Interactive comment on “Validation of refractivity profiles derived from GRAS raw-sampling data” by F. Zus et al.

We thank the reviewer for her/his comments and suggestions. Below we answer the reviewer's questions and describe proposed changes in a revised version of the manuscript (italic).

Review of the paper "Validation of refractivity profiles derived from GRAS raw sampling data" by F. Zus, G. Beyerle, S. Heise, T. Schmidt, J. Wickert, and C. Marquardt.

The paper describes the GRAS RO data inversion process developed at GFZ and presents statistical comparisons of the results with the ECMWF model. Because the GRAS receiver data is more complicated than that of other GPS RO receivers, discussions of the inversion process and results obtained by various authors and groups are important. Generally the paper is well written, and I recommend publication. However, before that occurs, I would like the authors to include more specific details about their processing and to respond to some questions. The comments follow (ref. to page number, line number).

Main comments:

(1829,23-1830,1) Please explain what are the "Internal navigation data bits, contained in EUMETSAT NetCDF file"; how are they obtained?

We will include the following explanation on page 1830, line 1: “Internal navigation data bits are obtained as follows: With the RS tracking at 1 kHz it is possible to find the navigation bits on the carrier phase measurement by analysing 20 sample points (the navigation message is at 50 Hz) centred around the known position of the navigation bit. Two phase reconstruction are generated, one as recorded by the receiver, and one with a navigation bit (phase shift) included. An internal navigation bit is identified if the phase reconstruction with phase shift is smoother around the 20 sample points centre position.“

(1830,1-3) Why and how is the CL data processed in the same way as the RS data?

We experimented with two options. Option 1: We assume that, if both the CL NCO phase and the CL in-/quadrature-phase correlation sum samples are provided, the total phase can be reconstructed following Eq.1-3. This is the option we used in the manuscript. Option 2: In CL mode we do not account for the residual phase; in CL mode the PLL (Phase-Locked Loop) steeres the residual phase towards zero, thus, the total phase does not deviate significantly from the NCO phase. At the bottom/top of a setting/rising occultation CL data is replaced by RS data anyway.

Does the GRAS receiver provide the NCO phase model on output? If not, what model is used to down-convert the CL signal in order to apply eq.(2)?

Yes, the NCO phase model is provided.

Re-connecting the CL phase, which already has been connected in the receiver, by eqs. (2,3) can only result in the difference of an integer number of cycles. Have you observed cycle slips in L1 CL phase from the GRAS receiver?

A possible way to detect L1CA-cycleslips is to compare the sign of CL-inphase data and the navigation data bits from our data base. We tried this for one day (doy: 280, year: 2007) and found large (~40%) deviations, i.e. a large number of cycleslips.

What sense does the demodulation (1829,17) have for CL data, once the data modulation has already been removed by the 2-quadrant phase extractor in the receiver?

If one wants to account for the CL residual phase, the demodulation is recommended.

Do you additionally check the CL phase for demodulation errors (half-cycles)? Have you observed half-cycle slips in the L1 CL phase from the GRAS receiver?

As mentioned previously, a possible way to detect cycle slips is to compare the sign of CL-inphase data and the navigation data bits. However, yet we are not sure how to repair half-cycle slips.

(1830,5) "We select the longest contiguous CL and RS record" (also (1833,4-5)). I don't understand this criterion. For any occultation there is either one (no gap between CL and RS) or no (gap between CL and RS) such record. Thus the "longest" is not relevant: there is no choice. However, there may be no gap between CL and RS, but gaps immediately above and below, so the contiguous CL+RS record may be very short and not useful for processing. It seems to me that the authors must have applied a criterion based on the length of contiguous and continuous (no gaps) record. This must be disclosed and explained.

The referee comment is correct. Our description is somewhat unclear. We will provide the following description of our processing on page 1830, line 4: "The phase of the L1 signal is assembled from CL data recorded at 50 Hz and RS data recorded at 1 kHz. No attempt is made to fill data gaps present in the CL and RS data. We select the longest continuous CL record and the longest continuous RS record. In this selection preference is given to RS data in the CL/RS overlap region. If there is a gap between the selected CL and RS record the occultation event is rejected from further processing. If there is no gap between the selected CL and RS record we continue to process the occultation event. The phase of the assembled L1 signal is in general not continuous, i.e. the contiguous CL and RS records deviate by a (constant) phase-offset. This phase-offset is determined from data in the CL/RS overlap region. The resulting continuous L1 signal is downsampled to 50 Hz. The phase of the L2 signal is solely available from CL data recorded at 50 Hz.The phase data are corrected for relativistic effects and a zero differencing scheme is applied to retrieve L1/L2 atmospheric excess phase paths (Beyerle et al., 2005)."

(1830,22-23) The authors refer to (Healy, 2001) where the statistical optimization is generalized by accounting for vertical error correlations, while eq.(4) is for the special case of zero correlations. This must be explicitly stated in discussion of eq.(4) (1831,1-8).

We will add the following sentence on page 1831, line 4: "The statistical optimization according to Eq. 4, does not take into account vertical error correlations, i.e. the backround and observation error covariance matrices are assumed to be diagonal matrices."

