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Interactive comment on "GPS-PWV jumps before intense rain events" *by* Luiz F. Sapucci et al.

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Response latter for Referee 2

General comments from Referee#2

The manuscript presents the behavior of GPS-PWV time series during severe precipitation events recorded by an X-band Radar during the CHUVA Vale measurement campaign in 2011. GPS-PWV jumps have been detected between 32 and 64 minutes before the more intense rainfall events. The statistical characterization of this phenomenon has potential for nowcasting. The reasoning of the paper is based on a

wavelet analysis of the GPS-PWV times series and on GPS-PWV derivative analysis and distinguishes meteorological events into 3 classes of precipitation. The main value of the article is to focus on the behavior of PWV during intense weather events, expecting to improve their forecasting. However, the article contains a number of imprecision that are important to dissipate : too many repetitions, a presentation that deserves to be more rigorous, more structured, more synthetic on the basic methodology and more explicit on the work done:

- 1. The presentation of GPS data processing is only too partial and often confusing.
- 2. The use of GPS-PPP times series sampled at 1-min intervals is interesting but the manuscript did not present well which specific PPP products were used to get it.
- 3. The use of wavelet analysis is interesting only for part "3.2 Wavelet cross-correlation analysis" even if shown correlations seem to be weak (figures 5 and 6). Part 3.1 "Wavelet power spectrum analysis" is the effect of the GPS-PWV jumps, a well know wavelet power spectrum of a Dirac function. Part 3 and 4 should be merged : part 3.1 for presenting the GPS-PWV jumps and part 3.2 for presenting time lag correlation.
- 4. Part 4 is really interesting and could be more developed. However, the criterion on GPS-PWV derivative > +9.5 mm.hËĘ(-1) and < -9.5 mm.hËĘ(-1) to characterize extreme weather events is not enough analyzed.

About GPS data processing Part "2.2 High temporal resolution GPS-PWV time series" is too confusing and must be structured and clarified: - Orbit and clock data products : what kind of products did you use ? What is the sampling of these products ? Orbit and clock data products from JPL for PPP applications are sampled at 5 minutes (https://gipsy-oasis.jpl.nasa.gov/index.php?page=data). This point determines the rest : I would like to be sure that the final sampling rate of the GPS-PWV values is really 1 minute, as usual. If you made a specific processing, you have to present it and made a comparison with a standard GPS data processing. - Elevation-Dependent Weighting used for GPS observations (constant ?, elevation dependent (aËĘ2/sin(elev)ËĘ2) ?) - Tropospheric models used : ZHD a priori (Is it GPT ?), ZWD time evolution constraint as a random walk ? Were tropospheric gradients estimated ?

Response: The presentation of the methodology and of the results analysis in the previous version of the work was significant improved taken into consideration the comments, suggestions and corrections pointed by reviser. Several imperfections and mistakes was corrected, particularly in the GPS data processing section, which was rewritten with more rigorous and structured way to present the work done. The main aspects treated in the manuscript in function of reviser's comment are:

- I. The bibliographic revision of previous work about the subject of this manuscript (in the introduction section and other parts of text) was improved and many phrase were rewritten. A total of 11 new papers was included, as suggested by reviser, and some important information from these mentioned references were included in the text.
- II. The manuscript was restructured and several section was rewritten. The GPS-PWV jump was moved to before wavelet analysis and parts of the section 3 and section 4 were merged, as well suggested. This restructure of the manuscript required very hard work and all sections had to be revised.
- III. The methodology used in the GPS Data processing to generate the PWV values in high temporal resolution was better described in the 2.2 section of the new version of manuscript, This section was totally rewritten and more details

about the GPS data processing was included. All items pointed by reviser were taken into consideration: a new table was included to organize these information.

- IV. GOA-II software was extensively explored to obtain the ZTD estimates in high temporal resolution and the configuration used here is the same suggested by JPL (default). The GOA-II, acronyms of GPS-Inferred Positioning SYstem (GIPSY) and Orbit Analysis Simulation Software (OASIS) software re-sampling the GPS satellite ephemeris using OASIS package which starts from specified initial orbits from JPL and uses several force models to integrate the dynamic equation to produce the orbit of the each GPS satellite.
- V. Incomplete information about the GPS antenna calibration was corrected following the observations and suggestions done by reviser. We used the phase center variation model for satellite and receivers antenna and the references were updated. Information about the kind of GPS antenna used in the CHUVA-VALE was included in the section 2.1.
- VI. We agree that the description of the methodology applied in the wavelet analysis was very poor in details. It was rewritten in new section 4 and information about the discrete and continuous wavelet are included.
- VII. The analysis of GPS-PWV derivative results were improved with the inclusion of a new figure and the derivative above +9.5 mm.hËĘ(-1) were better characterize during extreme weather events (upper tercile).
- VIII. Information about the stochastic model used in the data processing were presented, as well as information about azimuthal gradient estimation, and the constrains of the temporal evolution of these parameters. The used values were the default values suggested by JPL, which can impact the variability of the PWV estimates in high frequency and other values should be tested ahead in this research.

