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Energy Research and Development Division

FINAL PROJECT REPORT

The California Methane Survey

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

The California Methane Survey is the combined final report for the California Methane Survey project (CEC Contract Number 500-15-004 and ARB-NASA Agreement 15RD028 Space Act Agreement 82-19863) conducted by the Jet Propulsion Laboratory. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Methane point source emissions play an important role in the human (anthropogenic) methane inventory and present unique opportunities for mitigation. The researchers conducted a comprehensive survey of facilities and components in California, spanning the oil and gas, manure management, and waste management sectors, using an airborne imaging spectrometer capable of rapidly mapping methane plumes. Five campaigns were conducted over several months from 2016 to 2018, resulting in the detection, geolocation, and quantification of 564 strong methane point sources. This represents a major advance in the use of remote sensing to rapidly and repeatedly assess large areas at high spatial resolution for a poorly characterized population of methane point sources. The team estimated that emissions from methane point sources in California contribute more than a third (34 to 46 percent) of the state's methane inventory for 2016. Methane super-emitter activity occurs in every surveyed sector. Over the entire population of observed point sources, 10 percent of sources contributed nearly 60 percent of emissions. The largest methane point source emitters in California are 32 landfills and composting facilities exhibiting persistent, potentially anomalous activity. Production is responsible for nearly 80 percent of point source emissions associated with California's oil and gas sector. Point source emissions from natural gas infrastructure are primarily associated with a relatively small number of processing plants, compressor stations, refineries, and gas fired power plants. The project identified five low pressure natural gas leaks that were subsequently repaired by operators. This work highlights the potential for efficient point source monitoring to enable mitigation of a broad class of methane super-emitters, representing a significant contribution to California's climate stabilization targets, reduced natural gas product loss, and early warning of potentially hazardous leaks.

Keywords: natural gas, methane, emissions, mapping, remote sensing

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Introduction

Methane (CH_4) is a powerful greenhouse gas and is targeted for emissions mitigation by the State of California. It is increasingly prioritized for near-term climate action given its relatively short atmospheric lifetime and the potential for rapid, focused mitigation that can complement economy-wide efforts to reduce carbon dioxide emissions. Methane is also a precursor for tropospheric ozone and is strongly linked with co-emitted reactive trace gases targeted by California air quality and public health policies. California has established a methane emission reduction goal of 40 percent below 2013 levels by 2030. Efforts to understand the state's methane emissions are complicated by large inconsistencies between estimates of methane emissions derived from atmospheric measurements and greenhouse gas inventories.

Project Purpose

The team used advanced remote sensing methods to detect and characterize anthropogenic (human) methane emissions to support the state's objectives for mitigating short-lived climate pollutants, identifying methane "hotspots" in response to AB 1496, and supporting natural gas leak detection and correction for rate payer benefit. The project was performed in two phases with funding from the California Air Resources Board (CARB) and California Energy Commission (CEC), and co-funding from the National Aeronautics and Space Administration (NASA) Earth Science Division. Phase 1 primarily used data collected in 2016 and addressed CARB priorities spanning multiple methane emission sectors relevant to point sources—defined in this study as infrastructure components or localized (typically less than 10 meters in scale) surface features that emit plumes of concentrated methane—in California. Phase 2 collected data in 2017 and 2018 and focused on CEC priorities, particularly the natural gas sector, to improve understanding of leaks and to help enable mitigation. Phase 2 also included advances in data analysis, including estimating emission rates for individual sources and assessing total statewide emissions for each sector.

Project Approach

California was surveyed for methane point source emissions using the Jet Propulsion Laboratory (JPL) next generation airborne visible/infrared imaging spectrometer (AVIRIS-NG) remote sensing instrument. AVIRIS-NG is capable of rapidly mapping methane plumes over large areas using absorption spectroscopy. Absorption spectroscopy can detect and quantify a targeted substance (in this case, methane) in a sample based on how the sample interacts with different wavelengths of light (in this case, sunlight). AVIRIS-NG flights for this study were conducted during five campaigns: August – November 2016, March 2017, June 2017, August-November 2017, and September-October 2018. The survey imaged approximately 59,000 square kilometers (km^2) including revisits. The survey was designed to cover at least 60 percent of methane point source infrastructure in California and was guided by a newly developed geospatial data set known as Vista-CA. This technology mapped nearly 450,000 potential methane emitting infrastructure elements, spanning the oil and gas, manure management, and waste management sectors. Of that population of nearly 450,000 potential methane emitters, approximately 272,000 infrastructure elements were surveyed by the AVIRS-NG flights, including approximately 200,000 oil and gas wells and related production infrastructure as well as nearly 70,000 natural gas transmission and distribution pipeline elements. The survey included multiple overflights of the same infrastructure over several years to address source persistence – a major source of uncertainty in previous studies. This represents a major advance in the use of remote sensing to rapidly and repeatedly assess large areas at high spatial resolution for a poorly characterized population of methane point sources that often appear in an intermittent or unpredictable fashion, or both.

