Interactive comment on "Robust, spatially scanning, open-path path TDLAS hygrometer using retro-reflective foils for fast tomographic 2-D water vapour concentration field measurements" by A. Seidel et al.

We thank the reviewers for their constructive response and answer their questions one by one as listed below

Anonymous Referee #1

General Comments:

Overall I think the authors describe a novel and scientifically important instrument. They have performed useful sensitivity studies and characterized the precision and accuracy of the instrument. There are a few points which could be clarified, as described below. The main weaknesses I saw were in outlining motivation for tomographic water measurements in particular and in not explicitly describing how the absorption pathlength is calculated.

Specific Comments:

The motivation in paragraph 1 seems more applicable to methane or CO_2 emissions than water emissions. Is water emitted from soil really important as a greenhouse gas or to understand the emission of methane? Could use more specific motivation as to why we care about tomographic water vapor measurements. (Or if water is a stand-in and the goal is to measure methane by this method, to state that).

Question: 12828 Ln 8: "where greenhouse gas emission from certain soil structures shall be monitored" Are you considering water to be a greenhouse gas?

> *Answer:*
> Water is here, first of all, our first test case for a tomographic reconstruction. In the future we also plan to apply the same principles and similar setups to CO_2 and CH_4. But this is more challenging due to the smaller concentrations to be detected. Furthermore the spatial scales to be covered for CO_2 and CH_4 need to be adapted according to the scientific question and emitting soil structures.
>
> Water of course is the most important (natural) greenhouse gas. However, water emitted from soils into the planetary boundary layer is not acting as greenhouse gas, as it is emitted too close to ground. However, water transport across the soil-atmosphere interface is an important tracer for the transport of latent heat and also quite important to understand soil hydrology and soil-atmosphere interaction. For permafrost soil dynamics it would therefore be helpful to measure the spatio-temporal variations not only of CH_4 and CO_2 but also water vapor, see e.g. Boike [1,2].

[1] Boike, J., Ippisch, O., Overduin, P. P., Hagedorn, B., and Roth, K. (2008). Water, heat and solute dynamics of a mud boil, Spitsbergen. Geomorphology, 95(1):61–73.

[2] Boike, J., Kattenstroth, B., Abramova, K., Bornemann, N., Chetverova, A., Fedorova, I., Fröb,K., Grigoriev, M., Grüber, M., Kutzbach, L., Langer, M., Minke, M., Muster, S., Piel, K.,Pfeiffer, E.-M., Stoof, G., Westermann, S., Wischnewski, K., Wille, C., and Hubberten, H.-W.(2013). Baseline characteristics of climate, permafrost and land cover from a new permafrost observatory in the Lena River Delta, Siberia (1998-2011). Biogeosciences, 10(3):2105–2128

Question: 12829 Ln 15: What is the spatial scale of the soil structures that you are concerned with emitting greenhouse gases? You specify 0.5 m as the required length scale – how did you arrive at that number and what soil structures are that small?

Answer:
The tomographic system like the one described in our paper can be helpful
A) to understand soil-atmosphere interaction in permafrost soils, where quasi-periodic surface structures (e.g. lie the so-called mud boils) appear with typical structure sizes in the meter range (see [1,2] Boike et al.) and due to their topographic heterogeneity influence gas transport and H_2O, CO_2 and CH_4 release. Or B) to study the drying dynamics and water transport through (clay) soils, which happen to an undetermined fraction via the cracks formed during drying, which have widths in the range of 10 cm [3,4].
In both cases the topographical structures also interact with vegetational structures causes by the spatially structured soil coverage with e.g. with mosses or lichens. Such structures can have dimensions ranging from 10 centimeters up to several meters. Therefore, tomographic systems which can cover areas from 0.5 m^2 up to hundreds of m^2 are in the focus of our research.