Other minor corrections were done and imperfection removed, based in this rigorous and detailed revision presented by referee 2, which was very important to better organizing the methodology employed in the data processing and emphasize the results obtained in this research. Specific comments point-by-point are presented below. The numbers (in the new version of the manuscript) of the changed lines and respective page in each point are listed and highlighted in green.The numbers of figure in the response refer to 13 figures of the new version of the manuscript.

Specific comments

Page 1:

1) **Referee#2:** line 23: "an unconventional solution" This is a usual method to get PWV and it has been validated for some time now.
P1L24 Response: Evaluating of the reviser's point of view, we are agree that the term "unconventional" is not appropriated and it was changed by "indirect", which express the organized idea in the next phrases in the manuscript.

2) **Referee#2:** line 24: "delay is associated with the atmospheric density (i.e., temperature, pressure and water vapor)" Explanation too confused: the magnitude of this delay is related to the integral of the refractivity index of the air as a function of temperature, pressure and water vapor (Bevis et al. 1992) on the optical path followed by the GNSS signal.

P1L25-L26 Response: The phrase suggested by reviser was included in the manuscript replacing the mentioned phrase.

3) **Referee#2:** Explanation line 25-27 is too expeditious. - lines 25-26: "with an error of approximately 5% under all weather conditions (Wolfe and Gutman 2000)" The given reference is outdated using old version of GPS data processing software, relative calibrations of antennas etc. The evaluation of the accuracy of GPS-PWV at around 5% should also be given in millimeter. The accuracy of GPS-PWV estimates remains a active topic of research, especially during severe weather conditions when all other meteorological instruments are down. - lines 26-27 "and in near real time (Rocken et al. 1994)." Outdated reference that could be used to put into perspective the improvements made since. It could be very interesting to emphasize on the methodological improvements made from 2000 and the first utilization of the GPS-PWV estimate until now. (Guerova et al. , 2016) ! Guerova G, Jones J, Dousa J, Dick G, De Haan S, Pottiaux E, Bock O, Pacione R, Elgered G, Vedel H, Bender M (2016) Review of the state-of-the-art and future prospects of the ground-based GNSS meteorology in Europe. Atmos Meas Tech Discuss. doi:10.5194/amt-2016-125
P1L29-L30 P2L13-L15 Response: The referee is right, the retrospective about the evolution of the GPS-PWV estimates was very simplified and many important work are not mentioned. We included some information about the evolution of the GPS data processing, which has been minimized the uncertainty and improvement in the accuracy of this estimates has been obtained. The more recent works from Moore et al. (2015) and Shangguan et al. (2015) were included. We agree that is interesting to emphasize the improvements of this technique and its potential for nowcasting applications and to do this we used the results presented by Guerova et al. (2016), as suggested.

4) **Referee#2:** line 31: "high temporal resolution (minutes)." I know it is not easy to present it but this formulation hides many methodological points about the method-

ology of GPS data processing: zero, single, double difference analysis or PPP, the different ways to model ZWD in analysis: : : The easiest way to get high temporal resolution (minutes) on GPS-PWV estimates is the PPP strategy (Zumberge et al, 1997) ! Zumberge, J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb (1997), Precise point positioning for the efficient and robust analysis of GPS data from large networks, J. Geophys. Res., 102(B3), 5005–5017, doi:10.1029/96JB03860.
P2L1 Response: This reference was included in the manuscript after the phrase "high temporal resolution (minutes)" as well suggested by reviser. This reference is very appropriated to simplify the methodology involved GPS data processing in solution with high temporal resolution. The methodology used in the GPS data processing in this study is based on Precise point positioning (PPP) using the GOA-II software. More details about this process were included in the section 2, following the recommendation from reviser.

