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Comment

# ***Interactive comment on “A modification to the ionospheric correction method used in GPS radio occultation” by S. B. Healy and I. D. Culverwell***

**Anonymous Referee #2**

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General comments:

As already expressed in my review of the AMTD manuscript, the paper is

1. well written in terms of presentation quality,
2. suggests a potentially useful advancement of the current standard ionospheric correction method for RO data - which is the linear dual-frequency correction of bending angles - and
3. presents good justification why the suggested additional term - proportional to bending-angle-squared - should improve upon the standard.

Furthermore, while the demonstration results included in this paper are relatively slim and based on very simple idealized ionospheres, it is understood that a companion paper by Danzer et al. provides some further evidence with more realistic ionospheres.

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Therefore, overall, the paper is clearly a valuable and viable contribution to the RO field and, in the opinion of this reviewer, deserves publication in AMT.

Before such publication, several (minor) revisions should be implemented however, which are the following.

Specific suggestions:

1) Title:

Suggest to say "...to the standard ionospheric correction method used..."; the added word "standard" will help to indeed make most (expert) readers think of the dual-frequency correction of bending angles according to Vorobev-Krasilnikova-1994, otherwise it remains a bit vague.

2) Introduction section:

This section is well done, however, two aspects should receive better citation:

2a. the important ROTrends work on structural uncertainty was so far published by Ho et al. (2009), Ho et al. (2012), Steiner et al. (2013) - and since the AMT journal has no number-of-references restrictions clearly all three should be cited. It is therefore suggested to add also the Ho et al. (2009) and Ho et al. (2012) references in line 48. (Note, all additional references suggested here are listed at the bottom of this review, see below.)

2b. lines 87 to 98 give a good brief intro on recent work on residual ionospheric errors (RIEs) but do not include any reference to the recent work by Liu et al. 2013 and 2015 based on simulations, which was somewhat complementary to the cited work of Danzer et al. (2013); I am just checking also this Liu et al. work, it could be added such like "Complementary to Danzer et al. (2013), Liu et al. (2013) and Liu et al. (2015) performed end-to-end simulations to investigate residual ionospheric errors remaining after the dual-frequency bending angle correction. They also found clear evidence for negative residual bending angle bias, although smaller in size than the observation-based studies, likely since higher order ionospheric terms were not included in their

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simulation setup."

2c. as a side note, also in line 176, in section 2, Liu et al. (2015) should complement the Danzer et al. (2013) reference cited there.

3) Title of section 2:

Suggest better say "Ionospheric correction of GPS RO measurements" (and see also bullet 5 below)

4) Section 2, lines 196 to 198:

While the section 2 math derivation is mostly done in a concise yet still sufficiently understandable manner (with complementary details in appendix A), the formulation "...expand the denominator of the left hand side of equation 4 to estimate the second-order term for both the L1 and L2 frequencies." appears a bit too brief.

Readers can figure out with some more thinking, but please try to have a bit more clarification what exactly is done here to Eq.(4) - by improving this sentence to be more informative and/or by adding one more sentence (readers should not be forced to look back to VK94).

5) Section, 2, end of section:

Here is - or rather is missed in fact - what I see as the only more severe structural weakness of the paper: it appears that the key formula, the new advanced correction formula Eq.(9), is only introduced in the discussion and conclusions section 4!

This is awkward given that section 2 is the intro to the "ionospheric correction" and section 3 is "Results", all done before the key formula enters stage close to the end. I would suggest to extend section 2 and have Eqs (8) and (9) introduced here; I perceive it would be quite easier in this order to clearly comprehend what is demonstrated then by sections 3 and 4. Maybe, even name section 2 "Advanced ionospheric correction of GPS RO bending angles", making clear that here the advanced methodology is coming one-stop, as the key is extending the standard Eq. (3) to the advanced Eq. (9) (then becoming Eq.(7) after re-order).

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## 6) Sections 3 and 4:

Apart from what I said under bullet 5, I like these sections which give a pretty good account of what to expect from the advanced correction (including caveats), plus pointing to the companion paper by Danzer et al.

Therefore I suggest just to implement bullet 5 above - extracting Eqs (7) and (9) plus proper text context forward to section 2, becoming Eqs (6) and (7) there - but otherwise keep this flow.

## 7) Appendix and general remark:

7a. the equation in line 434, Eq.(A7), contains the term "TEC" which is awkward since one never should use multi-character symbols for a mathematical variable. Please substitute "TEC" by a mathematical symbol (typical candidates are an uppercase greek  $\mathcal{T}_e$ , or using  $N_e$ ; cf. e.g. Syndergaard (2000) which you cite). Note, this "TEC" as well appears in other places such as Eq.(A8) and in surrounding texts.

7b. finally there are also a couple of small typos, punctuation weaknesses, etc, especially throughout the Appendix, but also at a few places throughout the paper. Please give the full paper a very careful final copy-editing before it is published.

## Suggested additional references:

Ho et al. (2009):

Ho, S.-P., G. Kirchengast, S. Leroy, J. Wickert, A.J. Mannucci, A. Steiner, D.C. Hunt, W.S. Schreiner, S. Sokolovskiy, C. Ao, M. Borsche, A. von Engeln, U. Foelsche, S. Heise, B. Iijima, Y.-H. Kuo, R. Kursinski, B. Pirscher, M. Ringer, C. Rocken, and T. Schmidt, 2009: Estimating the uncertainty of using GPS radio occultation data for climate monitoring: Intercomparison of CHAMP refractivity climate records from 2002 to 2006 from different data centers. *Journal of Geophysical Research-Atmospheres*, 114, D23107, DOI: 10.1029/2009JD011969.

Ho et al. (2012):

Ho, S.-P., D.C. Hunt, A.K. Steiner, A.J. Mannucci, G. Kirchengast, H. Gleisner, S. Heise,

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A. von Engel, C. Marquardt, S. Sokolovskiy, W.S. Schreiner, B. Scherllin-Pirscher, C. Ao, J. Wickert, S. Syndergaard, K.B. Lauritsen, S. Leroy, E.R. Kursinski, Y.-H. Kuo, U. Foelsche, T. Schmidt, and M. Gorbunov, 2012: Reproducibility of GPS radio occultation data for climate monitoring: Profile-to-profile inter-comparison of CHAMP climate records 2002 to 2008 from six data centers. *Journal of Geophysical Research-Atmospheres*, 117, 38 pp, DOI: 10.1029/2012JD017665.

Liu et al. (2013):

Liu, C.L., G. Kirchengast, K.F. Zhang, R. Norman, Y. Li, S.C. Zhang, B. Carter, J. Fritzer, M. Schwaerz, S.L. Choy, S.Q. Wu, and Z.X. Tan, 2013: Characterisation of residual ionospheric errors in bending angles using GNSS RO end-to-end simulations. *Advances in Space Research*, 52, 821-836, doi:10.1016/j.asr.2013.05.021.

Liu et al. (2015):

Liu, C.L., G. Kirchengast, K. Zhang, R. Norman, Y. Li, S.C. Zhang, J. Fritzer, M. Schwaerz, S.Q. Wu, and Z.X. Tan, 2015: Quantifying residual ionospheric errors in GNSS radio occultation bending angles based on ensembles of profiles from end-to-end simulations. *Atmospheric Measurement Techniques*, 8, in press, doi:10.5194/amt-8-nnn-2015.

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