Dear F. J. Immler,

We have appreciated your valuable corrections and we have carefully considered your detailed comments on our manuscript. We would like to thank you for taking the time to provide such an insightful guidance. Herein, we explain how we revise the paper based on your comments and recommendations. We respond specifically to each suggestion below. Please find attached the revised version of the paper.

We carefully considered the comments of both reviewers and we revised the paper accordingly. The new version of the paper includes :

1) **A description of GRUAN requirements regarding the measurements and the uncertainties for addressing the monitoring of the water vapor in the UT/LS and studies of atmospheric processes (Sect. 1 Introduction)**
2) **A correction of the saturation of the signal is applied to the whole dataset (new Sect. 2.2.1) and the figures (as their analysis) are updated accordingly**
3) **A correction and an improvement of the calculation of the total uncertainty:**

   → Uncertainties of the external source of measurement for the calibration and of the temperature-dependence are taken into account (Sect. 2.3.6).

   → Uncertainties on the overlap function, on the fluorescence and on the correction of the saturation are discussed (new Sect. 2.2.2).
4) **A refinement of the methodology of calibration (Sect. 2.3): the determination of the outliers is optimized in order to decrease the impact of the uncertainty of the GNSS measurements.**
5) **A significant improvement of the radiosonde-based comparative calibration methodology (Sect. 2.3.4)**

In this report, the references to the first version of the article are written this way: P2-l10 (page number-line number), and to the revised version, specified this way: L65 (line number).

Interactive comment on “A Raman lidar at Maïdo Observatory (Reunion Island) to measure water vapor in the troposphere and lower stratosphere: calibration and validation” by Hélène Vérèmes et al.

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General comments:

The paper presents a novel instrument (LIDAR1200) with very interesting performance characteristics, new is probably also the concept of routinely calibrating such an instrument with GNSS IWV. The consideration about the accuracy of this technique are however somewhat questionable. **(1)** The paper states that with the presented technique water vapor measurements in the UT/LS region can be routinely performed. Given the potentially large uncertainty of these measurements the usefulness of these observations are not fully demonstrated.

The uncertainty of the GNSS measurements is high above Reunion Island because more than 50 % of the IWV is less than 10 mm (new Figure 5). The mean uncertainty of the GNSS measurement coincident with the lidar sessions was about 18%. It is way different from the 7% found in the

literature when using GNSS to calibrate the Raman lidar during field experiments. Your review make us rethink about this difference that led us to a refinement of our calibration methodology. Specifically, we refined the choice of the outliers. When the IWV < 7 mm or < 10 mm are not taken into account, the mean uncertainty of the GNSS measurement is around 9.5% and 7.5%, respectively. That's more in agreement with the literature. What's more, this value represents both systematic and random errors. The systematic error on the calibration associated with the GNSS measurement would probably be less than 7.5%. According Ning et al. (2013, 2016), the systematic part shouldn't represent more than 50% of this uncertainty. Thus, as an external source of measurement, the GNSS would imply a systematic uncertainty less than 7% and the statistical part should be minimized by the use of large samples. The use of GNSS IWV should randomize the calibration methodology and decrease the influence of this uncertainty as a systematic component of the total uncertainty budget on the lidar profiles. In the near future, we would like to use 10-min GNSS IWV to increase the sampling and lowered the statistical uncertainty.

Please note that even if the outliers are not taken into account to calculate the calibration coefficient of each IQSP, the outliers can be calibrated thanks to our specific methodology. This is important because regarding the literature, the high number of weak IWV seems cannot be explain only because of the 2.2 km gap with the sea level and is a potential specificity of Reunion Island. Thus, it is important to have high quality data to study this specific spatiotemporal variability of the water vapor.

(2) There are some significant doubts about the estimation of the uncertainty of the calibration technique.

It is true. We had not separated the two uncertainties: the transfer of the calibration from the GNSS to the lidar (the one we were discussing in Sect. 2.3.6 and taking into account in our calculation of the total uncertainty) and the uncertainty of the source of the external water vapor measurement, i.e. GNSS. This latter uncertainty was discussed but not included in our calculation, we had wrongly considered the uncertainty in the transfer of the calibration as the total uncertainty of the calibration. We correct that, it is explained in Sect. 2.3.6 (L456 to L458). We also differentiate the systematic and statistical components of each source of the total uncertainty on the calibration (L475 to L479), please see response to (1). It is discussed in Sect. 2.3.6.

(3) As pointed out above, not enough evidence is provided that the new technique provides sufficient accuracy to study variability and long term trends in UT/LS water vapor concentrations.

