Review of JGR paper, Manuscript Number: amt-2010-201

Response to the comments of Reviewer #2

We thank the reviewer for the constructive review and the important points raised. We took into account all the comments and revised the manuscript accordingly. Please see our detailed response below.

General remark:

Table 1 (giving the values of the error model parameters) distinguishes between the two RO processing systems WEGC and UCAR. This distinction is sensible, since RO processing algorithms introduce additional parameters (e.g. order/degree of the Doppler filter, cut-off altitudes, background models, etc.) whose values may affect standard deviations (and possibly biases) of the derived profiles. I would think, however, that a similar distinction should be made between CHAMP/GRACE and COSMIC data, since the occultation antenna's gain function constitutes a significant part of the instrumental effects. CHAMP and GRACE were/are equipped with (to the best of my knowledge) identical helix-type antennas to record the occultation signals; COSMIC, on the other hand, uses more advanced multi-element path antennas. As a consequence, COSMIC's signal-to-noise ratios at large occultation azimuth angles are significantly higher than those from CHAMP and GRACE and I would expect that an error analysis, performed separately for CHAMP/GRACE and COSMIC, yields statistically significant differences. I suggest to add a comment in section 3 justifying the approach selected by the authors, i.e. the combination of CHAMP/GRACE and COSMIC observations within the same (WEGC) data set ignoring the instrumental differences.

Data quality is not only affected by the antenna quality but also by the clock quality (while GRACE-A has an ultra-stable oscillator, which allows to perform zero differencing, CHAMP and F3C clocks are less stable, which requires single differencing to remove clock errors), and tracking mode (CHAMP and GRACE-A receivers operate in closed-loop mode, optionally with fly-wheeling in the lower to mid troposphere, F3C receivers operate in open-loop mode in the lower troposphere).

Bending angle noise at high altitudes is an indicator of receiver quality. Pirscher (2010) and Foelsche et al. (2011) compared bending angle noise of different satellites between 65 km and 80 km and found that CHAMP bending angle noise is about 1.5 to 2 times as large as GRACE and COSMIC bending angle noise.

In Fig. 1 we show that error characteristics of CHAMP, GRACE, and COSMIC atmospheric profiles are very similar. Largest differences are observed in raw bending angle above 35 km. Above about 42 km CHAMP raw bending angle observational error exceeds that of the other satellites by 1 %, which mainly derives from the larger bending angle noise observed in CHAMP data.

The top panels of the new Fig. 7 of the revised document show error characteristics for UCAR raw bending angle, optimized bending angle, and refractivity up to 50 km. The two slightly separated yellow lines in each panel show CHAMP and GRACE-A combined errors, which are somewhat larger than F3C combined errors. Differences between the satellites are again most pronounced in raw bending angle. It is noticeable that above 35 km, observational error differences decrease in optimized bending angle and refractivity, which is caused by the use of background information for bending angle initialization.

Fig. 3 shows CHAMP, GRACE-A, and F3C data characteristics at UCAR and WEGC. It is noticeable that differences between different satellites are small compared to retrieval differences and because of that we decided not to model CHAMP/GRACE-A and F3C separately.

We address this matter now and added the following statements in the revised manuscript text, in the abstract:

Above 35 km the increase of the CHAMP raw bending angle observational error is more pronounced than that of GRACE-A and F3C leading to a larger observational error of about 1 % at 42 km.

page 11, section 3.1:

Above about 42 km CHAMP raw bending angle observational error exceeds that of the other satellites by 1 %. This mainly derives from the larger bending angle noise observed in CHAMP data (Pirscher 2010; Foelsche et al. 2011).

page 15, section 3.3:

In the upper troposphere and lower stratosphere CHAMP and GRACE-A observational errors are slightly larger than F3C observational errors but differences rarely exceed 0.1 %.

and page 22, section 4:

Above about 35 km the CHAMP raw bending angle observational error increases stronger than that of GRACE-A and F3C. The difference exceeds 1 % above 42 km. Due to bending angle initialization at high altitudes, differences between the satellites above 35 km are smaller for other atmospheric parameters.

Minor comments

- *Page 2600, abstract, page 2601, introduction, and page 2617, summary: The abbreviation 'RO' is defined twice in the abstract (page 2600, lines 2 and 4), the introduction (page 2601, line 2), and the summary (page 2617, lines 18/19)*

  Thanks for pointing at the fact that we abbreviated RO twice in the abstract. We removed the second definition. However, since the abstract, the main body of the text, and the summary should be readable stand-alone, we decided to define abbreviations in each of these sections.