5) **Referee#2:** Page 1 Line 31 ! page 2 line 1: "Other promising applications become viable in dense networks and transects": using dense networks to do tomography is not a "promising application" even if it remains methodological issues (e. g. Champollion et al. (2005); Bastin et al. (2005); Brenot et al. (2014)) ! Bastin, S., C. Champollion, O. Bock, P. Drobinski, and F. Masson (2005), On the use of GPS tomography to investigate water vapor variability during a Mistral/sea breeze event in southeastern France, Geophys. Res. Lett., 32, L05808, doi:10.1029/2004GL021907. ! Brenot, H., Walpersdorf, A., Reverdy, M., van Baelen, J., Ducrocq, V., Champollion, C., Masson, F., Doerflinger, E., Collard, P., and Giroux, P.: A GPS network for tropospheric tomography in the framework of the Mediterranean hydrometeorological observatory Cévennes-Vivarais (southeastern France), Atmos. Meas. Tech., 7, 553-578, doi:10.5194/amt-7-553-2014, 2014. ! C. Champollion, F. Masson, M.-N. Bouin, A. Walpersdorf, E. Doerflinger, O. Bock, J. Van Baelen, GPS water vapour tomography: preliminary results from the ESCOMPTE field experiment, Atmospheric

Research, Volume 74, Issues 1–4, March 2005, Pages 253-274, ISSN 0169-8095, http://dx.doi.org/10.1016/j.atmosres.2004.04.003.
P2L5-L10 Response: The term "promising" was removed of this phrase, and works about the tomography were included in the new version of the manuscript, mentioning the application and localization of the experiments, as well suggested.

Page 2:

6) **Referee#2:** line 3: "the diurnal cycle": more discussion about meteorological processes who have been detected according to areas? (For West African Monsoon, Bock et al. (2007)) ! Bock, O., F. Guichard, S. Janicot, J. P. Lafore, M.-N. Bouin, and B. Sultan (2007), Multiscale analysis of precipitable water vapor over Africa from GPS data and ECMWF analyses, Geophys. Res. Lett., 34, L09705, doi:10.1029/2006GL028039.
P2L4-L13 Response: This phrase was rewritten and all references were chronologically organized and associated with the meteorological process evaluated and the area of study were mentioned. Bock et al. (2007) was included because this paper presents an important study in a region with poor humidity data base.

7) **Referee#2:** About §2 (lines 5-12) and §3 (lines 13-22): Is it possible to merge §2 and §3 to emphasize on links between PWV, deep convective activity and the occurrence of intense rainfall?
P2L17-L18 Response: These paragraphs were merged to emphasize on links between PWV, deep convective activity and the occurrence of intense rainfall. The reference Muller et al. (2009) was explored, which presented a model for this relationship.

8) **Referee#2:** line 7: "PWV data from a microwave radiometer (MWR) with high temporal resolution" Provide an order of magnitude.

P2L19 Response: This phrase was rewritten following the recommendation pointed by reviser in the next specific comments. The resolution was included. Really Miller et al. 2009 did not use MWR data.

9) **Referee#2:** Line 8: Wrong reference with Muller et al. (2009) who do not used MWR-PWV data. However, it remains interesting to provide a reference in the article about relationship between the PWV and tropical precipitation.

P2L17-L18 Response: This phrase was rewritten, the mistake about the MRW-PWV data was removed, and the reference was maintained to provide a reference about relationship between the PWV and tropical precipitation, as suggested.

10) **Referee#2:** Line 8: Using "Chan 2009" can be useful to discuss about differences between MWR-PWV and GPS-PWV during severe weather events (see in particular the interesting §3.3 Comparison with GPS receivers of the article).

P2L22-L23 Response: We agree that is important shows a discuss about differences between MWR-PWV and GPS-PWV during severe weather events. A comment about the results reported by Chan (2009) was included.

11) **Referee#2:** Line 9: "useful indications of the accumulation of water vapor" : be more specific, in which these indications are useful ?

P2L22 Response: This phrase "useful indications of the accumulation of water vapor" was deleted because are not important in the context.

12) **Referee#2:** Line 14: "Mazany et al. (2002) developed a lightning prediction index for Florida based on the GPS-PWV magnitude and its temporal evolution": if this index is interesting, can you write more about it?

P2L28-L30 Response: More information about this GPS application was included in the manuscript.

13) **Referee#2:** Line 19: "This study showed that prior to deep convective events in the central Amazon, a 4-hour “ramp up” in the time derivative of GPS-PWV is observed, reaching a maximum approximately one hour before heavy precipitation. This sentence should be in the next paragraph to better distinguish results from precedent studies and results of the article. It is a repetition of sentence line 26-27 "The sharp increase in the GPSPWV values approximately one hour before the occurrence of more intense rainfall events, as found in this study and that of Adams et al. (2013)" and should be merged with it.

