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Atmosphere sounding by GPS radio occultation: First results from CHAMP

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Abstract. The first radio occultation measurements of the CHAMP (CHALLENGING Minisatellite Payload) satellite using Global Positioning System (GPS) signals have been performed on February 11, 2001. By the end of April 2001 more than 3000 occultations were recorded. Globally distributed vertical profiles of dry temperature and specific humidity are derived, of which a set of 438 vertical dry temperature profiles is compared with corresponding global weather analyses. The observed temperature bias is less than ~ 1 K above the tropopause and even less than 0.5 K in the altitude interval from 12 to 20 km at latitudes $>30^\circ\text{N}$. About 55% of the compared profiles reached the last kilometer above the Earth's surface. In spite of the activated anti-spoofing mode of the GPS system the state-of-the-art GPS flight receiver aboard CHAMP combined with favorable antenna characteristics allows for atmospheric sounding with high accuracy and vertical resolution.

1. Introduction

The German CHAMP satellite [Reigber *et al.*, 2000] succeeds the pioneering U.S. American GPS/MET (Global Positioning System/Meteorology, Ware *et al.*, 1996) mission for GPS-based limb sounding from low Earth orbiting (LEO) satellites. It was launched from Plesetsk, Russia (62.5°N , 40.3°E) on July 15, 2000. The principal mission objectives are to determine the Earth's gravity and magnetic fields and to perform global limb soundings of the Earth's neutral atmosphere and ionosphere using the GPS radio occultation technique.

Due to the unique combination of global coverage, high vertical resolution, long-term stability and all-weather capability, the GPS radio occultation technique offers great potential for improving numerical weather forecasts and climate system studies [Kursinski *et al.*, 1997]. Assimilation studies using GPS/MET data have already shown, that GPS radio occultation significantly improves the accuracy of global and regional analyses and weather prediction [Kuo *et al.*, 2000]. The sub-Kelvin temperature accuracy and sub-Fresnel vertical resolution in the tropopause region [see e.g., Igarashi *et al.*, 2000] allows for detailed investigation of temperature gradients across the tropopause, which can provide

information on the global radiative budget change of the atmosphere within the next decades. It is therefore a powerful tool for detecting climate trends [Steiner *et al.*, 2001].

The GPS/MET experiment also demonstrated the potential of GPS radio occultation for a global monitoring of electron density distribution in the ionosphere [Hajj and Romans, 1998; Schreiner *et al.*, 1999; Vorob'ev *et al.*, 1999].

CHAMP carries the latest generation of the JPL (Jet Propulsion Laboratory) GPS flight receiver ("BlackJack"). The new receiver in combination with a directional aft-looking high gain helix antenna (+5 dB in relation to GPS/MET) provides improved signal quality and allows for application of advanced signal tracking techniques [Yunck *et al.*, 2000]. These capabilities enable sounding well into the lower troposphere provided that critical refraction layers do not occur within the planetary boundary layer [Kursinski *et al.*, 1997].

CHAMP will provide about 230 globally distributed vertical profiles of atmospheric parameters per day within the height interval of 0-50 km. The vertical resolution ranges from 0.5 km in the lower troposphere to 1.5 km in the stratosphere and the resolution along the ray path is around a few hundred km. In the troposphere vertical profiles of humidity will be derived using ancillary temperature data from meteorological analyses.

Part of the CHAMP project is the development and implementation of a complete ground infrastructure for occultation data processing at GeoForschungsZentrum (GFZ). The objective is a fully automated analysis of ground- and space-based GPS data, including an interface to the German weather service for GPS data assimilation. In the following we characterize the data processing at GFZ and present first results of the CHAMP GPS radio occultation experiment.

2. CHAMP orbit and first occultations

CHAMP was launched with a Russian COSMOS rocket on July 15, 2000, 12:00 UTC into an almost circular (eccentricity = 0.004), near polar (inclination = 87.2°) orbit with an initial altitude of 454 km. Atmospheric drag will lower the orbit altitude during the mission lifetime of 5 years by about 50 to 200 km depending on the actual solar activity. At least one orbit maneuver is planned to guarantee the five year observation period and maintain an altitude above 300 km.

