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Interactive comment

Interactive comment on "An Examination of Enhanced Atmospheric Methane Detection Methods for Predicting Performance of a Novel Multiband Uncooled Radiometer Imager" *by* Cody M. Webber and John P. Kerekes

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Referee #2 Comments Response: On behalf of myself and my coauthor I would like to thank you for taking the time to review and provide feedback on our paper. Your feedback was very helpful and much appreciated. We know that your feedback will help make our revision a better discussion of our work.

General Comments The manuscript (Webber and Kerekes 2020) compares the performance of three different analytical methods for detecting methane in remote sensing imagery taken using an uncooled multispectral infrared (IR) radiometer. Given the prohibitive cryogenic requirements of traditional thermal IR imagers, an uncooled instrument would lower barriers to deploying imagers for atmospheric methane detection. This paper provides a useful evaluation of this system for methane detection; however, the description of the methodology, and the discussion and conclusions require more development. In particular, more quantitative details about assumptions made and model input used should be included, and reasons for the values chosen should be explained

Author Response(AR): Thank you for your comments pointing out the potential benefits of an uncooled instrument and recognizing the utility of our studies. We have added details to the descriptions of the methodology and enhanced our discussions to clarify points raised by the reviewers.

Specific Comments Page 2 l. 9-10: The phrasing that HyTES has been used to develop an algorithm that can predict methane concentration from thermal imagery is somewhat vague and therefore confusing. It would be more helpful to identify the improvements in the HyTES retrieval algorithm in Kuai et al. (2016) that are most relevant to the research described in this paper

ARl: 9-10 Some of the data used to inform the models we used in this study is from Kuai et al. We reference this study here to give context of what thermal instruments have been used for in the past as attempting to retrieve methane concentration is out of the scope of this study.

l. 19: Given that sensors that operate in various regions of the IR spectrum are discussed, it would be helpful to briefly clarify why traditional thermal IR sensors require cooling and the advantage of thermal IR over shortwave infrared (SWIR) sensors, which also measure methane but do not have the same cooling requirements.

l:19 A brief discussion of the advantages of TIR over SWIR was added and a statement of why traditional thermal IR sensors require cooling was added to this section.

l. 21: What defines a "satisfactory performance"? What is the level of sensitivity, precision, accuracy, or another relevant metric needed for methane detection applications of MURI?

ARI:21 No specific quantitative metrics for environmental applications were defined for the MURI project. Rather, satisfactory performance was defined more qualitatively as the system demonstrating useful performance in environmental applications. The project was conceived primarily as a technology development effort. This has been clarified in our revision.

l. 23: What is the difference between the airborne and satellite system? Are they using the same FPA?

ARI:23 The airborne and the satellite system design utilize the same focal plane array and similar optics with an effective focal length of 120 mm and an fnumber of 1. The work presented here is focused on the airborne system and we have clarified that in our revision.

Page 3: l. 13: What assumptions were made about environmental conditions, particularly the concentrations of interfering molecules such as water vapor?

ARI:13 This has been clarified in the Data Set Creation section with environmental conditions specified in Tables 2, 3, and 4.

Page 4: l. 5-9: More details are needed for the methodology, particularly what assumptions were made in modelling the background and plume-present cases and why those assumptions were chosen. A discussion of the sensitivity of the model output to these assumptions should be included here if some a priori knowledge of the sensitivity factored into the choice of assumptions, and/or in the Results/Discussion section if relevant to determining the validity of the results.

ARI:5-9 Modeling of the background was done by choosing parameters which would match the model output to the HyTES scene. Additional details have been included in section 3 to address the model parameters and their derivations.

l. 8: What is the magnitude of the increased concentration of methane? How does this compare to the Noise Equivalent Concentration Length (NECL) and/or minimum detectable column density of the sensor?

ARI: 8 For the single pixel study, NEdT is chosen as the metric of comparison for detection as we are changing plume temperature and concentration and NECL will change for plumes of different temperature. Additional methane plumes were varied from 1 to 50 ppm. The graph was created using the following concentration plumes: 1, 5, 10, 20, 30, 50 ppm. The step sizes were chosen to ensure fine sampling such that the shape of the Tplume – Tbackground curves were not affected by the concentration intervals.

l. 13-15: Since only a single band is allocated to the methane feature, what is the purpose of the other bands? Section 2.3 demonstrates that the other bands can help constrain the methane retrieval, but if they have additional functions, those functions should be listed (in this paragraph, in the general description of the instrument, or in Table 1).

ARI:13-15: Additional information for each band has been added to Table 1 in order to describe their functions.

l. 21: Units associated with each of the variables would be helpful to conceptualize the relationships in Equation 3 and clarify what is meant by "signal", which can refer to multiple aspects of the data stream

ARI: 21 The signal is defined here as the spectral signature of a methane plume, which here is defined as absorption intensity, retrieved from hitran dataset. A clarifying statement as to what the signal is has been added. This assumed linear relationship is written in terms of sensor reaching radiance, so r and c are in terms of W/m2sr um, b is a absorption intensity, and α is a scalar proportional to the plume strength.