P3L3 Response: The phrase was moved for the next paragraph and adapted as suggested. The second mentioned phrase was rewritten to avoid inconsistency.

Page 3

14) **Referee#2:** line 8: "The CHUVA Vale campaign was carried out in São José dos Campos in São Paulo State in an elevated valley between the Mantiqueira and Serra do Mar mountain ranges." Add the reference of fig.1 given line 23: "Fig. 1 shows the geographic location of the CHUVA Vale campaign, emphasizing the sites at which the instruments were placed."

P3L28-L29 Response: A reference to Fig.1 was included in this sentence, as suggested. The geographic coordinates were added following the recommendation from reviser 1 (see specific comments 4-Referee1).

15) **Referee#2:** line 11: "During the CHUVA campaigns," Too many repetitions.

P3L30 Response: This phrase was completely removed following recommendation from reviser 1 to avoid this repetition (see specific comment 4-Referee1).

16) **Referee#2:** Lines 11-14: "GPS meteorology was used to monitor the horizontal and temporal variations in the PWV associated with the wide variety of convection-producing mechanisms for the 6 geographic regions. For example, Adams et al. (2015) described the temporal and spatial evolution of tropical sea-breeze convection with GPS meteorological transects during the CHUVA-Belem field campaign." Of topics in this part : be more concise. You can eventually add this point in your introduction part. You speak about "6 geographic regions" without using it after.

P3L30 Response: This first phrase about the different regions observed by CHUVA campaign was excluded of the manuscript, and the second was moved for introduction section, as suggested.

17) **Referee#2:** line 23: "Fig. 1 shows the geographic location of the CHUVA Vale campaign, emphasizing the sites at which the instruments were placed." See comments about line 11.

P4L7-L8 Response: This phrase was rewritten following the recommendation in this item and your comments about the line 11 in the item 14, excluding the repetitions.

Page 4

18) **Referee#2:** subsection "2.2 High temporal resolution GPS-PWV time series" is too confusing and must be structured and clarified.:

- GPS data of receiver sampled at one second frequencies ! under-sampling ?
- Orbit and clock data products : what kind of products did you use ? What is the sampling of these products ? Orbit and clock data products from JPL for PPP applications are sampled at 5 minutes (https://gipsyoasis.jpl.nasa.gov/index.php?page=data). This point determines the rest : I would like to be sure that the final sampling rate of the GPS-PWV values is really 1 minute and not 5 minutes, as usual. If you made a specific processing, you have to present it. In addition, you have to ensure that this kind of estimation is appropriated for your purposes and your estimation doesn't suffer the effect of an artifact.
- Elevation weight function used for GPS observations (constant ?, elevation dependent (a/sin(elev)ËĘ2) ?) - Cut-off (OK line 5)
- Tropospheric models used : mapping function (OK line 5), ZHD a priori (Is it GPT ?), ZWD time evolution constraint as a random walk ? Tropospheric gradients have been estimated ?

P4L25-27 P4L30-LP5L3 Table 1 Response: In this study the GOA-II software was extensively explored to obtain the ZTD estimates. The configuration used here are the same suggested by JPL (default in the software distribution) and some particular aspects used to generating the high temporal resolution are better described in the 2.2 section of the new version of manuscript. This section was totally rewritten and more details about the GPS data processing were included. All items pointed by reviser were taken into consideration:

- GPS datain for GOA-II: rinex format in sampling rate of 1 second;

- Origin of the Orbit and clock data products: precise from JPL website;

- Sampling rate of satellites ephemeris: 15 minutes for orbits and 5 minutes for satellite crock;

- Elevation weight function: elevation dependent and apply 3 coefficients depend on the latitude and height above sea level of the observing site and on the day of the year (Boehm et al. 2006);

- ZHD a priori: Constant using the a Tropospheric model in function of high of the GPS station: DZH=1.013*2.27*exp(-$h_0 * 0,116 * 10^{-3}) = 2.1260m;$

- ZWD a priori: constant 0.10 m;

- Data processing method: PPP (Precise Point Positioning)

- Process noise for tropospheric delay: Random walk;

- Maximum drift for tropospheric delay (Random walk parameter): 8.333E-8 (km per square-root second);

- Tropospheric Gradients estimates: yes;

- Sampling rate of the ZTD estimates: 60 seconds;

These information were organized in the new Table 1.

