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Atmospheric Measurement Techniques Discussions

Interactive comment on "High Spatial Resolution mapping of Precipitable Water Vapor using SAR interferograms, GPS observations and ERA-Interim reanalysis" *by* W. Tang et al.

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General response: We thank the anonymous reviewer for their supportive and valuable feedback, questions, and comments that help improve the quality of this manuscript. In the following, we are giving answers and explanations to their questions and comments. The text in the manuscript is revised and adapted in different places according to the reviewer's comments. Point-to-point responses to the comments are given below in red. And the modified text also mark in red in the revised manuscript.

1. The abstract discussion should also include the requirement of high temporal resolution of PWV maps for the application of weather modeling. Ans.: The main disadvantage of InSAR for water vapor mapping is that they refer to a temporal interval

depending on the revisiting period of the space-borne SAR satellite which in the case of ENVISAT is 35 days. With the launch of Sentinel-1A, every few days (12 days) a new SAR images can be acquired, this will improve the temporal resolution of InSAR-based water vapor maps. Text is added to the abstract in the revised manuscript.

2. The term dry delay is misnomer that is somewhat pervasive throughout the literature. The correct term is hydrostatic delay as this term also includes the contribution from the partial pressure of water vapor. Please change all instances of dry delay to hydrostatic e.g. p2: L18, L21, and many more. See Hansen (2001) p202 equation 6.1.8-6.1.9 for definition of the hydrostatic and wet delay, and also update k2-Rd/Rv*k1 to k2'. Ans.: The terms dry delay have been changed to hydrostatic delay in the revised manuscript. The term k2-Rd/Rv*k1 in equation (4) is equal to k2', we chosen not to update it in equation (4) but explained it in the text.

3. Throughout the text the term atmospheric noise or delay is used. This term groups tropospheric delay+ionospheric delay. Update equation (1) to include both terms and explain directly why the ionosphere can be neglected for most C-band studies. Ans.: Yes. We proposed to explain it in the text to make it more clearly and concisely.

4. Most of the occurrences of atmospheric delay throughout the manuscript should be changed to tropospheric delay, e.g. P2: L17, P4: L25, P5: L9: L14, and many more. Ans.: Modified.

5. Section 3.1: L25: Incorrect usage of atmospheric delay. This should be tropospheric delay, and equation (2) should be tropospheric delay = hydrostatic + wet + liquid. Elaborate why liquid component can be neglected. Ans.: Together with comment #3 above, text is added to explain this more clearly and concisely.

6. The authors refer to PWV maps as water vapour mapping. The latter refers to a 3D mapping of water vapour in throughout the atmosphere, while they are actually referring to it as 2D mapping of Precipitable Water Vapor. Therefore occurrences of water vapour mapping should be updated to PWV maps. E.g. P2: L12, L24, and many

more. Ans.: Agreed and revised.

7. p 5, L11-13: The hydrostatic component can be more than just a smooth gradient over the scene. It can introduce a spatially varying tropospheric signal. E.g. Bekaert et al., 2015 JGR. http://onlinelibrary.wiley.com/doi/10.1002/2014JB011557/abstract Ans.: Agreed and revised. At the scale of an interferogram (100 km$\times$100 km), the spatial variations of pressure are usually small (i.e., typically within an order of magnitude of 1 hPa), thus the hydrostatic delay is a long-wavelength (smooth) in space. However, in some cases it results in a spatially variable signal in the hydrostatic delay. This is why we use ERA-Interim model to predict and subtract this component of delay in our study.

8. Literature defines the PI factor as being $\sim$6.2, while in the manuscript a PI factor is defined as 1/Kappa. This is most confusing and needs to be updated throughout the text. E.g. Bevis, 1992 GPSM (equation 12); Bekaert et al, 2015 RSE; Walters et al., 2013 JGR http://radiometrics.com/data/uploads/2012/11/bevis_jgr92.pdf http://www.sciencedirect.com/science/article/pii/S0034425715301231 Ans.: Yes. Most literature define the PI symbol "Π" as the conversion factor from PWV to wet delay, it is confusing in my manuscript that I used it in the opposite way. I have revised and updated.

9. The authors use the ERA-I model to compute their Kappa factor. A discussion should be included on the spatial accuracy of their estimates. Does the timing accuracy of the weather model introduce a larger error than assuming an average value? If once takes the average of the spatial map one would get close to the default value again assumed in literature. Ans.: A constant value (PI=6.2 or Kappa=0.16) is often used for all the time and for the whole study area. But we have discussed in our manuscript that using a constant value is not appropriate for this study area (Section 3.2, Figure 3). Instead, we evaluate the weighted mean temperature T_m at each pixel of the radar scene using ERA-Interim to produce a map of the conversion factor κ. The outputs from ERA-Interim we used are the vertical profiles of temperature T and water vapor

partial pressure e, and use the most accurate way (equation (9)) to compute T_m and then computeκ. The accuracy of κ relies on the accuracy of the outputs of ERA-Interim. Another way to obtain T_m is to approximate T_m based on equation (8) with surface temperature T_s, this equation is an empirical formula (not accurate as equation (9)). We cannot use an approximate estimation to evaluate the accuracy of a more accurate estimation, and we do not have access to get the in situ atmospheric measurements in our study area. Therefore, we cannot provide a discussion about the spatial accuracy of κ factor from ERA-Interim in the manuscript.

