Remote Sensing of the Earth's Atmosphere by Radio Occultations for Numerical Weather Prediction

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Abstract. Radio occultations (RO) are a very promising technique for sounding the Earth's atmosphere. The physical principle of RO consists in the retrieval of atmospheric temperature, pressure, and humidity from measurements of GPS radio signals received by a space-borne instrument located on a low-Earth orbiter. Currently, CHAllenging Minisatellite Payload (CHAMP), launched in 2000, provides about 200 globally-distributed ROs per day. The data are operationally processed using the computation facilities of Max-Planck Institute for Meteorology (Hamburg). The processing software incorporates the most efficient mathematical solutions as well as the advanced data quality control and filtering scheme. This allows for extracting maximum information from the data and sorting out corrupted data sets. We present a statistical comparison of the inversions of CHAMP data with the re-analyses of German Weather Service (Deutscher Wetterdienst - DWD).

Keywords: Radio occultations, CHAMP.

1. INTRODUCTION

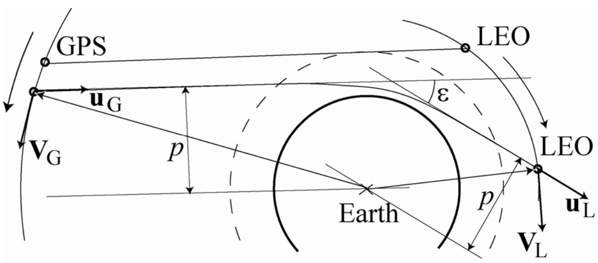


Figure 1. Layout of radio occultation geometry.

Radio occultations (RO) are a very promising technique for sounding the Earth's atmosphere. It has the following advantages: 1) minimum calibrations of the instrument, 2) all-weather capability, 3) a high vertical resolution of 100 m, or better, 4) global coverage, and 5) a small size, weight, and cost of the instrument. The physical principle of RO consists in the retrieval of atmospheric temperature, pressure, and humidity from measurements of GPS radio signals received by a space-borne instrument located on a low-Earth orbiter. Currently, CHAllenging Minisatellite Payload (CHAMP), launched in 2000, provides about 200 globally-distributed ROs per day (Wickert et al., 2001). The data are operationally processed using the computation facilities of Max-Planck Institute for Meteorology (Hamburg).

During a RO experiment, the GPS and LEO satellites move in such a way that the radio ray connecting them, immerses into the atmosphere (Figure 1) (Ware et al., 1996; Hajj et al., 2002). The experiment begins with the line-of-sight height of 70–120 km and it continues until the ray is obscured by the Earth or the signal track is lost. GPS system has two frequency channels: L1 – 1.57542 GHz and L2 – 1.22760 GHz, which are used in order to correct for the ionospheric effect using the fact that ionospheric refractivity is frequency-dependent, while real refractivity is not (Ladreiter and Kirchengast, 1996; Gorbunov, 2002). The two received radio signals are demodulated by numerical data processing, in order to remove the pseudo-random modulation and to subtract the reference phase variation. This allows for compressing the signal spectrum and reducing the sampling rate down to 50 Hz. The amplitude and phase of the demodulated signals are downloaded to ground-based stations, where the data are accumulated and transferred to data processing centers, such as GeoForschungsZentrum in Potsdam, Germany. RO data are distributed world-wide in order to be used for numerical weather prediction and climate monitoring.

In this paper we describe the algorithms and results of the processing of CHAMP data. The algorithms are the core of the data processing and assimilation system implemented at Max-Planck Institute for Meteorology in Hamburg and DWD.

2. DATA PROCESSING

Data processing consists of the following steps: 1) the derivation of vertical profiles of bending angle ε as a function of ray impact parameter p from the RO data. 2) the derivation of vertical profiles of atmospheric refractivity from bending angles $\varepsilon(p)$, and 3) the retrieval of atmospheric parameters from refractivities using the hydrostatic equation (Ware et al., 1996; Hajj et al., 2002).

