

Dear Editor,

This manuscript tests a low-cost sensor node containing a Figaro TGS 2600 and a Figaro TGS 2611-E00 metal oxide sensor, alongside a high-precision reference instrument. The sensor was tested both outside and inside. The outside dataset could not be used due to a lack of methane enhancements, despite efforts to artificially enhance the background. The inside dataset could however be used. The correlation of both sensors to various environmental conditions and methane concentration were presented, using the TGS 2611-E00 as the main methane sensor. This work took the approach of deriving a baseline resistance corresponding to methane concentration below 2.3 ppm, to incorporate non-methane environmental effects, which included a time component. A second baseline was also devised which included TGS 2600 measurements, as this sensor was assumed not to be methane-sensitive. The ratio between measured resistance and baseline resistance compared to methane concentration was poor for both approaches. Instead, the baseline was split into 10 pieces for which individual baseline coefficients were derived. This approach was slightly better. A sensitivity analysis was conducted on piecewise baseline variability components over time. In another analysis, the TGS 2600 was also treated as the main methane sensor, but this did not yield results better than treating the TGS 2611-E00 as the main sensor. In any case, any analysis on methane concentration is slightly dubious as most methane concentration measurements were obtained in background conditions. The greater value of this work is in baseline resistance modelling. This paper is a welcome addition to the growing body of literature on this subject. I was particularly impressed by the meticulous nature of this work. The standard of English and the presentation is very good. I suggest the following editions to the work, in addition to the two paragraphs below, where I address two key issues.

Using the TGS 2600 resistance measurements to derive a baseline fundamentally requires for TGS 2600 methane sensitivity to be negligible. The theory is that this (assumed) non-methane sensor can be used to characterise non-methane effects. Yet, if methane effects are not negligible, then methane sensitivity may be reduced in the resistance to baseline ratio, thus being counterproductive. Based on visual inspection of figure 7, there is not much improvement when comparing an eq 1 (no TGS 2600) baseline to an eq 2 (with TGS 2600) baseline versus methane concentration. The authors do not provide R^2 values for each fit and only provide values for their favoured fit (eq 2 piecewise). Unless the authors can prove that the eq 1 baseline approach is significantly better than the eq 2 baseline approach, I do not think using TGS 2600 measurements within a baseline is necessarily better. The authors' justification for using eq 2 instead of eq 1 is that it results in a better baseline fit (*i.e.* modelled baseline versus measured baseline). This is hardly surprising as this simply shows that two similar TGS units behave in a similar way. But the authors must also be sure that there is no TGS 2600 methane effect.

To test the TGS 2600 methane effect, the authors do apply a baseline correction to the TGS 2600 data (in the same way for the TGS 2611-E00 data), observing poor methane correlation. Yet, the authors fail to provide an R^2 value of the methane fit for comparison. Furthermore, most TGS 2611-E00 baseline attempts also failed, when compared to methane concentration. I think the 10 ppm limit and the number of data points may have been insufficient to reveal sufficient correlation for this sensor. I therefore question the conclusion from this manuscript to dismiss the utility of the TGS 2600 from further research. The authors must clearly state these caveats and limitations when discussing their views and outlook on the use of the TGS 2600. This work is not sufficient to conclude that the TGS 2600 is not sensitive to methane below 10 ppm.

General comments

Abstract

- This is concise and easy to follow. However, this section is written slightly vaguely. The abstract should include more specific details on the work presented in the manuscript and not be afraid to use a bit of technical language. For example, a crucial advancement in this work is the development of a baseline resistance model. This should definitely be in the abstract. The authors could also add some more details on the enclosure (such as size), if appropriate.
- I also think that the duration of testing time should be included here.
- I am interested by the decision not to specify that a Figaro TGS is being used either here or in the title. I do not insist that the authors do so. However, I would appreciate some rationale please, as I do not understand the value of this.

Introduction

- This section provides a very good summary of recent research on the TGS in methane concentration measurements, with good referencing. However, this first paragraph could provide a better overall motivation for the necessity of this work in the context of increasing methane emissions, with some citations.
- The way in which the narrative of this section is conveyed is sometimes confusing as it is not clear whether it is written in the context of methane or more generally. Based on the first sentence, this is a paper on methane measurements. It should therefore be emphasised throughout this section that points are being made in the context of methane sensors and not more generally.

Methods

- Overall, this section is well-constructed and covers the methods very well. The calibration section was particularly well-written and easy to follow.
- Regarding the timestamps, was the lag time of the TGS enclosure ever tested? The 30 s lag time of the LI7810 was assumed to be negligible, which is fine. However, the lag time of the TGS logger is a bigger issue. If a spike of methane was emitted just beneath the TGS enclosure, I wonder how long it would take TGS resistance to peak in response. It would not be short (a few seconds), as air is carried to the sensors by diffusion. I do not think 10-minute averaging will overcome this problem, unless TGS peak time is less than 1 minute. The averaging is however still necessary to account for the nature of diffusion, which is not instantaneous like a LI7810. The overall solution is both a lag-time correction in combination with averaging to smooth any emission spikes.

