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Atmospheric Chemistry and Physics Discussions



# *Interactive comment on* "Observing three dimensional water vapour using a surface network of GPS receivers" *by* S. de Haan and H. van der Marel

**S. de Haan and H. van der Marel**

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We thank the anonymous referees for his/her carefully reading the manusctript and thorough comments. We have considered all comments as valid and useful to improve the manuscript.

Below we give an item-by-item response to the helpful comments to the referees.

Response to comments of referee 1

1) General comment: horizontal grids of 10-15 km:

With the data set at hand and used in this study the optimal (in accuracy and computation time) resolution of the 3DVAR system is 30 km. We agree with the referee that



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Interactive Discussion
Discussion Paper

mesoscale analysis would be a major goal of a tomographic analysis system of GPS SWV. With the current density in the Netherlands (of around 50 km, with some close sites) a step in this direction could be made.

2) General comment: On the use of ECMWF+24 in the background characteristics

We calculated also the background error characteristics based on HIRLAM+06 based on the same 18 months period. The results are included in the revised manuscript and show no difference with the previous found background error characteristics. In the appendix of the revised manuscript a graph is shown with the values.

3) General comment: Manuscript style

We have updated the manuscript with the helpful "specific comments" of all three referees. For example the name of Section 3.2 is changed into "Slant water vapour error distributions" and Section 3.3 is now called "Systematic observation error covariances"

Specific comments:

Text changes are done as proposed by the referee: 19, 25, 27, 34, 61-72.

1: It is true that this manuscript is an application of existing methods to estimate the state of the atmosphere with respect to certain parameters. The emphasis of this manuscript lies more on observing 3D water vapour using a surface network of GPS receivers.

2: We have restated this sentence. It now reads: "At present, radiosonde observations are the most important operational source for upper-air water vapour data."

3: We have restated this sentence. It now reads: "For purposes of numerical weather prediction beyond the synoptic scales these observations are..."

4: We have added some words to the abstract on standard deviations and the last sentence "The used network,...." is removed.



**ACPD**

8, S11615–S11624, 2009

Interactive Comment



5: We have changed the word "standard deviation" in to "error".

6: We have added the sentence "The climatological values for the region under consideration here run from approximately 4 kg m$^{-2}$ in the winter to around 40 kg m$^{-2}$ during summer."

7: It is indeed better to use "carrier phase shift". We have restated the first line of Section 2 into: "A GPS receiver measures the carrier phase shift or the pseudo range of the GPS signal for every GPS satellite in view."

8: We agree. We have added a sentence "Note that this is a first order approximation of the ionospheric effect."

9: We have added explanation and the moment of the definition of the symbols $s, R_d, z$ and $\beta$.

10: We agree and we have changed the definition of geometric distance to the proposed one by the referee.

11: The GPS satellites transmit signals in the L-band at frequencies of 1.2 and 1.6GHz. The uncertainties in the constants of equation(2) limit the accuracy with which the refractivity can be computed to about 0.02% (Davis,et al 1985)

12: The two definitions of STD (eg.(4) and (6)) is confusing. We have added the subscript "comp" to STD in eq. (6) to distinguish the two.

13: The error due to this estimation is small (less than 1%). We have added this to the text in the paragraph following eq. (5).

14: The quality of the GPS$_{ZTD}$ estimate is indeed influenced by the type of orbit. The current processing scheme uses double differences which eliminates both the clock and receiver error. Our experience is that the quality of the GPS-ZTD estimate is practically the same for final and rapid orbits, and slightly reduced when the first 9 hours of the predicted orbits are used, but the quality will still be satisfactory.



**ACPD**

8, S11615–S11624, 2009

Interactive Comment



15: We added a reference for more information (van der Marel, 2002). Proper modelling of covariances means taking into account the mathematical correlations due to the double differencing. The elevation dependent weighting is $1/\cos(z)^2$. This weighting scheme has been verified using the least squares residuals. See also http://gnss1.lr.tudelft.nl/tough/datasets/2000_297-311/sres.html

16: Niell mapping functions are widely used and at the time of processing a very good choice. We acknowledge that better alternatives are available nowadays, e.g. the Vienna Mapping Functions (VMF).

