Ann. Geophys. Discuss.,
https://doi.org/10.5194/angeo-2018-84-AC2, 2018

Annales Geophysicae Discussions
Open Access

Interactive comment on “A comparison between the GNSS tomography technique and the WRF model in retrieving 3D wet refractivity field in Hong Kong” *by* Zhaohui Xiong et al.

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Received and published: 18 October 2018

Response to Reviewer #2:

Q1: The article shows an interesting study by combining two different approaches of retrieving 3-dimensional wet refractivity fields. However, in my opinion there are some major deficiencies, which need to be addressed before publication. What is the novelty of your approach and how can the NWP community benefit from this? This is not fully clear especially with respect to the huge effort in creating the tomography fields compared to a simple ZTD calculation.

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Response: The novelty of this manuscript is (1) we use an advanced tomography approach to retrieve the 3D wet refractivity filed; (2) we conduct a fair comparison between the tomography technique and the WRF model, which is seldomly done by the NWP community or the GNSS community. The benefits of this study are (1) provides insights for the NWP community about this new technique and the possibility of assimilating the tomography results into the NWP models; and (2) the GNSS community will get a better understanding of the WRF model and its capability in simulating the water vapor field. This has been clarified in lines 73-77.

Q2: lines 55-62: Are there also other NWP models than WRF, which make use of ZTD/PWV data assimilation?

Response: Yes, the AROME NWP system and Japan Meteorological Agency (JMA) Mesoscale Numerical Weather Prediction Model can also make use of ZTD\PWV data assimilation. We added the citations of the related models in lines 69-71. Here are the references: Nakamura H, Koizumi K, Mannoji N. Data assimilation of GPS precipitable water vapor into the JMA mesoscale numerical weather prediction model and its impact on rainfall forecasts[J]. Journal of the Meteorological Society of Japan. Ser. II, 2004, 82(1B): 441-452. Boniface K, Ducrocq V, Jaubert G, et al. Impact of high-resolution data assimilation of GPS zenith delay on Mediterranean heavy rainfall forecasting[C]//Annales Geophysicae. 2009, 27: 2739-2753.

Q3: line 77: What do you mean with “vertically flat” in this case. Is your statement related to the altitude difference of 344 m? I do not think that this can be considered as “flat”.

Response: In GNSS tomography, a network whose altitude differences are less than 1 km is regarded as a flat network. Flat networks bring difficulties in retrieving the vertical solutions of the WR. We have clarified this in line 88.

Q4: Line 84: maybe “dry” instead of “rainless”.

Response: Thank you for your suggestion. And we have used ‘dry’ instead of ‘rainless’ in the manuscript.

Q5: Lines 85-96: I think it is a good idea to show the applied parameters for Bernese in a separate table. In line 92/93, I guess you mean Niell in both cases. Are all GNSS receivers equipped with temperature and pressure measurements? If not, please mention how you derive the ZTD at the receiver locations.

Response: According to you and the other reviewer’s suggestions, we have moved the description about the GNSS data processing to Appendix A (lines 289-302). Sorry, it’s Niell, we made a typo and has corrected it. Yes, all the GNSS receivers are equipped with temperature, relative humidity, pressure measurements.

Q6: Lines 99-102: The general purpose of any data assimilation scheme is to obtain the best estimate of the atmosphere not only with respect to ZTD observations. Did you assimilate any other observations than ZTD? It is well known, that one should make use of all available observations to complement each other. Especially as the 3DVAR does not contain any dynamical component. How was the 3DVAR set up? Is it a rapid update cycle with e.g. an hourly update or did you ran the 3DVAR once at the beginning of your period of interest? Did you apply multiple outer loops? What is the ZTD error you used? All these details are important to know as this determines the weight/impact of the observations and the data assimilation in general.

Response: We delete the inaccurate expression “In this study, the WRFDA estimates the atmosphere state that best fits the ZTD observations.” The purpose of this manuscript is to conduct an interesting and fair comparison between the tomography technique and the WRF model. To be fair, we use only GPS data for both tomography and the WRF model, i.e. slant wet delay for tomography and ZTD for the WRF model. In addition, except for the GPS data, only the surface meteorological observations can be assimilated into the WRF model (the only radiosonde data will be left for validation), but assimilating the surface meteorological data into WRF can make very little difference, according to our previous tests. The physics options are unified Noah land-surface model (Tewari et al., 2004), Revised MM5 Monin-Obukhov scheme (Monin and Obukhov, 1954), and Yonsei University planetary boundary layer scheme (Hong et al., 2006). The Rapid Radiative Transfer Model (Mlawer et al., 1997) and Dudhia's scheme (Dudhia, 1989) were used for longwave radiation and shortwave radiation, respectively. The physics settings of WRFDA are the same with WRF (This has been clarified in lines 104-110). This experiment does not apply multiple outer loops and just run the 3DVAR once at the beginning of the period of interest. The ZTD error is output by the Bernese 5.0 software.