The Lidar1200 is able to provide water vapor profiles with high vertical and temporal resolutions in the troposphere on a routine basis. This instrument is able to detect only a few ppmv of water vapor in the tropical LS. Its ability to study water vapor variability in the UT/LS is discussed in the conclusion L819 to L830. The further optimizations planned to get closer to the GRUAN requirements are described from L849 to L859.

(4) The opportunity of accessing all data of the instrument should provide the opportunity to reproduce results. However, the description of calibration and validation techniques is not sufficiently clear to allow full reproduction of results, for example, how the values in table 1 are calculated is not well described.

The lidar data will be available on line, the other data (radiosondes profiles, GNSS IWV) would be available on demand. We intend to detailed the most clearly our methodology in order that the results might be reproduced. Obviously, there was a lack of clarity. The description of the calibration methodology is entirely rewritten (L324 to L354). Regarding the validation technique, please see the methodology of comparison between the lidar (calibrated by GNSS) and the CFH profiles in Sect.3.3 (L526 to L542). It is true that we didn't give the exact date and hour of each launch, those details are available on my thesis. The descriptions should now be sufficient to reproduce the results with the CFH, GNSS and lidar data.

1. **Thesis Hélène Vérèmes (in French), « Étude de la variabilité de la vapeur d'eau dans la troposphère et la basse stratosphère en région (sub)tropicale et des processus associés », Univ. de La Réunion, June 2016, available on : https://tel.archives-ouvertes.fr/.**

Specific comments:

Introduction: **(1)** Necessity and quantitative requirements (uncertainty, long term stability) could be better motivated: who needs this data for what (which modells)? Which uncertainty would be required to be able to detect long term stratospheric water vapor changes?

A paragraph is added to the introduction (L61 to L83) to detail the requirements on the measurement uncertainties and on the calibration stability for the detection of trends in the Upper Troposphere, detection of trends in the Lower Stratosphere and process studies, based on the requirements of the GCOS reports. Please see new Table 1.

(2) *Section 1* A formular demonstration how WVMR is calculated from signals could be shown.

As both reviewers advised it, we start with a fully detailed version of the lidar equation for the retrieval of WVMR (L192).

(3) *Section 2.1* It seems somewhat questionable that with a telescope of 1.2 m Diameter (and 4 m focal length?) a signal from 15m distance can be detected, normally direct beams from that low an altitude will be obscured by the secondary mirror. It is likely that the observed signal is created from multiple scattering. Some considerations of the validity of the retrieval method under these circumstances should be added.

The focal length is 3 m. In the equation of Measures (1984) on the overlap factor, a signal can be detected in the low altitude. However, it is possible there is a little signal due to multiple scattering in the first altitudes. But we assume that this uncertainty is included in the overlap uncertainty.

1. **Laser remote sensing: Fundamentals and applications. Authors: Measures, R. M.. Affiliation: AA(Toronto, University, Toronto, Canada). Publication: New York, Wiley-Interscience, 1984, 521 p.**

(4) *Section 2.3.1* The data indicate an uncertainty in the GNNS IWV measurements of 8 -20 %. The GNSS calibrated lidar measurements can hardly be better than that.

The uncertainty associated with the external source of measurement (i.e. the GNSS) is a mixture of both systematic and random uncertainties (Ning et al., 2013; 2016).

1. **Ning et al. (2013): Evaluation of the atmospheric water vapor content in a regional climate model using ground-based GPS measurements, JGR, vol. 118, no. 2, 329–339, 2013.**
2. **Ning et al. (2016): The uncertainty of the atmospheric integrated water vapour estimated from GNSS observations, AMT, vol. 9, no. 1, 79–92, 2016.**

(5) *Section 2.3.4* I am not quite convinced by this analysis. It would have been better to consider the radiosonde data as reference and compare to the GNSS calibrated lidar results.

At this point, there was no reference. Please see response to (8).

(6) *Section 2.3.5* This suggests that under dry conditions (IWV=3mm) the calibration error can be as high as 66%) (2mm accuracy in the GNSS IWV)

The bias is more about 1 mm. It is true that it represents a high uncertainty on the calibration. The water vapor content above the island and the obvious high variability of water vapor make the calibration process difficult. But it is necessary to do it to be able of further investigating the water vapor variability. The calibration methodology of the IQSP prevents from such high uncertainties, allowing in the same time the calibration of very weak water vapor content.

(7) *Section 2.3.6* I disagree to the statement :" the uncertainty on the calibration coefficient of each period is mainly due to the term corresponding to the standard deviation divided by the square of the number of nightly calibration coefficients." This calculation yields the uncertainty about the average of nightly coefficients, but this does not correspond to the uncertainty of the calibration, which is not based on this average. If I understand correctly, the lidar is re-calibrated every night using the GNSS, thus the uncertainty is not based on the average of the nightly coefficients but on the uncertainty of each individual calibration GNSS nightly value. This will be mainly determined by the uncertainty of the GNSS IWV measurement itself which, as pointed out earlier is not better than 8%, plus random errors.

