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Interactive comment on "GPS radio occultation with CHAMP: monitoring of climate change parameters" *by* T. Schmidt et al.

T. Schmidt et al.

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Dear Referee 2,

thank you for the helpful and useful comments and suggestions.

Before we give a detailed response to the comments we give a general remark: The paper was originally thought to give a short overview of the GPS radio occultation (RO) technique (1), demonstrate the data quality of CHAMP radio occultation (RO) data as the first longer GPS RO data set (2) and show some selected examples for application of the data with respect to the UTLS region (3). Because the continuous CHAMP RO data set (since May 2001) is relatively new this information is relevant for the COST 723 community and should be part of the special issue (Data exploitation and modelling for the upper troposphere and lower stratosphere). In the originally version the paper combines updated results of an earlier study on the tropical tropopause layer and QBO (Section 3) and introduces new results from a 1DVAR retrieval for water vapour in the middle and lower troposphere (Section 4). Only Referee 1 has accepted this with minor corrections, especially for the 1DVAR retrieval and a remark that the results in Section 3 are not very new.

The critics of Referee 2 is more complex, leading to the judgement that the paper can only be published after major revision. Although, from our point of view, not all comments are justified (see detailed response below), we have decided to submit a completely revised version. The main changes are:

(1) The title: "GPS radio occultation with CHAMP and SAC-C: global monitoring of thermal tropopause parameters"

(2) The study is extended to the global lapse-rate tropopause (LRT) based on the CHAMP data from May 2001-December 2004 and SAC-C data (August 2001-October 2001, March 2002-November 2002). Global differences are discussed with respect to seasonal changes of the LRT pressure, temperature, potential temperature, and LRT sharpness.

(3) The LRT altitude, pressure and temperature results are compared with operational ECMWF and radiosonde data.

(4) Section 4 of the current version (1DVAR retrieval for water vapour in the troposphere) will be removed because these results concerning the middle and lower troposphere and therefore are not a topic for COST 723. We follow here the suggestion of Referee 2.

In the following we respond to the comments. Because we have removed the section about the 1DVAR retrieval we do not answer and discuss the related points.

General Comments

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A revised version is submitted.

Major Scientific Comments

Paragraph 1:

In the original version of the paper not only the tropical tropopause height as a climate change parameter is discussed, but also (more or less indirect) the tropospheric water vapour (or a retrieval for the estimation of it from CHAMP RO data) and, even if not in the detail, the refractivity and temperature.

It could be shown here (Section 2) that both, refractivity and UTLS temperature, are in agreement with ECMWF and radiosonde data, respectively. The RO data quality and the potential of GPS RO data for application in climate research was already topic of different studies (see reference list, e.g., Hajj et al. (2004), Anthes et al. (2000), Kursinski et al. (1997)), but now demonstrations can start with the first longer RO data set from CHAMP.

We agree with the suggestion for changing the title of the paper as already mentioned in the introduction.

Paragraph 2:

In the revised version of the paper comparisons of CHAMP/SAC-C tropopause parameters with ECMWF and radiosondes are performed. Section 3 was rewritten and the main emphasis is now on the discussion of the global thermal tropopause and not the TTL alone.

Paragraph 3:

Because we removed the results related to the 1DVAR water vapour retrieval the only point to discuss here is the quality of CHAMP temperature data. These data we have used to determine the LRT parameters. A general comment to the remark that "the accuracy assessment is not done appropriately in the present version" and at the end

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of the review the statement that "the accuracy of GPS RO retrievals of temperature has not been quantified in this study,...": Beside the discussion of water vapour in the troposphere and the initialisation method for the integration of the hydrostatic equation (follows later) it should be pointed out here that the best indicator for the RO temperature data quality (especially in the UTLS) are comparisons with independent radiosonde data. Fig. 2 shows clearly a temperature bias between CHAMP measurements and about 15,000 nearby radiosondes of less than 0.5 K between 250 and 20 hPa pleading for the accordingly quality of the data and retrieval methods, respectively.