Q7: Lines 102-104: Does the model domain only encompass the area shown in Figure 1? If this is the case, you may only have approx. 30*25 grid cells. Assuming a boundary relaxation zone of 5 cells, you effective model domain will be 20*15 cells which is far too small. The model does not have a chance to develop its own state but is mainly determined by the boundary conditions. Please clarify. Did you apply the default layer settings in WRF by setting "eta_levs" to a certin value or did you define the levels on your own? How many layers are in the PBL? This may be important as the majority of the humidity is located inside the PBL. A lot more information is necessary here.

Response: Yes, the model domain only encompasses the area shown in Figure 1. And the relaxing zone is 4 cells. We just need the model reanalysis at the beginning of the interested period, we don't need the model to develop its state in time. Namely, we just need the model uses the observations to update the background data. We set 46 layers in WRF on our own and 10 layers in the PBL.

Q8: Lines 109-111: Did you apply the reanalysis of ERA-Interim, which has a resolution of 0.75âŮę and not 0.125âŮę or the operational analysis? Are the forcing data applied on model levels or on pressure levels? In case you applied the former data, I'm afraid that this is not a suitable data to study the behaviour of a convection permitting model especially at these short time scales although data assimilation is applied.

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Response: Yes, I applied the reanalysis of ERA-Interim. We use the ERA-Interim data on pressure levels and surface data. Its nominal resolution is 0.125°× 0.125° and the real resolution is 0.75°× 0.75°.

Q9: Line 115: To me the applied CV3 method is a major concern. I guess you know that this matrix is derived from a NCEP model climatology at a horizontal resolution of roughly 2âŮę and this is applied on the CP scale in your study. I am concerned if this is a scientifically valid approach.

Response: The ARW version 3 Modeling System User's Guide (published in July 2016) says that "However, CV3 (a BE file provided with our WRFDA system) is a global BE and can be used for any regional domain, while CV5, CV6, and CV7 BE's are domain-dependent, and so should be generated based on forecast or ensemble data from the same domain." in page 6-39. "Theoretically, CV3 BE is a generic background error statistics file which can be used for any case." in page 6-40. Based on these, we adopted the default CV3 background error. It may not be the best, but it could be used in this case.

Q10: Line 118: I think the word reanalysis is misleading here as you probably only used ZTD observations. I also do not really see from the Vedel and Huang publication how WR is derived. Please also include the units for k1 and k2. Are T and P only used at the surface? This is not clear here. Also, please use "p" instead of "P" for pressure.

Response: Thank you for your suggestion. And we revise the term 'reanalysis' to 'output'. Vedel and Huang (2004) didn't directly give the equation for WR calculation, but we can easily partition the equation for WR calculation from the equation for wet delay calculation. We attach a figure (Fig.1, in which the code is from da_transform_xtoztd.inc in WRFDA) to show Vedel and Huang's equation. In the equation, wzd is the zenith wet delay, which is calculated by integrating the product of WR and altitude difference (which represented by dh). Therefore, the wet refractivity can be easily derived by dividing the wzd increment by the dh. The unit of k1 is K/Pa, and the unit of k2 is K^2/Pa. We clarified this in the manuscript in line 124. We have replaced "P" with "p".

Q11: Line 137: Do you mean the ECMWF (re-)analysis or the new analysis obtained from WRFDA?

Response: The reanalysis means WRFDA and WRF output, namely the new reanalysis.

Q12: Line 138: What do you mean with "nearest four grids"?

Response: This part has been rewritten, no "nearest four grids" any longer. The new expressions are: "The vertical coordinates of WRF model output are converted to geopotential heights by NCL and the geodetic heights of tomographic results are converted to normal height. The slight differences between geopotential heights and normal heights are neglected. We interpolate the WRF output to tomographic nodes since the former has a much higher resolution (23 layers from 0 to 10 km height) than the latter (13 layers) and thus we can get a higher interpolation accuracy. We use a bilinear interpolation method in the horizontal domain and a linear interpolation method in the vertical direction.".

Q13: Lines 139-140: Why did you adjust the radiosonde data? This distorts the radiosonde observations. I strongly recommend to interpolate the GNSS and tomography fields to the radiosonde location. How did you interpolate the unevenly distributed WRF model layers to the tomography layers, which have a constant spacing? The native WRF model output is not on pressure levels but on terrain following coordinates. I think is it necessary to include a short paragraph here.