17: We believe that these time scales are small because we have removed long periodic effects caused by carrier phase multipath and antenna phase center variations in the multipath mapping. So what remains is mainly carrier phase noise and high frequency multipath, which will be reduced by averaging over 5 minute intervals. However, due to the differencing process, or estimation of clock offsets for that matter, correlations between stations will remain and continue to have an effect. This is inherent to the GPS technique.

18: We agree with th referee, and therefor we have added the following sentence at the end of Section 2 "Nevertheless, observation errors from a single station can be correlated with respect to time. This is not taken into account in this study by assuming this correlation to be small for convenience."

19: OK

20: We have added the words: "Note that here $N$ denotes the number of vertical levels."

21: Yes, we have added the words "horizontal positions".

22: In both cases beta is the elevation angle. To be more precise we have added the words that "$\beta(p_n)$ is the elevation at location $p_n$ with the horizontal plane at level $n$."

23: Yes we have added the words "vertical profile"



**ACPD**

8, S11615–S11624, 2009

Interactive Comment



24: The non-negative elements occurred in less than 1% of the time. We agree with the referee that a additional penalty would be more satisfactory; this improvement will be introduced in a updated version of the 3DVAR software.

25: OK

26: The sentence "By comparing the difference between observations (SWV) and the model ($Hx$) observations error covariances can be examined." is wrong in this context. We removed the words concerning this point.

27: OK

28: Yes, we mean the vertical background error covariance.

29: This is a very difficult matter. A single radiosonde profile is observed with the same sensor and introduces observation error correlations. However, one needs to assume something, and it is hard (if not impossible) to quantity all error covariances and is, in our view, outside the scope of this manuscript. We have added the following words on this: "Moreover, background error covariances are expected to be more systematic than observation error covariances because every radiosonde observation is performed with new equipment."

30: The references Daley (1991) and Eresmaa and Jarvinen (2005), which discuss the use of exponentional background error covariances are added.

31: More detail are : "The coefficients obtained by a least square fit...."

32: The coefficients are in kilometres and this is added to the table.

33: We agree and have changed the title of the section to "Slant water vapour error distributions".

34: OK

35: Yes, changed accordingly.



**ACPD**

8, S11615–S11624, 2009

Interactive Comment



36: Systematic errors are independent of site, site separation etc. These errors could be originating from erroneous satellites, ocean loading satellite positions etc. and would show up as a offset at large distances. This is not observed in the figures.

37: The lead time of the ECMWF forecasts is minimal 12 hours.

38: The ZTD observation error correlation are not independent of location and cannot be separated without additional information. We have added the following to the text: " Nevertheless, ZTD observation error correlations (which decreases to zero with increasing distance) are still present but these can not be distinguished by Hollingsworth-Lonnberg method"

Here a network solution is used to determine the ZTD estimates although errors in the a priori information will correlate with the ZTD estimate. Jarlemark (2005) showed that using a Precise Point Positioning method to estimate ZTD the atmospheric error is correlated over large distances due to errors in the orbits and clocks (which are used as apriori information in PPP).

39: The quality control is based on the requirement that the standard deviation in 5 minutes of ZTD mapped to the zenith is smaller than 12 mm.

40: We are aware of the fact that the nature run is rather "old". We have added to the conclusions that a new run is available and would like to use this data.

41: We changed the phrase "realistic error" into "Gaussian noise"

42: We added some words on this; it could be useful to include artificial errors on the lateral boundaries.

43: With the new nature run (Reale et al, 2007) we could extend our domain to UK and Germany. This remark has been added to the conclusions.

44: The observation of the referee is correct. We changed the word "solitary" in single. The resolution of the analysis grid is coarse which implies that ray path do not intersect



**ACPD**

8, S11615–S11624, 2009



(in general) more one grid cel.

45: We believe the truth is "wetter" than the analysis could be due to the difference in orography of the ECMWF nature run and the HIRLAM analysis.

46: No, we did not take into account the fact that in reality the number of SWV observations is 10 times larger that IWV.

47: Yes, 2003.

48: We changed the word "schemes" into "experiments".

49: It is indeed almost impossible to observe a bias; we changed the word "observed bias" in "observed mean difference between IWV from GPS and NWP".

