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REGIONAL SURVEYS OF CH_4 POINT SOURCES ACROSS NORTH AMERICA: CAMPAIGNS, ALGORITHMS, AND RESULTS

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ABSTRACT

The last five years have seen dramatic growth in the use of Visible Shortwave Infrared (VSWIR) and Thermal Infrared (TIR) imaging spectrometers to detect and characterize greenhouse methane sources. Targets include: dairy and animal husbandry emissions; landfills; fossil fuel extraction, storage, and transport infrastructure; geologic sources; natural emissions associated with sensitive arctic ecosystems; and more. These campaigns have resulted in significant new discoveries and advances in our understanding of the North American CH_4 budget. Recent algorithm improvements have been critical for these campaigns, enabling robust statistical CH_4 measurement, fully-automated image-space source identification, and quantification of flux. Here we survey recent campaigns by NASA's Next Generation Airborne Visible Infrared Imaging Spectrometer (AVIRIS-NG) and NASA's Hyperspectral Thermal Emission Spectrometer (HyTES). We describe their algorithmic advances and major findings.

Index Terms— One, two, three, four, five

1. INTRODUCTION

The last five years has seen dramatic growth in the use of Visible Shortwave Infrared (VSWIR) and Thermal Infrared (TIR) imaging spectrometers to detect and characterize methane point sources. Campaigns include scientific research and process studies, as well as surveys by commercial entities and government regulatory agencies. These surveys typically cover an order of magnitude or more geographic area than in prior years, leading to significant new discoveries and advances in our understanding of the North American CH_4 budget. Recent algorithm improvements have been critical to enable these campaigns, permitting robust statistical CH_4 measurement, fully-automated image-space source identification, and to some extent, quantification of flux. This brief paper surveys recent campaigns by NASA's Next Generation Airborne Visible Infrared Imaging Spectrometer (AVIRIS-NG), and NASA's Hyperspectral Thermal Emission Spectrometer, or HyTES, [1, 2]. We summarize some of their major findings, and describe algorithms used in these new investigations.

While anthropogenic point sources represent lost revenue to the natural gas industry, such leaks are highly significant due to their short term safety hazards and long term climate change impacts. Methane has a radiative forcing potential many times that of CO_2, and relatively short lifespan in the atmosphere. This means that mitigating point source methane emitters can have an outsized impact on near-term global radiative forcing. Additionally, methane sources are often characterized by "heavy tail" distributions [3, 4] where a handful of emitters are responsible for the majority of emissions. Identifying and remedying the main sources can have a large and cost-effective impact. Here we use the term *point source* to mean a single emission features where the enhancement arises from an identified process or event on the scale of centimeters or tens of meters. Salient examples include: dairy and animal husbandry [3]; landfills [5]; fossil fuel extraction, including storage and transport infrastructure [3, 6, 4]; geologic sources [7]; and natural emissions associated with sensitive arctic ecosystems [8]. Our definition excludes larger sources on the scale of neighborhoods, cities, or oilfields, where each spectrum may include many distinct sources.

2. ALGORITHMS

Most operational CH_4 detection algorithms look for the signature of excess CH_4 enhancement in the 2200-2350 nm absorption window. Algorithms can be categorized roughly into those that use scene statistics, such as matched filter approaches [9], and those that use only first-principles physical modeling, such as DOAS [10, 11]. To date, our operations and primary results use the former approach, though we have also used DOAS for case studies and additional physical interpretability. Scene-based statistical methods generally assume that spectral radiances observed at the sensor follow a Gaussian background distribution with mean μ and covariance Σ. This distribution manifests in a tested spectrum $\boldsymbol{x}$ by a CH_4 signature t, in direct proportion with with factor α to its enhancement level. This last linearity assumption follows from the first-order Taylor series expansion of Beer-Lambert absorption about the enhancement point of zero [6]. It is a safe assumption for optically-thin cases, and leads to the classical matched filter $\hat{\alpha}(\boldsymbol{x})$ that estimates the scaling factor α [6]. There are countless subtle variants on this basic approach [12], with one particular standout being the Adaptive Cosine Estimator normalizing for the radiance magnitude of the target. Here, for physical interpretability we define our target to be the change in radiance caused a unit mixing ratio length of CH_4 absorption. This perturbation was a Beer-Lambert attenuation of the background $\boldsymbol{\mu}$, appropriate for optically-thin CH_4 emissions enhancing the ambient CH_4. This gives the detected quantity $\hat{\alpha}(\boldsymbol{x})$ as a mixing ratio length in units of ppm m, the equivalent mixing ratio if the enhancement layer were one meter thick. To translate into a total column average, denoted $X\mathrm{CH}_4$, for a scale height of about 8 km [13] one can multiply the mixing ratio length by $0.000125\ \mathrm{m}^{-1}$. For example, 10000 ppm m translated to an CH_4 enhancement of 1.25 ppm.

