Generalized Canonical Transform method for radio occultation sounding with improved retrieval in the presence of horizontal gradients

M. Gorbunov, G. Kirchengast and K. Lauritsen

General comments

The authors present a new wave optics retrieval method aimed at mitigating "systematic errors" (line 15) in the lower troposphere. The central problem being addressed is that GNSS radio occultation (GNSS-RO) wave optics retrievals rely on a co-ordinate transform from time and Doppler to impact parameter and bending angle. However, impact parameter is not necessarily unique in the presence of horizontal gradients. This is sometimes called "impact multipath". The authors suggest a new transform, "CT2A", combining both bending angles and impact parameters, which depends on a tuneable parameter, β. It is noted that the optimal value of β will vary for each individual measurement, but it may be possible to estimate a value that is optimal in a statistical sense. A range of plausible values are tested in the paper.

The paper does a good job reviewing of GNSS-RO wave optics developments (many of which the authors have led), and presenting them in a broader physical context. The citation of other work is also fair. I do not follow all the mathematical details of the new approach, but the physical reasoning seems correct. However, major revision is required before publication. A significant difficulty with this paper is understanding whether the new approach ($\beta \neq 0$) is better than the current method ($\beta=0$). For example, the authors say that (line 374):

"Here the difference metrics for $\beta = 0$ and optimal β cannot be directly compared, because they are evaluated over different statistical ensembles."

This makes the interpretation of the results presented in Figures 3-11 extremely difficult. The penetration depth alone does not seem to be a strong argument, particularly when $\beta=0$ often provides more data above 1 km. It would be more useful to show the subset of refractivity values common to all retrievals.

In addition, the text says that the method mitigates systematic errors, but the metric shown in these figures combines systematic and random errors. I suggest that the systematic and random error estimates should be plotted separately. These points and the specific comments given below should be addressed before publication.

Specific comments

Line 225: "don't" should be "do not".

Line 293: "The angular component of the momentum $p\vartheta$ coincides with the ray impact parameter p, which is invariant in a spherically layered medium, but is perturbed by the horizontal gradients (Gorbunov and Lauritsen, 2009)". Healy (2001) also pointed this out.

Line 299: [Gorbunov2019] not listed in references. Format of reference in text.

The references appear to change format e.g., line 306 "[Zou2019]" and line 310 "[Gorbunov2009a, Zou2019]". These should be (Zou et al., 2019) and (Gorbunov and Lauritsen, 2009).

Line 364: "co-located ECMWF refractivity profiles". It would be useful to give more detail here. For example, does this computation include the tangent point drift? Do you compute the refractivity directly from the ECMWF P,T and Q fields. Are they ECMWF forecasts or analyses? What resolution?

Line 366: It would be useful to split this metric into to systematic and random errors instead of combining them, particularly if the transform is likely to improve systematic errors, as noted in the abstract.

Line 373: “The CT2A algorithm also improves the penetration increasing the number of data in the altitude range below 0.5 km.”

This is correct, but β = 0 appears to provide more data above 1 km. Why is this? Are you using the transformed amplitude to cut-off the data? Please explain.

Line 374: “Here the difference metrics for β = 0 and optimal β cannot be directly compared, because they are evaluated over different statistical ensembles.”.

This really makes it difficult for the reader to judge whether the new transform is an advantage or not in all the subsequent figures. Is it possible to present the results for a dataset common to all β values to help the reader interpret the results?