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Atmospheric Measurement Techniques
Discussions

# *Interactive comment on* "Atmospheric bending effects in GNSS tomography" *by* Gregor Möller and Daniel Landskron

**Anonymous Referee #1**

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General comments:

The paper studies bending effects in GNSS tomography. I recommend to consider the paper for publication. However, the following points must be addressed.

Specific comments:

(1) I recommend to rewrite the 'Introduction'. The section 'Introduction' must be more general. In the 'Introduction' there is no need for technical details and formulas. Technical details and formulas must be provided in the following section (see next point). Instead, provide a brief overview on the state of the art in tomography. Provide some relevant references, e.g. Bender et al., 2011, Champollion et al., 2005, Hirahara, 2000, and their findings. In all the above mentioned works bending effects were ignored. Therefore you should then provide references where bending effects are taken into account. Here you should mention Zus et al (2015) (not cited in the manuscript) and a paper that appeared two years later Aghajany and Amerian (2017) (cited in the manuscript).



(2) Section 1 ('Introduction') and 2 ('Atmospheric bending effects in GNSS signal processing') need a complete makeover. I suggest to merge the two sections to one section with the following title 'Atmospheric bending effects and WV tomography'. To my understanding you are concerned with SWDs and not STDs. In short, i recommend the following structure for this section:

2.1 Atmospheric bending effects

Here you should at first introduce the basic observable, i.e., STDs. You can either use eq 2 or 10. They are essentially the same. I recommend to use eq 2. Hence, you start as follows: The STD is defined as (Bevis et al. 1992)

STD = int n ds – g

n...index of refraction s...arc length of bent ray-path (refer to section 3) g...geometric distance between satellite and station

Then, you introduce refractivity N. In essence

n=10**(-6) N + 1

and therefore

STD = int 10**(-6) N ds + s – g

Then you introduce the hydrostatic and wet refractivity

N= Nh + Nw

and therefore

STD = int 10**(-6) Nh ds + s – g + int 10**(-6) Nw ds

Next, you introduce the following quantities

SHD = int 10**(-6) Nh ds + s – g

and

SWD = int 10**(-6) Nw ds

such that

STD = SHD + SWD

At this point it is again important to mention that the ray-path (and therefore the arc-length s) depends on the 'total' refractivity N (refer to section 3).

Then you claim that the SWD can be accurately estimated with the GNSS. In essence, you introduce the assembled STD that is used in the GNSS analysis (eq 11)

STD_GPS = ZHD_GPS * mh(e) + ZWD_GPS * mw(e) + mg(e) (N cos(a)+ E sin(a))

and provide the formula that you use to recover the SWD. I can only guess (please provide the details) something like this

SWD_GPS = STD_GPS - ZHD_NWM * mh(e)

or better yet something like this

SWD_GPS = STD_GPS - ZHD_NWM * mh(e) - mg(e) (Nh_NWM cos(a)+ Eh_NWM sin(a))

where ZHD_NWM is ZHD derived from a NWM (or derived from in situ pressure sensor) and Nh_NWM and Eh_NWM are the hydrostatic gradient components derived from a NWM. Here you can mention that the hydrostatic mf (which is derived under the assumption of a spherically layered troposphere) takes into account the geometric bending term. In essence,

mh = (int 10**(-6) Nh ds + s – g) / ZHD



With this details you are finished with 2.1 and prepared for 2.2

2.2 WV tomography

Since the observable you consider are SWDs, there is no need for eq 3 and 4. You can start directly with the following formula

SWD = int 10**(-6) Nw ds

and its numerical approximation

SWD ∼ sum_i 10**(-6) Nw_i ds_i

where you again explicitly mention that, because of ray-path bending, s does not equal g (refer to section 3). Then you can proceed with your eq 6 and 7. It is important that you explain what P and Pc is. I guess (please provide the details) that Pc tells us something about the uncertainty of the observations and P tells us something about the uncertainty of the a-prior (first-guess or background) wet refractivity?

With this you are finished with section 2 and proceed with your section 3.

(3) I suggest that somewhere in the manuscript you plot the following difference

dSWD = SWD_T - SWD_0

as a function of the elevation angle for some station. Here SWD_0 is the SWD calculated along the straight line path and SWD_T is the SWD calculated along the ray-path. In essence,

dSWD = sum_i 10**(-6) Nw_i ds_i - sum_i 10**(-6) Nw_i dg_i

I guess you will find that the following inequality holds true for any elevation angle

SWD_0 > SWD_T

due to the fact that the ray-path traverses the troposphere at higher altitudes than the straight line path. This would imply that when ray-path bending is not taken into account in tomography the reconstructed troposphere is too dry. To see this you could chose some 'true' wet refractivity field, say N_w0, and simply replace in your eq 7 the term

(SWD - A*N_w0)

by

dSWD. I strongly recommend to do this somewhere in the manuscript.

technical corrections:

Abstract:

L7: '...Thereby, the ray-tracing approach itself but primarily the quality of the a prior field has a significant impact on the reconstruction quality...' improve the writing.

Introduction:

L15: 'GNSS' abbreviation not introduced here.

Section 3.1

L24: What is the 'outgoing' elevation angle? Please provide a clear definition here.

L18: The inner loop you use is to solve the so called 'homing in problem' (you make use of a shooting method). Please state this more clearly here.

Section 3.2

L4: '...In consequence, the reconstructed...'. The phrase 'In consequence' can be avoided here and at various other places.

Section 3.2.2

I suggest to show in Fig 4. directly the difference in SWD[m] and not the difference in the bending angle[arcsec]. Also, i do not find the formula for the bending angle in the manuscript. I guess you mean something like arcos(v1,v2) where v1 is the tangent unit vector of the ray-path at the satellite and v2 is the tangent unit vector of the ray-path at



the station?

Section 4.1

I suggest to add in Fig 8. the difference for the a-prior (first guess or background) refractivity (ALARO). Is the radiosonde data assimilated into ALARO?

References:

Check all references carefully. For example,

Fritsche, M., Dietrich, R., Knofel, C., Rulke, A., and Vey, S.: Impact of higher-order ionospheric terms on GPS estimates, Geophys. Res. Lett., 32, 1–5, 2005.

Bender, M., Stosius, R., Zus, F., Dick, G., Wickert, J., Raabe, A. (2011): GNSS water vapour tomography – Expected improvements by combining GPS, GLONASS and Galileo observations. - Advances in Space Research, 47, 5, pp. 886âĂŤ897. DOI: http://doi.org/10.1016/j.asr.2010.09.011

In the manuscript the correct citation should be e.g. Böhm et al 2006 and not Böhm et al 2006a. Likewise the correct citation should be Hobiger et al 2008 and not Hobiger et al 2008a (there is no b).

Additional Reference:

Zus, F., Dick, G., Heise, S. and Wickert, J.: A forward operator and its adjoint for GPS slant total delays, Radio Science, 50, 393– 405, doi: 10.1002/2014RS005584, 2015.

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