Reply to referee #1

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.
Anonymous Referee #1
Received and published: 9 February 2016

Dear Editor:

We would like to thank the referees for their time and invaluable comments.

Please see the supplement for our reply to the reviewers. Note that the referees’ 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

Manuscript "Characterization of anthropogenic methane plumes with the Hyperspectral Thermal Emission Spectrometer (HyTES): a retrieval method and error analysis" of Kuai et al., submitted for publication in AMT, covers an important and relatively new topic, namely airborne observations of methane plumes emitted by localized methane emission sources, appropriate for AMT. The paper is well-written and contains new material. I therefore recommend publication after the major and minor comments listed below have been carefully considered by the authors.

Major comments:

Abstract: It is written that the "Total error from single retrieval is approximately 20%". This suggests that this includes not only random errors ("precision") but also systematic errors but it is also written that "With a 20% estimated precision…" which implies that random errors dominate and systematic errors are negligible. Is this really true taking into account that for plume enhancements relative to the background especially near-surface methane enhancements are relevant and the averaging kernels are close to zero near the surface (approx. 12%, see Fig. 3 bottom) and therefore the smoothing error is very important (see page 9, line 4: "The dominant sources of the total error are the smoothing error, : : :"). The smoothing error will correlate with the plume and will therefore be primarily a systematic error but not a random error, i.e., not part of "precision", with likely significant consequences if one wants to use the HyTES atmospheric methane retrievals to obtain quantitative emission estimates. These aspects need to be mentioned and described better in the manuscript to avoid misunderstandings.

We agree with reviewer. Although measurement error is the second largest error contribute to total error, there are also systematic error contributions. We should be careful about using 'precision' and to be consistent with the later statement we have revised the sentence in abstract as below:
'With a 20% estimated uncertainty, plume enhancements with more than 1 ppm are distinguishable from the background noise.'

There is a lack of citations of other relevant peer-reviewed publications. I recommend to add at least the following publications: Page 3, line 4 following: It is written that "Previous studies produced maps of methane distributions from airborne hyperspectral TIR sensor radiances using methods such as the Cluster-Tuned Matched Filter Detection (CMF) (Funk, 2001); however, such correlative approaches do not yield quantitative estimates of the methane plume concentrations or the corresponding methane emission rates. Our approach is based on : : :". Citing only Funk, 2001, is not sufficient as there are several more recent papers, which need to be considered in the discussion and cited in the manuscript. E.g., Tratt et al., "Airborne visualization and quantification of discrete methane sources in the environment", RSE, 2014, also needs to be cited (they also use TIR measurements and quantified their sensitivity in terms of methane emissions, which is not done in this manuscript). Furthermore, also airborne non-TIR methane measurements have been published (with averaging kernels close to unity at the surface) including detailed error analysis in terms of estimated methane emissions, e.g., Gerilowski et al., "Atmospheric Remote Sensing Constraints on direct Sea-Air Methane

Flux from the 22/4b North Sea Massive Blowout Bubble Plume", Marine and Petroleum Geology, 2015, and Krings et al., "Quantification of methane emission rates from coal mine ventilation shafts using airborne remote sensing data", Atmos. Meas. Tech., 2013. Furthermore I recommend to add on Page 2, line 24: Schneising et al., Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, Earth's Future, 2014.

More references have been added as recommended by reviewer. The text now reads, "Previous studies produced maps of methane distributions from airborne hyperspectral TIR sensor radiances using methods such as the Cluster-Tuned Matched Filter Detection (CMF) (Funk, 2001); such correlative approaches are quite useful to quickly identify point sources; however, do not yield quantitative estimates of the methane plume concentrations or the corresponding methane emission rates. More recent work by Krings et al., 2013, Tratt et al., 2014, and Gerilowski et al., 2015 all demonstrate the quantification of methane emission rates but using different airborne remote sensing data."

It is not clear where exactly which spectral information is coming from. I strongly recommend to add after Fig. 1 an additional figure based on radiance simulations showing how the radiance spectrum changes for a given perturbation of the key interfering parameters (methane, other gases, temperature, emissivity, : : :) (i.e., Jacobians) and how this compares with the (typical) noise level (please add info on how large each parameters is and by what amount it has been perturbed).

