Interactive comment on “On the inclusion of GPS precipitable water vapour in the nowcasting of rainfall” by P. Benevides et al.

Anonymous Referee #1

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This paper is well organized and written, and can be published after minor revisions, althougth more data in more locations are needed to provide more promising conclusions. Some minor suggestions/comments can be found in the annotated manuscript file.

Please also note the supplement to this comment:

http://www.nat-hazards-earth-syst-sci-discuss.net/3/C1802/2015/nhessd-3-C1802-2015-supplement.pdf

1- P.3862 L.24 (introduction)

For your information, recently, some new studies about new satellite systems and multi-GNSS water vapor:

Li, X., F. Zus, C. Lu, G. Dick, T. Ning, M. Ge, J. Wickert, and H. Schuh (2015), Retrieving of atmospheric parameters from multi-GNSS in real time: Validation with water vapor radiometer and numerical weather model. J. Geophys. Res. Atmos., 120, 7189–7204. doi: 10.1002/2015JD023454.

Xingxing Li, Galina Dick, Cuixian Lu, Maorong Ge, Tobias Nilsson, Tong Ning, Jens Wickert, Harald Schuh: *Multi-GNSS meteorology: Real-time retrieving of atmospheric water vapor from BeiDou, Galileo, GLONASS and GPS observations*. IEEE Transactions on Geoscience and Remote Sensing 06/2015; DOI:10.1109/TGRS.2015.2438395

Generally about new satellite systems and multi-GNSS water vapour, the following text was added (P.3863-L.9):

‘It is also expected that with the improvement of the current GNSS systems and the development of future new ones, this technique should provide more refined information about the atmospheric state, allowing also an interoperability in what concerns the water vapour estimation through multi-GNSS processing techniques (Li et al., 2015a) and multi-sensor approaches as SAR (Benevides et al., 2015).’

Development of these topics is performed in your comment #3.

2- P.3863 L.18

You talk about nowcasting, maybe high temporal resolution and low latency (e.g. real-time) is important, you can discuss about real-time water vapor. FYI,

Dousa, J. and P. Vaclavovic (2014), Real-time zenith tropospheric delays in support of numerical weather prediction applications, Adv Space Res, 53(9), 1347-1358.

Li, X., G. Dick, M. Ge, S. Heise, J. Wickert, and M. Bender (2014), Real-time GPS sensing of atmospheric water vapor: precise point positioning with orbit, clock and phase delay corrections, Geophys. Res. Lett., 41(10), 3615–3621.

The following text has been included in P.3863 L.18:

‘Some studies revealed the potential of the GNSS meteorology to analyse the water vapour distribution at near real time and its applicability for weather nowcasting (Haase et al., 2003; Brenot et al., 2006; Yan et al., 2009; Karabatic et al., 2011). Assimilation of GPS derived water vapour data into weather forecast models has already been studied, resulting in better forecast of severe rain events (Vedel et al., 2004; Cucurull et al., 2004), even at a convective scale (Yan et al., 2009). The technique allows to estimate water vapour measurements with high sampling rate with less than 1 hour of temporal delay. However a major drawback is the estimation of the near real time satellite orbit with high accuracy, which has an impact on the GPS atmospheric measurements (Karabatic et al., 2011). Nevertheless recent developments have improved the GPS PWV precision through near real time orbit, clock and phase delay corrections, using a large network of stations and multi-GNSS processing techniques (Li et al., 2014; Li et al., 2015a).’

Reference regarding PWV 1 to 2 mm precision added in P.3865, L5: (Li et al., 2014), but part of the text was modified and moved to the end of section 2.

3- P.3864 L.9

Now BeiDou is providing service since the end of 2012. Galileo also have several satellites are in orbit. Some discussions can further improve the manuscript. FYI,

Montenbruck, O., P. Steigenberger, R. Khachikyan, G. Weber, R.B. Langley, L. Mervart, and U. Hugentobler (2014), IGS-MGEX: preparing the ground for multi-constellation GNSS science, Inside GNSS, 9 (1), pp. 42–49.

Li, X., X. Zhang, X. Ren, M. Fritsche, J. Wickert, and H. Schuh (2015a), Precise positioning with current multi-constellation Global Navigation Satellite Systems: GPS, GLONASS, Galileo and BeiDou. Sci Rep., 5, 8328.

Li, X., M. Ge, X. Dai, X. Ren, M. Fritsche, J. Wickert, and H. Schuh (2015b), Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo. J Geod., 89(6), 607-635.