Results

- The investigation of various causes of baseline disparity is a welcome inclusion in the research on this topic. The correlation plots and the baseline analysis are both good. However, the work on a methane response using different baseline approaches lacks detail.
- In addition, this section must include an analysis of methane correlation excluding periods used to produce a baseline fit. Otherwise, it is mostly an analysis of the ability of the baseline to predict the baseline as the vast majority of datapoints were below 2.3 ppm, *i.e.* the baseline threshold.

Discussion

- The sensitivity analysis of the time component on the baseline is a very useful and robust way of identifying the nature of temporal variability.
- Testing the ability to derive a TGS 2600 baseline for methane correlation is a very good idea. However, the caveats must be discussed more clearly here. Furthermore, a plot of methane correlation would be welcome. It is not clear how much worse the TGS 2600 is than the TGS 2611-E00, when detecting methane.

Conclusion

- This is a nice overview of the work, but lacks a few key values and outcomes from the work, that could be included.

Specific comments

Line 11: We deployed the prototype sensor alongside a reference methane analyzer in two sites - one outdoors, one indoors - for several months each of data collection across a range of environmental conditions and methane levels.

- This sentence is difficult to follow.
- Also, please specify which types of environmental conditions. Variations in temperature?

Line 13: calibration models

- Please add a few very brief details on what sort of calibration models. What is the crucial basis of the calibration approach? Were linear models used? Was machine modelling used?

Line 14: background monitoring and enhancement detection

- Monitoring and detection of what? Presumably this is methane concentration.

Line 14: performance

- What does “performance” mean? Does this mean accuracy compared to the reference instrument? Please clarify.

Line 14: 2 to 10 ppm range

- Please specify that this refers to methane concentration.

Line 17: these and similar inexpensive MOx sensors

- Of which sensors? It is not specified which sensors have been used. The authors cannot refer to “these” sensors and compare them to similar sensors, if the sensor has not yet been introduced.

Line 17: near-background methane monitoring

- What does this mean? Perhaps state that this refers to up to 1 ppm (or whatever) concentration enhancement.

Line 19: scarcity of high-resolution ground-level data

- Please provide some references for this statement.

Line 21: variety of sensor mechanisms

- Please specify that this refers to methane sensors. It is better to write this section in the context of methane detection, rather than general low-cost sensor use.

Line 29: sensor array or “e-nose” configurations

- Please briefly explain how using a sensor array can overcome issues of selectivity.

Line 38: when calibrated in a laboratory setting

- Please specify that it was both calibrated and tested in a laboratory setting. This 1.7 ppm value refers to an indoor laboratory test.

Line 40: Cho et al. (2022) find

- Please write this in the past tense.

Line 41: above 100 ppm concentrations

- In the laboratory or in the field?

Line 41: 2 to 100 ppm range

- Again where? In the laboratory or at a glacier?

Line 42: but found that quantitative emission estimates had poor accuracy

- I don't understand the relevance of this. This is a manuscript on methane concentration measurements and not flux measurements.

Line 48: positive results

- Please clarify, positive results in what? In methane concentration measurements? It is previously stated that this sensor can be used to measure many gases, so this must be clear.

Line 48: Eugster and Kling (2012) report a

- Write this in the past tense.

Line 49: Other papers find

- Write this in the past tense.

Line 83: We burned in the sensors and regulator for a week prior to data collection.

- Why

Line 91: Our system performed well in both sections of the experiment, with 95% of all data showing a sensor supply voltage within ± 0.25 mV of the mean and 99.99% of all data showing a supply voltage within ± 0.80 mV of the mean across the full dataset.

- This is a very good demonstration of good practice and an excellent result. It is impressive.

Line 119: Our first site was an urban yard in Minneapolis, USA

- Perhaps provide the coordinates, if possible.

Line 125: The background methane concentration at our research site

- How is this known? Is this based on the LI7810? Please specify.

Line 127: 2.5% methane gas cylinder

- What was the rest of the cylinder filled with Synthetic air? Natural air? Argon? Nitrogen?

Line 129: These releases produced a maximum 10-minute averaged methane value of 5.8 ppm, with most of the releases producing methane concentrations between 3 and 4.5 ppm.

- Again, please specify how this is measured. Is this based on the reference gas analyser?

Line 133: Our second site was indoors in the Biosystems Engineering building at the University of Minnesota, Twin Cities campus.

- This is a little confusing. Quite simply, one test was conducted outside and one test was inside the building. However, it reads as if there were two totally different sites in different locations, which adds to the complexity. “Our second site” implies that there were two totally separate testing locations.
- In reality, there was only one site, not a first and second site.

Line 136: We also expected possible emissions of methane and other gasses from surrounding labs

- This could be a crucial point. The lab was filled with potential interfering gas sources, which could influence the TGS response. I think the authors may elaborate here on potential gases that could be present or, at least, provide some more specific details on the activities taking place in the vicinity.

