

Interactive comment on “Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane” by D. R. Thompson et al.

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Response to C2063, with reviewer comments paraphrased for brevity.

1. The study could benefit by being a bit more quantitative.

We agree that our treatment is mostly qualitative. In this work, we focused on real-time detection. This is important for applications like leak monitoring and detection, which only require knowledge of where the fugitive emissions are located. In such applica-

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tions exact quantification is generally not needed. Moreover, real-time detection can direct adaptive deployment of *in situ* sensors for precise mass balance estimation. A qualitative study enables us to consider a large number of diverse, poorly-constrained “real” sources, comparing detection approaches on a statistically-significant field sample. Our qualitative emphasis also helps keep focus; estimating true CH₄ emission rates typically requires wind and topography information via a plume structure model, which would be a significant expansion of scope. Instead, the goal is to leverage real-time analysis to get better data sets for later, offline quantitative analysis.

1a. Comparing MAMAP and AVIRIS-NG

We had wanted this figure to show that other instruments corroborated the presence of CH₄ enhancements at that location. However, following the reviewer’s suggestion, we compared the two retrieval numbers more directly. We describe these results with some caveats about their interpretation:

“[The figure] shows the agreement between the different instruments on Sept. 4. Colored pixels indicate CH₄ mixing ratio lengths from AVIRIS-NG. The monochrome dots show MAMAP retrievals: black signifies < 100 ppm m. A grey dot shows CH₄ of 0–200 ppm m near the plume, and a single white dot shows CH₄ exceeding 0 ppm m within the plume. There are several reasons why retrievals might differ. First, the two instruments have disparate spatio-temporal coverage; on Sept. 4 the MAMAP cross track instantaneous Field of View is $m(2.9^\circ)$, and the down track instantaneous Field of View is $m(2.64^\circ)$, with additional down track averaging of m during the integration time. Moreover, the acquisition time difference of several minutes is significantly longer than variability in wind speed and gusts due to local atmospheric turbulence at relevant spatial scales of <500 m. Emissions have been documented to vary on similar timescales. Finally, the optical paths differ so concentration measurements are not

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perfectly comparable.

With these caveats in mind, we directly compared the two measurements. We calculated a spatially-weighted average of the AVIRIS-NG estimated enhancement above background, matching it to the MAMAP response while simultaneously searching over the sounding's position uncertainty radius of m . The resulting estimates were as high as 3.5 ppm m (white dot) and 1.3 ppm m (grey dot), of similar magnitude to the MAMAP retrievals. Despite differences in observing conditions, both datasets evidence similar-scale enhancements at this site. In other cases, small plumes visible in AVIRIS-NG were sometimes invisible in MAMAP data.”

1b. IMAP comparisons

We agree that this comparison would be useful, though it is beyond the scope of this paper. In fact there is a comprehensive investigation underway comparing IMAP retrievals to matched filter results for a controlled release experiment. Since initial submission of this article, the Thorpe et al. (2015) manuscript detailing controlled release results was submitted for review. We have changed its status in this bibliography. Other new developments include the incorporation of real-time geolocalization. We have updated the discussion accordingly to reflect this.

2a. How are ppm calculated?

As the referee implies, CH_4 concentrations are underdetermined. Instead, the retrieval measures the total absorption path enhancement above background, agnostic to the vertical distribution. This concentration length, which we report in ppm m , is the *enhancement above background CH_4 absorption*, where the background is defined by

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the mean radiance spectrum of the local spatial neighborhood. It is unlikely that other atmospheric differences in the column would differ significantly on small spatial scales.

2b. Are the structures in the background image (Figure 8) related to unknown air column?

Due to the structures' well-defined geometries, we believe the most likely explanations are changes in the background substrate's reflectance shape, which can change the incidental projection of the test spectrum onto the matched filter, leading to structured differences in retrieved values near the noise level. It is possible that more indistinct background structures could relate to air column heterogeneity. In the concluding discussion, we discuss morphological and statistical approaches to mitigate these effects.

2c. Could the column be derived from other AVIRIS-NG measurements?

