Global monitoring of tropospheric water vapor with GPS radio occultation aboard CHAMP

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Abstract

The paper deals with application of GPS radio occultation (RO) measurements aboard CHAMP for the retrieval of tropospheric water vapor profiles. The GPS RO technique provides a powerful tool for atmospheric sounding which requires no calibration, is not affected by clouds, aerosols or precipitation, and provides an almost uniform global coverage. We briefly overview data processing and retrieval of vertical refractivity, temperature and water vapor profiles from GPS RO observations. CHAMP RO data are available since 2001 with up to 200 high resolution atmospheric profiles per day. Global validation of CHAMP water vapor profiles with radiosonde data reveals a bias of about 0.2 g/kg and a standard deviation of less than 1 g/kg specific humidity in the lower troposphere. We demonstrate potentials of CHAMP RO retrievals for monitoring the mean tropospheric water vapor distribution on a global scale.

Key words: CHAMP, GPS radio occultation, water vapor, troposphere

1 Introduction

The implementation of the Global Positioning System (GPS) enabled the development of the radio occultation (RO) technique (e.g. [Melbourne et al., 1994; Kursinski et al., 1997]) for remote sensing of the Earth’s atmosphere. This technique exploits atmospheric refraction of GPS signals observed aboard Low Earth Orbiting (LEO) satellites. Basic observable is the atmospheric excess phase which is used for the retrieval of meteorological quantities. The potentials of GPS RO measurements for providing vertical atmospheric profiles of refractivity, temperature and water vapor have been demonstrated for the first
time by the GPS/MET experiment (e.g. [Ware et al. 1996; Kursinski et al. 1997]). The CHAMP (Challenging Minisatellite Payload) GPS RO experiment was successfully started on Feb. 11, 2001 ([Wickert et al. 2001] and is activated continuously since mid of 2001. Considering current and planned LEO satellite missions (e.g. GRACE or COSMIC), GPS RO data will provide a valuable data base for climatological investigations and improvement of global weather forecasts in the future. One challenge in processing GPS radio occultation measurements is the data analysis in the lower troposphere. The refractivity retrieved from GPS RO data shows a negative bias in relation to meteorological data ([Ao et al. 2003; Beverle et al. 2004]), which leads to a corresponding bias in the retrieved specific humidity. Reasons for this bias are GPS receiver tracking errors, uncorrected multipath in signal propagation and critical refraction. The application of advanced retrieval techniques, as the Full Spectrum Inversion (FSI) method ([Jensen et al. 2003]), reduces the refractivity bias significantly ([Wickert et al. 2004]). The FSI is implemented to the current version (005) of the operational data analysis software at GFZ Potsdam, which is available since February 2004.

2 Retrieval technique

The retrieval of atmospheric profiles from GPS occultation measurements has been described in detail by a number of authors (e.g. [Melbourne et al. 1994; Kursinski et al. 1997; Wickert et al. 2004]). Briefly, the GPS measurements recorded by a receiver onboard a LEO (50 Hz sampling rate in case of CHAMP) are used together with high precision orbit information (LEO and occulting GPS satellite) to derive the atmospheric excess phase with millimetric accuracy. These data are transformed into profiles of the ray path bending angle $\alpha(a)$, where $a$ denotes the so-called impact parameter. Assuming spherical symmetry the Abel transform (e.g. [Fjeldbo et al. 1971]) is applied to invert $\alpha(a)$ into refractivity profiles $N(r)$, where $r$ denotes the ray path tangential altitude.

$$N(r) = 77.6 \frac{p}{T} + 3.73 \cdot 10^5 \frac{p_w}{T^2}$$  

(1)

The atmospheric refractivity $N(r)$ (Eq. 1) is related to air pressure ($p$), air temperature ($T$) and water vapor pressure ($p_w$). Assuming dry air conditions, refractivity is direct proportional to air density and the pressure profile can be derived by downward integration of the refractivity profile assuming hydrostatic equilibrium. The temperature profile is calculated consecutively by Eq. 1. The validation of CHAMP dry temperature profiles with radiosonde data as well as ECMWF analyses shows a temperature bias less than 0.5 K (RMS deviation 1–2 K) between 250–20 hPa ([Wickert et al. 2004]).
However, the dry air assumption is not valid over wide areas of the mid and lower troposphere, leading to an ambiguity of the dry and wet refractivity term (Eq. 1). To deal with this problem, additional meteorological information is necessary. There are different retrieval techniques using such information. Gorbunov and Sokolovskiy (1993) describe an iterative algorithm which uses external temperature information (e.g. from ECMWF analyses) to separate dry and wet part of the measured refractivity. In result, pressure and humidity profile are derived from the refractivity data. Another approach to retrieve both humidity and temperature profile is the 1Dvar technique (Healy and Eyre, 2000). This optimal estimation method requires background information (temperature, humidity and pressure) as well as error characteristics of the measurement (refractivity) and the background (e.g. ECMWF). A further approach, in the following referred to as direct water vapor pressure (DWVP) retrieval, has been developed at GFZ Potsdam. Here background (ECMWF) temperature and pressure information are used to calculate water vapor pressure ($p_w$) directly from refractivity data applying Eq. 1. The difference between the so derived $p_w$ and background humidity information is used to adapt the background pressure for a recalculation of $p_w$. The pressure values converge very quickly and the procedure is stopped after the second iteration step. The known negative refractivity bias in the lower troposphere (Fig. 1(a)) states a general problem for the humidity derivation. To avoid DWVP retrieval outliers especially in that region, deviations between background and retrieval humidity are restricted to the double ECMWF humidity error of the current profile during the iteration.