Errors could be derived from using ERA-Interim data computed at a time that differs from the SAR passing time. In our study, the ERA-Interim outputs were taken at 18:00 UTC which is closest to the SAR acquisition time 18:01 UTC, so the time differences is negligible. The text in caption of Figure 3 is added to explain this error due to time difference.

10. p7 L8-10: The formulation does not seem to correct, it states that it assumes water vapour to be concentrated for the lower 1.4 km. However this is not an assumption from the cut-off. Are not all GNSS satellites within the cone field of view used to estimate the zenith wet delay over a given time window, by using mapping functions. If this is the case then it would not really be an average over the cone area. Ans.: Actually, zenith wet delay estimates from GPS are derived by combining all available observations in the cone above the receiver, weighted by the elevation and azimuth angles of the individual ray paths from the GPS satellites to the receiver. It was assumed that the main contribution to the GPS wet delay comes from the atmosphere within this cone. Since most of the water vapor is located near the Earth's surface, we can approximate the radius of the cone. This value was computed assuming a minimum GPS satellite elevation of 15° and a tropospheric scale height 1.4 km. The radius is 5.4 km in our study, and the phase pixels located within the circular area around the GPS station are averaged, so that measurements of wet delay from GPS and interferometric SAR may be compared consistently. Text is modified.

11. The processing description of the data needs to be expanded and more references provided. In specific the following items needs to be addressed: The envisat oscilator drift correction is not included or mentioned (Marinkovic and Larsen). The authors should make a reference of this problem and elaborate the impact on their results. P. Marinkovic and Y. Larsen, On Resolving the Local Oscillator Drift Induced Phase Ramps in ASAR and ERS1/2 Interferometric Data âĔŸAĔĞTThe Final Solution. Ans.: Oscillator drifts induce a systematic phase ramp in the interferogram, they have been removed in the time series interferograms by the script provided in StaMPS software. Revised these in the manuscript.

12. What is the coherence threshold that is used for the selection of the InSAR points. Has the data been processed with a time-series method? If so appropriate reference should be included. Ans.: We used StaMPS software to form the small baseline interferograms and select the stable points. Revised it in the manuscript.

13. Include the reference for SRTM (Farr et al, 2007): http://onlinelibrary.wiley.com/doi/10.1029/2005RG000183/abstract Ans.: The citation has been included in the revised manuscript.

14. P8: L27: Include a reference for the DORIS InSAR processor (Kampes, 2003): Kampes, B., R. Hanssen, and Z. Perski (2003), Radar Interferometry With Public Domain Tools, 6âAĔŸ L'pp., Proc. Fringe 2003 Workshop, Frascati, Italy Ans.: Revised.

15. Was the data processed from SLC level? If not a reference and explanation should be included how you did it. E.g. roipac? Ans.: We used SLC data in the study. I have revised it in Section 2 to explain this in the manuscript.

16. Is there a citation for the GNSS network, or those who maintained the network? Ans.: The GPS data is obtained from UNAVCO. We have provided the web site in the manuscript, but we do not have any publications for citing this data.

17. How was the MODIS data processed, was the TRAIN package used in its

calculation or processing? If so mention this and include reference to Bekaert et al, 2015, RSE. http://www.sciencedirect.com/science/article/pii/S0034425715301231 Ans.: I used MERIS data not MODIS in the study. Yes, I used TRAIN package to process the MERIS data. I revised and added the citation in the manuscript.

18. P3 L9: It is unclear if the average look angles is used to convert from zenith to pseudo-range. If an average is used, elaborate on the implication of your results. Ans.: Actually, the value of look angle θ varies over the acquisition from near range to far range between 16.5° to 23.2°. Accuracy may improve, if local look angle of every pixels within SAR scene is considered when calculating the mapping function. We used the average look angle in our study. Text is added to manuscript.

19. How is the PI factor included. Is it averaged for the 2 SAR acquisition. Please include this in the text. Also this could related to why figure 10 shows Gaussian residuals. Is this because on of the SAR dates has an incorrect PI factor estimated? Please include a paragraph on this in the discussion. Ans.: We averaged the spatial maps of Π at the two interferometric acquisition time to derive the conversion factors for mapping the wet delay from interferogram onto water vapor. The text is included in the revised manuscript.