Before processing, the measurements need filtering to suppress noise and reject fragments corrupted due to the loss of signal track. The L2 channel is most susceptible to these errors. We perform the radioholographic filtering. The signal is multiplied with a reference signal, in order to compress the signal spectrum, and Fourier-transformed in small sliding apertures. The widths of the running spectra for L2 channel and the difference of the spectra for L1 and L2 are used for the computation of the weighting function of L2 data. Filtered L2 data are defined as a linear combination of

L1 data, L2 data, and the estimated ionospheric term, the coefficients being defined by the weighting function. This discriminates L2 data with degraded quality.

Bending angles are derived from filtered RO data by the advanced algorithms employing the technique of Fourier Integral Operators (Gorbunov and Lauritsen, 2004). The errors of bending angles are estimated using the radio holographic analysis, as a width of the running spectra. Bending angle errors define the errors of the retrieved temperatures.

3. RESULTS

Figure 2 and Figure 3 exemplify the processing of two radio occultations indicating different sort of large errors in the L2 channel. The running spectra are plotted in pseudocolor. Time and frequency are transformed to bending angle and impact parameter because each pair (time, frequency) corresponds to some observation point and ray direction, which defines bending angle and ray impact parameter. In the first example, the L2 signal is lost at a ray height of 7 km and the L2-spectrum indicates big deviations from the L1-spectrum. In the second example, the L2-signal is very noisy, and the L2-spectrum is much wider than the L1-spectrum. We compare the retrieved temperatures and the temperatures from the analysis of the German Weather Service (Deutscher Wetterdienst – DWD). Both temperatures are accompanied with their rms error bars, σ_{CHAMP} and σ_{DWD}. In these examples, the difference between CHAMP and DWD data is in a good agreement with the error estimates σ_{CHAMP} and σ_{DWD}. Figure 4 shows an example of a radio occultation, where the L2 channel indicates a good quality of data. Here, the L2-spectrum is only slightly wider than the L1-spectrum.

Figure 5 presents a statistical comparison of CHAMP and DWD data on the basis of 90 ROs observed on January 18, 2004. The left panel of the Figure presents the average and rms CHAMP–DWD difference of temperatures, ΔT and σ, respectively. The right panel shows the comparison of the error estimations σ_{CHAMP} and σ_{DWD} averaged over all the occultations, and the rms difference σ. The error estimations are consistent with the observed CHAMP–DWD deviations, except σ_{DWD} being slightly overestimated in height regions 8–15 km and above 25 km.

