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Dear Dr. Amiridis, Dr. Richter, Dr. Dave Adams and the anonymous reviewer,

Authors response to referees comments

The authors are grateful and thank the two reviewers, and specially Dr. Dave Adams for his review which improves the quality of this manuscript.

We have applied all the corrections suggested by Dr. Dave Adams (written in dark blue italic in the following text). Our replies to his questioning and our modifications applied to this manuscript are in regular font (in black). We also mention in regular font (in black) if we did not apply the suggested corrections, and explain why.

Referee #1 (D. Adams) review (Received and published: 31 December 2013):

General Comments

Brenot and co-authors have analyzed GPS data for a short-term (2 months) dense network of GPS receivers over Southeastern France to derive 3D water vapor fields using a tomographic inversion technique. The work aims at quantifying the error associated with the GPS technique for deriving water vapor fields with a particular focus on the dense network geometry. The authors take advantage of a collocated radiosonde and nearby weather radar to compare evolving water vapor fields during disturbed weather as reconstructed through the tomographic inversion technique. The work is important and publishable. A few minor points within the manuscript need to be clarified as well as some improvement of a couple of the figures.

Surprisingly, 3D water vapor fields research with GPS has advanced very little since its first inception around the early 2000's. Perhaps, the difficulty in constraining the water vapor fields from rather intermittent data will only lessen with the densification of GNSS satellite constellations. Hopefully, these authors and others will continue moving forward in this endeavor.

Major Comments

Equation 5 is not the typical meteorological definition of PWV. PWV is a measure (in mm or cm) of liquid water that could be condensed out of the atmospheric column. You have to divide through by the density of liquid water.

REPLY: text Pg 9521, line 9-10 has been changed to: "*Its expression is close to the integrated water vapour (IWV expressed in kg/m²). Considering a standard mean liquid water density for the vertical column (~1000 kg/m³),, this study assumes that IWV is equivalent to the precipitable water vapour (PWV expressed in mm).*"

Eq. 5 has been changed to:

$$IWV = \int \rho_V \, dz \sim PWV \qquad (5)$$

Pg 9523 "However, due to the exponential decrease of air density, most of the tropospheric variability is seen in the lower part of the troposphere, typically 2–3 km. " I think you mean here is that the water vapor scale height is about 2 to 3 km and this is what is important for the delay due to water vapor. The troposphere (the well-mixed dry components) has a scale height of 7 to 8 kilometers.

REPLY: thank for this correction. The text Pg 9523, line 20 has been changed to: "*However, due to the exponential decrease of air density, most of the tropospheric variability is seen in the lower part of the troposphere. The water vapour scale height is about 2-3 km.*"

Pg 9534. Section 5.2 I am a little confused as to why you convert to sea-level pressure first and then back to station height. Isn't it just the relative difference in height/pressure between sites that is important?

REPLY: You can (see Fig. 1 of the manuscript) the location of the meteorological data loggers. To obtain the pressures (and temperatures) at the locations of the GPS stations, as mentioned in the manuscript, all the pressures (and temperatures) have been converted to the same altitude (we choose the sea level), interpolated, and then back converted to the height of each GPS stations. You suggest to directly convert the measurements of the meteorological data loggers to the altitude of the selected GPS station. I agree that this approach looks more direct than what we have done, but the result is equivalent. To convince you of that, you can see on the following Fig. 1 the difference of PWV (interpolated image at 19H15 the 21st of October 2002) between a direct height conversion (your suggestion) and an indirect conversion (what we have done in this study). The difference is very close to zero (mean value of less than 0.0001 mm for all the pixels). The extreme value is obtained for AIGL station (located at 1619 m on the mount Aigoual). Nevertheless this difference is less then 0.0025 mm. To simplify and avoid the confusion, the text of the manuscript has been changed:

"The 5 meteorological stations deployed in the local network (Fig. 1) and measurements from the operational synoptic network (Météo-France) are used to estimate surface pressure at all sites by converting hydrostatically and interpolating the pressure measurements to the station heights."