Page 5: l. 9-11: Is the threshold applied to the CMFI value, or some statistics associated with it, such as a confidence interval or t-stat? Also, please provide a short explanation of how the ROC curve is used to assess the effectiveness of the method.

ARI: 9-11 The threshold is applied to the CMFI value. The ROC curves describes the hit and false alarm rate at each concentration, indicating where in the concentration space the system can reliably differentiate between on and off plume pixels. Another method of assessing ROC curves is to calculate the area under the curves, which we've provided in the supplementary materials. Section 4.2 includes a discussion of how the ROC curves are used to assess the effectiveness of the method, and the section has been updated in response to your suggestion.

l. 23-27: This explanation is somewhat confusing. Is this paragraph describing whether the methane feature is giving an absorption versus emission signal in the detection? The way that NDMI is described, it seems like it would be possible to have negative values that can be indicative of a methane plume, and if no plume exists, the NDMI would be zero. If so, it seems that a higher absolute value of the NDMI would indicate C3 higher methane. Please clarify.

ARI: 23-27 Thank you for this comment, we have added to the paragraph to clarify. This paragraph is meant to describe how the NDMI will be different for a plume that is hotter than the surface and a plume that is cooler than the surface. If a plume is hotter than the surface, the resulting at sensor radiance for the methane feature band (SB1) will be higher than if there was no plume present. This would mean that, given a scenario in which all other variables remain the same, NDMI would be a lower value as the difference between SB2 and SB1 will be lower and the sum of SB2 and SB1 will be higher. If the plume is cooler than the background surface temperature, the plume will absorb more energy than it emits and the at sensor radiance for the methane feature band (SB1) will be lower than if there was not a plume present. NDMI would then be a higher number as the difference between SB2 and SB1 will be higher and the sum of SB2 and SB1 will be lower than the plume not present case. The NDMI is only 0

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if SB1 and SB2 are equal and is not necessarily an indication of a plume presence or absence as SB1 and SB2 are defined as different spectral channels. It is possible to have a negative NDMI given a high enough temperature difference between the plume and the background surface. The NDMI is a relative measurement, and therefore can only be determined by comparing NDMI calculations across an image.

Page 6 l. 4: Please specify what band 2 has a comparatively higher transmission of: the atmosphere, instrument filter, etc.

ARI: 4 We have clarified that we mean the atmosphere has a higher transmission for band 2 than band 1.

l. 17: It's unclear what is meant by "on and off plume spectra". Are these the spectra for a single background pixel and a different pixel that has a methane detection? Also, what are the assumptions that were made for the MODTRAN simulated recreation of the data? If these are the same assumptions used in Table 2, please refer to that table in this paragraph

ARI: 17 The on and off plume spectra describe two pixels taken from the HyTES imagery shown in Figure 1. The on plume pixel refers to a pixel identified by the HyTeS dataset to contain a methane plume, and the off plume pixel refers to a pixel identified by the HyTES data set to not include an enhanced level of atmospheric methane. Some assumptions are shared between this simulation and the original Table 2, a new table has been included to specify the chosen values.

l. 18: Based on the radiance values in Figure 3, the RMSE for the methane plume case is about 2.5% – How does this contribute to the uncertainty in the methane column density amount?

ARI: 18 Our single spectral band approach does not allow for quantification of methane, making column density uncertainties outside the scope of this study.

l. 19: How is "reasonable" defined? High confidence? If so, what is the threshold?

ARI:19 The language in our manuscript was unintentionally vague. We meant to say this recreation gave us insight into scenes where enhanced methane has been detected before and the confidence to utilize MODTRAN to create controllable simulations that resemble real data that has been used to detect methane previously. The language has been changed to better reflect the intended meaning.

Page 8 l. 11: Is "only small amounts of CO2“ referring to the ambient concentration input into MODTRAN? Please provide the actual value used and why it was chosen. If these results are not sensitive to the assumed concentration of CO2 please state that; if the chosen concentration of CO2 impacts the results, however, provide justification for the value chosen (e.g. regional average concentrations taken from in situ or satellite measurements).

ARI:11 As stated on line 13-14 the effect of CO2 absorption is eliminated by our data set creation approach. The results are not sensitive to the assumed concentration of CO2 in this simulation. The chosen value is a small amount of CO2 that must be included to allow the MODTRAN simulation to run properly.

l. 12: What is the level of enhancement in the "enhanced concentration plume"? Please be quantitative.

ARI: 12 The enhanced concentration plumes refer to the varying quantities used in the experiments, which are identified in Figures 6, 7, and 8. The enhanced quantities vary from 1 – 20 ppm and this has been clarified in our revision.

Page 10 Table 2: Change "Plume Height" to "Plume Altitude", as the former could be confused with "Plume Thickness". Also, please add a row with the assumed ambient temperature

ARTable 2: Thank you, your suggestion has been added to Table 3 (formerly table 2).