Additional figure is added at the bottom of Fig. 1 for column integrated Jacobians to show the key interfering region in the spectrum. Noise level over plotted in dashed lines.

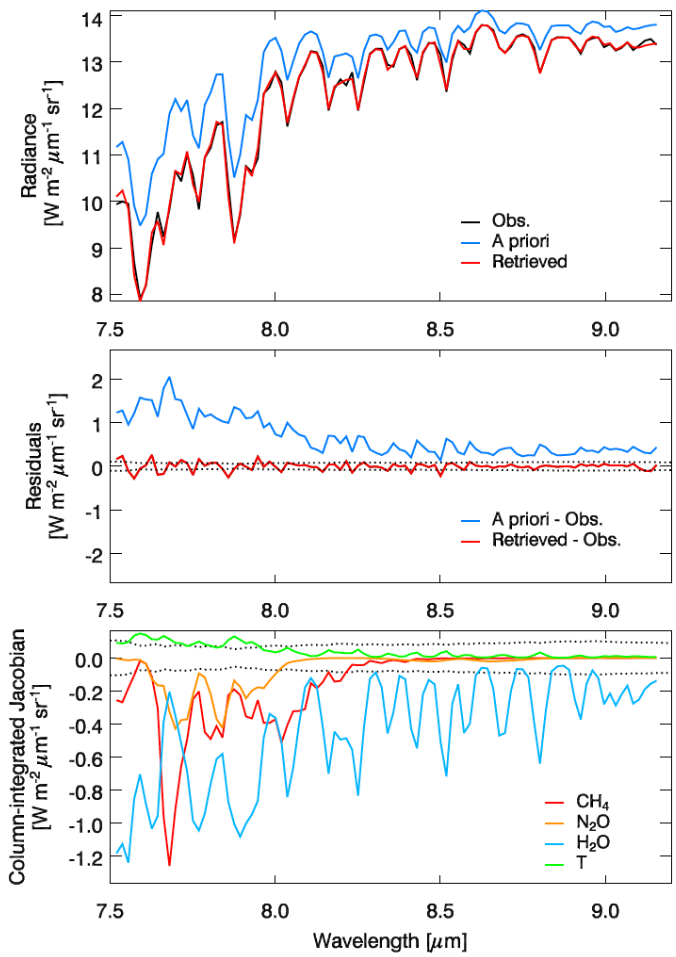

Figure 1. The spectral window for CH_4 retrievals. Top: HyTES measured radiances (black) and two model calcuated radiances from *a priori* (blue) and retrieved states (red). Middle: residuals to the observations. Bottom: column-integrated Jacobians (sensitivity of radiance to CH_4 and key interfering parameters). Noise levels are plotted in black dotted lines in both middle and bottom plots.

Page 9, line 4 following (see also above): "The dominant sources of the total error are the smoothing error, measurement error, atmospheric temperature error, H_2O error, and emissivity error." Is "measurement error" just noise (if yes please add this in brackets; if not what systematic errors are relevant in addition to noise?).
Yes, here we only used noise to estimate the measurement error. It has been revised as: 'The dominant sources of the total error are the smoothing error, measurement error (noise), atmospheric temperature error, H_2O error, and emissivity error.'

Which of these errors will likely be correlated with the plume and are therefore critical if one wants to get emission estimates. Please add at least a short discussion of this. In this context also page 10, top and middle: co-variations of parameters such as temperature and H2O are mentioned. Is the proposed chi-square filter (page 10, line 13 following) a solution that is supposed to eliminate these (potentially plume-correlated) error sources? I guess not, as Fig. 4 right does not show any data gaps in the plume. Please clarify.
Thank you for the comment. To clarify, the chi-square filter would only remove certain

extremely bad retrievals for pixels when systematic error is huge, e.g. surface emissivity or surface temperature is not well pre-retrieved from another frequency band, for example, sometimes over certain rooftops there is error in surface emissivity and surface temperature is much larger than uncertainty in the prior.

