Derivation of the Water Vapor Content from the GNSS Radio Occultation Observations

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Summary. The present work investigates the possibility of retrieving humidity profiles using the bending angle data obtained from GNSS Radio Occultations (Global Navigation Satellite System RO) without data constraint. In particular with the proposed approach, the dry pressure profiles are obtained by fitting the bending angles of the outer troposphere layers (from $h=h_{250K}$ up to the stratopause) using the Hopfield dry atmosphere model. In this model the ground pressure and temperature are the parameters to be estimated. The humidity profiles are extracted by subtracting the contribution due to the dry atmosphere from the measured bending angles. In the first part we discuss the mathematical approach adopted for the derivation of refractivity profiles without using the Abel inversion and water vapor directly from the bending angle. In the second part the results are shown from applying the method on CHAMP data. In particular, we have used refractivity profiles from CHAMP which were derived using a heuristic retrieval algorithm based on the canonical transform.

Key words: radio occultation, atmospheric remote sensing, water vapor profiles, inversion techniques, refractivity profiles

1 Introduction

The parameters of the neutral atmosphere (pressure "*P*", temperature "*T*" and water vapor pressure "P_{wet}") are retrieved from GNSS RO data, after having derived the refractivity from the bending angles, using two equations: the refractivity at microwave wavelengths according to Smith and Weintraub (1953) and the hydrostatic equilibrium law combined with the state equation of ideal gas (Kursinski et al. 2000). In the upper atmosphere water vapor is negligible, so two equations have just two unknowns, P and T: easy to solve for. The atmospheric quantities of interest can be obtained for the lower troposphere by integrating GNSS RO data with external information, e.g. from ECMWF or NCEP re-analysis. Thus, although GNSS RO is a very reliable technique for the measurement of neutral atmosphere key parameters, current retrieval methods for the water vapor content in the lower troposphere depend essentially on conventional observation systems (mainly RAOB, RAdiosonde OBservations). In previous works (Vespe et al. 2002, 2004a) a new method was described: the **B**oundary **P**rofiles e**V**aluation (BPV), which is able to derive tropospheric water vapor profiles using GNSS RO refractivities without additional external information. Efforts have been performed recently just to make the GNSS RO a standalone tool for water vapor retrieval (O' Sullivan et al. 2000; de la Torre and Nilsson 2003). A main drawback in the GNSS RO retrieval is the possible existence of horizontal gradients of the refractivity or non-spherical structure in the vicinity of the occultation location which could make the Abel inversion not fully accurate (Kursinski et al. 2000). For this reason it is preferable to work on the processing level of the bending angles; i.e. using the data on which the Abel inversion is not applied. Thus, we are going to describe the new release of the BPV in which the bending angles are used directly for the water vapor retrieval. The new BPV release implies also the reconstruction of the refractivity by applying a sort of variational technique. Thus the second non-negligible result is the possibility to derive refractivity in an alternative way to Abel inversion. The refractivity profiles obtained from CHAMP and GPS/MET data have a negative bias in relation to radiosonde and analysis data (e.g. Ao et al. 2003; Beyerle et al. 2004). We use two versions of CHAMP data products based on Geometrical Optics (GO): version 003 for Recife and Brest sites and 004 (Wickert et al. 2004). In addition we use preliminary results obtained applying a heuristic retrieval algorithm (CTss) based on Canonical Transform (CT) and the sliding spectral (ss) technique to reduce the refractivity bias (Beyerle et al. 2004; Wickert et al. 2004). The use of the wave optics based algorithms reduces the refractivity bias by a factor of ~2 in relation to the GO profiles. Such algorithms will be implemented to the operational CHAMP data analysis as of mid 2004 (product version 005). The new release of the BPV (Vespe et al. 2004b) was applied to the version 003 and 004 GO data, available online at GFZ web site (http://isdc.gfz-potsdam.de/champ/), as well as to the CTss results. Thus a comparison between the two sets of products is another outcome of the present paper.

2 Data Analysis

The refractivity N is defined as: $N = 10^6(n-1)$ with the refractive index n. For the neutral atmosphere N is the sum of a dry (N_{dry}) and a wet component (N_{wet}):

$$N(h) = N_{dry}(h) + N_{wet}(h) = \left[a_1 \frac{P_{dry}(h)}{T(h)} \right]_{N_{dry}} + \left| \frac{a_1 \cdot T(h) \cdot P_{wet}(h) + a_3 \cdot P_{wet}(h)}{T^2(h)} \right|_{N_{wet}} \tag{1}$$

where

N_{dry}	dry refractivity	P_{wet}	water vapor pressure (mb)
N_{wet}	wet refractivity	T	temperature (K)
h	height (km)	a_1	77.6 (K/mbar) ± 0.05
P	$P_{dry}+P_{wet}$ total pressure (mb)	a_3	$3.739 * 10^5$ (K^2/mbar) ± $0.012 * 10^5$

Assuming hydrostatic equilibrium and validity of the state equation of the ideal gas, together with Eq. 1 a system of two equations and three unknowns can be formed (T, P_{dry} and P_{wet}).