Response: Thank you for your suggestion. In the vertical troposphere, the tomography model only has 13 layers whose vertical resolution is only 800 m while the radiosonde has a vertical resolution of $\sim$23 layers from 0 km to 10 km height. It means the radiosonde data have a much better vertical resolution than the tomography results. Therefore, we think interpolating the dense radiosonde data to the sparse tomography layers in the vertical direction would be more accurate. We show the original radiosonde profiles in Figures 3 and 4 now. The vertical coordinates of WRF model output are converted to geopotential heights by NCL and the geodetic heights of tomographic results are converted to normal height. The slight differences between geopotential heights and normal heights are neglected. We interpolate the WRF output to tomographic nodes since the former has a much higher resolution than the latter and thus we can get a higher interpolation accuracy. We use a bi-linear interpolation method in the horizontal domain and linear interpolation method in the vertical direction. By these methods, we interpolate both WRF output and radiosonde results to the tomography nodes. This has been illustrated in lines 170-177 in the manuscripts.

Q14: Line 143: Is “Reanalysis 2” your control run mentioned in line 117 or is this an assimilation run where everything except ZTDs was assimilated?

Response: The “Reanalysis2” is the control run and assimilates nothing. This has been clarified in line 119-120.

Q15: Line 152: Why does this lead to a decrease in performance in the tomography and the WRF model?

Response: Figures 3 and 4 show that the WR was distributed evenly from 0 to 10 km in July period when Hong Kong rains heavily, while the WR concentrated from 0 to 6 km in August period. This means that the water vapor varied sharply in the vertical direction in the August period and was relatively smooth in the July period. Both the model and the tomography technique can better retrieve the water vapor with smooth distribution than that with sharp variations. This has been clarified in lines 185-189.

Q16: Line 154: Did you perform any significance tests or do you mean something like “considerably”?

Response: No, we did not. We treat the radiosonde data as the true values and use

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them to validate the other results. The expression “Compared with Reanalysis2, the Reanalysis1 is slightly improved, but the improvement is not significant” is kind of misleading, we have revised it to “Compared with Reanalysis2, the Reanalysis1 is slightly improved by reducing the MAE by 1.25 mm/km”. This has been revised in lines 190-192.

Q17: Line 173: Why does the tomography “may” perform better than WRF? I though you did investigate this?

Response: The RMS of the tomography results is smaller than the Reanalysis1 results at 400 m, 1600 m, and 2400 m height, which is shown in Figure 5f. From the statistical perspective, the tomography performs better than the WRF model at these heights. We have clarified this and deleted the term “may”, see lines 209-210.

Q18: Lines 196-198: This statement is very confusing and queries the results of your study.

Response: To be more specific and accurate, we have revised the whole paragraph to (lines 234-238): “In general, assimilating GNSS ZTD into the WRF model has slightly improved the WR retrieval by decreasing the RMS by 0.2 mm/km. The WR derived from Reanalysis1 and Reanalysis2 has apparently smaller RMS than the tomographic WR (4.15 mm/km vs. 6.50 mm/km and 4.31 mm/km vs. 6.50 mm/km, respectively). The results obtained from WRF and tomography are better in the wet period than in the dry period, which is mainly due to the sharp vertical variation of WR in the dry period.”

Q19: Line 208: With ZTD you do not assimilate the column water vapour. The signal delay is assimilated from which TCW can be derived.

Response: Yes, we just need to assimilate one of them.

Q20: Line 210: From your results I do not agree with this statement.

Response: Make full use of the vertical structure information of water vapor could benefit the data assimilation. It could provide more information such as the vertical

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water vapor distribution than ZTD. And the MAE of assimilating ZTD is 6.04 mm/km while the MAE of assimilating tomographic WR is 5.92 mm/km. This result shows that assimilating tomographic WR could improve the WR retrieve.

Q21: Line 213: How did you assimilate relative humidity only in WRFDA? If you use p and T from reanalysis (again the WRFDA analysis or ECMWF?), the tomography is not model independent anymore.

Response: According to the WRF data assimilation scheme, we can only assimilate the relative humidity together with T and p from WRF output. We tried to mitigate model dependence. We use the T and P from the WRF output (O1) without assimilating anything. Then we run WRFDA to assimilate the tomographic WR together with T and p, and then run WRF to generate the new output (O2). The T and P in O1 and O2 have very small difference, therefore we controlled the influence of T and P on the final results. The difference between O1 and O2 mainly lies in the humidity, which was caused only by the tomographic WR.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2018-84/angeo-2018-84-AC2-supplement.pdf