We added some text at Page 9 Line19 to discuss the impact of the retrieval error to the emission rate estimation:
'To get emission estimates, we would compute the total enhancement for the plume with respect to the local background. The local background value is computed by averaging the retrieved CH_4 at an area of clean are over upwind side of point source. Since the dominant error component for the precision is found due to the measurement noise (8%), which is usually random and can be removed by averaging. However, the systematic error due to H_2O error or temperature error or both, a source of accuracy (6-7%), is not random and difficult to be attenuated. Therefore, the systematic error component will propagate to the emission estimates. '

Minor comments:
Page 2, line 3: "wide swath"? Please add how wide the swath is (e.g., for 1 km flight altitude).
Information added as suggested:
'HyTES is a pushbroom imaging spectrometer that produces a wide swath (~1 km for 1 km flight altitude) Thermal Infrared (TIR) image with high spectral and spatial resolution that incorporates a number of key state-of-the-art technologies developed at JPL.'

Page 4, line 24: How are clouds modelled? In particular, where are the relevant parameters (altitude, optical properties) coming from to forward model the HyTES radiances?
The forward model has cloud parameters including cloud optical depth, cloud extinction, and cloud top pressure. However, HyTES only targeted cloud free sites. Therefore, we do not need to retrieve cloud in this study.

Page 5, line 11 following: "In addition the issue of spectral band misregistrations is eliminated." This is a bold statement but it is unclear where it is coming from. Please add more details and a reference.
To clarify, we revised and added a reference.
'In addition the issue of spectral band misregistrations between HyTES data and MODTRAN is eliminated by using ISAC method instead of MOTRN (Hulley et al., 2015).'

Page 7, middle, below Eq (6): "three terms"? I only see two terms? Please check and clarify/correct.
Reviewer is correct. Thank you. We have corrected the sentence as below:
'The first term on the right-hand side of this equation is the smoothing error, including the components of systematic errors by H_2O, N_2O, temperature, emissivity and so on. The second term represents the measurement error.'

Page 8, line 18: 0.32 means 32% a priori uncertainty, or? Please clarify.
Yes.
'This covariance has diagonal values of 0.32 (or 32%) (squared) and off-diagonal values of the empirical correlations between levels.'

Fig. 4, right: Seems there are hardly any values below 2 ppm as "white are missing data" and the color bar starts at approx. 2 ppm but Fig. 5 shown there are data in the range 1-2 ppm. This is a bit misleading for Fig. 4 and I recommend to select a lower limit for the color bar (e.g., 1 ppm). I wonder why there are no data below 1 ppm in Fig. 5? Is this because they have been eliminated by a filtering procedure (I guess not but please clarify).
The color bar used in Fig. 4 set values from 0 to 1 ppm to be white for missing data (rephrased as bad data now), from 1 to 2.3 ppm to be blue to represent background, and enhancement above the noise level in the plume to turn green and red. There is no values below 1 ppm expect the missing/bad data, which are set to be 0 ppm. The retrieved lowest value should be approximately background minus uncertainty (=1.8 − 0.36 ppm > 1 ppm). In Fig. 4, the regions in the four boxes showed not including any white pixels. Therefore no data less than 1 ppm is expected in histogram plots in Fig. 5.

We have revised paragraph about the bad retrievals as below:
'We used chi-square less than 1.2 as the quality control, where chi-square is the root mean square of the ratio of spectral residuals to the measurement noise. White pixels are those bad retrievals fail to pass the quality flag and are set to be 0 ppm. For example, two blocks at upper right side away from the point source are estimated of unusually elevated CH_4 for more than 7 ppm, which are resulting from abnormal large negative thermal contrasts. The chi-square more than 1.2 determined these pixels to be bad retrieved data.'

The caption for Fig. 4 rewrote as:
'Figure 4. Left: HyTES detected methane plumes (in green) from oil tanks on Feb. 5, 2015 in Kern County, CA and overlayed on grayscale surface temperature image. Right: The methane concentration of the same image from the retrieval estimation. White pixels are bad data, which is set to be 0 ppm.'

The caption for Fig. 5 revised as:
Figure 5. The distributions the methane concentrations in the area of four boxes defined in Figure 4. (a) Background area; (b) the point source region; (c) and (d) down wind areas.