19) **Referee#2:** Line 6: "To ensure the quality of the PWV time series with high temporal resolution required in this study, a rigorous data-processing strategy was adopted with possible noise sources taken into consideration." What does it mean? Give a reference if you used a validated data-processing strategy else explicit it please.
P4L23-L25 Response: We would like to highlight in this phase that in the GPS data processing carried out to generate PWV time series with high temporal resolution is necessary to take into consideration the modeling of the known uncertainty sources. This phrase was rewritten in new structure of this section, which this rigorous data-processing was demonstrated with details through the items listed and suggested by reviser in his specific comment (Number 18)

20) **Referee#2:** Line 8: “recommended by the International Global Navigation Satellite System Service” : use IERS conventions that are authoritative in the field. IERS Conventions (2010). Gérard Petit and Brian Luzum (eds.). (IERS Technical Note ; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6 https://www.iers.org/IERS/EN/DataProducts/Conventions/conventions.html.
P4L28 Response: This reference IERS Conventions (2010) was added as suggested replacing the "International Global Navigation Satellite System Service".

21) **Referee#2:** lines 9-10: "absolute calibration was performed to ensure the correct phase center variation, as reported by Görres (2006)" : It would be clearer to distinguish in absolute calibration (Schmidt et al., 2009) a and the specific absolute calibration of your antenna (Gorres, 2006) if you have done it. ! Schmid, R., P. Steigenberger, G. Gendt, M. Ge and M. Rothacher (2007), Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas, Journal of Geodesy, Volume 81, Number 12, 781-798, doi :10.1007/s00190-007-0148-y.
P4L28-L30 Response: The reviser is right. This phrase was incomplete and was rewritten and the references were updated. We did not do specific calibration for GPS antenna used in the study. We used the phase center variation model for satellite and receivers antennas (the reference suggested was used: Schmid et al. 2007), which is available in GOA-II with parameters provided by IGS web site and the reference cited is changed for Montenbruck et al. (2015). The current file is available in https://igscb.jpl.nasa.gov/igscb/station/general/igs14_1935.atx. Information about the kind of GPS antenna used in the CHUVA-VALE was included in the section 2.1.

22) **Referee#2:** Line 10: New paragraph to explain the conversion ZTD ! PWV? Line 13-14: Which TM and Pressure data have been used, and with which time resolution?

How are they computed at 1 minute sampling?

P5L4-L8 Response: The new paragraph was included to explain the conversion ZTD to PWV. A surface meteorological station measuring pressure, temperature and humidity every minute, was installed at a GPS antenna and coupled with the GPS receiver. These information are presented in the section 2.2 (GPS data collection) The TM values were calculated applying the model suggested by Sapucci (2014) in the same sampling rate that pressure and temperature were measured (1 minute). The sampling rate of Tm values was included in the manuscript.

23) **Referee#2:** Line 15: "The sampling rate of the GPS-PWV values was 1 minute." Again, if the sampling rate is 1 minute, that implies PPP products cannot be sampled at 5 minutes. Have you done a specific GPS data processing to compute your own PPP products to obtain a sampling rate of the GPS-PWV values at 1 minute?

P4L25-L27 P5L8-L11 Response: The data processing was done only applying the GOA-II software. The last version of this software is able to estimate parameters with high temporal resolution (one minute). The GOA-II software re-sampling the GPS satellite ephemeris using the Orbit Integrator package which starts from specified initial orbits from JPL and uses several force models to integrate the dynamic equation to produce the orbit of each GPS satellite. These force models are applied to treat the gravity force, solar pressure, atmospheric drag, earth tides and the relativity. The solution are obtained by numerical integration given the initial conditions. This information was added in the new version of the manuscript.

24) **Referee#2:** Line 16: "problems with the satellite ephemerides" Can you explicit these problems? I don't understand why you got a problem with it.

P5L10 Response: In some few periods the JPL ephemeris files are incomplete.

Ephemeris from IGS are not used to avoid discontinuity in the PWV time series.

25) **Referee#2:** Lines 16-17: "unavailable pressure measurements" Is it possible to complete it with a meteorological model the problem was not so important to solve it?

P5L10-L11 Response: The most important in the data processing is avoid the inclusion of uncertainty, which contaminate the global analysis of wavelet power spectrum. The values from meteorological model have large uncertain and the temporal resolution is of 6 hours over Brazil.

26) **Referee#2:** Lines 17: "other unknown causes": If we consider GPS data from receiver, orbit/ clock products for PPP processing and pressure measurements, I don't see which other unknown causes can be possible.