50: OK

51: We changed the sentence to "The difference between the bias curves of SWV and IWV is small and the standard deviation is..."

52: We suspect that moisture information is not correctly used in the assimilation because assimilation of moisture is difficult.

53: We agree; the word lowest is removed from the sentence.

54: We have corrected the text.

55: Yes, this is what we were trying to say. The better information from the background makes the difference.

56: We agree with the referee that these are indeed only two cases. We added the words that an intensive study is needed to support conclusion. The current data (of one month) set is not adequate enough. In only three occasions radiosonde, NWP and GPS data was available.

57: OK



**ACPD**

8, S11615–S11624, 2009



58: We changed the captions accordingly.

59: Yes, we mean error variance.

60: We have added an explanation of the fourth curve to the caption.

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Response to comments of referee 2

General comments:

We added a simulation to show that the current network is incapable of observing 3D WV at resolutions higher than approximately 30 km (see fig 10 in the revised manuscript).

We tried a higher resolution for the the 2003/05/03 case but observed no improvements. This is in line with the findings of fig. 10.

Specific comments:

p17194 line 22: remark has been removed.

p17196 line 15: statement removed

p17196 line 18: we highlighted the real SWV character of this manuscript

p17197 line 15: added reference Eresmaa (2007)

p17197 line 13: we have changed this equation according to the suggestion made by the referee.

p17197 line 23: symbol STD is changed in the second equation into $\mathrm{STD}_{comp}$

p17198 line 15: reference Niell(2001) is added.

p17199 line 13: specifications of the estimated paramters are added.

p17200 line 12: The conversion factor from IWV is simply applied to SWV. We think that



**ACPD**

8, S11615–S11624, 2009

Interactive Comment



the conversion factor will not change dramatically for elevation higher than 10 degrees. We added reference Braun et al. (2001)

p17201 line 12: Yes, curvature and bending are taken into account.

p17203 line 23: we have provided two references Daley (1991), and Eresmaa (2005)

p17206 line 20: month is specified

p17206 line 24: we changed the term "realistic errors" in "Gaussian noise"

p17207 line 23: we removed the word "solitary", the term was confusing. We rephrased the sentence.

p17208 line 23: We did not do an extra experiment to investigate the influence of the larger number of SWV obs. compared to the number of IWV obs. This should be done in later research when a longer time series of SWV obs. are available.

p17210 line 13: We observe biases due to differences in orography. These biases are removed from the observations before assimilation.

p17216 line 27: A denser GPS network will be beneficial for detecting water vapour inversion but this is, as the referee noticed, not the only constraint. Better understanding of the background errors as well as the model, will improve the retrieval of atmospheric water vapour. One can think of a rapid update of every 15 minutes, when this data becomes available. This has been added to the conclusions.

All other technical comments were applied.

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Response to comments of referee 3

General comments:

We added in the appendix the background error characteristics as observed with HIRLAM+06 and observed no difference.



**ACPD**

8, S11615–S11624, 2009

Interactive Comment



Spatial resolution: See comments above on this issue.

Specific comments:

1: We have changed this notation into "a previous analysis as a background"

2: this statement has been removed.

3: yes, the text is changed accordingly.

4: We changed the definition.

5: This was an error. It should read "at least 12 hours". It is necessary to use at least 12 hours forecast to determine the background error characteristics from the model and from the 4DVAR-ECMWF analysis (which spans over 9 hours).

6: We have added some words on significant levels.

7: We have changed the text.

8 : we changed the name of subsection 3.2. and added some words. The extreme outliers are not used in the 3DVAR analysis due to the simple qaulity control method described in section 4.2.1. (the standard deviation in 5 minutes of ZTD mapped to the zenith should be smaller than 12 mm)

9: We have added some words on the choice of 2.5 g/m2. This value is a conservative estimate based on previous studies (see e.g. Rocken 1997).

10: We added some words on the used interpolation method.

11: We have added a sentence to the caption describing the origin of the data

All other technical corrections were applied.

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Interactive comment on Atmos. Chem. Phys. Discuss., 8, 17193, 2008.



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8, S11615–S11624, 2009

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