Point source emissions mapping using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

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ABSTRACT

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) measures reflected solar radiation in the shortwave infrared and has been used to map methane (CH₄) using both a radiative transfer technique [1] and a band ratio method [2]. However, these methods are best suited to water bodies with high sunglint and are not well suited for terrestrial scenes. In this study, a cluster-tuned matched filter algorithm originally developed by Funk et al. [3] for synthetic thermal infrared data was used for gas plume detection over more heterogeneous backgrounds.

This approach permits mapping of CH₄, CO₂ (carbon dioxide), and N₂O (nitrous oxide) trace gas emissions in multiple AVIRIS scenes for terrestrial and marine targets. At the Coal Oil Point marine seeps offshore of Santa Barbara, CA, strong CH₄ anomalies were detected that closely resemble results obtained using the band ratio index. CO₂ anomalies were mapped for a fossil-fuel power plant, while multiple N₂O and CH₄ anomalies were present at the Hyperion wastewater treatment facility in Los Angeles, CA. Nearby, smaller CH₄ anomalies were also detected immediately downwind of hydrocarbon storage tanks and centered on a flaring stack at the Inglewood Gas Plant.

Improving these detection methods might permit gas detection over large search areas, e.g. identifying fugitive CH₄ emissions from damaged natural gas pipelines or hydraulic fracturing. Further, this technique could be applied to other trace gases with distinct absorption features and to data from planned instruments such as AVIRISng, the NEON Airborne Observation Platform (AOP), and the visible-shortwave infrared (VSWIR) sensor on the proposed HyspIRI satellite.

Keywords: methane, CH₄, carbon dioxide, CO₂, nitrous oxide, N₂O, emissions, point source, fugitive, Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), Coal Oil Point, power plant, wastewater treatment facility, oil refinery

1. INTRODUCTION

Methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O) are considered the three greenhouse gasses most important to climate change, and global concentrations of these long-lived gasses have increased rapidly since the Industrial Revolution, mainly as a result of human activity. Increasing radiative forcing due to higher concentrations of CH₄, CO₂, and N₂O makes up the majority of the total net increase in radiative forcing since 1750 [4]. On a 20 year time scale, one molecule of CH₄ is at least 70 times as effective at trapping radiant energy than a molecule of CO₂, while N₂O has a 20 year global warming potential 289 times greater than CO₂ [4]. In addition to being a potent greenhouse gas, CH₄ contributes to ozone (O₃) production and photochemical smog, while N₂O will be the most important contributor to O₃ depletion throughout the 21st century [5].

For each of these gasses, the majority of present-day emissions are anthropogenic and often emitted from concentrated point sources. Estimates indicate the majority of pre-industrial CH₄ emissions were from natural sources [6], while between 60% to 70% of CH₄ emissions are presently anthropogenic [7] and have an atmospheric residence of 8.4 years [4]. Approximately 75% of anthropogenic CO₂ emissions have resulted from burning of fossil fuels and cement production [4] and atmospheric residence varies between 5 and 200 years due to large differences in rates of CO₂ uptake.
About half of N₂O emissions are presently anthropogenic and emissions remain in the atmosphere on average for 114 years [4].

Existing spaceborne remote sensing provides an effective means of detecting continental scale variation in CH₄, CO₂, and N₂O concentrations using sensors that sample the mid-infrared (MIR) and thermal-infrared (TIR) [9, 10, 11, 12] as well as in the shortwave infrared (SWIR) [13]. These sensors lack the fine spatial resolution needed to detect near-surface local emissions, including individual plumes from concentrated point sources. Detecting faint gas signatures over heterogeneous surfaces remains challenging, however, one technique of particular promise is matched filters, which have successfully detected gas plumes in simulated data [14, 15]. A matched filter algorithm generates a linear weighting function that produces highest values when an image spectrum matches the shape of the gas target. When applied to a scene, this algorithm reduces noise while enhancing the gas signature and outputs an image indicating those regions with anomalous gas concentrations.