Since water vapor is negligible above the tropospheric height h_{250K}, P and T can be solved for considering only the dry component. Dry atmosphere approximation does not work in the lower troposphere, where water vapor pressure can be retrieved only if additional external data are available and assimilated as guess values in an iterative procedure. Such data are generally given by meteorological analyses carried out by the ECMWF and the NCEP.

In the first release of our approach (Vespe 2002; Vespe et al. 2004a) we adopted as dry refractivity the Hopfield model (Hf, Hopfield 1969) which relates the dry air refractivity to the fourth power of the height and to the surface values of pressure and temperature P_0 and T_0. We use the GNSS RO refractivity data of the atmospheric layers between the stratopause and the height, where T=250 K, through which the water vapor content can be considered negligible, for performing the fit. In this fit the surface pressure and temperature of the dry air refractivity (Hf) is estimated. Hf is extrapolated down to the ground with the assumption that the difference of the extrapolated and the observed GNSS RO refractivity is due to the wet part of the atmosphere. Finally Eq. 1 is applied to retrieve the wet pressure. The enhanced BPV is suitable to be applied directly to the bending angles (BA). The necessary steps to derive the water vapor partial pressure profile using the GNSS RO BA data are described in detail by Vespe et al. (2004b). They are briefly summarized here:

1. Fit the BA above h_{250K} up to the stratopause retrieved by GNSS RO.
2. From the estimated parameters T_0 and P_0 the dry BA is computed down to the ground by extrapolating the Hf model. In Fig. 1 the measured and dry BA are compared for selected sites.
3. A Taylor expansion is applied to the BA just to built refractivity profiles using the dry Hf as starting profile. The difference between total and dry refractivity gives the wet contribution as in (1).
4. When the refractivity is built, the first release of the BPV method is applied for the water vapor retrieval (Vespe et al. 2004a). Results are shown in Fig. 3.

3 Results and Discussion

The method proposed seems to be a promising alternative to the Abel inversion for retrieving refractivity profiles from the BA. The advantages of our approach is evident in the plots of Fig. 2. The profiles retrieved with the described technique are systematically very close to the RAOB data. In the previous work (Vespe et al. 2004b) the refractivity profiles seemed to be slightly positively biased if compared with CHAMP GO data for occultations reaching the Earth's surface.

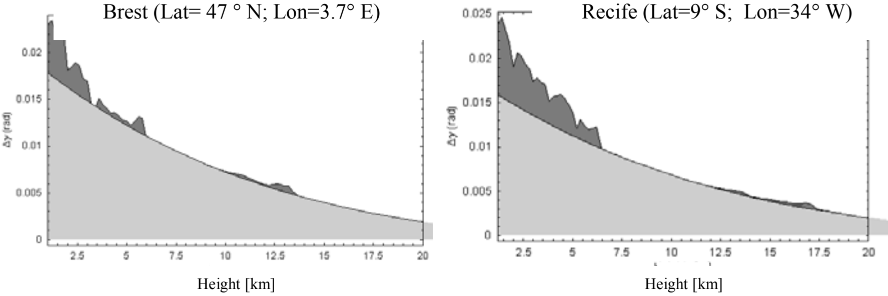

Fig. 1. The plots show the results of the fits of the BA with the dry Hf model (light gray). The differences with the measured BA (dark gray) are supposed to be due to atmospheric water vapor content. The equatorial site (Recife, right plot), as expected, show a larger difference than the European site.

Such positive bias not only vanishes with the new CHAMP data (CTss), their agreement is so close that they are practically identical (Fig. 2). We relate this to the CTss algorithms introduced, as described by Beyerle et al. (2004). The discrepancies of the refractivity with RAOB data were really huge for MANGALORE (Vespe et al. 2004b). The use of the CTss profiles has completely diminished these differences. Furthermore some humps, evident in the RAOB refractivity profile, were clearly detected by BPV (Recife profiles) using the GO based CHAMP data. Such humps are detected now also by using the new products. The main drawback of the GO profiles is the cut off when the refractivity deviates by more than 10% from ECMWF for quality check reasons (Wickert et al. 2004). The application of this criterion sometimes seems to be not wise because we have experienced, on the contrary, a good agreement of the cut GNSS RO data with RAOB observations. Combined with the BPV method these data can help to detect local atmospheric structures. In the Recife refractivity profile for example (see Fig. 2) the agreement with RAOB data is good also with GO data down to the ground (Vespe et al. 2004b). So it would be preferable to introduce only a warning flag. These preliminary results seem to confirm that the BPV applied to the BA could in part overcome the severe problem of the negative refractivity bias over the equatorial regions as previously announced (Vespe et al. 2003). We would emphasize that such comments are only weak suppositions for the small number of analysed profiles. A more extensive statistical investigation is planned to confirm them. The water vapor retrievals are shown in Fig. 3. Our results after applying the BPV on the CTss CHAMP data do not confirm the previous ones (Vespe et al. 2004b). The BPV applied to the GO profiles results in an overestimation of the water vapor content. The results in Fig. 3 on the contrary outline an underestimate. Such discrepancy must be carefully analyzed because it can be due to the efficiency of our approach in detecting irregularities and super-refractivity events but also on account of some inaccuracies in it. The reconstruction of the