At GFZ Potsdam both, 1Dvar and DWVP algorithms are implemented for tropospheric water vapor retrieval. In the following we present results from both techniques and compare these with radiosonde measurements.
Fig. 2. Comparison of vertical specific humidity (a), temperature (b) and refractivity (c) profiles derived from CHAMP DWVP and 1Dvar retrieval with radiosonde Lindenberg and ECMWF data. Example for occultation 226, October 25, 2002, 22:27 UTC, 51.44°N, 14.66°E.

3 Results and validation

To give an impression on the retrieval results, Fig. 2(a) shows an example of CHAMP 1Dvar and DWVP specific humidity in comparison to radiosonde and ECMWF data. Both CHAMP retrievals come to quite similar results revealing significant improvement of the background (ECMWF) specific humidity in comparison to radiosonde data. Nevertheless, 1Dvar shows a slightly smoother result than DWVP. This has been observed in several cases and can be considered as a general difference between both retrievals. Obviously, DWVP is more sensitive to vertical structures in the input refractivity than 1Dvar. Fig. 2(b) reveals good agreement between radiosonde and ECMWF temperature profiles. The 1Dvar temperature shows only small deviations from the background. Finally, radiosonde, ECMWF and CHAMP refractivity profiles are given in Fig. 2(c). Especially between 600 and 800 hPa the CHAMP refractivity shows better agreement to the radiosonde observation than ECMWF. This obviously corresponds to improvements of the CHAMP humidity retrieval above the background humidity in this altitude range.

The 1Dvar and DWVP retrieval results have been validated with radiosonde data. Fig. 3 (a)-(c) show the statistical comparison (bias and standard deviation) of vertical specific humidity profiles from ECMWF, 1Dvar and DWVP with coinciding radiosonde profiles on a global scale. For the years 2002 and 2003 about 13,400 coincidences have been found (see Fig. 3(e), coincidence radius: 300 km spatial and 3 hours temporal). Radiosonde data were quality checked by comparison with ECMWF and have been ignored in case of more than 10% refractivity deviation. As can be seen from Fig. 3(b) and (c), the
Fig. 3. Statistical comparison (years 2002-2003) of vertical specific humidity profiles from global radiosonde stations with: (a) ECMWF, (b) 1Dvar, (c) DWVP. Corresponding comparison of CHAMP and radiosonde refractivity is shown in (d). Blue lines represent bias, red lines standard deviation. Number of compared data points (coincidence radius: 300 km, 3 hours) is shown in (e).

The statistical comparison of 1Dvar and DWVP with radiosonde data comes to quite similar results. The negative CHAMP refractivity bias (Fig. 3(d)) leads to a specific humidity bias of about -0.2 g/kg in the lower troposphere. Nevertheless, the standard deviation is similar to the result from radiosonde comparison with ECMWF (Fig. 3(a)). By comparing Fig. 3(a)-(d) it has to be noticed that between 600 and 500 hPa DWVP shows a slightly stronger relation to the refractivity data than 1Dvar which seems to be more influenced by the background (ECMWF) data in this region.

4 Global application

The CHAMP humidity profiles may be used for investigation of mean seasonal or medium term water vapor distribution on a global scale. Due to rather low data exploitation in the lower troposphere (see Fig. 1(b) and Fig. 3(e)) and accuracy restrictions at low humidity levels in the upper troposphere, the mid troposphere region is most appropriate for such investigations. Fig. 4(a) shows the mean global water vapor distribution at 500 hPa pressure level derived from DWVP results for the northern summer season of 2002 according to a grid of 2.5° resolution in latitude and 5.0° in longitude respectively. The corresponding data coverage (profiles per pixel) is shown in 4(b). It has to be mentioned that current and planned LEO RO missions like GRACE and COSMIC will provide a significantly extended data base which will allow for global coverage within much shorter time scales than the CHAMP mission alone. Furthermore, RO data will be of growing interest for climatological investigations in the future if first medium and long term RO data sets become available.
5 Conclusions

The 1Dvar and DWVP techniques state valuable tools for the humidity retrieval from occultation refractivity measurements in the mid and lower troposphere. Statistically, both methods come to comparable results. Even if a unique separation of dry and wet refractivity components is not possible, the derived humidity information may be improved above the background (e.g. ECMWF) provided that temperature background and refractivity measurement are of sufficient quality. Advanced retrieval techniques like the FSI method significantly reduced the negative refractivity bias in the lower troposphere. Nevertheless, the refractivity retrieval needs further improvement. Potentials of CHAMP RO data for global water vapor monitoring have been demonstrated. The CHAMP RO experiment generates the first long-term RO data set. Following satellite missions like GRACE and COSMIC will significantly extend the RO database improving the capabilities for global water vapor monitoring and climatological investigations.

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