Paragraph 4:

As mentioned, if one use temperature data as in this study to discuss LRT parameters there is no question to show the temperature data quality in comparison with independent temperature data as done here with nearby radiosondes (Section 2). This is the link to Section 3. And, of course, we therefore included a section describing the measuring principle and data quality. Once again we compare the deduced CHAMP temperature not with ECMWF temperature data, but with independent radiosondes!

Paragraph 5:

The questions raised here are mainly addressed to the water vapour retrieval and will not be further considered. However, we give one comment to the question "What is the quality of GPS RO profiles of T and H if no ECMWF data is available?" In the current retrieval version (005, see Wickert et al., 2004) we only use ECMWF pressure at 43 km for the initialisation of the hydrostatic equation. This is one atmospheric scale height above the upper level for which profile data are published (35 km). As shown by Hajj et al. (2004, see reference list), but for the use of ECMWF temperature for the initialisation of the hydrostatic equation, the differences between the temperature means by the initialisation with ECMWF at 32, 35, and 40 km are less than 0.05 K below 20 km and $<$0.02 K for heights below 15 km. The authors followed that the retrieved temperatures, at least in the mean, are not very sensitive to the initialisation

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height between 32 and 40 km. They also answered the question how a bias influences the retrieved temperature and showed that a 2 K (or 5 K) bias at 40 km maps into a 0.03 K (0.08 K) bias at 15 km.

A similar study was performed by Wickert (not published yet). He shows the influence of the initialisation of the hydrostatic equation at different heights with pressure from ECMWF on the temperature profiles. The results are comparable to those reported in the Hajj et al. paper, with nearly no influence at the tropopause altitude.

In case of no availability of ECMWF data climatologies, as MSISE90 are needed. The refractivity results are identical then, the temperature then deviates at higher altitudes.

Paragraph 6:

We follow the referee and remove the section on 1DVAR retrieval for water vapour.

Paragraph 7:

The discussion of error sources is very important and topic of several publications. Comprehensively discussions are made in Kursinski et al. (1997), Ao et al. (2003), Beyerle et al. (2004), Hajj et al. (2004) that are all listed in the reference list. It would be blow up the frame of the paper to discuss all of them, but you are right they should be mentioned. The same refers to the problem of using the RO data in NWP and climate models.

Specific Comments

We agree until p. 7841, line 1-2

p.7841, line 2-4:

This works not only in the stratosphere. Since the saturation water vapour pressure decreases with decreasing temperature water vapour in the troposphere can be ignored if the temperature is below 250 K (Kursinski et al., 1997). This condition extends down to the Earth's surface especially in Polar regions.

p.7841, line 6-7:

The results from the Abel inversion are refractivity profiles N(r) (Eq. 1-3). Please note, that this measured refractivity is derived without any meteorological background information. This is an important advantage of the GPS RO technique. We use this (measured) refractivity and not the ECMWF refractivity for the initialisation which we describe now.

Neglecting the moist term in Eq. 3 leads to N=77.6p/T. Combining this with the equation of state of an ideal gas gives density ρ as a function of refractivity: ρ(r)=N(r)m/bR (m: mean molecular mass of dry air; b=77.6; R: gas constant). Pressure p(r) can be obtained from density ρ by integrating the equation of hydrostatic equilibrium δp/δr=-g(r)ρ(r) where g(r) is the acceleration due to gravity. To not integrate to infinity we use initialisation with the ECMWF pressure at 43 km. This is one atmospheric scale height above the upper level for which we provide temperature profile data (35 km). Then we calculate the dry temperature by T=77.6p/N.