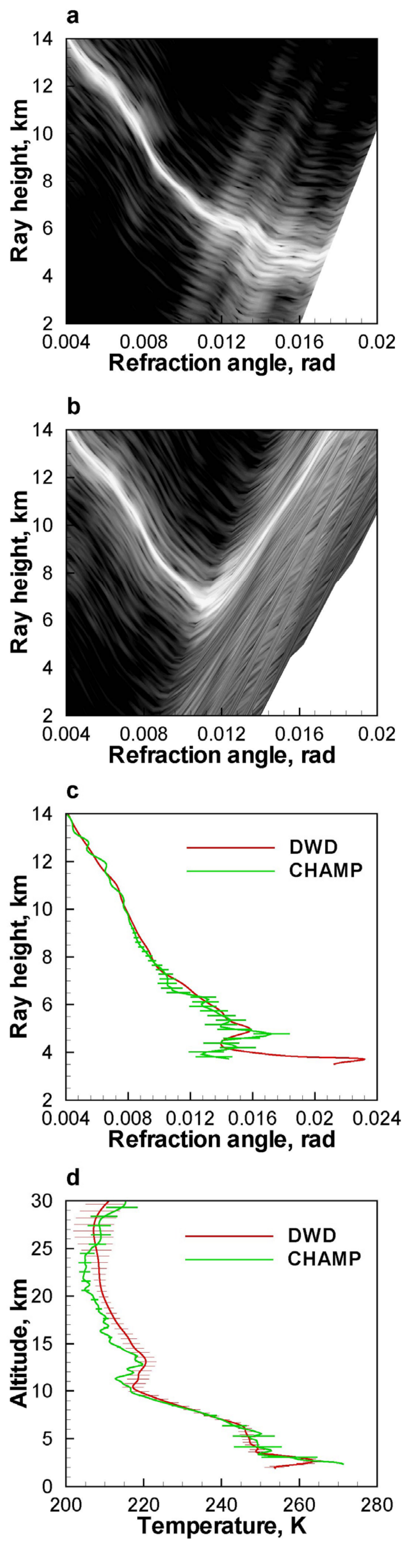


Figure 2. Radio occultation 0004, January 18, 2004, 00:24, 50.4ºN 116.1ºW: a) running spectra for L1, b) running spectra for L2, c) bending angles computed for the DWD analysis and from the CHAMP data, d) temperatures from the DWD analysis and from the CHAMP data.

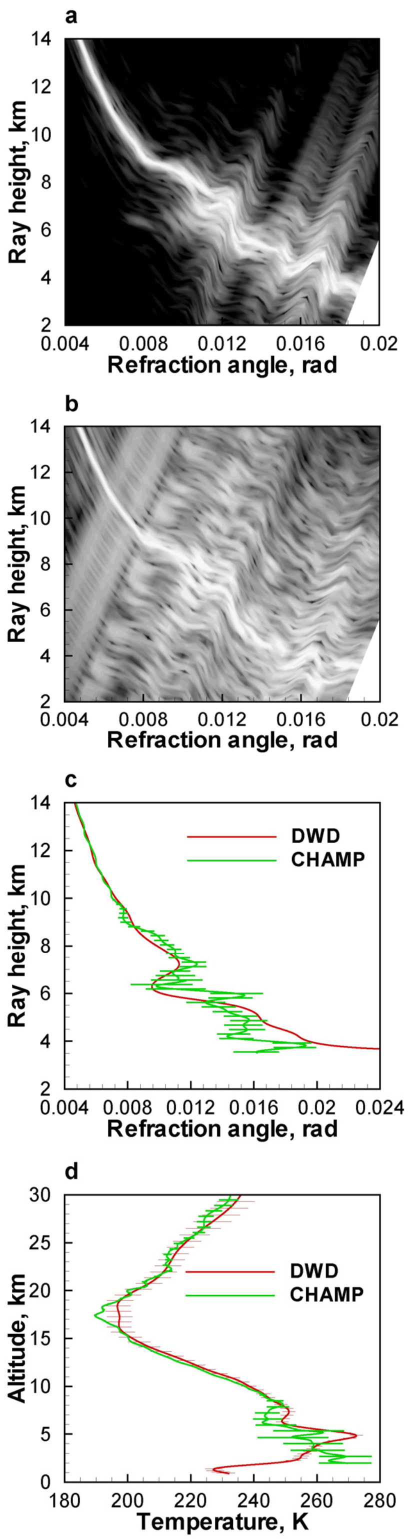


Figure 3. Radio occultation 0041, January 18, 2004, 04:09, 26.0ºS 19.4ºE (below): a) running spectra for L1, b) running spectra for L2, c) bending angles computed for the DWD analysis and from the CHAMP data, d) temperatures from the DWD analysis and from the CHAMP data.

