mid troposphere.

Significant progress in the occultation data analysis with CHAMP was especially made in the GPS data processing for the correction of satellite clock errors. Standard method for GPS/MET was a double differencing technique (see Fig. 1), requiring the acquisition of additional ground and satellite GPS measurements for a precise correction or elimination of the clock errors. The availability of only 6 ground stations for GPS/MET led to “gaps” in the global coverage of the occultations, i.e. areas with reduced coverage of occultations [Wickert, 2002]. Using the CHAMP data for the first time the application of a space-based single differencing method was demonstrated [Wickert et al., 2002]. This technique allows for the precise occultation processing without direct use of ground station data and consequently leads to significant simplification of the occultation data analyses. Precondition for the application of space-based single differencing was the termination of the Selective Availability (S/A) mode of the GPS on May 2, 2000 [see, e.g. Wickert et al., 2001b]. A still more advantageous differencing technique, zero-differencing (i.e. exclusion of a reference GPS link for the derivation of the atmospheric excess phase), could be first applied to the processing of the GRACE data [Beyerle et al., 2005a] and was made feasible by the improved (more stable) clock characteristics of the GRACE satellites. A reduction of the satellite links involved in the clock correction process by single and zero differencing reduces the data amount and also the error influences (e.g. ionosphere, multipath, or measurement noise) to the derived atmospheric excess phase.

Another step forward in relation to GPS/MET is the possibility to improve and include wave-optics based retrieval algorithms (e.g. Canonical Transform (CT) or Full Spectrum Inversion (FSI) techniques) to the operational occultation data analysis for the elimination of the influence of multipath signal propagation to improve the accuracy of the derived atmospheric bending angles [see, e.g. Gorbunov and Kornblueh, 2003; Jensen et al., 2003, or Gorbunov, 2001]. These activities were stimulated by the continuous availability of the CHAMP occultation data. Currently the FSI technique is implemented to data analysis software, at, e.g. GFZ or UCAR (University Corporation for Atmospheric Research). Another unique scientific result, which was derived using the wave-optics based CHAMP occultation analysis, was the detection of signal components which were caused by reflections at water or ice surfaces [Beyerle et al, 2002]. The reflected signal components contain additional information on the reflecting surface and can potentially be used by future satellite missions as a new remote sensing technique [e.g., Komjathy et al., 2000].

![Fig. 3: Time delay between CHAMP occultation measurements and availability of analysis results at GFZ from February 2003 until end September 2005. Black (blue) 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 the first period until ~ day 450 is reached. The minimum time delays are marked by grey (red) triangles. Due to improved GPS ground station data handling for the provision of precise GPS orbits the mean delay was reduced to ~4 hours since end April 2004.](image-url)
4. VALIDATION AND DATA QUALITY

The quality of the CHAMP data was evaluated within numerous validation studies using independent atmospheric data from meteorological analyzes, radiosondes and other remote sensing satellites [e.g. Gobiet et al., 2005; Kuo et al., 2005; Wickert et al., 2005b; Wang et al., 2004; Wickert, 2004; Marquardt et al., 2003]. As an example for such studies Fig.4 shows a comparison of more than 210.000 CHAMP refractivity profiles (GFZ product version 005) with corresponding analysis data from ECMWF (Gaussian grid with 0.5° x 0.5° resolution at the Equator, 60 altitude levels) between 10 and 30 km. The comparison shows nearly bias–free refractivity. The standard deviation is ~1 % and less. The deviations depend on latitude and may help to identify weaknesses of the ECMWF analysis. E.g., the “wavelike” structures in the bias (CHAMP–ECMWF) in the Antarctic region (Fig. 4, left) are related to known problems of ECMWF in the southern hemisphere due to the assimilation of other satellite data (AMSU, Advanced Microwave Sounding Unit, and AiRS, Atmospheric Infrared Sounder; G. Kelly personal communication). The studies of Kuo et al. (2005) and Wickert (2004) demonstrated, independent from each other, that CHAMP data can be used to reveal differences in the data quality of different types of radiosondes.

