

Dear Editor,

The authors should be commended for extensive revisions and improvements to this manuscript, having responded to all reviewer comments. I have a few minor comments and suggestions which I trust that the authors can adequately address without need for a further round of review.

Dear anonymous referee, thank you for your kind words. In this document, I present you with the answers to your suggestions and minor comments in green.

Specific comments

Line 2: “UAS-based systems”

- It’s not too clear what a UAV-based system is; it is not well-defined. This translates to “uncrewed aircraft systems-based systems”. Perhaps this is fine but it is something for the authors to consider.
 - UAS and UAV are synonyms. UAS is considered the more gender-neutral term, and we updated the manuscript in response to the suggestion of anonymous reviewer 2. We clarify the acronym in the abstract (Line 16) and Introduction (Line 64), which refers to the first part of the word (i.e. UAS). The second part involves everything added to the drone to make it a new system and includes additional sensors (e.g., the in-situ sensor or AirCore).

Line 19: “applied”

- It may be worth stating that a bespoke water correction was both derived as well as applied. This emphasises the additional work of the authors. Otherwise, it may seem like a generic water correction was used.
 - Thank you for the suggestion. We changed the sentence to: “Furthermore, the tests revealed the necessity of temperature control, and a water vapour correction was derived and applied to ensure accurate measurements.”

Line 29: “Overall, our results demonstrate that a cost-effective sensor can provide reliable CH₄ mass emission rate estimates with uncertainties comparable to those of established UAS-based systems.”

- This sentence is confusing as it compares a “cost-effective sensor” to a “UAV-based system” which is not the same thing.
 - Thank you for pointing this out. We updated the sentence to: “Overall, our results demonstrate that a cost-effective sensor integrated onto a UAS can provide reliable CH₄ mass emission rate estimates with uncertainties comparable to those of established UAS-based systems.”
- It is not too clear what a “UAS-based system” is, as it has not been defined. Is it a UAV with an integrated methane sensor? Does the “UAS-based system” include the flux quantification methodology?
 - See previous comment

Line 23: “global warming to below 2 °C”

- Perhaps clarify that this is compared to pre-industrial levels.
 - Added the clarification to the manuscript: “Reducing CH₄ emissions is essential for mitigating climate change and represents a key strategy for limiting global warming to below 2 °C compared to pre-industrial levels (UNEP and CCAC, 2021).”

Line 66: “altitudes”

- Consider replacing this with “heights” as altitude conventionally refers to the height above mean-sea level.

- Thank you for pointing this out. We already tried to ensure all mentions of altitudes were changed to height above ground. This one must have slipped through. We replaced “altitudes” with “heights”.

Line 117: “Water vapour experiments were performed to determine the effect of water vapour on sensor readings.”

- I also assume that this water effect test was used to correct raw Axetris measurements. It should probably be stated here that as well as determining the water effect, this water characterisation was used to correct all field sampling data.
 - This is correct. We clarified this in text as follows: “Water vapour experiments were performed to determine the effect of water vapour on sensor readings and correct the raw observations”

Line 140: “critical functions”

□ What sort of functions?

- Pump state and temperature control. We clarified that in the text by adding “(e.g. set temperature or pump state).”

Line 164: “optical cavity operating at standard conditions of 40 kPa”

- This is a bit confusing as “standard conditions” is usually defined as 1 bar (or 1 atmosphere). It would be better to state that the LI-7810 uses “a pressure-controlled optical cavity operating at standard pressure of 40 kPa”.
 - The LI-7810 can be set to three modes: standard operation, reduced flow rate, and high-altitude. For this reason, we decided to refer to it as operating standard conditions. But for clarity we decided to remove “standard conditions of”.

Line 164: “ V_{eff} ”

- What does this mean?
 - We changed it to “(i.e., effective cavity volume of $\sim 2.5 \text{ cm}^3$)”
 -

Line 179: “The LI-7810 system linearity was confirmed by extensive laboratory tests (ICOS, 2020).”

- I still think it is important to state here explicitly that the linearity characteristics of a different LI-7810 are assumed to hold here for the LI-7810 used in this work. I appreciate that the authors added some text about generalising in the previous paragraph, but it is important to additionally state this here explicitly for full clarity. From my point of view, there is nothing wrong with this approach, but it should be clear to avoid ambiguity.
 - We included the following to address this point: “The LI-7810 system linearity was confirmed by extensive laboratory tests (using a different, but similar instrument; ICOS, 2020).”

Line 187: “ $\text{CH}_{4_{\text{AX}}}$ ”

- Has this term been defined?
 - It was not, but we defined it in the paragraph after

Line 187: “ $\text{CH}_{4_{\text{LIC}}}$ ”

- Has this term been defined?
 - It was not, but we defined it in the paragraph after

Line 187: “120”

- Consider including the units here. I appreciate that they are given below, but there is no harm in including them here as well.
 - Thank you for the suggestion. However, we decided against this, since we would have to include the units for all variables in the linear equation. This would make the equation less clear.

