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Atmospheric Measurement Techniques Discussions

# *Interactive comment on* “Errors in GNSS radio occultation data: relevance of the measurement geometry and obliquity of profiles” *by* U. Foelsche et al.

**U. Foelsche et al.**

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We would like to thank referee 1 for the thorough review of our paper and his/her constructive and useful comments. We have answered all comments below (for easier comparison the original comments are included in *italic*).

*General Remarks: 1. Experimental setup: why only focus on dry temperature? Such an investigation has also relevance for bending angle and refractivity, and these are the data assimilated into NWP models. And the processing to temperature severely*



*smoothes the data. This becomes even more relevant when considering that the main impact of the slant occultation is found at lower altitudes, where the data use is primarily in the NWP area.*

When preparing the manuscript we were convinced that sophisticated NWP assimilation systems make use of the Tangent Point Trajectory anyway (when this information is available). A survey we have performed in the meantime, however, showed that this is not always the case. We therefore gladly follow the referee's suggestion, and would like to show refractivity errors as function of azimuth sector (as in Fig. 6 and Fig. 7, respectively), in order to increase the potential impact of the paper in the NWP community.
The point about “severe smoothing” of the dry temperature data, however, is not entirely right. Errors in pressure ($p$) show indeed a smooth behavior. But refractivity ($N$) errors are largely a mirror of the dry temperature errors (since $dN/N = dp/p - dT/T$), as long as $dp/p$ is smaller than the other two, which it usually is in the troposphere. In general, dry temperature is not smoother than refractivity. In a previous study on the influence of horizontal variability (Foelsche and Kirchengast, 2004) with a similar setup (but fewer occultation events, ECMWF fields in T213L50 resolution with less horizontal variability) we found the results shown in Fig. 1, which nicely illustrate this behavior.
The theoretical error propagation background of this has been detailed in a paper by Rieder and Kirchengast(2001), which we will cite in the revised manuscript.

Foelsche, U., and Kirchengast, G.: Sensitivity of GNSS radio occultation data to horizontal variability in the troposphere, Phys. Chem. Earth, 29, 225-240, doi:10.1016/j.pce.2004.01.007, 2004.
Rieder, M.J., and G. Kirchengast.: Error analysis and characterization of atmospheric profiles retrieved from GNSS occultation data, J. Geophys. Res., 106, 31,755–31,770, 2001.

*2. Measurement geometry: I somehow have trouble with the azimuth angles going all* *the way to +/- 70 degrees. GRAS measures up to +/- 55 degrees and when looking at the data, only very few occultations appear at absolute angles larger 50 degrees. You however claim that more than 10 % are located between absolute angels of 60 and 70 degrees (Table 1). I wasn't able to confirm your results even with EGOPS, where I used a simple azimuth angle calculation based on the position of LEO, GNSS and the velocity direction. Can you check this. I might be wrong here though.*

We should have been more precise to avoid potential confusion, and will therefore change the sentence to: **In contrast to the actual GRAS receiver on MetOp-A, which measures RO data up to 55° azimuth, we used data up to an azimuth angle of 70°** . . . The choice of the GRAS cutoff at 55° is very reasonable (also confirmed by our results), but there are RO profiles beyond 55° that could be measured. We have carefully checked the geometry calculation and found no problems with it.

*3. Measurement geometry: It might be instructive to also include the duration of the event into Table 1. The ones at high sectors are likely also rather long in time.*

This is a good point – thank you very much for the suggestion. We will include the event duration in Table 1. You are right, the duration increases with increasing azimuth sector. The mean event durations (between 80 km and minimum altitude reached) in sectors 1 to 7 are: 43.3, 44.2 s, 46.2 s, 54.2 s, 65.4 s, 65.6 s, and 99.6 s. The value in sector 5 is almost as high as in sector 6, since there is a disproportionately high number of events at low latitudes (with pronounced tropospheric bending).

*4. Observation system modelling ...: Why did you include a realistic receiver model, wouldn't it be more instructive to exclude that and look at the impact of the slant profile separately? One could then show one plot / a short discussion on what the realistic receiver model adds in errors. And as far as I remember EGOPS, this can be done without doing the time consuming ray tracing again.*

This would be a different way to look at the problem, but we think that it is more instructive to show the quasi-realistic data. With our design we show the total errors one is



faced with as a user, and that they become significantly smaller when exploited (such as compared with reference profiles) along the retrieved tangent point trajectories.

*5. Results: The impact of the local radius of curvature selection is mentioned in the discussion of absolute bias. Can you comment on whether there are better ways to select the reference point for this radius calculation, e.g. as a function of the azimuth angle?*

Figure 2 indicates that our definition of the mean tangent point (which corresponds to altitudes between 10 km and 15 km) – and the corresponding radius of curvature – provides quite a good trade-off for a reasonable fit in the troposphere and stratosphere (in all sectors). Regarding the radius of curvature, in the next version of our retrieval we will test if the results can be further improved when also the radius of curvature is allowed to change during an occultation event (in order to better represent the surfaces of constant refractivity).