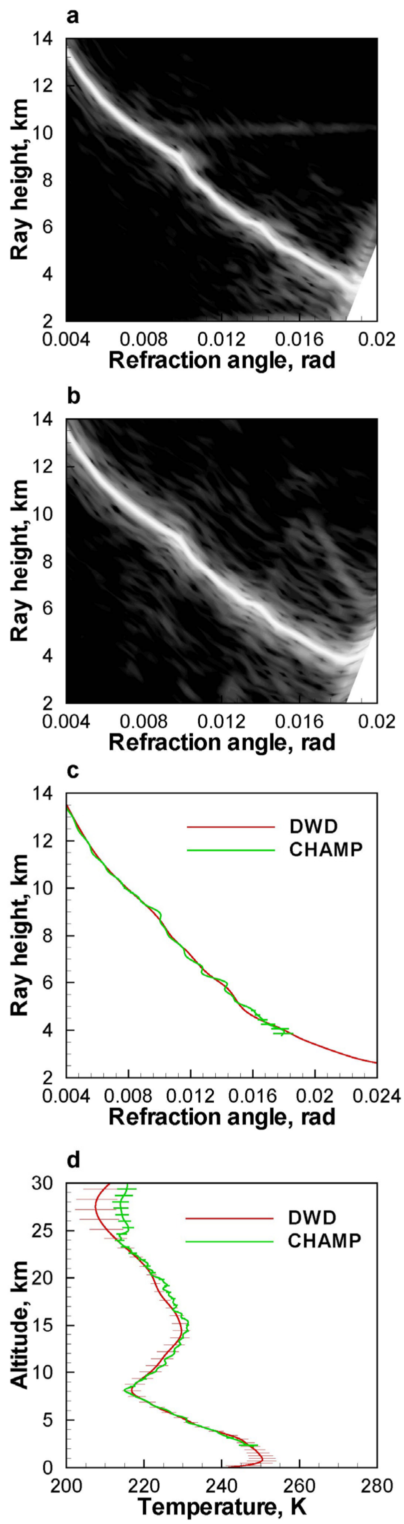
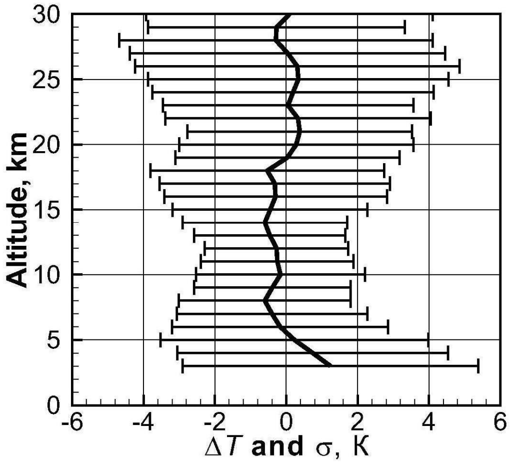


Figure 4. Radio occultations 0097, January 18, 2004, 00:24, 50.4ºN 116.1ºW and 0041, January 18, 2004, 78.8ºN 125.6ºW: a) running spectra for L1, b) running spectra for L2, c) bending angles computed for the DWD analysis and from the CHAMP data, d) temperatures from the DWD analysis and from the CHAMP data.



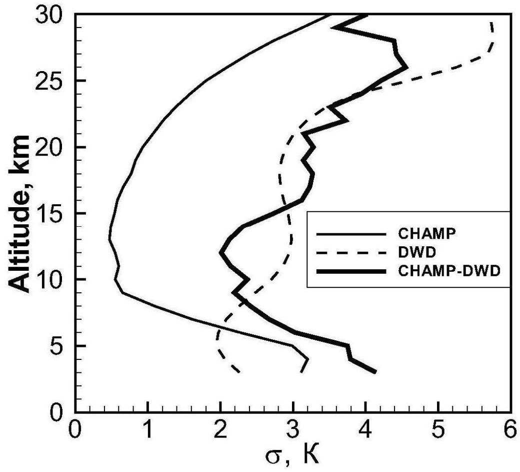


Figure 5. Left: statistical comparison of CHAMP and DWD temperatures on the material of radio occultations observed on January 18, 2004: average and rms difference. Right: average error estimations σ_{CHAMP} and σ_{DWD}, and rms CHAMP–DWD difference σ.

4. CONCLUSION

The data processing algorithms are at present time applied to the real-time processing of CHAMP data. The filtering of corrupted and noisy data makes the algorithms robust. The error estimation is performed on the basis of the data analysis for each occultation individually, with minimum a priori assumptions. Our statistical analysis indicates that the error estimates of the CHAMP and DWD data are consistent with the observed CHAMP–DWD difference. This makes this data processing scheme especially valuable for the applications for the assimilation of RO data into numerical weather prediction models.

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6. ACKNOWLEDGEMENTS

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