Reply to referee #2

Interactive comment on **"Characterization of anthropogenic methane plumes with the Hyperspectral Thermal Emission Spectrometer (HyTES): a retrieval method and error analysis"** by **L. Kuai et al.**

F. Prata (Referee)
fp@nicarnicaaviation.com

Dear Editor:

We would like to thank the referee, F. Prata for his time and invaluable comments.

Please see the supplement for our reply to the reviewer. Note that the referee's comments are in black and our responses are in blue.

Please contact us if there are further questions.

Best regards,
Le Kuai, PhD
Lead author
University of California, Los Angles

This paper is admirably brief and describes a CH4 retrieval methodology with some results for the HyTES airborne instrument. The paper is generally well written, although some grammar needs correcting (an edited version of the paper has been sent to the lead author). The results demonstrate that point source CH4 concentrations can be retrieved within a small spectral interval where CH4 absorbs strongly. A comparison with airborne in situ and ground based measurements show that the retrieval accuracy is around 20% for column abundance. Apart from some minor corrections (indicated on an annotated m/s sent to the author) there are just a few items that could be included in a minor technical correction:

1. A discussion of the correlation between adjacent spectral channels would be nice to see. The use of a diagonal covariance matrix, while common needs some elaboration.

We agree. Line 1 on Page 9 has been revised as below.

'$\mathbf{S}_n$ is the covariance matrix of the spectral noise, where the diagonal is (spectral uncertainty)^2 calculated using the noise equivalent temperature difference (NeDT) for the HYTES sensor. We assume that the noise-correlation among the spectral channels (i.e. off-diagonal values of $\mathbf{S}_n$) are simply zero because such correlation are usually difficult to quantify while they do not make significant impact to the retrieval.'

2. The effect of the thermal contrast between the surface and the boundary layer atmosphere has an important effect on the retrieval. A paragraph on the optimal time for making such measurements is needed. For example, how do the retrievals change if there is a boundary layer temperature inversion?

We agree with the reviewer. We specifically chose measurements around noontime so that the effect of temperature inversion should be minimal. We have added a statement on Line 5 on Page 11:

'In addition, to avoid the effects of boundary layer temperature inversion, the HyTES measurements are taken between noon and early afternoon.'

3. The authors state that they made measurements on three different dates, but only one date is provided. Also, there is mention of emission rates but none are provided nor is there any discussion of how these could be determined by HyTES.

The size and the intensity of the plume both highly depend on the wind condition. CMF plot suggest the day we showed in this paper has the largest plume. Therefore, we currently only processed the retrieval for this day only.

We have added the statement to discuss about quantifying emission rate at Line 14 on Page 11:

'In order to use these CH_4 concentration estimates for quantifying emissions, we compute the total enhancement of the plume with respect to the local background, similar to the mass balance approach used by Tratt et al., (2014). The dominant error component for the precision is due to the measurement noise (8%), which is usually random and can be greatly reduced by averaging. However, the systematic errors due radiative interferences is approximately 7% and this error will directly propagate into any corresponding emissions estimates.'

Overall the paper should be accepted subject to some minor corrections and consideration
of the above items.

Minor changes and comments:
Page 2, Line 18: Not sure I understand the meaning of this expression.

'over-sized impact' has been replaced with 'significant impact'. The complete sentences are as below:

'Quantifying and reducing uncertainties associated with anthropogenic CH_4 emissions generally depend on the capability to monitor and quantify these emitters or leaky sources (e.g., Caulton et al., 2014 and refs therein). These significant impacts of a few leaky sources is one hypothesis for explaining inconsistencies between top-down and bottom-up estimates of the CH_4 emission inventories for large cities or gas exploration regions (Wunch et al., 2009; Hsu et al., 2010; Frankenberg et al., 2011; Wennberg et al., 2012; Peischl et al., 2013; Jeong et al., 2013; Kort et al., 2014; Schneising et al., 2014; Wong et al., 2015; McKain et al., 2015).'

Page 2, Line 26: I think you need a bridging statement here that discusses why high spatial resolution is needed. For example, saying that satellites can't resolve the sources (because they are often point sources) might be sufficient.

Thank you. We have revised the words as below (Line 24 on Page 3):
'Spaceborne measurements cannot resolve these sources because the satellite footprints are usually much larger than the spatial scale of such sources. This study describes a quantitative, robust and reliable retrieval algorithm for estimating CH_4 concentrations in anthropogenic methane plumes at the 10–100 m scale using airborne radiance measurements from the airborne Hyperspectral Thermal Emission Spectrometer (HyTES) (Hook et al., 2013, 2015).'