[3] Kurt Roth, Field-Scale Water and Solute Flux in Soils, Springer Basel AG, ISBN 978-3-7643-2510-7, 1990

[4] J. Boike, M. Langer, H. Lantuit, S. Muster, K. Roth, T.Sachs, P. Overduin, S. Westermann, A. D. McGuire, *Permafrost – Physical Aspects, Carbon Cycling, Databases and Uncertainties* in "*Recarbonization of the Biosphere*", pp 159-185, Springer, 2012

Question: How do you measure the pathlength? You alluded to it in 12837 ln 11, but more detail is needed. Accuracy in the pathlength measurement is essential to the accuracy of the instrument, and given that the beam is moving it does not seem trivial. A detailed explanation of this calculation and the uncertainty in the calculation are needed.

Answer:
The absorption path length of each scan was calculated based on the geometry of the setup and the absolute position of the scanning mirror. The total H_2O concentration uncertainty was calculated as described in [5], but with the values from our experiment.

We added text to clarify this (Section 3) and added reference for uncertainties (Section 4)

[5]   Buchholz, B.; Böse, N.; Ebert, V. (2014): Absolute validation of a diode laser hygrometer via intercomparison with the German national primary water vapor standard. In Applied Physics B 116 (4), pp. 883–899. DOI: 10.1007/s00340-014-5775-4.

Question: Why is the exterior boundary square? Wouldn't setting the reflectors in a circle make the reflections stronger and the pathlength calculation more accurate?

Answer:
Our setup with the flexible, retro-reflecting foils has the advantage to be easily adoptable to any boundary shape. For the first laboratory realization we chose the square shape for simplicity reasons: It is easier to realize technically, simple to characterize by just measuring four angles and four lengths, and it is also easier to determine the path length for the individual path by the geometrical determinations. The square shape is also compact and easy to transport when taken into pieces, which is important for field measurements in remote areas, and furthermore well suited for typical quasi-periodic surface structures known to appear in permafrost soils see [1-4].

Question: Is there any pathlength that the laser travels within the instrument before entering the field (between the collimator, polygon-mirror, and exterior, or exterior and detector) which is unaccounted for in the calculation, and have you demonstrated that it will not impact your measurement?

Answer:
You are right, there is an additional path within the scanning unit. But this path is accounted for in two ways: First, the scanning unit is purged with dry air or nitrogen (see section 3). Second, we subtract the additional absorption inside the scanning unit from our signal. This is also important if purging is not possible. In that case, it is essential that we keep the parasitic absorption in the scanning unit constant. The atmosphere in the scanning unit needs then to be sealed off from possible variations in the outside air. A detailed treatment of such problems is discussed in our recent publications [6, 5].

[6]   B. Buchholz, V. Ebert, Offsets in fiber-coupled diode laser hygrometers caused by parasitic absorption effects and their prevention, Meas. Sci. Technol. 25 075501 2014 doi:10.1088/0957-0233/25/7/075501

Question: How high above the ground is the measurement made? Would be useful to specify (particularly because at first I got the impression that you were actually measuring the soil water content, not the air).

Answer:
In this paper we discuss laboratory measurements were we measured at a more or less arbitrary height of about 25 cm above the optical table. For future field measurements the height above the soil would of course be an important parameter which also reflects the amount of mixing which takes place before the measurement. By height dependent tomographic studies the mixing could thus also be investigated similar to our studies about the boundary layers of plant

leaves [7]. In order to represent the soil humidity or the humidity transport through soils structures like cracks as good as possible, we would then need to place the measurement height as close to the soil as possible.

Note: The 2D spectrometer could also be arranged with the measurement plane perpendicular to the ground level, then it should be possible to detect vertical structures in the boundary layer.

[7] Wunderle, K.; Rascher, U.; Pieruschka, R.; Schurr, U.; Ebert, V. (2014): A new spatially scanning 2.7 μm laser hygrometer and new small-scale wind tunnel for direct analysis of the H2O boundary layer structure at single plant leaves. In Applied Physics B. DOI: 10.1007/s00340-014-5948-1.

Question: 12834 Ln 25: What are the accuracies of the temperature and pressure sensors and are their uncertainties included in the stated instrument accuracy?