- *Page 2613, line 4 and page 2614, line 16: Typo: "Figure 4 shows UCAR (top two rows) and WEGC (bottom two rows) refractivity error estimates [...]". In my copy of the paper figure 4 consists of just a single plot. I assume the sentence quoted refers to figure 5 instead. Likewise, "Fig. 4" in line 16, page 2614 should read "Fig. 5".*

Yes thanks, these sentences refer to Figure 5. We changed the manuscript accordingly.

- *Page 2618, line 6ff: Since WEGC uses ECMWF forecasts for bending angle initialization, I'd expect to see reduced biases and standard deviations in the bending angle data at higher altitudes. Therefore, I suggest to extend the altitude range of the bending angle error analyses beyond 35 km, to, e.g., 50 km or 60 km (figure 1, figures 2, 3, and 7, top panels).*

  We followed this suggestion, also raised by the other reviewer, and provide information on error characteristics of bending angle and refractivity up to 50 km including also information on error correlations. Since the WEGC profiles are not operationally available above 35 km, we restrict this analysis to UCAR data but note that the error correlation model is applicable to WEGC data over their domain as well.

  To show error characteristics above 35 km, we substituted WEGC optimized bending angle error characteristics of different satellites, shown in Figure 1, for UCAR raw bending angle error characteristics and show this plot up to 50 km. Furthermore, we added one Figure, which shows error characteristics and error correlation functions and their models for raw bending angle, optimized bending angle, and refractivity up to 50 km (new Figure 7 in the revised document, Figure 1 here).

  In the manuscript we added the following paragraphs in Sect. 3.4:

  The error model is applicable up to 50 km for raw bending angle, optimized bending angle, and refractivity (up to 35 km for the other parameters). In addition, information on the error correlation structure is provided for these variables, for construction of error covariance matrices and their use, e.g., in NWP assimilation systems. Figure 7 shows global error estimates, error correlation functions and their models for UCAR raw and optimized bending angles, as well as refractivity up to 50 km.

  The impact of statistical optimization can clearly be seen comparing raw and optimized bending angle (Fig. 7, top panels). While the raw bending angle observational error exceeds 8 % near 45 km, the observational errors of the statistically optimized bending angle and of refractivity remain smaller than 4 % up to 50 km (larger errors can occur in the lower troposphere). To account for the impact of background information at high altitudes, the observational error model for the optimized bending angle uses a lower z_{bot} and a larger H_{S0} and ΔH_{S}.
  The bottom panels of Fig. 7 show the empirical and modeled error correlation functions. Very good agreement with the results obtained by Steiner and Kirchengast (2005) is given and we follow their approach to model error correlations for raw bending angle by using a Mexican Hat function of the form