![Fig. 4: Comparison of CHAMP refractivity data with corresponding ECMWF analyzes (CHAMP-ECMWF) in the upper troposphere/stratosphere (left: bias; right: RMS) between May 14, 2001 and September 10, 2005 (~210, 000 profiles)](image)

In contrast to the excellent agreement of CHAMP with ECMWF between 10 and 30 km, which can be observed in Fig. 4, systematic deviations are observed in the lower troposphere below 5 km, which is combined with a decreasing data yield. The refractivity, observed by CHAMP is systematically lower than that of corresponding analysis or radiosonde data. This phenomenon is referred as the negative refractivity bias, which depends on latitude and is most pronounced in the tropics, where it reaches a value of 5 % at 1 km. It was observed by Rocken et al. (1997) in the GPS/MET data, but a detailed explanation on the origins of this feature could not be given. In contrast, in mid latitude and polar regions the CHAMP data are nearly bias free throughout the entire troposphere.

A number of studies, also stimulated by the CHAMP measurements, were performed during the last years to investigate the origins of the observed bias [see, e.g., Beyerle et al. (2005b), Ao et al. (2003a), Sokolovskiy (2001)] and brought a significant improvement in understanding and avoiding it. Causes of the bias are, beside multi-path propagation, also signal tracking errors of the GPS receiver and super refraction, a physical limitation of the RO technique. Pioneering part of these studies was the inclusion of the GPS receiver tracking process in the end-to-end simulations, to investigate in detail the influence of the receiver tracking to the quality of the analysis results and the related negative bias. Further progress in reducing the bias and increasing the data yield is expected by the application of advanced signal tracking methods (e.g., Open Loop (OL) or modified CL (Closed Loop) technique, see, e.g. [Sokolovskiy, 2001; Beyerle et al., 2005b]) and improved signal strength due to the use of more advanced occultation receivers and antenna configurations (foreseen, e.g., for COSMIC or Metop).
5. APPLICATIONS

CHAMP refractivity and temperature data in the upper troposphere/lower stratosphere region are not affected by background temperature fields and are most accurate in this altitude region [Kursinski et al., 1997]. Therefore they can be used to investigate climate change processes. CHAMP’s continuous measurements initiated first long-term climatological investigations, especially of temperature, tropopause parameters or gravity wave characteristics [see, e.g., Foelsche et al., 2005; Ratnam et al., 2004; Schmidt et al., 2005a, 2004]. Also, characteristics of the global boundary layer were derived [e.g., v. Engeln et al., 2005].

Recently, first successful impact studies using CHAMP data for the Numerical Weather Prediction were documented [e.g., Healy et al., 2005a]. Stimulated by the encouraging results, ECMWF started activities to assimilate GPS radio occultation data [Healy and Thepaut, 2005]. Fig. 5 shows a result of this study. Two months of CHAMP data (~12,500 bending angles per 12 h assimilation window) were assimilated to the operational 4D–Var system in addition to the ~2 million observations, that are operationally used (EXP2 run). The assimilation run without GPS data was used as control (CTL). Comparing the 12 h forecast and analysis fit to radiosondes in Antarctica, it can be seen that assimilating the RO improves both the mean and standard deviation of the fit to radiosonde temperature values. In particular it can be noticed, how the sharp structure in the mean fit is smoothed as a result of assimilating the RO data. This sharp structure is a well–known problem with the ECMWF operational system (see also Chap. 4). It is a very encouraging result of this study, that the occultation data try to smooth it, despite of the fact that a really small number of occultations was assimilated.

6. CONCLUSIONS AND OUTLOOK

The status of the CHAMP occultation experiment was briefly summarized, main achievements of 4 years GPS radio occultation were reviewed in comparison with the proof-of-concept GPS/MET mission and in view of the upcoming missions as COSMIC or Metop.

As main achievements of 4 years GPS radio occultation with CHAMP are regarded: generation of the first long-term radio occultation data set; operational and continuous provision of GPS radio occultation measurements and corresponding analysis data via the CHAMP data center using an operational ground infrastructure; demonstration of the feasibility of advantageous techniques for the simplification of GPS data processing (single and zero (only GRACE) differencing), implementation of wave–optics based analysis techniques to the operational data processing, extensive validation studies using data from meteorological analyses, radio sonde and other satellites, climatological investigations of global gravity wave and tropopause characteristics, and last but not least first successful and promising impact studies to the global numerical weather prediction. In addition the work CHAMP data helped to prepare various processing centers to install and improve their occultation data analysis software. CHAMP radio occultation
measurements (soon complemented by GRACE) are an important milestone for the establishment of the GPS radio occultation technique as an integrative component of the Global Earth Observing System. Next steps will be the launch of the operational occultation missions COSMIC and Metop in spring 2006 and TerraSAR-X, a German RO mission, end 2006.

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8. REFERENCES