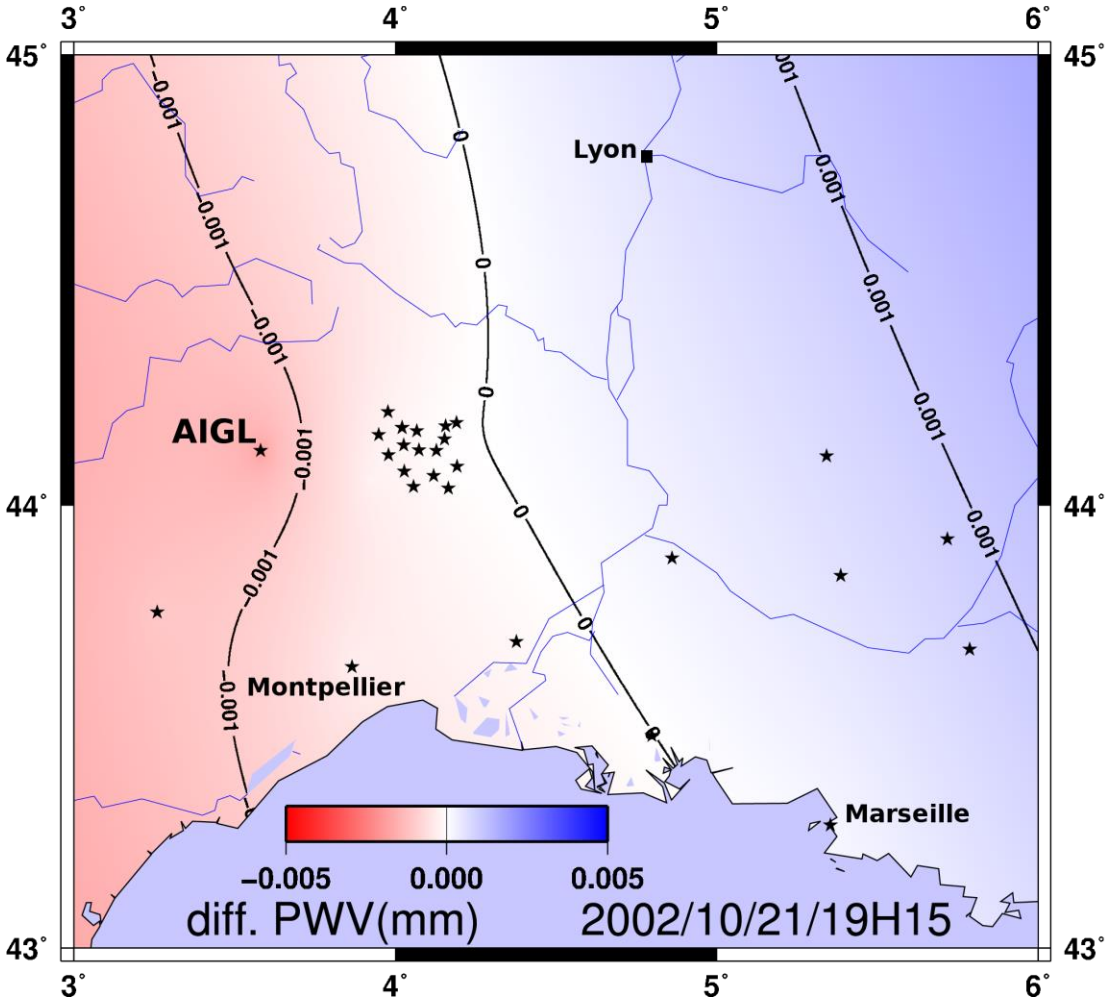

Figure 1: Difference of PWV from two different estimations of pressures at GPS stations.

Also, with your assumed lapse rate 6 C/km, you might what to mention the sensitivity of GPS PWV to surface temperature. I assume it's not very large.

REPLY: The surface pressure is the key parameter for the estimation of PWV. The influence of the surface temperature is less significant. A linear temperature gradient of 6°C/km is commonly used in meteorological applications.

Pg 9540 m_0 (g m^{-3}), what is this first guess? An exponential decrease with a scale height of about 2.5km? How sensitive is your final vapor fields to this initial guess? This is probably the most important point that needs to be clarified.

REPLY: Text Pg 9540 line 24 has been modified:

"first guess that is needed in order to solve underdetermined problems. This first guess is an exponential decrease based on standard atmospheric values adjusted with the average IWV measured by GPS throughout the domain. Note that the tomographic retrievals are sensitive to this first guess showing an uncertainty up to 2 g/m3 for the low troposphere (Reverdy, 2008)."

Technical comments.

Abstract Line 13. Change to: Also, the dense local network provided data which have been inverted using tomographic techniques to obtain the 3-D field of tropospheric water vapour content.