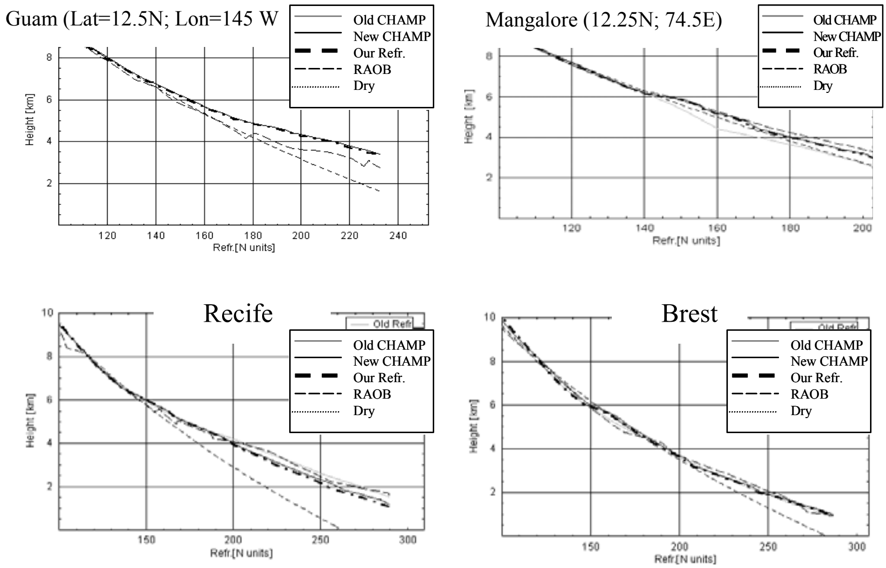

Fig. 2. The figures show the refractivity obtained applying our approach (dash-dot thick line) and compared with RAOB (dash line), CHAMP CTss data (black line), CHAMP GO (old 003 gray line, new 004 black) and dry model (small dashed).

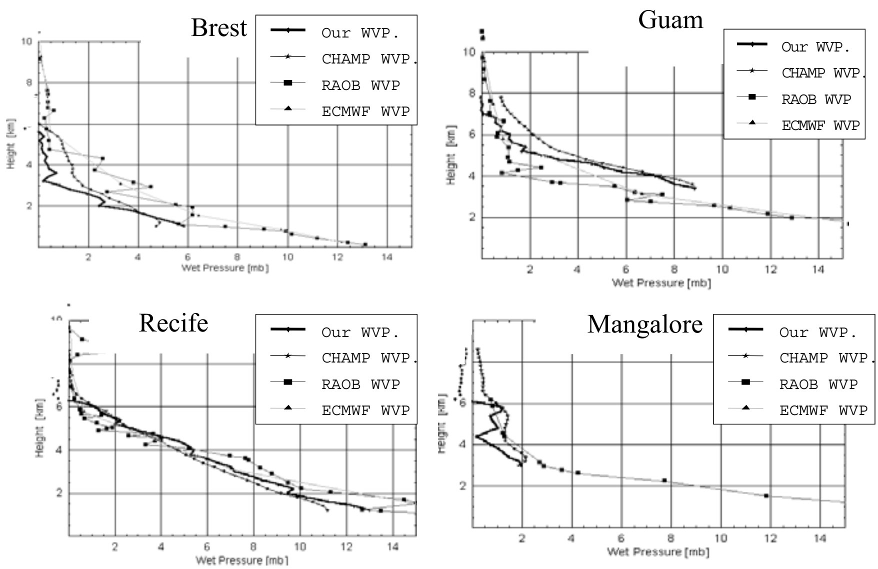

Fig. 3. The water vapor profiles retrieved by using the BPV approach, compared with CTss CHAMP, ECMWF and RAOB data.

temperature profiles in the lower atmosphere is one of the pending solution in the proposed procedure. The linear interpolation of the temperatures between the surface values as given by the Hf model (h=0) and the height where T_{dry} is <250 K, sounds not so rigorous. It is worthwhile to be investigated if our approach improves its performance in case of applying the same algorithms described by O'Sullivan et al. (2000). The extension of the BPV method to the BA has confirmed the promising results achieved in previous studies on refractivity (Vespe et al. 2002 and 2004a).
The results of the present work, together with efforts of other groups (O'Sullivan et al. 2000; de la Torre and Nilson 2003), are encouraging to make the GNSS RO a standalone technique for supporting weather forecasts and climate research.

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