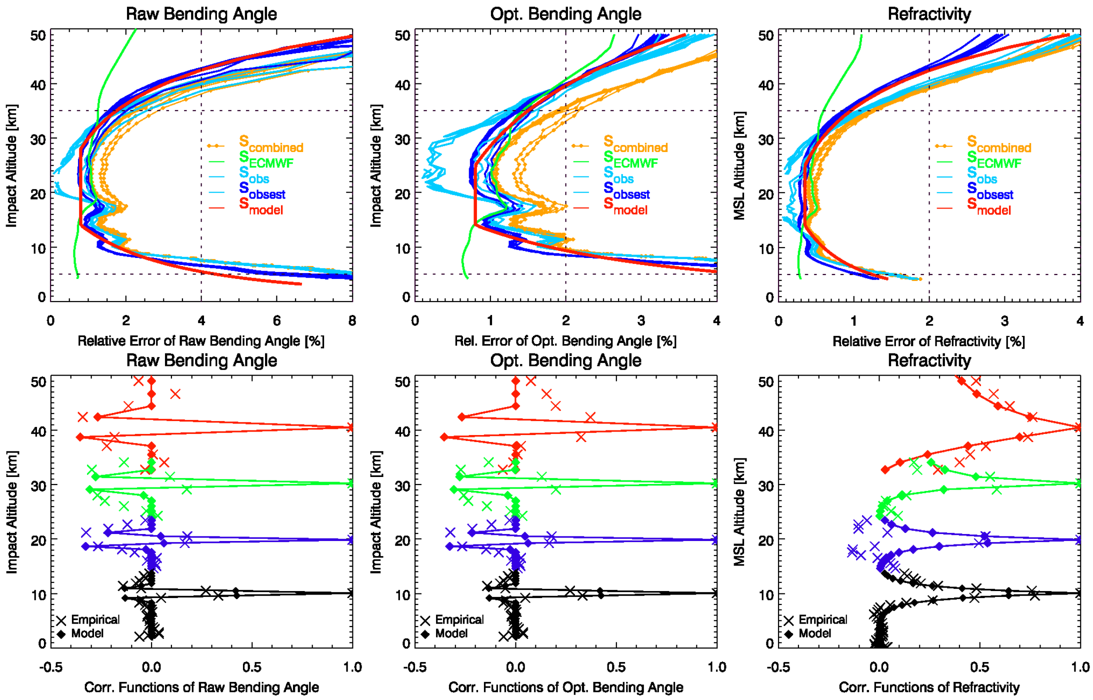

Figure 1: UCAR global error estimates (top) and error correlation functions (bottom) in July 2008 for raw and optimized bending angle as well as for refractivity up to 50 km. Empirical (x-symbols) and modeled (connected diamonds) correlation functions are shown based on GRACE-A data for four representative altitude levels from 10 km to 40 km.

$$\mathbf{S} = S_{ij} = s_i s_j \cdot \left(1 - \frac{(z_i - z_j)^2}{(c \cdot L)^2}\right) \cdot \tilde{f}, \tag{1}$$

where $\mathbf{S}$ is the error covariance matrix with elements S_{ij}, s_i and s_j are the standard deviations at height levels z_i and z_j, respectively, c is a stretching factor, and $L = L(z)$ the height dependent correlation length. The function $\tilde{f}$, representing the Gaussian exponential factor in the Mexican Hat function, is modeled for robust invertability of $\mathbf{S}$ after Gaspari and Cohn (1999) as formulated in detail by Steiner and Kirchengast (2005).

We choose c to be $c = 1.0$ below 14 km (hardly any overshooting of error correlations that allows error correlation values to be negative), linearly decreasing to $c = 0.8$ at 50 km (stronger overshooting). The correlation length L was estimated to be 1.5 km at 50 km, linearly decreasing to 0.7 km at 14 km and kept at this value downwards. The error correlation model obtained from raw bending angle data is also plotted for cross-check for the statistically optimized bending angle, which is generally not used for assimilation. The model almost perfectly fits also these data up to the 30 km level below which background information is negligible, but above the influence of background information becomes noticeable through a much larger error correlation length and no overshooting. Error correlations at these altitude levels would require a different model such as, e.g., applied for refractivity.

Refractivity error correlations are modeled after Steiner et al. (2006) using an exponential function of the form

$$\mathbf{S} = S_{ij} = s_i s_j \cdot \exp\left(-\frac{|z_i - z_j|}{L(z)}\right), \tag{2}$$

where the correlation length $L(z)$ was estimated to be 1 km up to 30 km altitude and then linearly increasing to $L = 10$ km at 50 km. This increase accounts for an increasingly larger amount of background information at higher altitudes.
The error correlation functions are also usable for the WEGC data over their domain of availability up to 35 km.

- *Page : Page 2628, figure 3: The fractional refractivity errors (between about 15 km and 35 km) shown in figure 3 differ significantly from the ones shown in Schreiner et al. (2009) (DOI 10.1007/s10291-009-0132-5), figure 5. Please comment.*

Refractivity errors shown in Fig. 3 of our manuscript and Fig. 5 of Schreiner et al. (2009) are in very good agreement in terms of standard deviation (please note that Schreiner et al. (2009) show fractional errors, while we give errors in percent). The standard deviation is about 0.5 % (0.005) in the altitude range of 15 km to 25 km. Above it increases to 1 % (0.01) at 35 km and below to 1.5 % (0.015). However, vertical profiles of systematic differences of refractivity to ECMWF indeed show slightly different characteristics. This difference is to a main part caused by an older COSMIC data version used by Schreiner et al. (2009). They used data processed with retrieval version 2007.3200. Data of that data version were affected by a positive bias in the retrieved bending angles on the order of 0.1 % to 0.2 % above 10 km to 20 km (CDAAC Team 2010), which also affected refractivity and other atmospheric profiles.

A small difference may also be caused by colocated profiles drawn from ECMWF analyses fields at different resolution. While Schreiner et al. (2009) used ECMWF fields at fine horizontal resolution (T799), we used ECMWF profiles with reduced horizontal resolution (T42), approximately which matches the resolution of RO. Furthermore, it is possible that interpolation routines, used to extract co-located profiles, induce small systematic differences. Indeed, comparison between co-located ECMWF refractivity profiles provided by WEGC and UCAR revealed a small systematic difference of the order of 0.1 %, which is nearly constant with height. Future (already started) work on investigating such subtle differences will further increase our understanding of them and also reduce them.

- *Figs. 3, 5, and 7 are quite hard to read (at least for eyes my age). I suggest to increase their size.*

  The figures will be increased in the final AMT format.

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