Sentence in P.3863, L9-10 was removed and a new paragraph is inserted, following P.3864 L.24:

‘In addition to GPS, the most popular GNSS systems are GLONASS, BeiDou, and the future Galileo. The availability of multi-GNSS sensors represents an opportunity to improve the precision and reliability of GNSS measurements, including the atmospheric water vapour sensing. The multi-GNSS data processing increases the number of satellite observations throughout the atmosphere, improving the geometry, the processing time, the redundancy, and consequently the robustness of the integrated water vapour measurements (Li et al., 2015a, Benevides et al, 2015b). In particular, the new signals frequency provided by the GPS modernisation and the future Galileo will result in better ionospheric noise estimations reducing the tropospheric delay error (Karabatic et al., 2011). Nevertheless, currently BeiDou and Galileo are not at their full potential affecting the technique performance in some regions, and most of the GNSS receivers have to be updated in order to collect data from all of the present systems, implying that this technique has room to evolve in the coming years.’

4 – P.3865 L.18

As you mentioned, horizontal gradients may have stronger correlation with rainfall than vertical PWV? The correlation between high-resolution gradients and rainfall can be discussed or investigated in the near future? FIY,

Li, X., F. Zus, C. Lu, T. Ning, G. Dick, M. Ge, J. Wickert, and H. Schuh (2015c), Retrieving high-resolution tropospheric gradients from multiconstellation GNSS observations, Geophys. Res. Lett., 42, 4173-4181, doi:10.1002/2015GL063856.

We agree entirely and that is something to explore in future work, namely in cases where the vertical structure of the water vapour field can be assessed.

Nevertheless some considerations about this topic are provided in the answer to your comment #8.

5 – P.3865 L.25-26 (chap 2) remove 'double difference'

Corrected.

6- P.3870 L-15 (chap 4)

What about the latency of ECMWF reanalysis? For nowcasting (e.g. real-time or near real-time), do you have suggestions?

Ideally GNSS stations for nowcasting should have pressure, temperature and humidity sensors coupled, in order to calculate the ZHD at real time with sufficient precision and reasonable *a priori* ZWD. Otherwise, these meteorological values could be extracted from NWP models (ex: Era-Interim) and interpolated to the GPS geographical height and location.

But the main issue in this is the precise orbit determination, which has a latency of several days. Therefore the following text was included at the end of section 2 (P.3868):

'As for the estimation of the PWV in near real time for nowcasting proposes, a compromise in the GPS processing between the adoption of ultra-rapid orbits and its coarser precision has to be taken into account (Byun and Bar-Sever, 2009). Furthermore, the application of precise point position GPS processing instead of a network solution speeds up the processing time, but at the cost of degrading the PWV accuracy up to 2 cm (Karabatic et al., 2011).'

7- P. 3878 l.10 (final chap 5)

From my point of view, the analysis in this manuscript is very good. Yes, as you mentioned, more data in more locations are needed to provide more promising conclusions.

The analysis of more data in different locations with distinct climatological characteristics is feasible and should be exploited in future work, since the paper at this state is relatively large, and the inclusion of more data analysis would enlarge it too much (more text and mainly more figures).

8 – P.3878 l.23 (chap 6)

Please have some discussions or comments about "high-resolution gradients for nowcasting" or further studies in the future.

Recent rapid development of GNSS multi-constellations bring significant potential for high-resolution gradient estimation:

Li, X., F. Zus, C. Lu, T. Ning, G. Dick, M. Ge, J. Wickert, and H. Schuh (2015c), Retrieving high-resolution tropospheric gradients from multiconstellation GNSS observations, Geophys. Res. Lett., 42, 4173-4181, doi:10.1002/2015GL063856.

In this work, the 2D PWV map shown on Figure 8 is produced only with integrated PWV values derived from ZWD, i.e., not using any zenithal tropospheric gradients. We use the inverted weighted distance algorithm to generate a surface, interpolating the PWV values from each of the stations displayed in Figure 1 (left).

However, this sentence was added to the text (P.3879 l.10):

'For example, the use of accurate high-resolution tropospheric gradients from multi-GNSS processing could allow to identify more clearly strong humidity gradients in severe weather situations (Li et al, 2015b).'

The following references were included in the document:

Li, X., Dick, G., Ge, M., Heise, S., Wickert, J., and Bender, M.: Real-time GPS sensing of atmospheric water vapor: precise point positioning with orbit, clock and phase delay corrections, Geophys. Res. Lett., 41(10), 3615–3621, 2014.

Li, X., Dick, G., Lu, C., Ge, M., Nilsson, T., Ning, T., Wickert, J., Schuh, H.: Multi-GNSS meteorology: Real-time retrieving of atmospheric water vapor from BeiDou, Galileo, GLONASS and GPS observations, IEEE Transactions on Geoscience and Remote Sensing, doi:10.1109/TGRS.2015.2438395, 2015.

Li, X., Zus, F., Lu, C., Ning, T., Dick, G., Ge, M., Wickert, J. and Schuh, H.: Retrieving high-resolution tropospheric gradients from multiconstellation GNSS observations, Geophys. Res. Lett., 42, 4173-4181, doi:10.1002/2015GL063856, 2015b.