Answer:
The accuracy of the temperature over the entire measurement filed was estimated to be 1.5K. The accuracy of the pressure sensor about 0.3 mbar. Both values are included in the total uncertainty. We added that information to the text.

Question: 12835 Ln 24: Why are you fitting 19 lines? Are these other absorbers which interfere with the absorption line at 7299.43 cm-1? If so, how do you know the concentrations of the other absorbers?

Answer:
The 19 lines are the main absorption line at 7299.43 cm^{-1} and 18 smaller neighboring H_2O-absorption lines nearby. These have to be included in the fit in order to get an accurate (and not only a precise) absolute water concentration. For environmental applications this 19 lines have proven to be capable of accurately reproducing the water spectrum around the main target line. To compensate this spectral neighborhood around the target line is important, in order to accurately extract the line area for the main target line.

Question: Based on better accuracy from the stepwise measurement and the possibilities for improving the speed of the measurement with a VCSEL laser, would it be possible to achieve a step-wise measurement at 1Hz or better to take advantage of the better accuracy of a stepwise over a scanning instrument?

Answer:
This might be possible with improved stepper-motors, which have to have the ability for much faster step-to-step-speed. In a previous version we had tested much faster scanning via galvanometers, but, we didn't achieve the presented accuracy due to pointing instabilities. The presented configuration is not optimized for stepwise scanning. The high inertial mass of the polygon mirrors leads to rapid accelerations which impose a quite high mechanical stress for the setup, which could cause problem in longer term measurements. We believe that continuous acceleration-free rotations with the polygon mirrors are the way to go in order to achieve high

repetition speed and frame rates beyond 10Hz. We also believe that we can improve the performance of the continuous scanning system significantly once we integrate our experience in µsec fast in-situ TDLAS in engines [8] in the future.

[8]   O. Witzel A. Klein, C. Meffert, S. Wagner, S. Kaiser, C. Schulz, and V. Ebert, VCSEL-based, high-speed, in situ TDLAS for in-cylinder water vapor measurements in IC engines, Optics Express, 21, pp. 19951-19965 (2013)

Technical Corrections:

12829 Ln 5: "They not only have to be quantified" *- has been changed in the updated manuscript*

12829 Ln 15: "In the special case of permafrost monitoring, measurement areas of at least 0.5 m edge length to several meters have to be covered." *- changed*

12829 Ln 19: What velocity are you measuring, wind velocity? Vertical or horizontal? *- modified*

12829 Ln 27: "they are based on robust, industrially available components." *- changed*

12829 Ln 29: "into a tomographic setup" *- changed*

12830 Ln 4: "field measurement rate equals the rate at which the concentrations" *- changed*

12830 ln 8: "Ma et al., 2013) or are somewhat . . ." *- changed*

12830 Ln 17: "minimal amount of equipment" *- changed*

12830 Ln 26: "amounts to" *- changed*

12832 Ln 6: "After passing through the absorption medium" *- changed*

12833 Ln 1: "field edges are covered" *- changed*

12834 Ln 6: "TTL signals" – acronym not explained. *– explanation added*

12834 Ln 22: "with a high field measurement rate" *- changed*

12836 Ln 15: "In the left column, all four fan-beam units, represented by channels 0–3, are shown for a 2-D field measurement rate of 2.5Hz; the same is shown in the right column for 1.25Hz." *- changed*

12836 Ln 23: "amounted to" *- changed*

12837 Ln 4: "from the reference measurement" *- changed*

12837 Ln 10: "inaccuracies in the assumed" *- sentence deleted with regard to changes above*

12837 Ln 23: "This might be a source of measurement error, as well as inaccuracies of absorption lengths of both reference and scanning channels..." Unclear. Also, why would there be pathlength uncertainty in the reference channel? Suggested revision:

"This may be the reason for the better accuracy of the step-wise measurement compared to the scanning channel, in which there are more likely to be inaccuracies in the absorption pathlength." *- changed*

12838 Ln 9: "amounted to"; Ln 10: "amounted to" *- changed*

12838 Ln 17: "As static measurements with distances of more than 5 m between the emitting side and the retro-reflective foil have been . . ." *- changed*

Anonymous Referee #2

1 General comment:

In this study the development of a novel 2D scanning TDLAS instrument for measuring water vapour fields is described. The functionality of this instrument is described in good way. Accuracy and precision is determined with a homogeneous water vapour field and a reference instrument. In general, this is an appropriate contribution to AMT. I recommend minor revisions, i.e. some issues should be clarified before the manuscript can be accepted for publication.