The first occultation measurements with CHAMP were performed on February 11, 2001 between 19:04 and 20:04 UTC. Seven occultations of good quality, each lasting more than 30 sec, were recorded. Fig. 1 shows the location of these events and the corresponding ground track of CHAMP.

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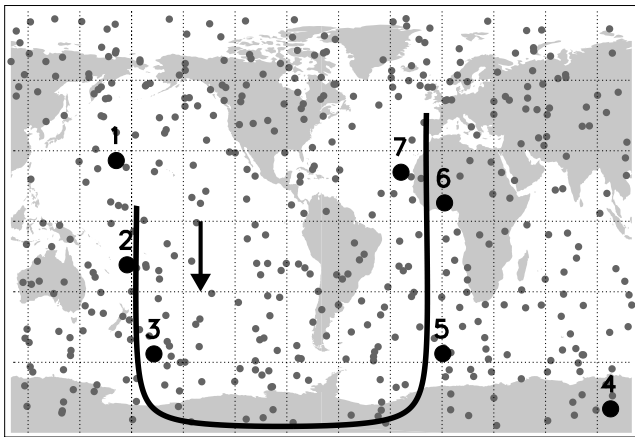


Figure 1. Locations of the first occultations (numbered) on February 11, 2001 with corresponding ground track of CHAMP and locations (gray) of those occultations used for the comparison with ECMWF.

3. Data analysis and processing

The analysis software is embedded in a dynamically configurable and extendable system for operational data processing and product generation [Wehrenpfennig *et al.*, 2001], which also provides an interface to GFZ's data archive. The atmospheric retrieval algorithms were validated by re-analysis of GPS/MET satellite and fiducial ground data, complemented by satellite orbits, generated by GFZ [Kang *et al.*, 1997]. Comparison between vertical profiles of dry temperature derived by UCAR and GFZ shows no statistically significant differences [Wickert *et al.*, 2001].

Three types of input data are required for our occultation processing: GPS (occultation) data from CHAMP, GPS ground tracking data of the fiducial network, and precise orbit information of the satellites involved.

The GPS and CHAMP orbit ephemeris are provided by GFZ's precision orbit determination for CHAMP. Typical position errors for dynamically computed 1 day CHAMP orbits are presently 20-30 cm [Neumayer *et al.*, 2000]. Improvements to the sub-decimeter level can be expected after gravity field tuning.

A double difference technique is used to eliminate satellite clock errors and to derive the atmospheric excess phase of the occultation link [Wickert *et al.*, 2001]. The 50 Hz phase data, measured by CHAMP, are synchronized with interpolated 1 Hz data of a fiducial ground network. This fiducial network, consisting of about 30 stations [Galas *et al.*, 2001], was installed and is operated jointly by JPL and GFZ. This large number of ground stations guarantees a high redundancy and allows for global coverage of occultation events [Wickert *et al.*, 2001]. Details of the excess phase calibration are given by Schreiner *et al.* [1998] and Hajj *et al.* [2001].

Atmospheric bending angles are derived from the time derivative of the calibrated atmospheric 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].

Vertical profiles of atmospheric refractivity are derived from the corrected bending angle profiles by Abel inversion. For dry air, the density profiles are obtained from the known relationship between density and refractivity. Pressure and

temperature ("dry temperature") are obtained from the hydrostatic equation and the equation of state for an ideal gas. Detailed descriptions are given e.g. by Melbourne *et al.* [1994] or Hoche [1997].