This study aims to improve methods for fine spatial resolution gas detection using a cluster-tuned matched filter technique originally developed by Funk et al. [3] for simulated thermal data. The cluster-tuned matched filter improves performance over traditional matched filter algorithms because it first applies k-means clustering to partition the background surface, then creates a matched filter that is specifically tuned for each cluster. These algorithms were modified for the airborne imaging sensor AVIRIS, which samples 224 contiguous spectral channels between 350 nm and 2,500 nm. To test the feasibility of this approach, the cluster-tuned matched filter was applied to a diversity of locations known to emit CH₄, CO₂, and N₂O and results were analyzed for consistency with known or probable emission sources.

Developing techniques to map local emissions using airborne imaging spectrometry could permit emission monitoring and hazard detection over large areas. For example, detecting fugitive CH₄ emissions from leaking natural gas pipelines [16], hydraulic fracturing [17], and coal bed fields is of increasing concern. High resolution mapping of trace gases from concentrated sources could also improve national greenhouse gas budgets, partitioning between anthropogenic and natural sources, and compliment ongoing global monitoring efforts at coarser spatial resolutions.

2. METHODOLOGY

2.1 AVIRIS data and Modtran radiative transfer model

AVIRIS measures reflected solar radiance over 224 contiguous spectral channels between 350 nm and 2,500 nm, with a spectral sampling interval and nominal Full Width Half Maximum (FWHM) of 10 nm, 34° field of view (FOV), and 1 mrad instantaneous field of view (IFOV) [18]. AVIRIS encoded radiance data are georectified and radiometrically calibrated by the Jet Propulsion Laboratory (JPL). Flown on aircraft, AVIRIS has a high signal-to-noise ratio and a ground-instantaneous field of view (GIFOV) typically ranging between 3 m to 20 m, which offers the potential for detecting gaseous emissions from point sources. This has enabled detection of CH₄ over the Coal Oil Point Seeps offshore of Santa Barbara, CA [1, 2], however, these techniques are limited to water bodies with high sunglint and are not well suited for terrestrial scenes.

CH₄, CO₂, and N₂O have absorptions in the SWIR that can be resolved with the 10 nm spectral sampling of AVIRIS. Examples of transmittance spectra are shown in Figure 1, calculated using a Modtran 5.3 radiative transfer model parameterized for an AVIRIS flight at 3.8 km altitude for a Los Angeles scene. Absorption features for CH₄ and CO₂ have some spectral overlap with H₂O, however, CH₄ absorptions at 2,300 nm and CO₂ absorptions around 1,572 nm, 1,602 nm, and 2,058 nm have the least overlap with H₂O absorptions (Figure 1a). CH₄, CO₂, and N₂O transmittance spectra were calculated with Modtran parameterized for different flight lines and convolved to AVIRIS wavelengths using the band centers and FWHM supplied by JPL. These transmittance spectra were used as gas targets for the cluster-tuned matched filter analysis; CH₄, CO₂, and N₂O gas targets for a Los Angeles scene are shown in Figure 1b, 1c, and 1d.
Figure 1. (a) Transmittance spectra for trace gases convolved to AVIRIS bands generated using Modtran 5.3, parameterized for a mid-latitude summer model atmosphere and 3.8 km sensor altitude. (b) CH$_4$ exhibits prominent absorptions between 2,150 nm and 2,450 nm. (c) CO$_2$ has strong absorptions centered at 1,958 nm, 2,008 nm, and 2,058 nm. (d) N$_2$O absorptions at 2,109 nm and 2,258 nm are weak compared to those of other trace gases due to low N$_2$O concentration in the atmosphere.

2.2 Study sites

To identify AVIRIS images for the cluster-tuned matched filter analysis, four flight lines containing likely point source emissions of CH$_4$, CO$_2$, and N$_2$O were identified (Figure 2). The first scene was acquired over the Coal Oil Point Seeps offshore of Santa Barbara, CA, one of the largest and best studied natural sources of CH$_4$ emissions and oil with total atmospheric emissions estimated at 100,000 m$^3$/day [19]. A second AVIRIS flight near Moss Landing, CA imaged a natural gas power generation station with multiple smokestacks, providing an anthropogenic CO$_2$ emission source. An additional scene covered the Mid-Wilshire district of Los Angeles, known for natural CH$_4$ and oil seepage, and the Inglewood Oil Field, with active natural gas and hydrocarbon extraction. The final AVIRIS flight line covered the El Segundo neighborhood of Los Angeles and included the Hyperion wastewater treatment facility, a potential source of CH$_4$ and N$_2$O emissions.
2.3 Cluster-tuned matched filter algorithm