Line 221: “In practice, water vapour concentrations were either measured directly or taken from model simulations.”

- I am not sure what it means to take water mole fraction from model simulations. I would assume that any water mole fraction needs to be based on some sort of measurement.
- In any case, if the Axetris water correction is based on LI-7810 water mole fraction measurements, it should only be applied in the field using LI-7810 water measurements (which are empirical and have not otherwise been calibrated). Otherwise potential errors in empirical LI-7810 water measurements would not automatically be eliminated.
 - Thank you for pointing this out. The wording of this sentence is indeed not ideal. What we are trying to say here is that you can either pick the water vapour concentrations from in field empirical data OR nearby meteorological stations that report relative humidity. We did clarify this later in the manuscript (Lines 445 – 447).
 - We changed the sentence to: “In practice, water vapour concentrations were either measured directly in the field (using the LI-7810) but could also be taken from nearby meteorological stations.”

Line 222: “With this, we assume that the non-dilution part of the water vapour correction remains the same at ambient levels as at high concentrations.”

- I am very pleased that the authors have included this statement, which does a great deal to clarify the rationale for the approach. I am not totally convinced that spectroscopic effects remain the same across the methane mole fraction range. I would expect a lot of spectral overlap at 1 650 nm between methane and water. It would be a real added bonus if the authors could provide some justification for this assumption, but it is fine as it is and a major improvement.
 - Thank you for your comment. We do agree that spectral overlap at the 1650 nm wavelength can introduce concentration-dependent effects. In our experiment we did try to verify this by showing the effect at high and low concentrations. Since we also included high concentration experiments, this spectroscopic effect should be more pronounced, compared to lower concentrations. We therefore still believe it is a good assumption to use the correction for lower concentrations as well, to be on the safe side.
 - Due to the noise levels, the water vapour effect at lower concentrations cannot be completely determined (since it would create an offset of approximately 5-10 ppb). and we are therefore not able to fully justify this assumption. We hope this explanation is enough and we will leave the manuscript as is.

Line 236: “more turbulent conditions”

- The conditions on a UAS are turbulent in what way?
- I do not think atmospheric turbulence should affect temperature-controlled Axetris measurements sampling from a controlled reference calibration bag. The poorer precision could be due to UAS vibrations.
- But I think some brief discussion is required here on what turbulence means in this context and why the authors believe it can affect sensor measurements.
 - Turbulent might not have been the best choice of words. In this context turbulent refers to more to the movement of the drone to which we subject the sensor. We indeed refer to the

UAS vibrations but also the rapid changes in direction and change in airflow around the sensor. We tried to clarify by changing the sentence to: “These tests gave insight into the sensor's precision when experiencing flight induced vibrations and aerodynamic disturbances.”

Line 258: “show that turbulent conditions”

- Following the previous comment, I do not think this statement can be made unless the authors are absolutely sure of the cause of poorer precision when sampling on-board the UAS. As a minimum, this should be replaced with “show that turbulent conditions may reduce its precision”, with addition of the word “may” to indicate that this is a hypothesis. But some brief discussion is really required on what turbulence means here and why it effects the measurements.
 - We included the “may” which resulted in the final sentence being: “These results demonstrate the sensor's performance without additional temperature control and show that flight induced disturbances may reduce its precision”
 - Since we did change the wording to be clearer, we believe we do not need to further clarify the term “turbulence”.

Line 312: “The dairy cow farm quantified”

- Strictly speaking, it is emissions from the dairy cow farm and not the farm itself that is quantified in this work.
 - You are correct. We changed “quantified” with “investigated”.

Line 332: “possible mildly convective”

- I do not see any details on convection in Table 1.
 - You are correct, this is not a part of Table 1. Only the wind speed is presented in the table. We therefore removed the reference.

Line 403: “compensation for water vapour dilution”

- Which water mole fraction measurements were used to correct Axetris methane mole fraction measurements? Was the LI-7810 used? If this is the case, then this entire methodology relies on both an Axetris and a LI-7810, which is no longer a cheap solution.
 - This is indeed the case and is mentioned a bit later. We also only state the equation we use and we suggest that everybody using the Axetris will derive a correction function themselves to ensure proper determinations.
- In a future solution, water mole fraction can perhaps be derived from relative humidity and pressure measurements. However, the derived water correction presented in this work would no longer be valid, as empirical (non-calibrated) LI-7810 water mole fraction have been used to derive the water correction coefficients. The authors may wish to discuss this.
 - You are indeed correct and our correction does rely on the LI7810 H₂O observations. However, we believe using the relative humidity as an indication of the H₂O content in the air still to be a good approximation of the dry mole fractions. This however, does come with increased uncertainty but is likely a very small term. We also showed that at ambient concentrations, the water vapour effect is negligible and cannot be picked up due to noise (Appendix D).

