

## ***Interactive comment on “Optimal Estimation of Water Vapour Profiles using a Combination of Raman Lidar and Microwave Radiometer” by Andreas Foth and Bernhard Pospichal***

### **Anonymous Referee #2**

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Review of “Optimal Estimation of Water Vapour Profiles using a Combination of Raman Lidar and Microwave Radiometer” by Foth and Pospichal

This paper presents an optimal estimation technique for retrievals of water vapor mixing ratio profiles by combining Raman lidar (RL) and microwave radiometer (MWR) data. The paper is well organized, and well written for the most part. I believe it represents a valuable contribution, but I found some of the text and mathematical details a bit difficult to follow. I have provided a number of comments and suggestions that I feel may help clarify some of the presentation.

Page 2, lines 18-19: The author states “However, water vapour Raman lidars need to

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be calibrated with an instrument measuring simultaneously for example a microwave radiometer (MWR) or radiosonde (RS) ...” This statement should be rephrased. For example ... “However, water vapour Raman lidars should be calibrated using simultaneous and collocated measurements from for example a microwave radiometer (MWR) or a radiosonde (RS).

Page 2, lines 19-20: The author states “Until now, lidars were mainly used as research instruments that did not work unattended or automatically on a routine basis.” Although, the author uses the word “mainly” to qualify his statement it is still a bit misleading as there is at least one system that I’m aware of that has operated nearly continuously for over 20 years now.

Page 2, line 31: I suggest changing “In contrast to the already presented remote sensing observations...” to “By contrast, ...”

Page 2, line 32: I suggest changing “RS launches ...” to “Routine RS launches...” or “Operational RS launches...”

Page 3 lines 24-26: The author states “Calibration methods only based on RS (England et al., 1992; Mattis et al., 2002; Reichardt et al., 2012) are inappropriate for continuous monitoring of the tropospheric water vapour with Raman lidar because of their low temporal resolution.” I take exception to this blanket statement. It is true that temporal resolution is an issue with the RS. However, the primary advantage in using the RS (as opposed to MWR) is that the RS provides detailed vertical information that is useful for determining height-dependent calibrations, including overlap corrections, and any possible variations in response of the detectors (eg PMTs). It would be impossible to estimate these height-dependencies using integrated water vapour measurements.

Page 3, line 34: change “the focus of the presented work is to routinely retrieve a continuous...” to something like “the focus of the present work is to develop a method that enables routine retrieval of a continuous...”

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Page 4, lines 15-16: The author states “However, the overlap of both Raman channels is assumed to be identical and for that reason the overlap effect is negligible regarding water vapour measurements.” This is a huge assumption that needs to be verified or justified in some way. Our system, for example, exhibits some residual overlap effect that requires correcting (and we use RS to do that).

Page 4, line 31: change “Their uncertainties amount to...” to “Their uncertainties are...”

Page 6 line 10-11: The author states “This state is then combined with the current lidar measurement  $y_k$  to the filtered state  $x_{Fk}$  using the Kalman filter.” The meaning here is not clear. It would make more sense if it read “This state is then combined with the current lidar measurement  $y_k$  to obtain the filtered state  $x_{Fk}$  using the Kalman filter.” Please clarify.

Page 7, line 2: Change “accounts” to “is equal”

Page 7, line 3: The author states “The benefit of using the logarithm is the limited range of variation...” I would think that the limited range of variation would make your job harder. Please clarify.

Page 7, line 10: change “errors at certain height levels” to “errors at different height levels”

Page 7, line 11: The author states “The second measurement vector, from now on observation vector, is given as...” I’m not clear what is meant by “from now on the observation vector”. One suggestion is “The second measurement vector, which we refer to as the observation vector, is given by...” But I’m not sure if this alters your meaning. Please rephrase.

Page 7, line 17-18: The author states that the diagonal and off-diagonal elements of the MWR covariance matrix is set to  $0.25K^2$  and  $0.01K^2$ , respectively. Please provide some justification (or reference) for these numbers.

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Page 7, line 20: change “...amounts to...” to either “...is...” or “...was determined to be...” Which ever is more appropriate. Also please provide some justification for the uncertainty that you quote (0.1 g/kg).

Page 7, line 20-21: The author states “However, the uncertainty is increased due to the distance between the observation platform and the surface humidity sensor (see Sec. 2) and is assumed to be 0.3 g/kg.” First, what is the “observation platform”? Are you referring to the lidar?. Second, if I understand correctly you are trying to account for the fact that the lidar and the surface met sensor are not collocated. Correct? The meaning is a bit obscure. Please clarify.

Page 7, line 22: Change “...certain amount...” to “...certain number...”

Page 7, line 23: The author states that 211 RS profiles were used to determine mean profiles and covariance matrix. Were these profiles taken during the span of the HOPE campaign? Please specify the time period covered by these RS profiles.

Page 7, line 24: Change “...serves as first guess...” to “...serves as a first guess...”

Page 7, line 31: Change “...cloud base due the ...” to “...cloud base due to the ...”

Page 7, line 32: Change “...using previous informations.” to “...using previous information from the lidar and the RS.” (If that doesn’t alter your meaning)

Page 8, line 7: The author states “The transition error  $e_{t;k}$  corresponds to the covariance matrix  $S_{t;k}$ ”. What do you mean by “corresponds to”? I assume this means that the diagonal elements of the covariance matrix are the (squares of the) transition errors. Please clarify the statement.