There is in addition a related point, which was brought up by Michael Rennie (Met Office, UK, personal communication, 2010) during discussion outside of the AMTD discussion phase: Other centers use different definitions of the mean location of an RO event. UCAR (Boulder, USA) uses a definition, which corresponds to altitudes of about 3-4 km, while GFZ (Potsdam, Germany) chooses the lowest tangent point of the RO event. In both cases there is a better fit in the lower troposphere, but increasing deviation at higher altitudes – which should be avoided too, since this is the region, where the RO data quality is best.

We will add this point in the revised paper as it is also useful to be aware of as a general user.

*6. Results: The tangent point movement tends to be mainly in the North-South direction I guess (polar orbit). Can you comment on the potential impact for climate assessments, in particular for occultations at high absolute azimuth angels? Also, when a lot of occultations are recorded at certain latitude ranges in one specific sector, what is the climate data impact? What about the antenna characteristics impact?*

The tangent point movement is not only in North-South direction (especially at higher latitudes), but the North-South component could potentially have the largest impact for climate applications. Let us consider an RO receiver for setting occultations only (aft looking antenna), on a northward flying satellite: tangent points in the upper part of the RO profile will always be further south than in the lower part of the profile, and we can expect an altitude-dependent bias when comparing individual RO profiles with vertical reference profiles at mean tangent point location. During the descending branch of the orbit, however, the situation reverses, and we can expect the effect to compensate to a high degree, when ensembles of RO profiles are collected for climate applications (but not necessarily for small-scale means). Even for (setting-only) RO receivers on exactly polar orbiting satellites there is a net tangent point movement in east-west direction, since the Earth rotates under the orbiting satellites.

Next we take the same satellite as above, but now also equipped with a forward looking antenna for rising occultations: For rising events the upper part of the profile is always further north than the lower part. The compensation will therefore happen earlier, provided that there are no further selection effects (different penetration depth, number of rising vs. setting occultations. . .).

An exact quantification of these effects is beyond the scope of the current work, but we can provide an estimate of the magnitude by computing the mean latitudinal tangent point movement (between 80 km and minimum altitude reached) in sectors 1 to 7. Even though we are averaging over only a single day, the mean displacements per sector are only (positive for South-North movement): 0.64 km, -5.38 km, 0.52 km, -3.23 km, 6.91 km, 16.34 km, and 53.24 km.

Thank you also for this comment - we would like to add this information to Table 1.

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Interactive comment on Atmos. Meas. Tech. Discuss., 3, 4261, 2010.



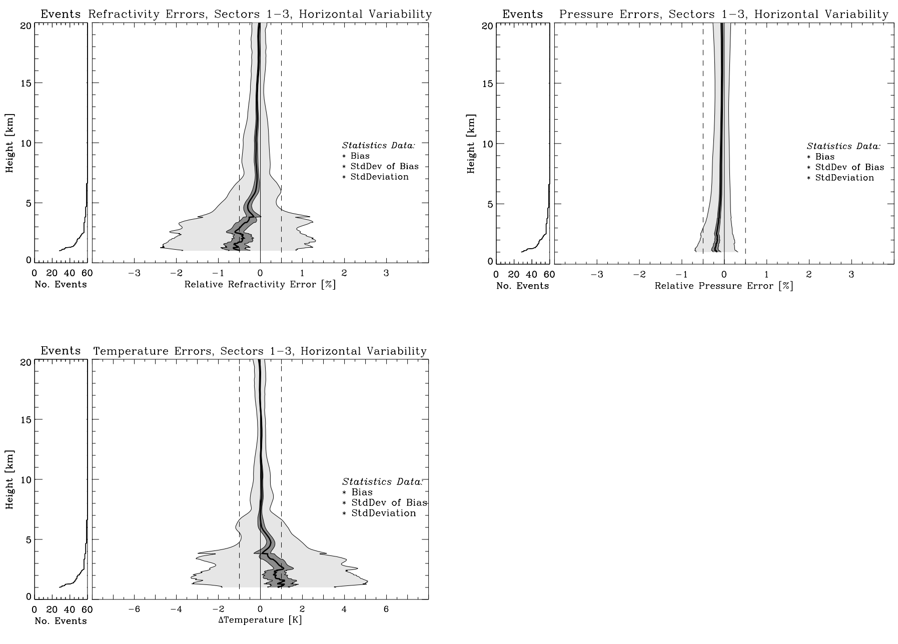


**Fig. 1.** Refractivity, pressure, and dry temperature errors statistics for an ensemble of 60 occultation events (from Foelsche and Kirchengast, 2004, Figures 4, 5 and 7).