P5L11 Response: An example of unknown causes would be the traffic of the people and vehicles around the GPS antenna during process of instrument maintenance, which multi-path can be generate. This phrase was rewritten and the term "other unknown causes" was excluded.

Subsection "2.3 Precipitation time series

27) **Referee#2:** Line 23: "very small spatial scale": Provide an order of magnitude.

P5L18 Response: The sampling area of the Joss-Waldvogel brand acoustic impact disdrometer (model RD 80) used in this work is of the 50 cm2. This information was included in the manuscript.

28) **Referee#2:** line 5-6 "The dimensions of the precipitation area that influences the GPS-PWV is a key factor in the development of this study": If it is the case, you should explicit what you have really done and not summarize quickly your tests to directly provide the area of 22x22: 1. "Different areas were tested": explicit 2. "found to be more representative of the observed area by GPS": what criteria have been used? 3. "better for exploring the correlation between the precipitation occurrence and GPS-PWV": Could you please provide quantified results?

P5L28-P6L10 Response: Three areas around GPS antenna were tested: 4.4km per 4.4km, 12km per 12 km and 22km per 22km. The Fig. 1 (final of this response latter) shown the first precipitation event observed, in which a study about the radar data in different area around GPS antenna were tested and compared with GPS-PWV time series. It is possible to observe that even during strong precipitation registered by radar taken in count the areas 12km per 12 km and 22km per 22km, the PWV time series not change the increase tendency, but before the precipitation occur in the area 4.4 km per 4.4km the PWV present the peak and decrease the values, after some moment the stronger precipitation begin. Note that during the PWV increase (called PWV-Jump) precipitation over GPS antenna not is observed. As we already mention in the text this area were used here are not should be used in other experiment without suitable investigation. The correlation between GPS-PWV time series and precipitation is very explored in this study by wavelet and lag analysis .

The rainfall area employed in this study is only a reference for the description of GPS-PWV jump. For instance, if a raingauge is employed only an area of 20 cm radius is recorded and it is considered represents the rainfall from a large region. From another side, if the whole radar area is employed a rainfall over 100 km radius is recorded and could be associated to the GPS-PWV. In both cases representativeness and the

lead time (for a nowcasting application) should be considered. In the raingauge case, rainfall will be underrepresented because only rainfall over the raingauge will be considered and for the radar case rainfall far from the GPS-PWV will be considered and cannot be associated to the local increase in PWV. The representativeness of the GPS measurement is still an open question because it depends from the vertical distribution of the water vapor and mainly from the combination of elevation angles of the GPS satellite and the elevation angle threshold employed in the PWV processing. Actually, the area employed presented as the best for this location, but it is expected to vary as function of the region and satellite configuration. These information and discussion, such as the tested areas, are included in the manuscript.

29) **Referee#2:** Line 14: "around" Can you specify?

P6L10 Response: The square area around the GPS antenna was better specify in the new version of the manuscript.

30) **Referee#2:** Line 22-24: "the statistical measurements calculated from the radar data were in the 95th percentile of the intensity of the precipitation observed in the area of 4.4 km per 4.4 km around the GPS antenna" OK it is a statistical way in order to examine the intensity of the precipitation.

- 1. Lack of data DOY 319 from Xpol radar?
- 2. b and c should be at the same scale.
- 3. On 3 rainfall events, precipitation intensities are above 125 mm/h according to Disdrometer (Fig. 2b) whereas the 95th percentile of the intensity of the precipitation observed by Xpol radar radar are below 100 mm/h (Fig. 2c): It seems strange that the disdrometer measures a statistical anomaly 3 times on 20 (>95th).

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P4L13-L14 Fig.2 P6L29-L32 Response: (1) Due to a technical problem the radar was turned off during the 12:32 of the DoY 318 until 19:41 of the DoY 319, as indicated in Fig.2. This information was included in the manuscript. (2) The scale in plot (c) was changes para o range between 0 and 200, as suggested. (3) The total precipitation from disdrometer (Parsivel) is always larger than the one measured by raingauge and radar. The problem is the large droplet concentration, normally the integration cut off the largest raindrops in 4 mm (see Giangrande et al, 2016 JGR , doi: 10.1002/2015JD024537). In our case we didn't apply any filter and therefore the total value is larger than the radar and raingauge as you can see in Figure 1. We clarify this point on the text.