Project Results

Emissions from methane point sources in California were estimated to be equivalent to 34 percent to 46 percent of the state's methane inventory for 2016. Methane point sources were observed at a total of 564 of the surveyed facilities and infrastructure elements (0.2 percent). Super-emitter activity occurs in every surveyed sector. Over the entire population of observed point sources, 10 percent of sources contributed ~60 percent of emissions.

The largest methane point source emitters in the state (43% of the total emissions in this study) are 32 landfills (including 2 composting operations). Flight imagery includes examples of strong methane plumes at these landfills associated with gaps in intermediate cover and/or leaking gas capture wells. (Intermediate cover is compacted earthen material of at least 12 inches placed on the surface of a fill where no additional solid waste will be deposited within 180 days.) These plumes represent significant mitigation opportunities. Study results suggest that the majority of waste disposal facilities emit methane as area sources or as point sources below this study's detection limit and that landfills exhibiting point sources are a unique sub-population.

The team found that about 26 percent of methane point source emissions in California are from the oil and gas supply chain, with nearly 80 percent of that due to production. Spatially, 85 percent of point source emissions from production are concentrated in the southern San Joaquin Valley (the highest oil- and associated-gas producing region in the state), 14 percent in Los Angeles and Ventura counties, and 1 percent in the Sacramento Valley. These emissions are attributed to a variety of oil and gas production infrastructure, including well heads, gathering lines, and storage tanks. The researchers found no compelling evidence of strong methane emissions from abandoned oil or gas wells or specific to fracking operations, although more detailed analysis is recommended to confirm.

Methane point source emissions from natural gas infrastructure in California appear to be due to a combination of normal process emissions and anomalous leakage at processing plants, a small number of compressor stations on transmission pipelines and underground storage facilities, gas-fired power plants, and leaks in distribution pipelines. The methane point source emissions observed at most refineries and at seven power plants in California appear to be generally higher than reported to the EPA; however, additional study is recommended to pinpoint the causes. The team estimates that California's refineries and the outlier power plants contribute about 5 percent of the total methane point source emissions in the state. Overall, the team found that methane point source emissions from the natural gas sector in California are generally consistent with the State's 2016 methane inventory, with the aforementioned exceptions as well as a caveat that this study was not designed to address the potential for a large number of small leaks downstream of production, processing, and transmission. In particular, this study cannot rule out large disagreements between reported and actual fugitive methane emissions from the dense natural gas distribution system in some major urban areas.

The team surveyed 443 confined animal feeding operations in California – an estimated 71 percent of all such facilities in the state. Manure management at large dairies in the San Joaquin Valley is recognized as one of the top methane emitting sectors in California. The survey results are consistent with this, and wet manure management – particularly settling ponds and anaerobic lagoons – is found to be responsible for about 26 percent of total methane emission from point sources in California. Methane emission sources at these facilities are diverse and complex and could benefit from additional intensive study, including on-farm measurements. Methane digesters are increasingly being deployed at California dairies in an effort to reduce the net greenhouse gas impact of each facility while offering additional revenue opportunities, such as biogas for energy production. The survey covered about 25 known dairy digesters in California, including a combination of facilities in operation and still undergoing construction. In principle, a well-functioning digester should capture methane from manure management; however, the study indicated significant and fairly persistent methane point sources at four dairy digester facilities in the San Joaquin Valley. This suggests that future monitoring for atmospheric methane around dairy digester facilities before and after digester construction could prove useful for assessing their efficacy in meeting mitigation objectives while helping operators avoid unintentional biogas product loss.

A total of 58 wastewater treatment facilities across California were surveyed, of which ten exhibited methane point source plumes. Of these ten, three were persistent point sources, suggesting potentially anomalous activity. Based on AVIRIS-NG survey results, this entire sector is estimated to be responsible for about 2 percent of total methane point source emissions in California.

As a general finding, with the exception of the landfill emissions, many of the methane point sources detected by this survey were highly intermittent so for every source the researchers calculated a persistence or frequency that is simply the number of observed plumes divided by the number of observations. This resulted in a median persistence of 0.20 for the entire population (mean 0.33, range 0.02 – 1.0). In some cases, the intermittent emissions can be explained by normal operations (e.g., periodic waste flushing at large dairies). In other cases, more persistent activity appears to be due to sustained venting at a small number of anaerobic digesters at dairies and wastewater treatment plants or leaking bypass valves at natural gas compressor stations. The researchers found a similar distribution of persistence (.20 to .35 on average) and emissions in the manure management, wastewater treatment, and oil and gas sectors. Persistence numbers are applied to the emission estimate for each source, effectively lowering the average emission rates for most sources. This intermittency highlights the need for more frequent sampling.