Line 435: “CH₄ mole fraction enhancement”

- It would be nice to remind the reader that this is a dry mole fraction enhancement above a dry background here.
- The laboratory-derived water correction is applied to this data.

- Thank you we clarified it in text as: “ Δc gives the dry CH₄ mole fraction enhancement above the background in ppb”

Line 442: “Additionally, the ambient H₂O mole fractions were obtained using the LI-7810 analyser.”

- Were these same LI-7810 water mole fractions used to derive dry methane mole fractions? Please make this totally clear.
 - Yes, they were. We tried to clarify this in text as follows: “Additionally, the ambient H₂O mole fractions used to determine the dry-air correction of Δc mole fraction and the calculation of M_{vol} were obtained using the LI-7810 analyser.”
- Water mole fraction is required twice in this methodology. It is used to calculate both dry molar value and dry methane mole fraction. Both parameters require a water mole fraction value in their calculation. Make it clear where both water mole fractions come from (or if the same value is used for both parameters).

Line 485: “We use only the raw signal in subsequent analyses.”

- This is not strictly true, as a water correction is also applied to the data. Perhaps “raw” is not the best word here.
 - We changed the wording to “corrected” instead of “raw”

Line 654: “uncertainties”

- Replace this with “uncertainty”.
 - Replaced “uncertainties” with “uncertainty”

Line 699: “drift”

- Is sensor drift evaluated in this analysis? I can see that noise is evaluated, but a drift test does not seem to be described.
 - You are correct and we did not directly evaluate drift. We therefore removed the mention of it. “To the point of our study sensor noise does not emerge from the uncertainty analysis as dominant”

Line 709: “Table 3”

- Is “Everything 0” the best term? The standard scenario is to have a single flight, not zero flights.
 - That is correct and we understand the confusion. However, the combined uncertainty only includes a single flight and is not a variable we change. The other uncertainties considered (and set in the combined uncertainty analysis in paragraph 4.2.5.) are all set to 0.
 - To ensure no confusion is possible we changed “everything 0” to “baseline” and added an additional clarification.

Line 717: “flight repeats”

- Perhaps “repeats” is not the best word here. I understand what this means. But a single flight is not a repeat. And six consecutive flights are five repeats of a single flight.
- The same issue arises in Table 3.
- Maybe it is better to count the repeats from zero to five. Then, the previous comment (about “Everything 0”) is easier to resolve.
- The same applies to Figure 4a. It may be better to plot it from zero repeats (*i.e.* a single flight) up to five repeats (*i.e.* six consecutive flights).

- We agree that the word “repeat” is not the best and therefore decided to remove it here and in all other instances. We now refer to it as 1-6 flights. We also updated the figures and the captions to reflect this.

Line 812: “quantitative assessment of the sensors’ performance”

- Consider ending this sentence with “in mass emission flux quantification”.
 - Thank you for the suggestion. We changed the sentence to: “Furthermore, large-scale controlled release experiments could provide a quantitative assessment of the sensors’ performance in mass emission rate quantification.”

Line 827: “Active AirCore technique”

- It would be good to say here that the AirCore was used in conjunction with a high-precision gas analyser to measure its contents.
 - The high-precision gas analyser is a part of the technique used for the Active AirCore, one does not exist without the other. We do specify this at multiple occasions in the manuscript and since we do not refer to the Active AirCore but the full technique we believe it is implied and should not be further clarified.

Line 835: “sufficiently large”

- Perhaps this should be replaced with “sufficiently intense”. The word “large” infers that this refers to the physical size of the source.
 - Noted, changed “sufficiently large” to “..particularly when emission sources have a sufficiently large source strength and plume coverage is sufficient in space and time.”

Line 838: “since errors in background estimation can account for more than 100% of the total uncertainty for a mass emission rate of 10 kgCH₄/hr”

- Please specify here that this 100% value is specific to simulating the UAS sampling in this particular study. This 100% uncertainty contribution may not apply to a different UAS sampling in a different way downwind of a different source, with a different set of environmental conditions.
 - Not really actually. The uncertainty in the background determination can be introduced in various ways (e.g. due to malfunctioning of the sensor or wind variability and therefore varying backgrounds). However, the effect will still be the same. Even when sampling differently incorrectly determining the background can still introduce errors larger than 100%.

Line 1009: “Table A1”

- Please change “UAV” to “UAS”. Consider replacing “Licor” with “LI-7810”.
 - Changed “UAV” to “UAS” and “Licor” to “LI-7810”.

Line 1026: “28°”

- Replace this with 28° C.
 - Replaced “28°” with “28°C”

Line 1051: “Figure D2”

- Please indicate here (either in the figure or the caption) that the water mole fraction measurements come from the LI-7810.
 - We updated the caption to: “Figure D2: Regression model used to determine the water vapour correction as described in section 2.4. The linear relationship between the wet and dry fractions is used to correct for water vapour during field experiments. Water vapour concentrations in this Figure are obtained from the LI-7810. The R² value is 0.86.”