Improving Imaging Spectrometer Methane Plume Detection with Large Eddy Simulations

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Abstract

Methane's high heat trapping potential has made it a priority for quantification and mitigation efforts worldwide. Ground-based surveys and in-situ measurement techniques to quantify natural and fugitive methane emission sources are time-consuming, expensive, and often lead to sparse measurements. Failure to accurately quantify emissions at the point-source scale have thus led to poorly constrained emission estimates. Airborne imaging spectrometers such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) and the Global Airborne Observatory (GAO) have been employed to map the often stochastic and intermittent point-source emissions from a diverse set of source types including oil and gas, dairy, etc. A matched filter is applied to the methane-absorption relevant spectral features of the instrument's radiance cube. Machine learning models are then trained to recognize methane plumes from these column-matched filter methane maps. However, current Convolutional Neural Network (CNN) models suffer from a high false-positive rate and poorly generalize to new scenes. False-positive detections are primarily due to methane absorption-mimicking surface spectroscopic features, as well as a lack of training data. To supplement the available training data, we utilize Large Eddy Simulations (LES) of methane point-source emissions to train a Convolutional Neural Network (CNN) on a plume-classification task. We observe a significant distribution shift between LES and AVIRIS-NG plumes, primarily caused by high LES plume enhancements. Through a series of image transforms verified through an adversarial approach using a discriminator network, we minimize the distribution shift between synthetic LES plumes and plumes observed by AVIRIS-NG and GAO. CNNs trained on a mixture of LES and real-world plumes, and tested on flightlines from multiple campaigns exhibit an error reduction compared to previous models. The reduction in false-positive plume detections demonstrates that supplementing the limited training data of real methane plumes with LES provides an avenue to make automatic detection more robust for future airborne and spaceborne missions such as SBG, EMIT, and Carbon Mapper.

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Background

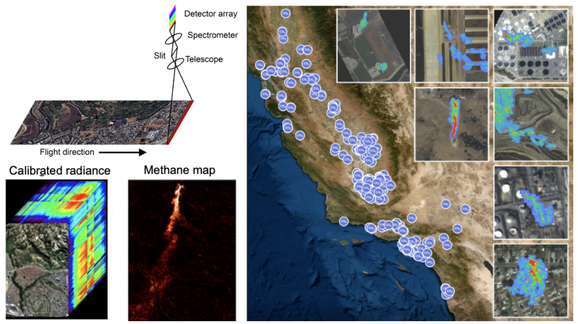
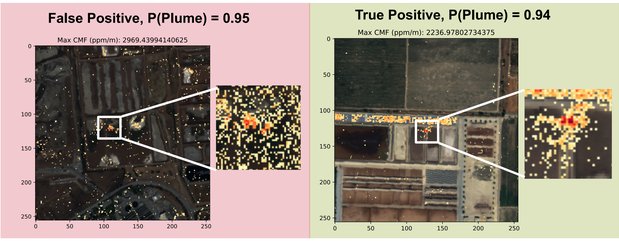


Figure 1. (Left) AVIRIS-NG 2D radiance cube is passed through a matched filter CH_4 retrieval to produce a CH_4 map. (Right) The California Methane Survey identified that 10% of point-source 'super-emitters' are responsible for 60% of emissions in California.

- Methane is the second most important anthropogenic greenhouse gas.
- Mitigation requires accurate quantification of stochastic and intermittent point-source emitters [1]

Problem Description

- Current efforts to quantify emissions from point-source emitters at the space-borne level lack sufficient spatial resolution; In-situ measurements are sparse. This has led to **ambigious regional budgets** [2]
- Airborne measurements with AVIRIS-NG and GAO maps CH_4 plumes at a high spatial resolution and allows **source attribution + emission quantification** (Figure 3).
- Convolutional Neural Networks (CNNs) can efficiently learn spatial information from hyperspectral imagery when trained to classify CH_4 plumes from AVIRIS-NG airborne data.
- **Problem:** Current CNNs trained on a plume-classification task have a high false-positivity rate and poorly generalize to new campaigns and ground terrain.



Problem

Lack of High Quality Training Data; Availability of Diverse Plumes Restricted to Field-Collected Datasets

Research Question

Can synthetic CH4 plumes generated with Large Eddy Simulations (LES) [3] improve robustness of CNNs to false-positive plume detections and create cross-campaign generalizable classifiers?

Methodology – Constraining Enhancement Distributions

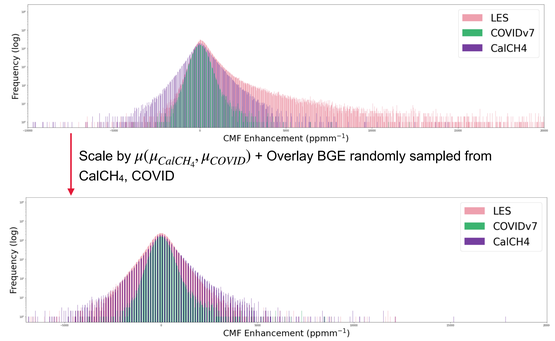


Figure 2. Long-Tailed, high enhancement distribution of Synthetic LES plumes constrained by mean-scaling and overlaying Background Enhancements randomly sampled from California COVID Campaign (2020), and CalCH_4 Campaign (2018)

Synthetic LES plumes had a significantly higher mean enhancement with a long tailed enhancement distribution. CNNs easily distinguish synthetic plumes from real data captured in the California COVID campaign (2020), and the Cal-Methane Campaign (2019).