In Figure 10, the PWV residuals between InSAR and MERIS follow a Gaussian distribution with a mean close to zero and a standard deviation below 2 mm, suggesting that this two data sets have similar probability distributions. In other words, the PWV maps derived from InSAR show strong agreement with the data from MERIS. We cannot expect a perfect agreement between them because there is noise in both data sets. And this is not because an incorrect PI estimation on SAR dates.

20. P10: L12: A citation is needed for the 0.16 gmĔĘ-2. Ans.: Revised. The citation is included in the revised manuscript.

21. Minor comments: - P2: L12, L19: The recent fleet of SAR satellites have swath up to 250 km. Mention this as this make it even more attractive for PWV application.

Ans.: Yes, Sentinel-1 provides SAR images with a wide swath up to 250 km. Revised to mention this in P2, L12. But in L19, we just described in the typical interferogram of the ASAR image used in our study. So we do not need to mention the wide swath of Sentinel-1 again in L19.

22. P2: L32: L-band platforms such as ALOS will experience an ionospheric delays. Therefore less preferred for this type of PWV application. Ans.: Yes, we agreed this comment. Ionospheric effects are caused by variations in free electrons along the travel path, resulting in a phase advance of the radar signal that becomes more significant for larger wavelengths (such as ALOS L-band SAR) and in the high latitude areas. Not all ALOS SAR images show a significant effects from ionosphere, and the ionospheric effects can also be mitigated using techniques developed in the literature (Chen and Zebker, 2014; Liu et al., 2014). So it is also possible for the application of mapping atmospheric water vapor, but need to account for the ionospheric effect carefully.

Chen, A. C. and Zebker, H. A.: Reducing ionospheric effects in InSAR data using accurate coregistration, Geoscience and Remote Sensing, IEEE Transactions on, 52, 60-70, 2014. Liu, Z., Jung, H.-S., and Lu, Z.: Joint correction of ionosphere noise and orbital error in L-band SAR interferometry of interseismic deformation in southern California, Geoscience and Remote Sensing, IEEE Transactions on, 52, 3421-3427, 2014.

23. P2: L18: in time and space while => in time and space, while Ans.: Modified.

24. P3: L8 mages => images Ans.: Modified.

25. P4: L15: deccorrelation => deccorrelation Ans.: Modified.

26. P4 L18: decribed in (Jolivet et al, 2011) => described in Jolivet et al (2011) Ans.: Modified.

27. P4 equation 3 and 4: Introduce lamba in the text as the radar wavelength. Ans.: Text is added.

28. P5 L5: . . . and the factor 1/theta => . . . and the factor -4pi/lambda is a scale factor to convert from pseudo-range increase to phase delay. Ans.: Modified.

29. Equation (5), suggest to change ZWD_insar to Delta ZWD to be consistent with Delta PWV. i.e. it becomes more obvious when substituting equation (5) into (6). Ans.: Agreed and modified.

30. P6: L1: introduction of w in equation is unnecessary. Keep it as rw/rd. Ans.: Modified.

31. P7: L1: reword sentence: temporal diff . . .. . . are not directly comparable -> PWV estimated from GNSS is not directly comparable with Delta PWV estimated from InSAR. Ans.: Modified.

32. P7: L25: include a reference in support of high accuracy retrieval of water vapour. E.g. Li et al 2003. Ans.: The citation is added in the revised manuscript.

33. P10 L10. . .. . . water vapor measurements => water vapor pixels. Ans.: Modified.

34. P11 L8: radar => Synthetic Aperture Radar Ans.: Modified.

35. Table 1: mater => master Ans.: Modified.

36. Table 2: include reference for coefficients. Ans.: The citation is added into the caption in Table 2.

37. Table 3. . .obtained by InSAR => . . . obtained by InSAR after calibration of offset using GNSS. Ans.: Modified.

38. Figure 1, 2: Indicate SAR LOS in figure and in caption Ans.: An arrow is added to indicate the LOS direction in Figure 1 and Figure 2.

39. Figure 2: replace: re-sampled to radar-coordinates => at interferogram pixels Ans.: Modified.

40. Figure 3: Indicate UTC time of satellite. taken at 18:00 => taken at 18:00 UTC

(close to the SAR acquisition time of XXX UTC). Ans.: Modified.

41. Figure 6: include a legend for the stations. Ans.: Figure 6 shows an example of the 24-hour time series of PWV from 29 GPS station at different dates which represents the four different seasons. The value of PWV is similar for most GPS stations in this area except the ones with high latitude, so we just indicate the WLSN station in the figure. It is unnecessary to distinguish each station and we can see that the lines in the figure almost overlap with each other.

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/amt-2015-391/amt-2015-391-AC1-supplement.pdf

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