Line 16. This is unclear. What are "the optimal tropospheric GPS retrieval methods, "?
Do you mean "using optimal tropospheric GPS retrieval methods"

REPLY: Yes, text changed to "Using optimal tropospheric GPS retrieval methods, ..."

pg 9517
Line 1. Change to: "Within the OHM-CV framework, we completed the available measurements of humidity in a very significant way using GPS observations ..."
Line 5. Change to: " ...radiosonde measurements or water vapour radiometers (within 1 to 2mm of precipitable water)"

Line 15-20. You should probably be a bit more consistent as to how you term the dense network (18 stations #30 km x 30km).

REPLY: OK, text has been modified

"In addition, to study the fine-scale variability of the water vapour field within the precipitating system regions, we set up a very dense network of 18 stations (covered an area of 30 by 30 km) to retrieve the three dimensional water vapour field by tomographic inversion techniques."

When you say tomographic network, does it mean only these 18 stations or do it include the larger network with permanent stations?

REPLY: It includes also the larger network. Nevertheless, the mean distance between each GPS station is about 5 km in the dense network, which allows a well-coverage of the area. By comparison, RENAG/IGN GPS stations (large network) are 50 km spaced.

Pg 9518
Line 4 Change to: "...field evolution and the rainfall estimation provided..."
Line 5. Change to: "...water vapour in the convective system's life cycle." I think this is what you want to say.

REPLY: Yes, thanks.

Line 6 Change to: " ...21st of October..."

REPLY: Such change has been applied in all the manuscript.

Pg 9519
Line 3 "excluding any instrumental drifts." This is a bit unclear, what are you referring to?

REPLY: text has been modified
"Effectively, GPS ZTD measurements are based on the exploitation of propagation delays excluding any instrumental drifts (contrary to other sensors like spectrometers onboard polar orbiting satellites)."

Line 5 "However, the effect on the tropospheric parameter estimates is limited as an error in the vertical positioning is down-weighted by a factor of about 3 for the tropospheric parameter estimation" This sentence is unclear, please clarify what you mean by "down-weighted by a factor of about 3 for the tropospheric parameter estimation"

REPLY: This means that in the process of adjustment to estimate the vertical position and the tropospheric parameters, the error of the vertical position is about 3 times more important than the error of the tropospheric parameters: *"error in the vertical positioning is down-weighted by a factor of about 3 for the tropospheric parameter estimation"*

Line 8. I suspect readers will not know what "major ocean loading component M2" is.

REPLY: The text has been modified
"(mainly induced by the amplitude of the major ocean loading component that is related to the semi-diurnal lunar tides, so-called component M2)"

Line 18. Change to: "ground-based" and throughout

I think after each of your points a), b), c), you should probably use a comma or semicolon, not a period, since it is all one idea.

REPLY: OK, the text has been modified

"The main applications of tropospheric water vapour estimates from ground-based GPS data are:

- *The analysis of meteorological events from post-processed GPS data (e.g. Bock et al., 2004; Walpersdorf et al., 2004; Brenot et al., 2006; Van Baelen et al., 2011; Labbouz et al., 2013) and process-oriented studies (such as understanding the fundamentals of deep tropical convection, see Adams et al., 2013)*

- *Climatological applications by post-processing long time series of data with the same coherent analysis strategy (e.g. Wang et al. 2007; Sguerso et al., 2013)*

- *The assimilation of ZTD in operational numerical weather prediction (NWP) systems (e.g. Gutman et al., 2004; Bennitt and Jupp, 2012) and the use of GPS observations by forecasters (such as an indicator of deep convection, see Brenot et al., 2013). The operational applications require near-real time analysis of the data, done by downloading hourly data followed by a time optimised processing to provide tropospheric parameters with a latency of 1 hour (EC COST 716/MAGIC/TOUGH recommendations (Elgered et al., 2001; Van der Marel, 2004; Guerova et al., 2006) and the EUMETNET GPS Water Vapour project (E-GVAP; Haan et al., 2006))*

- *Tomographic inversion of line-of-sight tropospheric delays to establish 3D water vapour fields. This tomographic technique has the potential to provide atmospheric water vapour fields with a horizontal resolution of several kilometres, a vertical resolution of 500 m in the lower troposphere and 2 km in the upper troposphere, and a time resolution of 15 minutes, but it requires a dense homogeneously distributed network of GPS stations. First comparisons of tomographic observations with other measurement techniques (WVR, radiosondes) and with meteorological models give encouraging results (Elgered et al., 1991; Gradinarski, 2002; Gradinarski and Jarlemark, 2004; Champollion et al., 2005; Bastin et al., 2005; Troller et al., 2006; Perler et al., 2011; Van Baelen et al., 2011). However, to obtain the indicated resolution, the tomographic inversion requires data from a dense network of GPS stations (5 – 25 km spacing), possibly with stations at different altitudes. This calls therefore for dedicated networks. The permanent GPS networks currently available in France provide about one station each 50 km."*

Line 21 Change to: "and process-oriented studies"

Page 9520
Line 4. For clarity, I would write "This latter technique ..." or "This tomographic technique..."