What is the spatial and temporal resolution of these data (NCEP atmospheric data)? Are they appropriate for your high resolution data?
The NCEP atmospheric data is a daily data in a 1° resolution. Although they are not the best choice, we only used water, temperature data from NCEP for a priori and will simultaneously retrieve them with methane. It has been showed if the NCEP data is within the uncertainties about the true states, we can well retrieve the methane plume. The interference by water or temperature is less than 8%.

Hmm... I suspect a diagonal matrix is not really correct because there are bound to be correlations between different channels. Maybe you should mention this, but I understand it is difficult to obtain the full covariance matrix of the measurements.
We have revise the statement as below:
'$\mathbf{S}_n$ is the covariance matrix of the spectral noise, where the diagonal is (spectral uncertainty)2 calculated using the noise equivalent temperature difference (NeDT) for the HYTES sensor. We assume that the noise-correlation among the spectral channels (i.e. off-diagonal values of $\mathbf{S}_n$) are simply zero because such correlation are usually difficult to quantify while they do not make significant impact to the retrieval..'

Can you show that? Can you plot the wind vectors on the plot? Maybe the data are not high enough in spatial resolution for that?
Yes. I have included wind information in Figure 4 now.
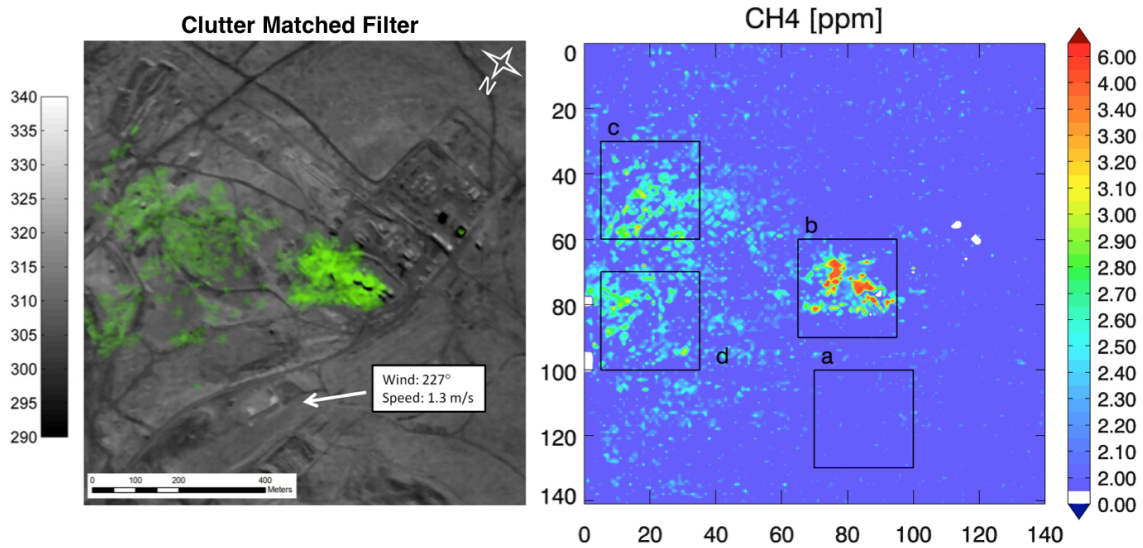
Figure 4. Left: HyTES detected methane plumes (in green) from oil tanks on Feb. 5, 2015 in Kern County, CA and overlayed on the grayscale surface temperature image. Right: The methane concentration of the same region from the retrieval estimation. White pixels are bad data and are set to be 0 ppm. The arrow is showing a wind direction of 227° to the north with the 10-minutes averaged speed of 1.3 m/s.

But I think if you have no thermal contrast then this will be a big problem. You should discuss this more. There must be an optimal time to make these measurements, for example when there is a well developed boundary layer. Nightime inversions must be an issue.

We have added a statement on Line 5 on Page 11:

'In addition, to avoid the effects of boundary layer temperature inversion, the HyTES measurements are taken between noon and early afternoon.'

Figure 4: I think it would be nice to see what the temperatures are. One issue with using TIR is that the thermal contrast essentially determines whether a retrieval is possible. What was the time of day for this image?

We agree. Figure 4 has been added a color bar of surface temperature on CMF figure. The thermal contrast above 5 K will ensure a success of the retrieval. Therefore, the flight to take the measurement of this line started local time about 11 am on that day.

Figure 4 caption: In the RH panel these are concentrations, right? So they must be at some level in the atmosphere. What is that level?

These are the vertical averaged concentrations below aircraft altitude. I made this clarify at Line 5 on Page 12.

'A map of the retrieved CH_4 concentrations in the boundary layer is shown along with an image of CH_4 concentration variability calculated using CMF method (Hulley *et al.*, 2015) in Figure 4. The concentration of each pixel is the vertical average from the retrieved CH_4 profile. The maps of both quantitative retrieval and CMF are the cut-off area over the plume from a whole line.'