The cluster-tuned matched filter algorithm first applies k-means clustering to classify the image and partition the background surface (clutter) to minimize within-class variance. To do so, the algorithm uses the first few principle components of the image to assign extreme locations for each of the k-class centroids [3]. After the k-means algorithm assigns a specified number of classes (defined \textit{a priori}) and creates a k-means class image, matched filters specifically tuned for each class are applied to the scene using the following equation,

\[ q_j = \frac{C_j^{-1}b}{\sqrt{b^T C_j^{-1}b}} \]

where \( q_j \) is the cluster-tuned matched filter for class \( j \), \( C_j^{-1} \) is the inverted covariance matrix for the \( j \)-th class, and \( b \) is the gas target spectrum. Multiplication by the inverted covariance matrix in the numerator ‘whitens’ the data by removing spectral cross-correlation in the background clutter. The denominator standardizes the filtered data so that the expected filtered results have a standard deviation of 1. These filtered pixels are then recomposed as a final output image that reduces noise and sensitivity to surface features while enhancing the gas signature and outputs an image indicating gas anomalies. Cluster-tuned matched filters were applied to each AVIRIS image using transmittance spectra as gas targets, calculated with Modtran parameterized for each flight line.
3. INITIAL RESULTS AND DISCUSSION

Cluster-tuned matched filters were effective for mapping CH₄, CO₂, and N₂O anomalies for concentrated marine and terrestrial emission sources. On 19 June 2008, AVIRIS acquired an image containing the Coal Oil Point marine seeps near Santa Barbara, CA with a spatial resolution of 7.5 m. The scene was characterized by high sunglint and a relatively homogeneous ocean surface, which permitted detection of prominent CH₄ anomalies (Figure 3). The anomalies emanate from known seeps, including the Trilogy Seep and IV Super Seep, and are consistent with southwesterly wind measured at the time of image acquisition. These CH₄ anomalies also closely resemble results obtained using the band ratio technique developed by Bradley et al. [2]. Marine seeps are significant but poorly constrained sources of CH₄, releasing an estimated 20 Tg yr⁻¹ [20].

![Figure 3. CH₄ matched filter results for Coal Oil Point seeps.](image)

Analysis of an AVIRIS scene from 19 July 2011 with a spatial resolution of approximately 6 m revealed a prominent CO₂ anomaly for the Moss Landing Power Plant (Figure 4), which is powered with natural gas and generated 1,435,507 MT CO₂ in 2010 [21]. This anomaly crosses over multiple k-means classes and thus different land cover types and is consistent with a CO₂ plume emitted from four, closely-spaced smokestacks and transported by northwesterly winds. Power plants are a significant emissions source, with 76% of U.S. CO₂ stationary source emissions attributed to electricity production [22].
For an AVIRIS scene covering the El Segundo neighborhood of Los Angeles with a spatial resolution of approximately 3 m (Figure 2), multiple N₂O and CH₄ anomalies were present at the Hyperion Sewage Treatment Plant (Figure 5). CH₄ anomalies appear throughout the scene (green pixels in Figure 5), while N₂O anomalies are observed in close proximity with egg-shaped digesters and settling tanks (red pixels). Wastewater treatment facilities produce CH₄ and significant N₂O emissions, which result from denitrification and nitrification in both anoxic and anaerobic environments [23, 24]. In 2009, U.S. emissions of CH₄ and N₂O from wastewater treatment were estimated at 24.5 Tg CO₂ Eq. and 5.0 Tg CO₂ Eq. respectively [23].