In practice it is often more important to estimate the background distribution accurately than to pick the right detection metric . Here our refinements include partitioning the scene into backgrounds using clustering [7]. For pushbroom instruments, we assign each column of the detector array its own distribution, capturing the unique response properties of those elements at the time of the acquisition [9]. This measure can significantly reduce "striping" effects, reduce the overall noise and artifact load, and improve sensitivity overall. We have also adopted other robust covariance methods include regularization using shrinkage estimators [14]. Finding the subtlest emissions from diffuse arctic sources has required extra postprocessing. In this campaign, emissions were very low relative to systematic distoritons caused by background spectral structure. We used statistical strategies to control for this confusion [8]. After CH_4 detection, we performed an atmospheric correction operation to estimate the surface reflectance spectrum. We then split the dataset horizontally into rectangular segments with several tens of downtrack rows, and extracted a set of reflectances. The reflectance only included wavelength intervals *without* CH_4 *absorptions*. We then fit a multivariate linear regression within each segment that predicted the CH_4 enhancement. We attributed its predictions to surface materials that were unrelated to methane, and subtracted them from the estimated enhancement to produce a clean image. This method significantly improved the noise floor, resulting in a more or less uniform white noise distribution without systematic effects (Figure 1). We confirm it did not modify or bias estimates of true sources.

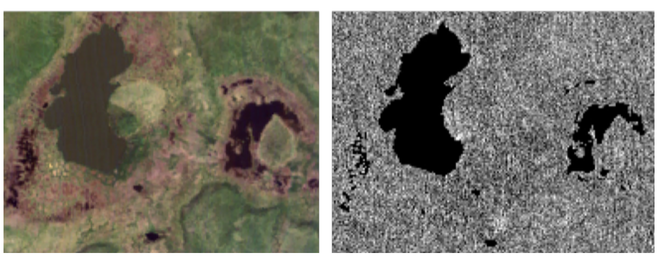

Fig. 1. Typical lakeside CH_4 enhancement in the Mackenzie Delta area (ang20170731t215130). The left column shows the RGB channels from the original AVIRIS-NG data. The right column shows the enhancement level, with brighter pixels signifying more CH_4 excess above the background.

Other improvements to matched filter retrievals are under study [15]. An L1 sparsity prior that assumes that CH_4 enhancement is rare within an image reduces background noise, and an iterative approach can be used to correct for spatially varying surface albedo. This iterative approach also has the benefit of removing the spectral signature of methane enhancement from the background covariance matrix. Grouping adjacent columns for covariance calculation can improve processing speed while still suppressing striping effects.

3. CAMPAIGNS

Perhaps the single largest campaign undertaken to date is the California baseline Methane Survey, which ran for several years beginning in 2016 [3]. It used AVIRIS-NG to survey a large fraction of the infrastructure elements associated with oil and gas industries, waste management, wastewater treatment, the energy sector, and manure management (Figure 2; over 449000 facilities in total. Under flight survey conditions, AVIRIS-NG can detect and quantify methane point sources with emissions typically as small as 2-10 kg hr^{-1} for surface winds of 5 m s^{-1}. Sensitivity depends somewhat on surface brightness, aircraft altitude and ground speed. For further information on the translation from enhancement images to flux, we refer the reader to the material in Duren et al. [3]. Over 590 sources were discovered during this campaign and many were revisited to evaluate their persistence over time. The total emissions inferred from the survey were 0.511 Tg CH_4 yr^{-1} from which slightly higher state-wide values were inferred after accounting for the small fraction of sources that were never measured.