(1831,18) "The RO signal in time domain is not truncated..." This must be revised as later (1836,15-24) the authors do apply the truncation in excess to that already done by the GRAS receiver.

On page 1831, line 18, we will simply state that: "The RO signal in the time domain is not subject to any filtering."

(1831,22) It is necessary to add "smoothed" to the "FSI amplitude" (truncation using raw FSI amplitude unlikely makes sense).

This is correct, the raw FSI amplitude is smoothed prior to the truncation. On page 1831, line 22, we will state that: "The bending angle profiles are truncated at that impact parameter value where the smoothed FSI amplitude drops below 50% of the maximum value."

(1832,1-11) Somewhere in sections 2.2.3 or 2.3, determination of the latitudes and longitudes from RO (for interpolation of the ECMWF grid data) must be included.

In section 2.2.3 we will include the following sentence: "The occultation point, the point on Earth's surface to which the retrieved refractivity profile is assigned, is estimated under the tangent point where the GPS-LEO line-of-sight altitude equals 10km."

(1832,14) What does the "examination of CL and RS data gaps" mean: only their identification for the purpose of data truncation (see comment to 1830,5 above) or something else?

The referee comment is correct. We do not 'examine' CL and RS data gaps, we identify data gaps to reject occultation events. Please, also see the following comment.

(1832,15) What does the "if needed" rejection mean?

Occultation events are rejected if there is a gap between the selected CL and RS record (see section 2.1), the ratio of L1/L2 excess phase path forward differences do not meet the criteria proposed by Beyerle et al. 2004, JGR, and the retrieved bending angle profile does not cover the altitude range 10-40km. The section 2.4 (Quality Control) will be written as follows: "Quality Control (QC) is applied at different stages of the processing. The early stage QC is applied at Level 1 and Level 2 and identifies CL and RS data gaps, examines the CL/RS overlap, SNRs, and L1/L2 excess phase path ratios. Specifically, occultation events are rejected if there is a gap between the selected CL and RS record (see section 2.1), the ratio of L1/L2 excess phase path forward differences do not meet the criteria proposed by Beyerle et al. (2004) (excess phase path forward differences are analyzed in the ionospheric calibration procedure) and the retrieved bending angle profile does not cover the altitude range 10-40 km. The final stage QC compares the retrieved refractivity profiles to the ECMWF refractivity profiles. Profiles where the fractional refractivity deviation exceeds ±10% at any altitude between 5 km and 30 km are rejected. No final stage QC is applied for altitudes <5 km."

(1833,5-6) It is said that CL data gaps are not filled; what about RS data gaps? Also, see related comments to (1830,5) and (1832,14).

RS data gaps are not filled. We will include the following sentence on page 1833, line 4: "Since our retrieval algorithm relies on the longest continuous CL record and the longest continuous RS record, and gaps between the selected CL and RS records are not filled (see section 2.1), a large number of rising occultation events are rejected by our QC."

(1834,17-18) "...compared to RO data recorded in CL mode, RO data recorded in RS mode strongly improves the ability to probe deep into the lower troposphere". Generally, I would agree with this statement, but there is no supporting comparison in the paper. If the authors have made such comparison, it would be sufficient to present comparative numbers (e.g. 50% penetration depths) supporting their statement; otherwise this statement must include a reference to other study where such comparison has been done.

As suggested by the reviewer we will include on page 1834, line 18, a reference to Gorbunov et al. 2011, AMT, where such comparison has been done.

Technical comments:
(1833,10) and hereafter. "...shows the fractional refractivity deviation". Deviation from what?

We will write "...shows the fractional refractivity deviation from the ECMWF analysis."

(1833,11) and hereafter (incl. figure captions). What does the "one-sigma standard deviation" mean? The standard deviation = one sigma by definition. Use either "standard deviation" or "one-sigma deviation".

We will use the term standard deviation throughout the manuscript.

(1834,12) and hereafter. "...is attached to the figure". Use standard way of discussing figures: e.g., left panel, right panel.

We will use the proposed way of discussing figures throughout the manuscript.

(1834,26) "...setting occultations extend deeper..." Not the occultations but the retrieved profiles (since this sentence is related to the retrieved profiles but not to the signals as functions of SLTA).

We will correct this.

(1836,11) "extend", must be "extent".

We will correct this.

Figs. 3, 4, 5, 6, 7, 8, 11, 12 (right panels). Since the [fractional] number of profiles is limited by 0% and 100%, there is no reason to extend X-axis beyond those limits.

All figure X-axis will be changed accordingly.

References:

M. E. Gorbunov, K.B. Lauritsen, H.-H. Benzon, G.B. Larsen, S. Syndergaard, and M.B.Sørensen, Processing of GRAS/METOP radio occultation data recorded in closed-loop and raw-sampling modes, Atmos. Meas. Tech. Discuss.,4,1061-1077, 2011

Beyerle, G., Wickert, J., Schmidt, T., and Reigber, C., Atmospheric sounding by global navigation satellite system radio occultation: An analysis of the negative refractive bias using CHAMP observations, J. Geophys. Res., 109, D01106, doi:10.1029/2003JD003922, 2004.