When water vapor is present, additional information is required to determine the humidity and density from refractivity profiles. At microwave frequencies the refractivity is very sensitive to water vapor. Temperature profiles from operational meteorological analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) are used to derive humidity profiles from the calculated refractivity in an iterative procedure [Gorbunov and Sokolovskiy, 1993]. This algorithm suffers from a high sensitivity to even small errors in the analyses temperatures, resulting in large uncertainties of the derived water vapor profiles [Marquardt *et al.*, 2001]. More elaborate retrieval methods based on optimal estimation of both temperature and humidity [e.g. Healy and Eyre, 2000] show more potential for obtaining water vapor profiles with high accuracy. Nevertheless, the algorithm used here delivers results of good quality (e.g. see Fig. 2b).

Uncorrected multipath effects in the lower troposphere due to the water vapor distribution itself will also lead to errors in the refractivity and consequently to errors in the derived humidity. The application of advanced wave optical retrieval techniques shows great potential to solve this problem [e.g. Beyerle and Hoche, 2001; Pavelyev *et al.*, 1996; Gorbunov *et al.*, 2000].

4. Results

Analysis of GPS/MET data was primarily focused on "prime-times", i.e., periods when anti-spoofing (A/S) encryption of the GPS signals was disabled [Rocken *et al.*, 1997]. In contrast to the L1 carrier phases, the L2 data were significantly noisier during A/S-on, requiring more effort in data analysis (the SNR for L2 was about one order of magnitude lower compared to A/S-off). The CHAMP GPS receiver yields SNR values exceeding typical GPS/MET values during A/S-off by about a factor of 2 for L1 and 1.1 for L2. Although A/S was turned on during Feb. 11 and April 19-21, 2001, it turns out that the CHAMP data quality during A/S-on is equal or even exceeding the quality during GPS/MET "prime-times".

Fig. 2 shows vertical profiles of dry temperature and

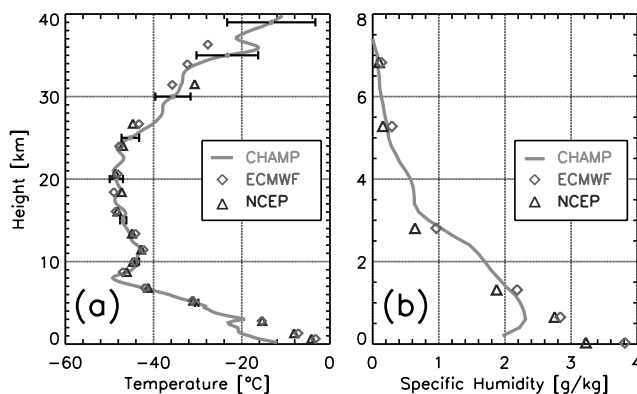


Figure 2. Vertical profiles of (a) dry temperature and (b) specific humidity, derived from one of CHAMP's first occultation measurements (no. 5) on February 11, 2001, compared with data from ECMWF and NCEP (0.5°W, 53.2°S), 19:43 UTC.

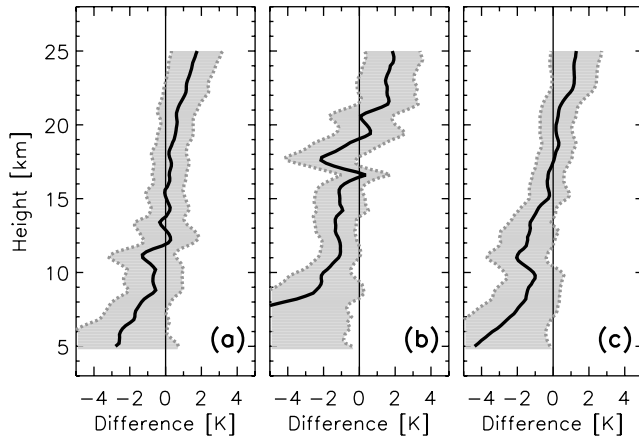


Figure 3. Statistical comparison between dry temperature profiles, derived from CHAMP measurements and 6-hour ECMWF analyses during April 19-21, 2001. The differences (CHAMP-ECMWF) are plotted for (a) 166 profiles in the northern hemisphere ($>30^{\circ}\text{N}$), (b) 118 profiles at low latitudes (30°N to 30°S) and (c) 154 profiles in the southern hemisphere ($<30^{\circ}\text{S}$).