In the AVIRIS scene covering the Mid-Wilshire region of Los Angeles (Figure 2), a CH₄ anomaly was detected at the Inglewood Oil Field that crosses multiple land cover classes and is consistent with local meteorological data indicating a 2.2 m s⁻¹ southwesterly wind (Figure 6b). The spatial resolution is approximately 3 m for this scene and Google Earth imagery was used to resolve surface features, including what appears to be two hydrocarbon storage tanks located immediately upwind of the anomaly (Figure 6a). Nearby, an additional CH₄ anomaly was identified centered on a flaring stack at the Inglewood Gas Plant (Figure 6c and 6d) and sensor saturation in the SWIR indicated active flaring at the time of image acquisition. Fugitive CH₄ emissions associated with hydrocarbon production are considerable, estimated in 2009 at 221.2 Tg CO₂ Eq. for natural gas systems, 71.0 Tg CO₂ Eq. for coal mining, and 30.9 Tg CO₂ Eq. for petroleum systems [23].
Figure 5. Matched filter results overlain on a visible band image of the wastewater treatment facility (darkened for presentation). N$_2$O anomalies (red pixels), appear near two groups of waste digesters. CH$_4$ anomalies (green pixels) are also present, causing considerable overlap of N$_2$O and CH$_4$ anomalies (orange pixels).

Figure 6. (a) Close-up of hydrocarbon storage tanks (Location L1; Google Earth, 2012). (b) CH$_4$ anomaly downwind of L1, shown using median smoothing filter. (c) Close-up flaring stack (Location L2; Google Earth, 2012). (d) CH$_4$ anomaly centered on stack at L2, shown using median smoothing filter.
Despite these promising results, ‘speckle’ and false positives observed in matched filter results make interpretation of anomalies challenging. False positives result for surfaces with strong absorptions located at the same wavelengths as gas absorption features; for example, the CH₄ cluster-tuned matched filter produced false positives for roofs with limestone pebbles that exhibit strong carbonate (CO₃) absorption at 2,338 nm. Therefore, to distinguish trace gas emissions from false positives, methods of smoothing results and suppressing false positives must be developed.

While cluster-tuned matched filters are well suited for detecting anomalies, they do not provide concentrations necessary to calculate fluxes or generate maps of gas concentrations. In order to create robust techniques for detection and quantification of trace gas emissions in AVIRIS data, additional research is required. A sensitivity analysis using synthetic images and radiative transfer simulations is necessary to determine minimum detectable gas concentrations by the cluster-tuned matched filter approach and determine how surface composition and albedo influence matched filter scores. Multiple approaches will be used to estimate concentrations, including MODTRAN 5.3 radiative transfer simulations to generate synthetic spectra with elevated gas concentrations that will be best fit to AVIRIS radiance data as well as additional residual based techniques. Evaluating the accuracy of these concentrations is an important prerequisite for creating maps of gas concentrations and estimating fluxes from individual point sources to better constrain regional emissions.

4. CONCLUSIONS

The cluster-tuned matched filter technique is effective for mapping CH₄, CO₂, and N₂O anomalies for concentrated natural and anthropogenic emission sources in AVIRIS imagery, including the Coal Oil Point marine seeps (CH₄), the Moss Landing Power Plant (CO₂), and the Hyperion Sewage Treatment Plant (N₂O and CH₄). These long-lived trace gases are often emitted at concentrated sources; an estimated 4,507 stationary point sources produced 63% of U.S. CO₂ emissions from fossil fuel combustion in 2008 [22]. Therefore, targeting reductions in anthropogenic CH₄, CO₂, and N₂O emissions from concentrated sources is a particularly efficient means of mitigating their effects.

Airborne imaging spectrometers are well suited for monitoring local sources because they provide areal coverage with high spatial resolution necessary to resolve point source emissions. Developing gas detection techniques for airborne platforms could better constrain local emissions as well as improve national greenhouse gas budgets and partitioning between anthropogenic and natural sources. To create robust techniques for mapping trace gas emissions in AVIRIS data, additional research is required to determine minimum detectable gas concentrations by the cluster-tuned matched filter, reduce false positives, and develop techniques for estimating gas concentrations.

Given these promising preliminary results, the cluster-tuned matched filter might be capable of detecting additional trace gases with distinct absorption features and could be applied to data from planned AVIRIS-like instruments such as AVIRISng, the NEON Airborne Observation Platform (AOP), and the proposed HyspIRI VSWIR sensor. The addition of these planned sensors could greatly improve mapping of local and regional emissions by providing the spatial coverage necessary to detect individual emission sources and potential for repeat temporal coverage to monitor global change.

REFERENCES