Line 153: we removed two hours of data after each reboot

- Can the authors confirm that 2 hours was sufficient for the sensor to stabilise after power loss? I suggest a plot showing this.

Line 156: dataset averaged to a 10-minute timescale

- Was it a 10-minute running average or were 10-minute averages taken next to each other. Please clarify this both here and throughout the manuscript.

Line 172: We chose to include sensor run time to incorporate any effects of sensor aging;

- This is a very good idea. Is this the absolute time or the time of the sensor being switched on to account for data gaps?

Line 177: Relative humidity is dependent on water vapor concentrations and temperature

- And also, pressure.

Line 179: we decided a priori to include water vapor concentrations and not relative humidity as a possible term in our analysis.

- I totally agree with this rationale. Perhaps cite some other research that preferred to use water concentration instead of relative humidity.
- Another important detail is missing here. Is this water concentration from the LI7810 or is it derived from the SHT? If it is derived, the authors must state how it derived.

Line 193: The TGS2611-E00 sensor response is expected to deviate from the predicted baseline response as a result of methane levels as shown in Equation 3a.

- Why was this equation chosen? It is based on any previous work? I have never seen a purely linear fit applied to a resistance ratio. This is no criticism, but I am interested to know where it comes from.

Line 212: We observed a diurnal cycle in methane levels

- How? Using the reference gas analyser?

Line 213: soil processes

- What does this mean?

Line 240: humidity

- What does this mean? Is this water concentration? The term “humidity” is used regularly throughout the manuscript. However, I do not think this is wise as it could mean either water concentration or relative humidity. I suggest that the authors replace all “humidity” terms in this manuscript with a more precise term (either water concentration, relative humidity or something else) to avoid ambiguity.

Line 248: relative humidity

- I'm not too sure in the value of including relative humidity here in this list and in the previous analysis. As the authors themselves state, relative humidity and water mole fraction are related. So, it is hardly surprising that both influence TGS resistance.

Line 252: by including TGS2600 in the baseline response, we can possibly remove influence from nontarget gasses and other unexpected factors.

- The authors also remove the baseline from the TGS2600 dataset? This should be mentioned in this section somewhere.

Line 260: 1.46, 1.56, and 2.81 k Ω

- These values should include a plus-minus sign as the square root has a negative and positive solution. The same for RMSE below.

Line 293: The fit is the best quality

- Which fit?

Line 306: with $R^2=0.46$ and $RMSE=0.65$ ppm

- The authors should also provide RMSE and R^2 values for periods not used to derive a baseline (*i.e.* above 2.3 ppm). This would help to evaluate the capability of the approach when not applied to the same data used to derive a baseline fit.

Line 317: we calculated the absolute change in methane concentration with the data immediately before and after each point

- What is the time distance between each point? Are they 10-minute running averages of averages next to each other?

Line 338: occurrence after a data gap (D)

- What are the red dots? I think this figure could be improved with the different colours given as a legend in each subplot. The figure caption is not clear as all of the points are plotted.

Line 371: Figure 7: Sensor calibration results using the different baseline regression approaches.

- Please change the axis from “actual CH₄” to “LI7810 CH₄” or similar, as “actual” doesn't mean much.

Line 439: However, neither possible fit (with the Equation 1 or Equation 2 baselines) for methane had R^2 better than simply predicting the mean, nor RMSE better than 4.5 ppm.

- Unless R^2 values are provided, corresponding to the plots in Figure 7, it is not clear whether the TGS 2600 is truly worse than the TGS 2611-E00. The non-piecewise baseline attempt for the TGS 2611-E00 also failed and only one model worked.

Line 452: parts cost of under \$200

- This is very impressive. It should be included in the methods section.
- Also, please provide the cost of telemetry data transfer in the methods section. Presumably there is a regular subscription charge of some nature.

Line 457: We suggest that work finding TGS2600 to respond to methane in a low concentration range should consider possible co-emitted gasses, algorithmic overfitting, or other experimental factors.

- I do not think that this sentence should be in the conclusion as they are not key findings from this work and are simply the opinion of the authors. We do not know for sure why the TGS2600 has worked in previous studies

Line 462: above 10 ppm

- Why above 10 ppm? This work was below 10 ppm. All available data above 10 ppm were excluded from the analysis so I do not understand why this point is being made.

Line 463: Our sensor response correlates with methane levels with moderate accuracy in the lower 2 to 10 ppm range

- This is misleading for two reasons.
- First, the authors must be precise what they mean by “moderate accuracy”.
- Second, most of the analysis was performed on data below 2.5 ppm. Only a small percentage of data was anywhere near 10 ppm. So, the sensor was mostly tested at background levels and not mostly over a range up to 10 ppm.

Line 474: controlling water vapor levels and temperature in the sensing chamber

- Why would this help if the baseline model already accounts for these effects? Surely the problem is unknown environmental factors. What is the use of controlling known variables?

Line 476: methane concentrations above the near-background range

- What does this mean?