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# High resolution mapping of methane emissions from marine and terrestrial sources using a Cluster-Tuned Matched Filter technique and imaging spectrometry

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ABSTRACT

In this study, a Cluster-Tuned Matched Filter (CTMF) technique was applied to data acquired by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) over marine and terrestrial locations known to emit methane ($CH_4$). At the Coal Oil Point marine seep field, prominent $CH_4$ anomalies were consistent with advection from known areas of active seepage. For a region with natural $CH_4$ and oil seepage located west of downtown Los Angeles, significant $CH_4$ anomalies were identified for known sources at the La Brea Tar Pits and in close proximity to probable sources, including an office complex documented as venting $CH_4$ continuously and hydrocarbon storage tanks on the Inglewood Oil Field. However, interpretation of anomalies was complicated by noise and false positives for surfaces with strong absorptions at the same wavelengths as $CH_4$ absorption features. Segmentation of results identified 16 distinct locations of contiguous pixels with high CTMF scores and segments were classified into probable $CH_4$ anomalies and confusers based on the spectral properties of the underlying surface over the full spectral range measured by AVIRIS. This technique is particularly well suited for application over large areas to detect $CH_4$ emissions from concentrated point sources and should permit detection of additional trace gasses with distinct absorption features, including carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$). Thus, imaging spectrometry by an AVIRIS-like sensor has the potential to improve high resolution greenhouse gas mapping, better constraining local sources.

## 1. Introduction

Methane ($CH_4$) is a long-lived greenhouse gas with an average atmospheric residence of approximately 7.9 years (Lelieveld et al., 1998). One molecule of $CH_4$ is 72 times more effective at trapping radiant energy than a molecule of carbon dioxide ($CO_2$) on a 20 year time scale (IPCC, 2007). Global atmospheric $CH_4$ has more than doubled in the last two centuries with an annual growth rate that has been highly variable since the 1990s with renewed growth starting in 2007 (Dlugokencky et al., 2009) and average concentrations exceeding 1.8 ppm in 2012 (NOAA, 2012).

Emission sources and sinks exhibit high spatial heterogeneity and large-scale interannual variability (Bousquet et al., 2006) and estimates for total sources of atmospheric $CH_4$ have considerable uncertainty, ranging between 500 and 600 Tg year$^{-1}$ (IPCC, 2007). Between 60 and 70% of $CH_4$ emissions are presently anthropogenic (Lelieveld et al., 1998) and include emissions from domestic ruminants, rice agriculture, waste handling, and fossil fuel production. Wetlands, termites, and geological seeps are significant natural sources (Etiope et al., 2009), while major $CH_4$ sinks include oxidization by the hydroxyl radical (OH), loss to the stratosphere, and consumption by methanotrophs in soils (Lelieveld et al., 1998). Approximately 90% of $CH_4$ destruction is due to OH oxidation (Lelieveld et al., 1993), however, $CH_4$ destruction is minimal on the time scale of minutes to hours relevant to studying local emissions nearby the source.

On global scales, partitioning between natural and anthropogenic $CH_4$ sources remains uncertain and emission estimates for individual source categories can vary by as much as a factor of two (Dlugokencky et al.,

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2011). On regional scales, uncertainties for anthropogenic $CH_4$ emissions are considerable, between 9 and 17% in the United States (EPA, 2011) and 19 and 36% for a number of countries in northwest Europe (Bergamaschi et al., 2010).

$CH_4$ has strong rotational-vibrational transitions causing absorption in the mid-infrared (MIR) and thermal-infrared (TIR), permitting detection by satellite sensors like the Infrared Atmospheric Sounding Interferometer (IASI: Aires et al., 2002), the Tropospheric Emission Spectrometer (TES: Beer et al., 2001), and the Atmospheric Infrared Sounder (AIRS: Tobin et al., 2006). Because detection in the TIR requires a strong thermal contrast between ground and lower atmosphere and is limited by sensor saturation due to a high $CH_4$ absorption coefficient, current sensors cannot provide near-surface concentrations.

In addition to absorptions in the TIR, $CH_4$ has absorptions in the shortwave infrared (SWIR) between 1400 and 2500 nm (Fig. 1, top). In this region, water vapor has considerable spectral overlap with $CH_4$, particularly beyond 2300 nm, which complicates $CH_4$ detection (Fig. 1, bottom). These SWIR absorptions enabled global $CH_4$ mapping by the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) onboard the Envisat satellite, a grating spectrometer with eight channels operating from 240 to 2,400 nm with a spectral resolution between 0.2 to 1.4 nm and spatial resolution ranging from 30 × 60 km to 30 × 240 km (Buchwitz et al., 2004). The Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) retrieval algorithm (Buchwitz et al., 2000) was applied to 2003 data from SCIAMACHY channels 4, 6, and 8 to estimate column amounts of CO (carbon monoxide), $CO_2$, and $CH_4$ (Buchwitz et al., 2005). Frankenberg et al. (2005) developed an iterative maximum a posteriori-DOAS (IMAP-DOAS) algorithm using DOAS and the linear relationship between vertical column-densities for $CO_2$ and $CH_4$ to estimate global $CH_4$ column-averaged mixing ratios over terrestrial surfaces and detect regions with high column averages, including the Red Basin in China and the Sudd wetlands of southern Sudan (Frankenberg et al., 2011). While the Envisat satellite mission ended in 2012, the Greenhouse Gas Observing Satellite (GOSAT: Saitoh et al., 2009) continues to provide global $CH_4$ mapping in good agreement with ground based measurements (Butz et al., 2011) and results from global 3-D chemical transport models (Parker et al., 2011).