specific humidity for one of CHAMP's first occultations (no. 5) on February 11, 2001 over the South Atlantic (53.2°S , 0.5°W , 19:43 UTC). Interpolated data from the 6-hour operational meteorological analyses of the ECMWF and National Centers for Environmental Prediction (NCEP) are plotted for comparison. The dry temperature profile (Fig. 2a) reaches the Earth surface and matches well with both weather analyses at heights above 5 km. The sounding clearly resolves the tropopause at a height of 8 km. Due to significant presence of water vapor below 5 km the measured dry temperature profile deviates from ECMWF and NCEP temperatures.

For the corresponding humidity profile (Fig. 2b) also good agreement down to the marine boundary layer at about 1.5 km is found.

The estimation of the dry temperature error (indicated by the error bars in Fig. 2a) was performed according to Steiner *et al.* [1999]. A bending angle error was assumed to be due to the optimization approach [Hocke, 1997] with the MSISE-90 model for the upper stratosphere and mesosphere [Hedin, 1991]. For applications such as climate monitoring of the stratosphere our implementation of the statistical optimization approach has to be improved. Also, the occurrence of systematic temperature biases at stratospheric heights due to ionospheric residual errors has to be investigated [Kursinski *et al.*, 1997; Syndergaard, 2000].

A set of 438 selected vertical dry temperature profiles, measured during period April 19-21, 2001 (Fig. 1) was used to compare with corresponding ECMWF profiles in the height interval from 5 to 25 km. The occultations were separated into three subsets, high latitudes (northern hemisphere), low latitudes and high latitudes (southern hemisphere). The mean deviation (CHAMP-ECMWF) and their standard deviations with 0.2 km vertical sampling are depicted in Fig. 3.

In each subset the CHAMP measurements at the tropopause (between 16 and 19 km at low latitudes, about 11 km in the other regions) are systematically colder than the analysis. This warm bias of the analysis is due to higher vertical resolution of the radio occultations compared to the analysis

which was available on standard pressure levels only. This has also been observed for GPS/MET data [e.g., Rocken *et al.*, 1997]. Above the tropopause, however, the agreement between CHAMP and the analysis is better than 1 K with a standard deviation of ~ 1.5 K or less. In the northern hemisphere the mean difference is less than 0.5 K between 12-20 km altitude. Below the tropopause the presence of water vapor leads to negative bias of the dry temperature profiles compared to ECMWF temperature. The negative bias, as expected, is strongest at low latitudes due to the high absolute humidity in this region. About 55% of the selected profiles reached the last kilometer above the Earth's surface.

5. Conclusions and outlook

First results from the GPS occultation experiment aboard CHAMP are presented. A statistical comparison between vertical profiles of dry temperature, derived from CHAMP measurements and corresponding ECMWF data shows that the agreement above the tropopause is better than 1 K with a standard deviation of ~ 1.5 K or less. At latitudes $>30^{\circ}\text{N}$ this temperature bias is even less than 0.5 K. The first CHAMP measurements indicate that the L1 and L2 signal strength with A/S-on is comparable with or even better than the corresponding GPS/MET signal strength during A/S-off. Due to the improved GPS receiver performance we expect that the amount of profiles reaching the Earth's surface will be significantly larger than with GPS/MET.

On the basis of these first results the CHAMP occultation experiment is expected to successfully fulfill its anticipated 5 year pilot mission function for continuous global sounding of the atmosphere by a new promising remote sensing technique. The CHAMP data set will be valuable for improving the GPS radio occultation technique per se, especially by enhancing the retrieval techniques in the lower troposphere. These data processing advances plus the availability of profiles within a few hours should lead to improvements in numerical weather forecasts. Furthermore the long term availability of occultation data will enhance global climate change studies.

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