Section 4.1: Please provide rationale for the model inputs listed in Table 2 in this section. For instance, was the plume thickness derived from data, a model, or experiments? Was the ambient temperature measured locally, or taken from a model, and if so, which one? Assumptions that don't have a significant impact on results can be stated as such; however, justification should be provided for assumptions that alter the results and especially conclusions of this paper.

AR_Section 4.1: Model assumptions were derived by adjusting MODTRAN inputs to produce simulated radiances that matched the HyTES data. Ambient temperature was recorded by a local weather station and retrieved from Wunderground. Additional rationale has been included to inform their reason for inclusion in the study in our revision.

Page 11 l. 1-6: It is unclear why the sensitivity described was framed in terms of the temperature gradient between the plume and the ambient air, as it is the temperature gradient between the surface and the plume that drives the sensitivity in hyperspectral imagery. There might be a reason to frame the conclusions in the terms used, but it is difficult to evaluate those conclusions without knowing what ambient air temperature was chosen. The minimum detectable concentration of methane is lower when the thermal contrast between the plume and the surface is high; for example, a very hot plume should be more detectable over a low-temperature surface. Thus, the assertions made in this paragraph would not apply in all cases and would depend on the relative ambient, surface, and plume temperatures. Since the paper is evaluating the performance of new instrumentation, characterizing which conditions the conclusions hold for would be helpful in evaluating the applicability of these techniques for conditions that deviate from those chosen for this study.

ARl: 1-6 . Results were framed as plume to ambient atmospheric temperature differences as this is how our models are defined. We have included the ambient temperature in our revision and have describe our results with context of surface and plume temperature differential. Additionally, a supplemental figure has been added to display the results in terms of the plume/background temperature difference.

l. 12-14: When determining the false positive rate, what is used as truth? Is there ground-truth, or is the HyTES detection mask considered truth? Also, what is the region of interest threshold chosen? That is, does the algorithm require a certain number of contiguous pixels with methane detection before the plume is accepted?

ARI:12-14 As described in Section 3, MURI images were simulated using a HyTES image containing no enhanced concentration methane plumes. One image was created to be the background image, and a set of images were created simulating enhanced concentration methane plumes. We therefore have two separate images, one with methane and one without. This makes for an easy identification of hits, false alarms, correct rejections, and misses. Section 3 has been updated to clarify how the truth map is defined.

Technical Suggests: Page 1 l. 16-17: A citation is missing after "While the concentration of methane is lower than that of CO2, the world has seen a rise in methane emissions since 2007, primarily from anthropogenic sources." Page 2 l. 3: "Thrope" should be changed to "Thorpe". l. 5: It would be useful to specify that HyTES is a longwave infrared (LWIR) imager. l. 18: Since the abbreviation for methane, CH4, is used earlier in the paper, it should be continue to be used consistently. This applies to the remainder of the paper, as well. l. 11: A comma is missing after "(GOSAT)". l. 17: A comma is missing after "infrared". l. 24: "FPA" should be changed to "focal place array (FPA)". l. 25: A comma is missing after "channels". l. 28: Both μm and um are used in this paragraph. One convention should be chosen for the entire paper. Page 3 l. 5: Elsewhere in the paper, pixel is also used to describe both the physical pixel on the FPA (e.g. page 2) and the spatial pixel in the image (e.g. page 4). For clarity, change this instance and other references to the spectral pixel to "channel", which is used later in the paper. Page 4 l. 16: Add "spatial" between "N" and "pixel"

Page 5 l. 21-22: Specify whether SB2 or SB1 includes the methane feature. Page 6 l. 11-12: Specify what "after" is referring to in the sentence "[...] a scenario in which a rogue emission source has been detected was chosen to model the simulated data after." l. 15: Change "Prupulsion" to "Propulsion" (applies to other instances of this citation in the manuscript). Page 7 Figure 1: Specify units after "7.68". Also please add the ground sampling distance (GSD) of the image. Page 8 l. 10: Remove the typo in "for at sensor radiance". Page 9 l. 7: Change the reference to "Table 3" to "Table 2". Page 10 l. 1-2: Citations are needed after "Modern estimates of ambient atmospheric methane concentration are at about 1.8 ppm, dangerous levels for 8 hours of daily exposure to methane for humans is 1000 ppm, while the lower explosive limit is around 50,000 ppm." l. 8: Remove "or" before "the methane feature band".

Page 11 l. 15: An adjective is missing between "very" and "false". Page 12 l. 14: Change "pixel" to "channel" or "band" if spectral pixel is what is meant.

AR Technical Suggestions: Thank you for the technical suggestions and for being so thorough. We are grateful and believe the additional technical suggestions you've provided have certainly improved the quality of the paper.

Please also note the supplement to this comment:
https://www.atmos-meas-tech-discuss.net/amt-2020-53/amt-2020-53-AC2-supplement.pdf

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