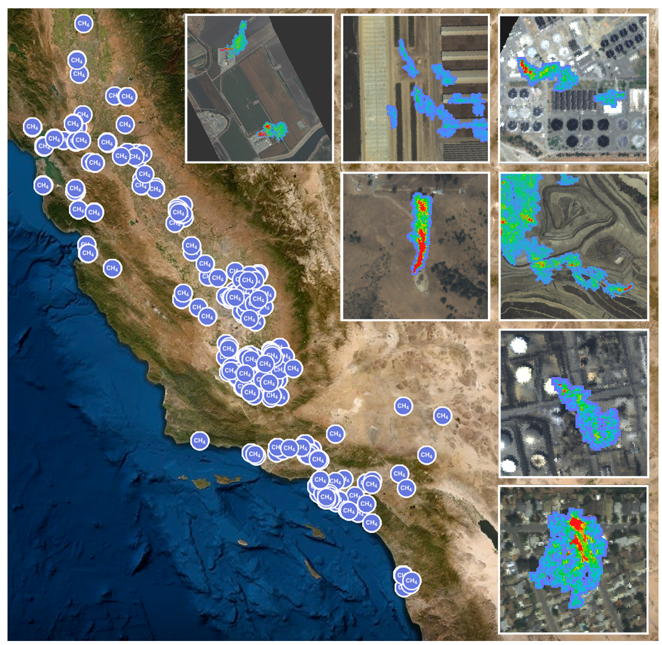

Fig. 2. AVIRIS-NG CH_4 source locations from the California Methane Survey [3]. Example CH_4 sources include from top left to bottom right: gas storage facility, dairy, wastewater treatment facility, oil well, landfill, tank, and underground natural gas distribution line leak.

Other campaigns aimed for localized temporal studies that evaluate a point source's evolution over time. These exploited real-time analysis onboard the instrument, which enabled radiometric calibration, detection, quantification, mapping, and finally geolocation [9]. A real-time display let flight operators adjust later flightlines and instruct ground teams to make corroborating measurements. AVIRIS-NG used these techniques in a campaign of 2015 [4] characterizing the Four Corners area of the United States. This area had been identified as a CH_4 emission "hot spot" but the partitioning of this emission into natural and anthropogenic sources was not well understood [4]. HyTES [16] and AVIRIS-NG mapped a large fractional area of this region, identifying over 200 distinct sources including well-pad unloading events, drilling operations, storage venting. These measurements enabled a reliable statistical characterization of the emitter population, and accounted for a large fraction of the overall emissions observed from the region. However, the real-time detection also enabled instant confirmation of these sources using thermal camera images acquired from the ground.

Another important case study campaign involved Visible/Shortwave Infrared and Thermal sensors viewing the Aliso Canyon event, a large accidental release of CH_4 from an underground storage facility in Fall 2015 – Winter 2016. This was the largest single emission source yet mapped, and was successfully detected by the Hyperion instrument onboard the Earth-orbiting EO-1 spacecraft [6]. The EO-1 spacecraft was only able to image the plume under suboptimal illumination conditions, resulting in an extremely low SNR; nevertheless, it observed the plume morphology on three occasions to achieve the first ever detection and attribution of a single CH_4 point source from orbit. Followup observations by an airborne instrument confirmed these detections and helped to fill in the time series.

The ABoVE Arctic Camapaign has recently produced new discoveries about the distribution of point sources in Alaska [8]. It has been known for some time that arctic methane emissions included point sources from geologic sources as well as biogenic CH_4 from permafrost thawing. However, this had only been demonstrated through laborious field campaigns that visited just a few sites at specific geographic locations. Such studies lack the ability to scale CH_4 observations across diverse landscapes, or to extrapolate to geographic scale to understand the climate impact of the rapidly warming Arctic. During the ABoVE campaign, AVIRIS-NG surveyed CH_4 emission patterns across Alaska and western Canada covering more than 30,000 km^2 with 25 m^2 spatial resolution and approximately 1 billion individual measurements. This enabled analyses and statistical population studies across many scales. It detected thousands of hotspot emissions areas, most of which were associated with standing water like lakes and ponds near active permafrost thawing (Figure 1. This enabled regional assessments of environmental variables influencing CH_4 emission probability. Both individual detection events and larger-scale spatial trends have been validate *in situ* through selective followup of specific sites of interest with ground instrumentation.