Page 6 "3 Wavelet analysis"

31) **Referee#2:** Lines 15-16: "In this study, both continuous and discrete wavelets are investigated to achieve intra- and interrelation analysis, respectively." Distinguish what wavelet decomposition should be used to answer to what scientific questions.
P9L12-L25 Response: We agree that the description of the methodology applied in the wavelet analysis was very poor in details. It was rewritten in new section 4 and information about the discrete and continuous wavelet are included.

Page 7

32) **Referee#2:** Lines 6-7: "The methodology employed to process the GPS data in one-minute intervals did not provide any additional information. Fig. 3 shows that the

GPS-PWV energy variability begins to be significant only for time scales longer than 16 minutes." The influence of stochastic constrains applied on temporal evolution of ZWD during the GPS data processing must be taken into account. If you have used a too small random walk parameter, that could explain what you have observed.
P10L15-L16 P14L17-L20 Response: This phrase was removed because the range of power spectrum associated with color scale used in the Fig. 6 did not permit showing the time scale lower than 16 minutes, which was selected to make possible see the results. Information about this range and the color scale used in Fig. 6 was included in the paper. The parameter used in the random walk process noise for zenithal tropospheric delay estimate was the default value suggested by JPL (8.333E-8 km per square-root second). We agree that these values can influence the variability of the PWV estimates in high frequency, and others values should be tested. Some comment about the impact of these values in the GPS-PWV variability was included in the manuscript in the final of the derivative analysis sections.

33) **Referee#2:** line 8: "Therefore, the one-minute time series representativeness is not a limitation, and if there is noise, it is white noise." Can you explicit and prove it?
P10L15-L16 Response: This phrase was removed (see specific comment 32-Referee2).

34) **Referee#2:** It is obvious that a jump in a time series will produce what is described lines 13-15: "there are expressive changes in the power between different time scales in those cases in which an increase in the power of the oscillation from low to high frequency is observed." It is the well known example of the Wavelet power spectrum of a Dirac signal.
P10L21-L23 Response: Although it is well known the example of the Wavelet power

spectrum of a Dirac signal, we believe it is important to reinforce it in this case. The phrase was rewritten and the GPS-PWV jump discussed the previous section of the wavelet analysis (as suggested by reviser) was mentioned here. Similar sentence in the conclusion section were also rewritten.

35) **Referee#2:** Figure 3: GPS-PWV presents a jump DOY 358 with a strong signal in the Wavelet Power Spectrum but Xpol radar did not detect any precipitation : have you any comment on it?

P10L30-L32 Response: At 23:00 DoY 358 a precipitation was observed, which was included in the Lower tercile. The problem pointed by reviser is pertinent if taken in count the GPS-PWV jump observed in the final of DoY 357, which the radar did not detect precipitation. If the nowcastig tool was based on GPS-PWV jump, this case would be a false alarm, which is a metric used by evaluate the its skill. A comment about this case was included in the text.

36) **Referee#2:** lines 31-32: “The results show that the wavelet correlation between the PWV and precipitation intensity is more evident and significant for the time scale between 32 and 64 minutes”. Again it would be clearer to speak about PWV jump before speaking about the lag between GPS-PWV jump and rainfall and introduce wavelet to determine the lag precisely.

P12L1-L4 Section 4 Response: This phrase was rewritten in the new version of manuscript. The section 3 titled "Behavior of PWV time series before precipitation events: the GPS-PWV jumps" present the GPS-PWV Jump before wavelet analysis. The section 3 and 4 from previous version of the manuscript were merged, as suggested in your general comments, in the new section 4, denominated "High temporal resolution GPS-PWV time series analysis", which wavelet analysis and time lag correlation analysis are explored to evaluating which the timescale of the GPS PWV oscillations are associated with a more intense rainfall. This section was divided in the

following subsection: - 4.1 Wavelet analysis - 4.1.1 Wavelet power spectrum analysis - 4.1.2 Wavelet cross-correlation analysis - 4.2 Time lag correlation analysis - 4.3 GPS-PWV derivative analysis: potential for nowcasting application.

37) **Referee#2:** lines 31-32: Correlations shown figure 5 do not exceed 0.15 and do not look significant: it seems clear there is a lag between GPS-PWV and rainfall and the evaluation of this lag seems good but the correlations of figures 5 and 6 diminish the strength of the demonstration.