2 Major comments:

1) Several remarks concerning the 2D water vapour field, which have to be explained in the manuscript.

Question: a)   The TDLAS technique allows you to get an average water vapour concentration along the light path. How will you be able to reconstruct the 2D water vapour field? There is nothing stated how the reconstruction of the field is working. Can you please provide information about the general approach.

Answer:

Yes, as in medical X-ray tomography (XRT), the sensing beam determines a path averaged property. Therefore the very basics of the reconstruction principles are quite similar to XRT (see also "Radon transform") and described very extensively in XRT and tomographic literature. In the interest of a concise AMT article we refrain from explaining this often published fundamentals and refer to suitable literature, but we added some brief information (and some references [9–11]) at the end of the introduction.

[9]   Gabor T. Herman. Fundamentals of Computerized Tomography. Advances in Pattern Recognition. Springer London, London, 2009

[10]   N Terzija, J L Davidson, C Garcia-Stewart, P Wright, K B Ozanyan, S Pegrum, T J Litt, and H McCann. Image optimization for chemical species tomography with an irregular and sparse beam array. Measurement Science and Technology, 19(9):094007, September 2008.

[11]   K.J. Daun. Infrared species limited data tomography through Tikhonov reconstruction. Journal of Quantitative Spectroscopy and Radiative Transfer, 111(1):105–115, January 2010.

Question: b)   The instrument is built for measuring inhomogeneities in the water vapor field. How large can these inhomogeneities be to resolve the right values? And to which spatially resolution do can measure small-scale structures in the water vapor field?

Answer:

This is an understandable but very complex question, which we plan to answer in greater detail in two follow up papers on the spatial resolution of the setup and the

tomographic principles, which are currently in preparation.

Very coarsely, if we had a signal to noise of 1/10000 on a single path average, we would be able to see a 3% concentration change on path section which corresponds to 3% of the total path length with about a S/N of 9. However, as the number of spatial concentration grid points is larger than the total number of beam paths, and since the information content in the individual beam paths is not independent but correlated, it is obvious that the describing equation system is under determined, and the spatial resolution is probably lower than this coarse estimate. This is one of the main "problems" to solve in all tomographic approaches.

Additionally, for laser optical tomography, it is frequently a problem that the number of paths and number of projection angles - is – compared to XRT with hundreds of angles and hundreds of paths - very limited, due to practical limits (e.g. cost + space requirement of reflectors) in realizing the optical setup. In our case we partially relaxed the beam number problem by using a continuous and very low-cost reflector strip, so that the number of beams can be raised quite easily. Furthermore we plan to cope with the *information deficit* by using prior information on the expected distribution of the gas, which we derive from the topography and vegetation status of the soil section to be studied. Finally, we also plan the gas distribution to be compared with and linked to a transport model in order to take maximum advantage of the information retrieved via the 2D scanning TDLAS setup. In the next paper we will describe the tomographic reconstruction of spatially inhomogeneous gas concentrations for the case of CH_4 and then also discuss the spatial resolution of the setup. In the framework of the paper presented here the question, however, this cannot be extensively discussed due to the length restrictions.

It might be useful to note that the instrument has a very large dynamic range from a few hundred ppm up to several tenth of thousand ppm, the integrated values can vary strongly. Using the dynamic range, the signal to noise and the number of beams and angles we estimate that the setup should be capable of detecting stronger "structures" in the range of a few centimeter.