The thermal regime offers additional leverage on many gases without obvious VSWIR absorption signatures. The Hyperspectral Thermal Emission Spectrometer (HyTES) is a pushbroom imaging spectrometer that produces a wide swath Thermal Infrared (TIR) image with high spectral (256 bands from 7.5- 12 μm) and spatial resolution (2 m at 1 km altitude) [1, 16]. For the detection of greenhouse gases such as methane, TIR spectrometers rely on the thermal emission and thermal contrast between the ground and the target gas. Given sufficient thermal contrast, this makes detection of gas species possible over a wide range of land cover types independent of their reflective features 3. TIR observations also allow night-time operation during which the collapsed nocturnal planetary boundary layer results in higher near-surface concentrations of source gases – translating to easier detection. Another key advantage of TIR data is the ability to distinguish between different trace gas signatures within a single plume. Using a hybrid Clutter Matched Filter (CMF) method [16] and quantiative retrieval algorithm [17], HyTES has the ability to both detect and quantify the concentration of methane and other criteria pollutants (H2S, NH3, NO2, and SO2) with plume enhancement uncertainties of 20%. In the context of climate change and air quality, the ability to detect and characterize individual point sources of greenhouse gases such as methane or criteria pollutants such as sulfur and nitrogen oxides from key emitting sectors is a promising tool for improving understanding of the distribution of emissions sources and for supporting emissions mitigation.

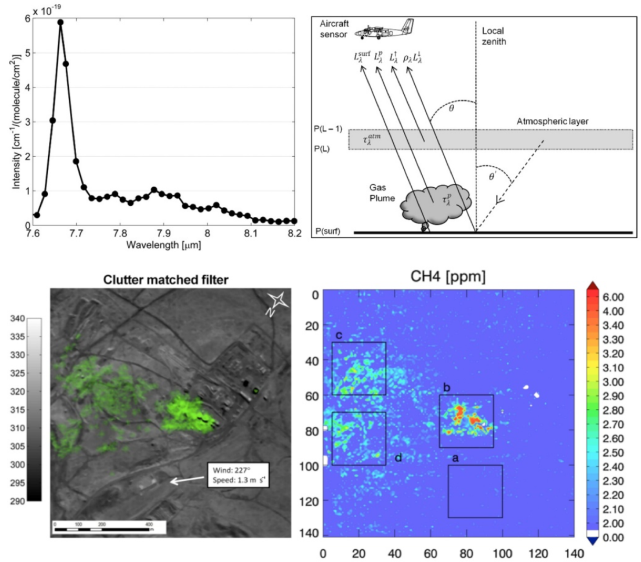

Fig. 3. From clockwise top left: HyTES data have sufficient resolution to resolve the strong methane rovibrational band ($\nu 4$) in the 7.2–8.3μm spectral region; plume physics and radiative transfer in the TIR; HyTES detected methane plume (in green) from a storage facility on 5 February 2015 in Kern County, CA; methane concentration in ppm of the same region from the quantitative retrieval estimation.

4. DISCUSSION

VSWIR Imaging spectroscopy has proven a powerful tool for understanding point source emissions of greenhouse gases like C_4. There is also demonstrated potential to detect combustion byproducts such as H_2O and CO_2 [11], making them a compelling option for monitoring anthropogenic point sources in addition to natural emissions. This has led many scientists and missions to consider the possibility of a dedicated CH_4 detection satellite, or of commensal studies with future orbital imaging spectrometers like EMIT. Preliminary assessments based on modeling larger spatial scales suggest that these instruments should indeed be able to detect and quantify a significant number of superemitters [18]. This will capture the heavy tail of large point sources and forming the first truly global catalog of major methane point sources. Future work will continue to advance towards accurate morphological detection of plumes as well as flux quantification based on windspeed modeling [3] and where possible, residence times derived from the plume morphology [19].

5. ACKNOWLEDGEMENTS

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