P11L15-L16 Fig8 Fig.9 Response: We agree the correlations are not very high, however, significance test shown that this results are statistically significant into 95% confidence interval, which taken into consideration a Gaussian Distribution after applying the Fisher‘s Z Transformation. This comment was included in the paper and information about the bars were included in the Captions (Fig. 8 and 9): "The 95% Confidence Interval for each WCC is estimated considering a Gaussian Distribution after applying the Fisher‘s Z Transformation (Whitcher et al 2000)."

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38) **Referee#2:** “4 Behavior of PWV time series before precipitation events: the GPS-PWV jumps”: I appreciate the meteorological interpretation of GPS-PWV jump during severe weather events but this interpretation seems to be founded only on a single reference (Adams et al., 2013): Is there any other references on these meteorological processes during severe weather events?

P7L1-P8L24 Response: We explore the results reported by Adams et al. (2013), because they showed the behavior of PWV time series before precipitation events over same region that we discussed here. However, we agree that would be interesting include another papers. So we included Kursinski et al (2008), Solheim et al. (1999) and Shi et al. (2015).

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39) **Referee#2:** line 3-5 “This result corroborates the pattern observed in Fig. 7, showing the GPSPWV maximum before the precipitation event and its minimum after the maximum precipitation” It would be clearer if the zoom of figure 7 has shown precipitation.
Fig. 3 Response: The precipitation values were included in zoom of Fig. 3, as suggested by reviser.

40) **Referee#2:** “4.2 GPS-PWV derivative analysis” Line 20-21: “Fig. 9 clearly shows an expressive change in the pattern of the derivative distribution as a function of the different precipitation intensity terciles.” : I suppose you did it but did you check that for each severe weather event of upper tercile you got around 7.8% of GPS-PWV derivative >+9.5 mm.hËĘ(-1) and around 5.47% of GPS-PWV derivative < -9.5 mm.hËĘ(-1) because if I have well understand, you proposed section 4.3 to use this criterion to detect severe weather events for nowcasting application.
P13L30-P14L5 Fig.13 Response: In the fact, this analysis about the derivative >+9.5 mm.hËĘ(-1) and <-9.5 mm.hËĘ(-1) was not present in the section 4.2. Some comments about this results had been present in the 4.3 section, which the reviser 3 suggested to change it to section 4.2. (see specific comment 29-referee3). The section 4.2 was merged with 4.3 in the new version of manuscript. These derivatives are better explored in the discussion of the results shown by new Fig. 13.

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41) **Referee#2:** line 28-30: “The wavelet analysis for the GPS-PWV time series was explored, and it clearly shows that during precipitation events, there are expressive changes in the power spectrum between different time scales, in which an increase of the power of the oscillation from low to high frequency is observed.” It is a logical result due to the fact there is a jump in GPS-PWV time series during severe weather events (see comment 34).
P15L8-L9 Response: This phrase was rewritten to "The wavelet analysis for the GPS-PWV time series was explored to characterize the strong changes in the power spectrum between different time scales during precipitation events generated by the occurrence of the GPS-PWV jumps.".

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/amt-2016-378/amt-2016-378-AC3-supplement.pdf

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-378, 2016.

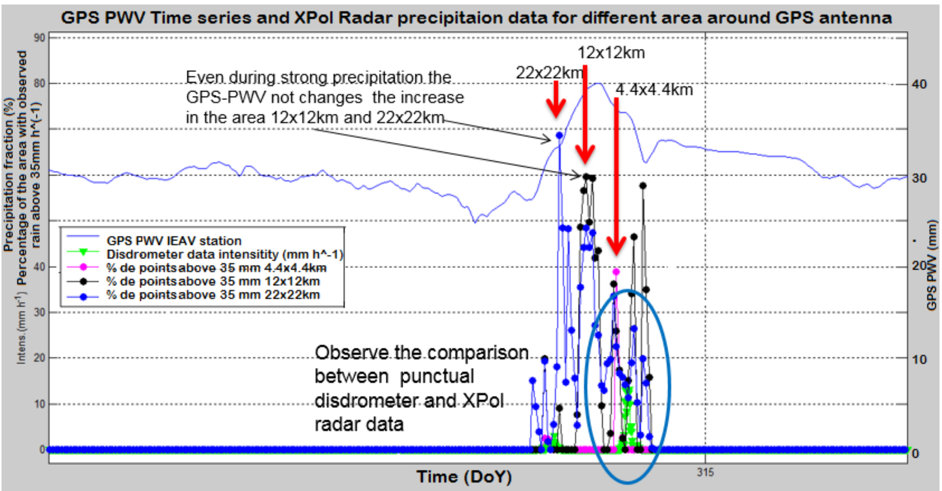

Fig. 1.