The lidar is not re-calibrated each night. In fact, we use the temporal series of the hourly coefficients in order to visualize the instrumental quasi-stationary periods (IQSPs) of the calibration coefficient. In this way, we have identified instrumental changes (P7-l32) that can alter the coefficient, by crossing the temporal series of the hourly coefficients in which IQSPs appeared visually, with the logbook detailing all the technical operations that has been made on the system. The final calibration coefficients used for the raw data are the average coefficient of each periods when the profiles are including in these periods (but not the hourly coefficient). A single calibration value is calculated for all the measurements belonging to the same IQSP. Thus, the uncertainty of the calibration coefficient is referring to the average. It is true that the uncertainty of the GNSS IWV measurement itself drive the error, we didn't firstly discuss enough of the systematic uncertainty associated with it. It is also driven by the method, we used GNSS IWV in order to randomize the calibration method, to decrease the systematic impact on the calibration procedure. We improved the description of the calibration methodology (Sect. 2.3.3, L324 to L354). that we didn't wrote clearly enough according to both of your reports. Regarding the uncertainty of the GNSS IWV measurement, please see response to (4). Thanks to the method of the IQSPs, the calculation of the calibration coefficient is based on the most reliable GNSS measurements. The outliers correspond to the IWV< 5 mm (i.e. a mean total uncertainty of the GNSS measurement of about 11%). With the future use of the dataset of 10-min IWV, we should have a larger sampling. We should be able to increase the threshold to 10 mm which would diminish the systematic uncertainty associated with the GNSS measurement to less than 7.5 %.

(8) *Figure 3* shows the differences between the GNSS calibration and other calibrations based on radiosonde, these differences are quite large and illustrate the uncertainty of the GNSS calibration technique.

You are right. We are comparing the different techniques available during the MORGANE campaign. We have improved the calculation of the calibration coefficient with the sondes based on Whiteman et al. (2012). Now, that the methodology is based on the algorithm used in Whiteman et al. (2012) (L400 to L408), the results are refined. They show that the GNSS calibration coefficient is in agreement within 5% with the RS92 and the CFH mean calibration coefficients. The new results are discussed from L408 to L423.

(9) *Section 3.4.* It is unclear whether the lidar has been calibrated by the GNSS IWV or by the CFH data.

The lidar profiles are calibrated by the GNSS IWV (as described in Sect. 2.3.3). After checking, we noticed that it was not specified, it was only implied. A statement is added to the methodology: « For these comparisons, the lidar is calibrated with the GNSS IWV-based methodology described in Sect. 2.3.3. » (L528-L529).

(10) The *conclusion* is not quite true, between 14 and 16 km the two instruments are not in agreement.

It is true that there still is a bias in the 14-17 km partial column which was already noticed P10-l37 to l39. Regarding both instrument uncertainties, CFH and lidar are in agreement. The standard deviation of the CFH in the right panel of figures doesn't correspond to the uncertainty of the CFH but to the variability of the 5 CFH profiles. Thus, we change the right panel of Figure 6, the standard deviation is substituted by the CFH uncertainty (black dotted line), the lidar uncertainty (blue dotted line) and the sum of the CFH and lidar uncertainties (magenta dotted line). We reconcile this analysis in Sect. 3.4 with the conclusions. (L567 to L576; L815).

(11) Typos: In *line 33-34* a full sentence is repeated.

The number of the page is missing and we haven't found this repetition.

Quality of the Presentation: A good overview of related work and results is provided in the *introductory* part. The number of figures and tables could be reduced. **(12)** *Table 2* and **(13)** *3* could be omitted, e.g the vertical resolution has already been shown in *Fig. 1*;

Table 2 can be omitted considering that all information are in Sect. 4.2. Table 3 and 4 are merged (new Table 3) and the categories heading each column are consistent with new Table 1 (i.e. GRUAN requirements). They are: range, temporal resolution, filter, vertical resolution, systematic uncertainty, statistical uncertainty and total uncertainty. It is true that the vertical resolution is already shown in Fig. 1 (P20), nevertheless we don't want to delete it from the table to give all the information to the reader into a glimpse.

(14) the campaigns in fig. 5.

The campaign being described in Sect. 3.1, this figure might be dispensable. Fig. 5 is removed.

(15) *Fig 13* and *14* are also not particularly useful.

Fig. 13 and 14 are removed.