

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.

Response: The novelty of this manuscript is (1) we use an advanced tomography approach to retrieve the 3D wet refractivity field; (2) we conduct a fair comparison between the tomography technique and the WRF data assimilation, 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 WRFDA and its capability in simulating the water vapor field. This has been clarified in lines 71-75.

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 67-69.

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 lines 85-87.

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 your and the other reviewer's suggestions, we have moved the description about the GNSS data processing to Appendix A (lines 296-308).

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 WRFDA. To be fair, we use only GPS data for both tomography and the WRFDA, i.e. slant wet delay for tomography and ZTD for the WRFDA. In addition, except for the GPS data, only the surface meteorological observations can be assimilated into the WRFDA model (the only radiosonde data will be left for validation), but assimilating the surface meteorological data into WRFDA can make very little difference, according to our previous tests.

The physics options are the Kain-Fritsch scheme (Kain and Frisch, 1990), WRF Single-Moment (WSM) 5-class scheme (Hong et al., 2004), 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. (This has been clarified in lines 123-128).

This experiment does not apply multiple outer loops and just run the 3DVAR once at specific epoch such as 0:00 UTC, 21st July in 2015. 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 certain 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 in the manuscript. And the relaxing zone is 4 cells. We find that we caused a lot of confusion by running the WRF model. Previously, we first run WRFDA 3DVAR to assimilate ZTDs and generate the output, labeled as output1. Then, we run the WRF using output1 as the background value to generate output2 at the same epoch. Actually, we just want to do data assimilating other than hindcasting, we don't need to run WRF to generate output2. I think running the WRF after 3DVAR caused a lot of confusion, we have removed the WRF part from the manuscript and redone the validation using output1 instead of output2. By these revisions, we have focused on the data assimilation and the WRFDA model. So, the statistic of bias, STD and RMS is same.

We set 46 layers in WRF on our own and 10 layers in the PBL.

In order to figure out how sensitive the wet refractivity output is to the domain size, we carry out a sensitivity test at 00:00 UTC 22nd July in 2015. And we increase the domain size gradually from 30 × 24 grids to 190 × 184 grids. In each run, we validate the wet refractivity derived by the WRFDA output using the radiosonde data. The statistical results of the sensitivity test are shown in Figure R1. It shows that the smaller domain size has the smaller bias, STD, and RMS. So, the domain size of the data assimilation experiment is set to 30 × 24 grids which just cover the study area. This has been discussed in lines 115-138 in the manuscript.

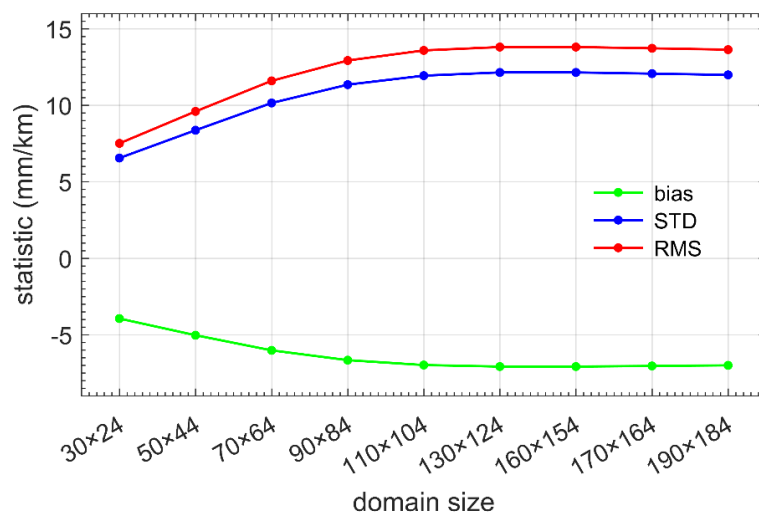


Figure R1. Statistics of sensitivity test with different domain size.

Q8: Lines 109-111: Did you apply the reanalysis of ERA-Interim, which has a resolution of 0.75° and not 0.125° 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.

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 $0.125^\circ \times 0.125^\circ$ and the real resolution is $0.75^\circ \times 0.75^\circ$.

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 2° and this is applied on the CP scale in your study. I am concerned if this is a scientifically valid approach.

Response: 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 k_1 and k_2 . 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 (the code is from `da_transform_xtoztd.inc` in WRFDA) to show Vedel and Huang's equation as follows. In this figure, 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 k_1 is K/Pa, and the unit of k_2 is K^2/Pa . We clarified this in the manuscript in line 113. We have replaced "P" with "p".

```

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  $wzd = \sum WR * dh$ 
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

```

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

Response: The reanalysis means WRFDA output and background data. And the data assimilation output is labeled as Output1. The output from WPS and real.exe is labeled as Output2.

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 the Output1 and the Output2 are converted to geopotential heights by NCAR Command Language (NCL) (NCL, 2013) 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 Output1 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 it is 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 ~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 4 and 5 now.

The vertical coordinates of the Output1 and the Output2 are converted to geopotential heights by NCAR Command Language (NCL) (NCL, 2013) 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 Output1 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. By these methods, we interpolate the WR derived from the Output1, the Output2 and radiosonde data to the tomography nodes. This has been illustrated in lines 182-189 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: It is the control run. “Reanalysis2” is changed to “Output 2” now which is the output of real.exe. This has been clarified in line 109-110.

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

Response: Figures 4 and 5 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 WRFDA and the tomography technique can better retrieve the water vapor with smooth distribution than that with sharp variations. This has been clarified in lines 196-200.

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 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 Background output, the WRFDA

output is slightly improved by reducing the mean absolute error (MAE) by 1.25 mm/km.. This has been revised in lines 201-202.

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

Response: The RMS of the tomography results is smaller than the WRFDA output results at 400 m, 1600 m, and 2400 m height, which is shown in Figure 6f. From the statistical perspective, the tomography performs better than the WRFDA at these heights. We have clarified this and deleted the term “may”, see lines 218-219.

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 242-246):

“In general, assimilating GNSS ZTD into the WRFDA has slightly improved the WR retrieval by decreasing the RMS by 0.2 mm/km. The WR derived from WRFDA output and Background output 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 WRFDA 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 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 background data. We tried to mitigate model dependence. We use the T and P from the background data output (O1) without assimilating anything. Then we run WRFDA to assimilate the tomographic WR together with T and p, and then run WRFDA 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.