Methodology – Synthetic Data Filtering as a 2-Player Adversarial Game

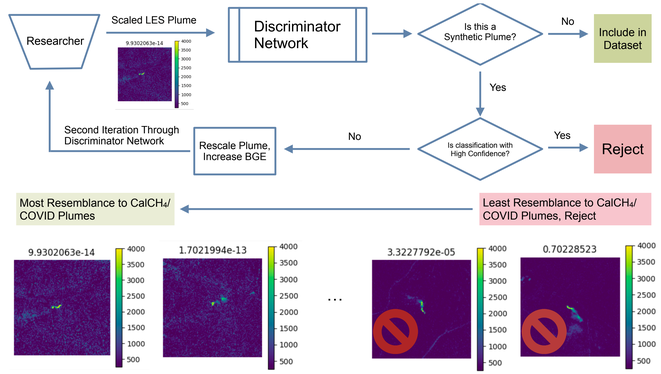


Figure 3. (Top) Filtering for realistic plumes is reformulated as a 2-player adversarial game. Scaled LES plumes are posed to a discriminator network that classifies the plume as **synthetic** or **real**. LES Plumes successfully classified as a real-campaign plume are included in training datasets, while LES-identified plumes are re-scaled/ rejected based on a CNN confidence output. (Bottom) Selected LES plumes are ranked according to a 'realism' metric; Top N most realistic plumes are selected for training.

References

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[3] S. Jongaramrungruang, C. Frankenberg, G. Matheou, A. K. Thorpe, D. R. Thompson, L. Kuai, and R. M. Duren, "Towards accurate methane point-source quantification from high-resolution 2-d plume imagery," *Atmospheric Measurement Techniques*, vol. 12, no. 12, pp. 6667–6681, 2019.

Results

Multi-Campaign Tests

To simulate flightline-level test-time imbalance, we sample a total of 60 plumes evenly distributed over 3 campaigns and append 13000 background tiles, creating a plume:background ratio of 1:217.

Train Dataset	Test dataset	Precision	Recall	F1
LES + COVID + CalCH$_4$	Imbal	0.32	0.90	0.47
COVID + CalCH$_4$	Imbal	0.20	0.85	0.34

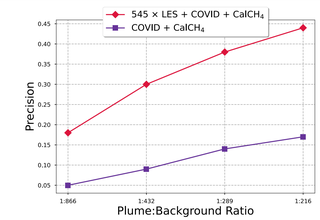

Figure 4. Plume classification precision vs Dataset Imbalance (Higher = More Realistic)

LES-aided CNNs exhibit a lower false-positivity rate when trained on realistic datasets spanning multiple campaigns.

Analysis

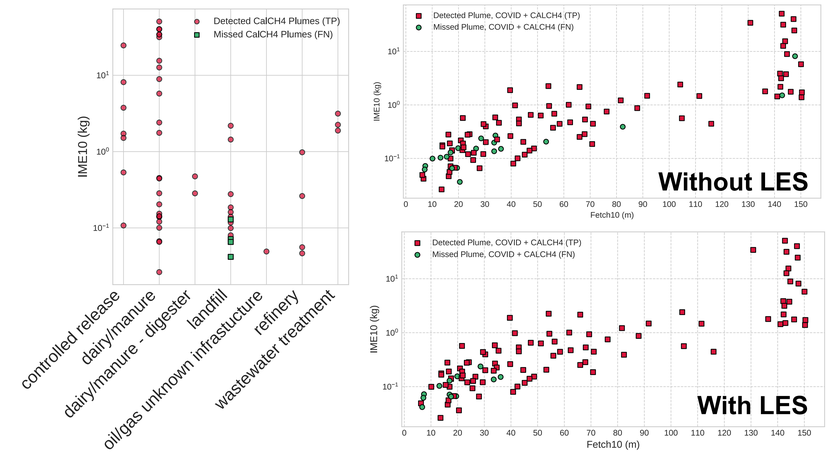

Figure 5. Missed Plume Analysis: (Left) Source-Type vs Integrated Methane Enhancement (IME) for LES-aided CNNs. (Right) Fetch-IME plot for LES (Bottom) and non-LES-aided (Top) CNNs.

Conclusion

- LES-trained CNNs show improved precision and recall performances and classify plumed previously missed by traditional models.
- LES plumes show significant precision and recall improvements with large class imbalance, outperform real-world plume datasets.
- However, LES-trained CNNs predict small, weak plumes as background with near-certainty.
- LES plumes are not equipped to replace weak, diffused plume data such as those found near landfills (Figure 5).

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