Page 8, line 11: change “...is to start with RS climatology covariance as previous covariance...” to “...is to start with the RS climatology covariance as the previous covariance...”

Page 9, line 1: insert “where” at the beginning of this line.

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Page 9, line 2: change "... at time step k to the filtered state..." to "... at time step k to obtain the filtered state..." Page 9, line 8: change "servee" to "serve"

Page 8 and 9, equations (6) through (10): I think it is appropriate that the author present these equations in general form, as he has done. However, given the assumptions mentioned on page 8 ( $H_k$  and  $M_k$  are both unity), these equations do simplify quite a bit. I believe it would be useful to also present the simplified equations.

Page 9, line 19: The author seems to indicate that the MWR also contains a pressure sensor? If this is so then it should be mentioned in section 2.2.

Page 9, line 23: The author states "The forward modelling of the surface mixing ratio is trivial. It is a one: one translation to the lowest level of the state vector  $x$ ." The second sentence is a bit confusing. What do you mean when you say "one transition to the lowest level"? Please clarify.

Figure 5. It would be helpful to label the two boxes on the right as "lidar" and "MWR"

Page 13, line 1: change "written out Eq (13) becomes" to something like "with each term written out Eq (13) becomes"

Page 13, line 5: change "...matrices of the a priori and the observation..." to "...matrices of the a priori state and the observation..."

Page 14, line 5: change "...might converge at a false minimum..." to "...might converge to a false minimum..."

Page 14, line 17: change "...are no peaked..." to "...are not peaked..."

Page 14, line 25: change "...that means the higher the correlations, the smaller..." to "...the higher the correlations and the smaller..."

Page 15, line 7: change "...amount to..." to "...is..."

Figure 7: I'm a little perplexed by panel (d) showing the averaging kernels. Shouldn't

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these functions be centered on the heights listed in the panel? Or am I missing something here.

Page 16, line 1: change "...according..." to "...corresponding..."

Page 16, line 4-5: The author states "The precise vertical information from the lidar results in small differences to the RS that is used as reference." This statement implies that the RS profile is modified by the lidar profile, and I don't believe that is the intended meaning. Also, I'm not clear what the author means by "precise." Is the author referring to the vertical resolution or low random uncertainty? Please rephrase, or eliminate this sentence entirely.

Page 16, line 14: change "...driven by the accurate a priori that..." to "...driven by the accurate a priori state that..."

Page 16 line 21: change "The according profile with..." to "The profile corresponding to..."

Page 17, line 16: change "...according..." to "...corresponding..."

Page 18, lines 3-4: The author states "In summary, the presence of a lidar measurement results in more accurate retrievals compared to RS, whereas retrievals without water vapour profiles from lidar are mainly driven by the MWR observation for example during daytime." The first part of this sentence could be interpreted to mean that the retrievals are more accurate than the RS, which is not the intended meaning. I would suggest rewording this sentence. One suggestion is: "In summary, the presence of lidar measurements results in retrievals that are in better agreement with the RS compared to retrievals without the lidar measurements. Retrievals without lidar measurements are mainly driven by the MWR observation."

Page 19, line 4: change "The according relative differences to..." to "The corresponding relative difference with..."

Page 20, line 12: Change "...according..." to "...corresponding..."

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Page 20, line 14: change "...amounts..." to "...is..."

Page 20, line 13: change "breakdowns" to "malfunctions"

Page 20, line 14-15: The author states "Although, the data coverage is larger as for Raman lidar (Fig. 12a), but the vertical resolution is much coarser." This needs to be rephrased. One suggestion is "Although the data availability for OEM\_MWR is larger than the lidar, the vertical resolution is coarser."

Page 21, line 16: The author states "This issue might be caused by slightly to small determined Raman lidar calibration factors resulting in too small lidar mixing ratios." This sentence needs to be rephrased. One suggestion is "This issue might be caused by Raman lidar calibration factors that are slightly too small, resulting lidar mixing ratios that are too small."

Page 21, lines 19-20; The author states: "Hence the retrieval tends to overestimate the mixing ratio in larger heights to minimize the difference between the modelled and the observed brightness temperatures." This sentence should be reworded. One suggestion is "Hence the retrieval tends to overestimate the mixing ratio at higher altitudes in order to minimize the difference between the modelled and the observed brightness temperatures."

Figure 13: It would be helpful to add annotation indicating how the difference is defined, e.g. is it retrieval-RS or vice versa? Also in the caption the author uses the term "bias to RS." It would be clearer to say something like "mean difference between the retrieval and the RS."

Page 22 lines 11-12: The author states "... RS can have a dry bias (Miloshevich et al., 2001)." Careful here. This is a bit of an oversimplification. According to Bomin et al. (2010) the sondes used in this study (DFM-90) tend to show a daytime dry bias, but its not quite as bad the widely used Viasala sondes/

Bomin Sun, Anthony Reale, Dian J. Seidel, and Douglas C. Hunt, 2010: Comparing

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radiosonde and COSMIC atmospheric profile data to quantify differences among radiosonde types and the effects of imperfect collocation on comparison statistics. JGR, 115, D23104.

Figure 14: See comment for Fig13. Also, in the caption change "absorbtion" to "absorption".

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