Question: c)   The derived concentration depends on temperature along the line of sight. You assume a constant temperature in the complete field. If there is any inhomogeneity in the temperature field, how large can the temperature inhomogeneity be so that the error of the water vapor measurement are within their stated uncertainties?

Answer:

The systematic errors due to the temperature uncertainties/heterogeneities are mainly governed by the "relative temperature coefficient" (relTco) of the chosen absorption line. For our currently used main target absorption line we determined a *relTco* of 0.5 %/K (at room temperature).

This means: if we have a spatially homogenous T-error of 1K across the entire path length this leads to a systematic relative concentration error of 0.5%.

If T is spatially heterogeneous the effect is diminished proportionally to the length scale of the heterogeneity: a 1K error on 10% of the path length leads to only 0.05% systematic concentration error in the H_2O path average.

The effect of T heterogeneity on the retrieved 2D field can only be analyzed via a

simulation based on the tomographic retrieval algorithm chosen for the spectrometer, which we plan to investigate in future studies.

However, as mentioned below, we also still have the option to further minimize temperature effects by using other H_2O absorption lines with much smaller relTco. The smallest relTco of a H_2O line we found so far is in the range of 0.02%/K which should make the H_2O concentration virtually insensitive to typical atmospheric T errors or T heterogeneities at ground level.

3 Minor comments:

Question: - l. 12 - 25: It is not clear, why the standard deviation for step-wise measurement is the same as for continuously moved laser beam. It seems that standard deviation isn't depending on the movement? Why standard deviation is so large compared to the reference? Is it because of the inaccurate knowledge of the path lengths. Can you please state on this. - Please provide information about the height of the instrument walls and the height of the laser beams above ground.

Answer:
The standard deviation of the scanned measurements (step-wise or continuously) are dominated by strong intensity fluctuations possibly due to non-uniform reflectivity of the retro-reflecting foil. Further more if the edges of the foils or the scanning units are hit the S/N can drop substantially. This can be however improved by a better placement of the foils to avoid gaps and edges.

Since we discuss laboratory measurements in this paper, we measured about 25 cm above the optical table. In future field experiments the height above the soil can be adjusted according to the needs of the scientific question. (See also similar comments from reviewer 01).

Question: - As the derived water vapour concentration depends on the current temperature and pressure, the location of the temperature/pressure sensor has to be described. It would also be helpful to include the two sensors in Figure 1.

Answer:
The placement of the p-sensor is uncritical as any spatial pressure inhomogeneity is very quickly leveled off due to air currents. More critical <u>can be</u> the placement of the temperature sensors, as spatial T inhomogeneities can much longer persist. This effects however can be minimized selecting absorption lines with a minimized temperature coefficient [12]. With relative temperature coefficients down to 0.1 %/K it is possible to effectively dampen +-5K temperature variations or sensor inaccuracies so that they lead to only 1% changes in the path integrated absorption signal. The line used in this paper was not optimized in this respect but already has a relatively small relative temperature coefficient of 0.5%/K.
We added the position of p and T-sensors in figure 1.

[12] Wunderle, Karl; Fernholz, Thomas; Ebert, Volker (2006): Selection of optimal absorption lines for tunable laser absorption spectrometers. In VDI BERICHTE 1959, pp. 137–148.

4 Technical comments:

p. 12828 l 17: missing word: can be considered "as" a good basis **- *changed***

p. 12830 l 18: missing bracket: Ma et al., 2013) **- *changed***

p. 12830 l 24: rewording: "100 ms per field scan" instead of "field scan – 1" **- *changed***

p. 12833 l 7: typo: center –> centre **- *changed***

l 19: typo: tomografic –> tomographic **- *changed***

p. 12834 l 9: rewording: revolution speed –> rotating speed **- *changed***

p. 12835 l 3: typo: TLDAS –> TDLAS **- *changed***

l 5: Please specify the acronym: PXI rack.**- *added***

l 14: Please specify Channel 0. Which of the polygons is Channel 0? Maybe denote this also in the Figure 1. **- *added***

Figure 1:

Caption: I suggest to replace broken lines –> dashed line **- *changed***