Please note, that N is the measured refractivity and not taken from ECMWF!

p.7841, line 10-12:

Once again: Fig. 2 shows a comparison of CHAMP with radiosonde data. The radiosonde measurements are completely independent from retrieved RO temperature data leading to the statement of excellent data quality (bias $<$0.5 K between 250 and 20 hPa) in the UTLS.

p.7850, Fig. 2 - p.7841, line 19: we agree

p.7841, line 23:

The vertical resolution of a single bending measurement is determined by the contribution of individual atmospheric layers to net bending along the ray path (see Eq. 1). As discussed by Kursinski et al. (1997) for limb-sounding geometry appropriate to GPS RO, horizontal resolution may be defined by the distance traversed by the radio path as

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it enters and exits a layer having a vertical resolution of ΔZ. Then, the horizontal and vertical resolution are related by the approximate expression ΔL=2(2RΔZ)$^{1/2}$, where ΔL is the horizontal resolution, ΔZ is the vertical resolution, and R is the radius of the atmosphere at the ray path tangent height (Fig. 1). By using the geometrical optic approach the vertical resolution is limited by the diameter of the first Fresnel zone Z_F. In the absence of significant atmospheric bending (stratosphere) it is given for the ray path tangent level by Z_F=2(λD)$^{1/2}$, where λ is the GPS signal wavelength and D is the distance from the receiver (CHAMP) to the tangent point. With λ=19 cm and D=2600 km (orbit altitude at 500 km) results Z_F=1.4 km (ΔL about 270 km). Because of the exponential increase of the refractivity to the Earth's surface Z_F decreases to about 0.5 km (ΔL about 80 km). By consideration of diffraction effects and applying of radio holographic methods or wave optics (FSI; Jensen et al., 2003) the vertical resolution can be improved significantly (to about 50 m). In our current software version (005; Wickert et al., 2004) we have implemented both, the geometrical optics approach for heights above 15 km and the FSI method for heights below 10 km. In the transition zone from 10-15 km a combination of both is used. For data provision we interpolate all data between the lowest level and 35 km with a vertical resolution of 200 m.

The vertical resolution, especially with respect to tropopause studies, will be topic of further investigations. One objective of these investigations could be, e.g., how are the differences to the present LRT results if the FSI is applied for the complete altitude interval.

p.7842, line 4,5 - p.7842, line 19,20: we agree

p.7842, line - p.7843, line 18:

The question about the vertical resolution is answered above. In the revised version differences to ECMWF will be shown and discussed.

p.7843, line 5,6 and entire paragraph:

This paragraph will be removed and rewritten completely in the revised version.

p.7853, Fig. 5 and p.7854, Fig. 6:

Fig. 5 is removed in the revised version. The colour scale of Fig. 6 was selected according positive (red) and negative (blue) temperature deviations and will not be changed.

p.7843, line 24 - p.7844, line 2:

We do not understand this comment because this kind of plot is the first (of course here an update from Schmidt et al. (2004)) shown with CHAMP data for the considered time interval. On the other hand, one can simulate as match one wants, here are derived temperatures from real (!) CHAMP measurements are shown. The remark that "no interpolation is necessary" refers to the bins itself, so that no interpolation between neighbouring bins was necessary.

p.7844, line 6-18:

Yes, the same plot but only for the first 31 months (May 2001-November 2003) of CHAMP data is shown in the reference list (Schmidt et al. (2004)). In the revised version we present an updated plot extended to December 2004.

p.7844, line 22,23 - p.7845, line 12-19:

We followed the recommendation of Referee 2 and remove Section 4.

p.7845, line 22:

We do not agree with this comment. As already answered in the general comments (Paragraph 3 and 4) we compare our temperature results with independent radiosondes. These results serving as an argument for accuracy of the temperature data and retrieval methods, as also discussed, shown and published in various papers (see reference list).

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p.7846, line 2,3:

As already answered above in our current software version (005; Wickert et al., 2004) we have implemented both, the geometrical optics approach for altitudes above 15 km and the FSI method for altitudes below 10 km. In the transition zone from 10-15 km a combination of both is implemented.

It is true that the reduction of the refractivity bias (Fig. 3, left) in the lower troposphere was not demonstrated here. But only because we did not show a comparison of ECMWF refractivity and CHAMP refractivity by using the geometrical optics approach. This was shown in several other studies. With the geometrical optics approach the bias reaches in the Tropics about 5 percent below 2 km increasing up to about 7 percent in the last km. In the mid-latitudes about 1 percent deviation between CHAMP and ECMWF is reached (see Wickert et al. (2004)). The corresponding lower values of reduced refractivity can be clearly seen in Fig. 3 if the FSI method is applied.

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