In principle, AVIRIS-NG could measure the air column using the absorption of well-mixed gases such as O_2 . We currently estimate the ground pressure altitude using the Oxygen A band for calculating scattering and absorption terms during atmospheric correction. However, background CH_4 concentrations in the atmospheric column vary over broader spatial scales, so our statistical estimation of the background radiance should account for them already. The only exception, which we have seen in some rare cases, is a plume large enough to fill a substantial fraction of the field of view and contaminate the background statistics. This is not a problem in practice, since the plume itself is still visible. The retrieved values are very large, but still underestimate the actual plume concentration length because the “background” is artificially elevated.

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3. Technical comments

P6284, I3+ We have added these citations to the literature review, as prior examples of real-time spectroscopic measurements onboard aircraft (Vogel) and of plumes (Lubcke, Stremme, Krueger).

P6288, I17+ What does column-wise mean? We have rephrased to clarify: “The cross-track pushbroom elements are separate detectors, so it is often better to model their noise distributions independently. Thus, we apply an independent matched filter to each column of the (non-orthorectified) image, calculating a new μ and Σ for each cross-track element. This columnwise matched filter dramatically reduces the number of samples available for estimating each Σ .”

What dimensions are the variables μ and t ? We clarified the exposition: “The matched filter tests each spectrum against a target signature t while accounting for the background covariance. Here t is a vector with one element per wavelength. If the background spectra are distributed as a multivariate Gaussian with mean vector μ and covariance matrix Σ ...” Note the use of bold font to indicate that μ is a vector. In section 2.4, we use an alternative functional form $\mu(\lambda)$ to represent a single wavelength of the mean vector. Additions to the text, and the bold font math notation, now make this more obvious.

Why does Σ change boldface? This was an oversight, now remedied. We have changed each instance of Σ to boldface Σ .

What do “hat”-ed variables signify? We have added text explaining the “hat” - it means that these values are estimated from the image statistics.

Clarify scalar/matrix operations in Equation 6 and 7 We have clarified that q are column vectors, so that qq^T is a matrix.

P6289, I12 Fixed.

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P6290, I14 We agree, and have removed ambiguity by using the script font ℓ .

P6290, section 2.4. Is the approximation $\log(x) = x - 1$ really carried out at zero absorption path? ... CH₄ and H₂O absorption at 2.37 micron is optically thick. The key is that we assume a short optical path relative to the local mean spectrum μ (which already includes considerable attenuation by background CH₄ and H₂O). The target spectrum represents the additional spectral perturbation obtained by inserting a unit concentration length of ground-level CH₄. The difference in shape between the blue and red curves in Figure 2 illustrates this visually. The red is the the CH₄ transmission spectrum, while the blue is the signature t which estimates the radiance perturbation. Note the deep "spike" at 2.375 microns - the perturbation of the radiance (blue) is more muted since this feature lies in a saturated area.

p6291, I5+. As far as I understand, what you actually do is that you calculate the Jacobian at absorption path $l=0$ and then, you assume that the zero-path Jacobian is also applicable to the case with realistic absorption path. The attenuation due to background CH₄ is taken into account by estimating the local mean radiance μ . The Jacobian represents the differential change in this radiance produced by an optically-thin cloud of CH₄.

Are derivations carried out for the (infinitely resolved) atmospheric spectrum? The calculation of unit absorption is made at high resolution (1 wavenumber), and then convolved to AVIRIS-NG wavelengths with a FWHM of approximately 5 nm to create a target vector t . However, the matched filter calculations take place at AVIRIS-NG wavelengths, so the target signature and radiance spectra are combined in approximation at low spectral resolution. This is an intrinsic limitation of the matched filter approach whenever in-scene data is used to estimate the background, because in this case the spectrum μ is only known at the instrument resolution.

Is the target signature the same as the slant column? We have modified our text to clarify the interpretation of the target signature: “The target signature represents

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the perturbation, in radiance units, of the background radiance by an additional unit concentration length of CH₄ absorption, which acts as a thin Beer-Lambert attenuation of the (already attenuated) background μ .”

Interactive comment on Atmos. Meas. Tech. Discuss., 8, 6279, 2015.

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