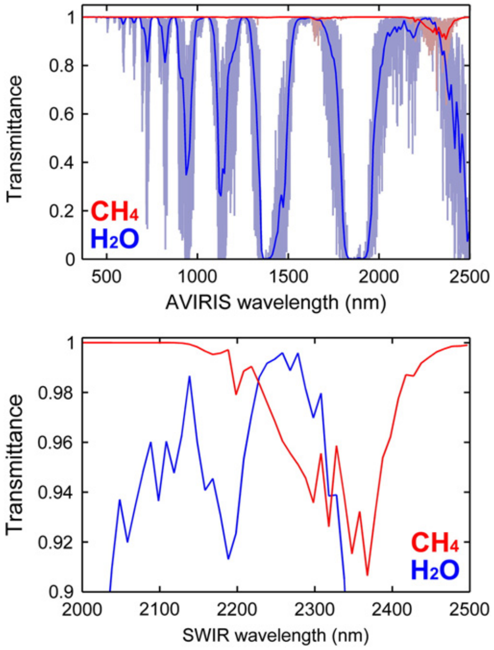

**Fig. 1.** (Top) $CH_4$ and $H_2O$ transmittance spectra generated using Modtran 5.3, parameterized for a mid-latitude summer model atmosphere and 8.9 km sensor altitude for the COP scene. Transmittance is shown in high resolution for $CH_4$ (light red) and $H_2O$ (light blue) and convolved to AVIRIS wavelengths for $CH_4$ (dark red) $H_2O$ (dark blue). (Bottom) SWIR region showing considerable spectral overlap between $H_2O$ and $CH_4$.

Global $CH_4$ concentrations are well constrained due to existing spaceborne remote sensing that provides an effective means of detecting continental scale variation in $CH_4$ concentrations. However, spaceborne sensors lack the fine spatial resolution needed to detect near-surface emissions. Local emission monitoring typically relies upon ground-based measurements with limited spatial coverage, such as gas chromatography, tunable diode lasers (Hsu et al., 2010), or Fourier transform spectrometers at fixed sites (Wunch et al., 2009). Airborne sensors could provide valuable data for constraining emissions at local to regional scales (NRC, 2010). Improved constraint of emissions at these scales is critical for improving national greenhouse gas budgets and the partitioning between anthropogenic and natural sources (Bovensmann et al., 2010). Airborne measurements could also help address discrepancies between top-down and bottom-up estimates of emissions (Montzka et al., 2011) and complement ongoing global monitoring efforts at coarser spatial resolutions (Schepers et al., 2012).

Airborne imaging spectrometers are well suited for monitoring local sources because they can provide coverage over large regions with the fine spatial resolution necessary to resolve point source emissions. The Airborne Visible Infrared Imaging Spectrometer (AVIRIS) measures reflected solar radiance across 224 contiguous spectral bands between 350 and 2500 nm with a signal-to-noise ratio that should permit $CH_4$ mapping (Leifer et al., 2006b). Roberts et al. (2010) used AVIRIS data acquired over the Coal Oil Point (COP) seep field in the Santa Barbara Channel, California to calculate spectral residuals for $CH_4$ above background and a $CH_4$ index derived from the average residual between 2248 and 2298 nm. Although strong $CH_4$ anomalies were detected in close proximity to known seeps, mapping proved challenging given results were overly sensitive to albedo (Roberts et al., 2010).

Using a high-glint AVIRIS scene acquired over COP, Bradley et al. (2011) developed a band ratio technique using radiance for a $CH_4$ absorption band (2298 nm) and a $CO_2$ absorption band (2058 nm) to generate the AVIRIS $CH_4$ index, $\zeta$ ($L_{2298}/L_{2058}$). In the absence of strong local sources of $CH_4$ or $CO_2$, these gasses are well mixed and a regression of $CH_4$ and $CO_2$ bands produces a straight line. If additional $CH_4$ above background is present in the lower boundary layer and $CO_2$ is well mixed, radiance for the $CH_4$ band decreases due to increased absorption, resulting in a lower $CH_4$ to $CO_2$ band ratio. Despite variations in surface albedo, this method clearly detected a $CH_4$ plume that was consistent with wind advection from a sonar-quantified source (Bradley et al., 2011).

While Roberts et al. (2010) and Bradley et al. (2011) demonstrate that $CH_4$ from marine sources can be detected using AVIRIS scenes with high sunglint, these techniques cannot be applied to terrestrial locations that rarely exceed 50% albedo, where the majority of anthropogenic emissions occur (NRC, 2010). Although water can often be assumed spectrally flat in the SWIR (Roberts et al., 2010), this assumption is unrealistic for most land cover types. Spectral variation in surface reflectance arising from heterogeneous land cover invalidates the use of a ratio, where a change in radiance at 2298 nm relative to 2058 nm could either be a product of changing $CH_4$ or $CO_2$ absorption, or a change in surface reflectance with wavelength.

This study aims to improve methods for detecting absorption features of $CH_4$, thereby permitting high spatial resolution mapping of local emissions over marine environments and heterogeneous terrestrial surfaces. We applied a Cluster-Tuned Matched Filter (CTMF) technique (Funk et al., 2001) to AVIRIS scenes from the COP seep field and a portion of Los Angeles known for natural $CH_4$ and oil seepage. The CTMF algorithm identified a number of significant $CH_4$ anomalies over known and probable $CH_4$ sources, including natural marine and terrestrial $CH_4$ seepage and a $CH_4$ plume at the Inglewood Oil Field.