REPLY: "*This tomographic technique*" has been written

Line 5 Change to: "horizontal resolution of several kilometers,..."
Line 6 Can you be more precise on the vertical resolution?

REPLY: This is 500 m in the lower troposphere and 2 km in the upper troposphere

Line 19. Change to: ground pressure to surface pressure (here and throughout)
Pg 9523
Line 4. Change to: "For that study, the tomographic routine (LOFFTK) was employed for the GPS inversion."
Line 5. This is a little unclear "Based on this experience, a new software, called TSAAR (Tomography Software for wAter vApor Retrieval) has been developed by the authors." Do you mean TSAAR is based on or a modified version LOFFTK developed by the present group of authors?

REPLY: Yes. TSAAR is based on LOFFTK as the general inversion equations are from the same references. However, LOFFTK used strong outside constraints as first guess to carry out the inversion (radiosondes). As a result, the GPS data have low impact on the final water vapour field results. TSAAR has been developed to work solely with GPS data without using any external water vapour information to see how much could be extracted from GPS alone.

Line 7 Change to: "A full series of tests and validations are presented ..."
Line 9. Change to "TSAAR will be used ...."

Pg 9524
Line 3. Change to: "...completed by 5 meteorological data loggers ..."

REPLY: OK. Note that the caption of Fig. 1 has been also modified.

Line 11 Change to: "Therefore, ...

Pg 9526
Line 4 Write "from the 20th to the 22cd of October 2002"

Line 21 This is unclear.

"The choice of the geometry of the network has also shown some results about the uncertainty of the two components (NS, EW) of horizontal gradients."
Do you mean horizontal gradients are shown throughout the results of this study to be sensitive to the geometry of the network?

REPLY: Yes. This is why for an optimal estimation of gradients, we suggest sub-networks with regular sub-sampling of the whole network.

Pg 9528
Line 3 Change to; "We tried to identify a more appropriate reference frame..."

Pg 9530
Line 10. Change to: "For three days from the 20th to the 22cd October 2002,... "

Pg 9531
Line 4 Change to: "In this section, ..."
Line 24. Define doy

REPLY: text modified.
(16h – 04h UTC on day of year (doy) 300-301 and 0h – 12h UTC on doy 305, respectively)

Pg 9533
Line 9 Change to: "the signal due to the underlying topography prevails over ..."

Pg 9539
Line 9. Change to: "...widely used in the literature."

Pg 9542
Line 16. Change to: "network for the 21st of October 2002" And throughout. Or October 21st, 2002

REPLY: All the date has been modified in the text of the manuscript and the caption of figures (e.g. 20 to 22 October 2002; The 21st of October 2002).

Tables and Figures
Figure 1 Change "temporal" to "temporary"

REPLY: OK Fig. 1 changed, and temporal station replaces by temporary station in all the manuscript.

Figure 3 is very hard to see. I have it magnified to 300% and it's still difficult. Can you maybe just do 4 stations?

REPLY: For the edition on AMT, Fig. 3 should take the whole page and be clear enough for the reader. We prefer to keep the 6 stations (4 temporary stations at each edge of the local network, 1 temporary regional station, and 1 permanent station). If needed, this figure can be cut in two part in two different pages.

Figure 15 is too small also. Is the last column d of the vertical profiles really revealing?

REPLY: The interest of tomography is to provide 3D information. If we cut the column d) the vertical information is lost. We prefer to keep it. For the edition on AMT, Fig. 15 should take the whole page and be clear enough for the reader. If needed, this figure can be cut in two parts in two different pages.

Note that the caption of Fig. 12 has been modified:

Figure 12: Instantaneous 2D field of zenith delay variation (October 21th, 2002, at 19H15 UTC), interpolated from measurements at GPS station locations uncorrected (a) and topography-corrected (b and c) for station altitude by subtracting the average ZTD over the two months measurement campaign. The ZTD field (b) is established without and (c) with integrating horizontal delay gradients. Site locations are indicated by stars, vectors correspond to horizontal gradients (scale vector corresponds to 0.01 m). The colour code indicates ZTD variations in m.

Anonymous Referee #3 (received and published: 8 January 2014)

publish as is

Thank you for your corrections which help,

Yours faithfully,

Hugues Brenot