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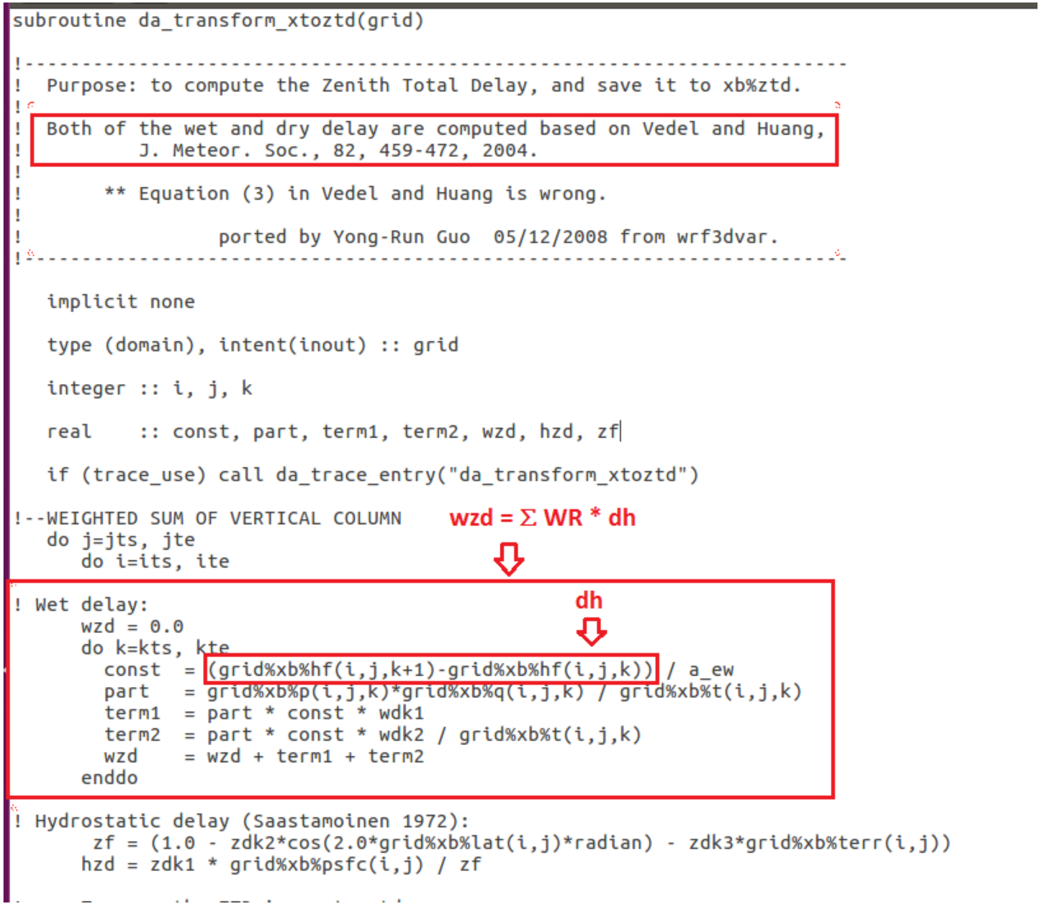
Interactive comment on Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2018-84, 2018.



```
subroutine da_transform_xtoztd(grid)

!------------------------------------------------------------------------
!  Purpose: to compute the Zenith Total Delay, and save it to xb%ztd.
!
!  Both of the wet and dry delay are computed based on Vedel and Huang,
!          J. Meteor. Soc., 82, 459-472, 2004.
!
!        ** Equation (3) in Vedel and Huang is wrong.
!
!                 ported by Yong-Run Guo  05/12/2008 from wrf3dvar.
!------------------------------------------------------------------------

   implicit none

   type (domain), intent(inout) :: grid

   integer :: i, j, k

   real    :: const, part, term1, term2, wzd, hzd, zf

   if (trace_use) call da_trace_entry("da_transform_xtoztd")

!--WEIGHTED SUM OF VERTICAL COLUMN
   do j=jts, jte
      do i=its, ite

! Wet delay:
      wzd = 0.0
      do k=kts, kte
        const  = (grid%xb%hf(i,j,k+1)-grid%xb%hf(i,j,k)) / a_ew
        part   = grid%xb%p(i,j,k)*grid%xb%q(i,j,k) / grid%xb%t(i,j,k)
        term1  = part * const * wdk1
        term2  = part * const * wdk2 / grid%xb%t(i,j,k)
        wzd    = wzd + term1 + term2
      enddo

! Hydrostatic delay (Saastamoinen 1972):
       zf = (1.0 - zdk2*cos(2.0*grid%xb%lat(i,j)*radian) - zdk3*grid%xb%terr(i,j))
      hzd = zdk1 * grid%xb%psfc(i,j) / zf
```

Fig. 1. Fig1