The preliminary findings, including high resolution methane plume images, were shared with the operators of methane point source facilities, who provided verification with surface observations or explained the underlying mechanisms for the observed emissions, or both. Several of these collaborative efforts directly led to mitigation of the methane sources detected by the survey, including four leaking natural gas distribution lines and one leaking liquified natural gas storage tank.

Knowledge Transfer

Much of the data analysis system used in this study was developed under parallel NASA programs. Those data analysis capabilities, including a web-based methane data portal (http://methane.jpl.nasa.gov) that displays all methane plumes detected during this study are to be transferred to the California Air Resources Board for sustained operation. Additionally, over the course of this study the project team organized multiple meetings and briefings to share and discuss interim findings with stakeholders, including staff from the Energy Commission, Air Resources Board, CalRecycle, Bay Area Air Quality Management District, South Coast Air Quality Management District, Southern California Gas company, Pacific Gas and Electric company, Milk Producer's Council, City of Los Angeles Department of Sanitation, Sunshine Canyon Landfill Local Enforcement Agency, and several operators of individual facilities. These interactions resulted in two-way knowledge transfer, including feedback on the utility of the methane data sets as well as ground truthing and explanations about potential causes for observed emissions. Another source of knowledge transfer was the publication of a paper in the journal *Nature* (Duren *et al*., 2019).

Benefits

This project has provided new insights into California's methane inventory with the first systematic assessment of the relative contributions of methane point sources, including their distribution by space, time, and emission sector. These findings may lead to improvements in California's greenhouse gas inventory and to efforts by state and local agencies and businesses to both prioritize future investments in methane emissions mitigation and assess overall progress towards emissions reduction goals.

This work also highlights the potential for efficient point source monitoring techniques to directly enable mitigation of a broad class of methane super-emitters, representing a significant contribution to California's climate stabilization targets. Based on this research, point source emissions for the oil and gas sector in California are estimated to be 0.158 $TgCH_4/yr$ (95 percent confidence interval 0.135-0.184 $TgCH_4/yr$). If translated to natural gas equivalent, these emissions represent about $28-$39 million in annual product loss using July 2018 United States prices. This indicates the potential value of mitigation for California ratepayers, additional to climate benefits.

CHAPTER 1: Project Purpose

Motivation

Methane is a powerful greenhouse gas and is targeted for emissions mitigation by the State of California (California 2017). Methane is also a precursor for tropospheric ozone and is strongly linked with co-emitted reactive trace gases that are the focus of air quality and public health policies, particularly in high priority regions such as the San Joaquin Valley (SJV) and the South Coast Air Basin (SoCAB). Globally, the atmospheric growth rate of methane is likely strongly influenced by anthropogenic emissions from a population of spatially condensed point sources distributed over large areas and spanning diverse socio-economic sectors. However, "bottom-up" (inventory-based) estimates of methane emissions are often in disagreement with top-down (atmospheric measurement based) estimates (Wecht *et al.,* 2014, Turner *et al.,* 2015, Wong *et al.,* 2016, Jeong *et al.,* 2017, Cui *et al.,* 2019).

Limitations in process-based understanding of methane emissions is exemplified by the ongoing scientific discussion on both the hiatus in the atmospheric growth rate of methane in the early 2000's and the unexpected rise starting in 2007 (Kirschke *et al.,* 2013). Emissions and process attribution remain highly uncertain but are needed to resolve key elements of the global carbon budget, generate accurate greenhouse gas inventories and inform emission mitigation decisions. A key factor is that many current methane monitoring methods (bottom-up and top-down) are limited to regional or coarser scale resolution and often cannot detect individual sources or attribute fluxes to specific activity and facilities. Other methods are sufficient for studying previously known sources but are not well suited to surveying large areas for unknown sources. Hence methane emissions remain a challenging target for abatement since the locations and emission fluxes of many significant sources are still mostly unknown. These challenges are reflected in the recently enacted California AB 1496 law: "*there is an urgent need to improve the monitoring and measurement of methane emissions from the major sources in California*" and directs the California Air Resources Board to "*undertake, in consultation with districts that monitor methane, monitoring and measurements of high-emission methane hot spots in the state using the best available and cost-effective scientific and technical methods*". Another motivation is supporting efforts by natural gas utilities to improve leak detection and repair, a general benefit to California ratepayers.

Prior Studies

California has benefited from a number of top-down studies focused on methane. The 2010 CalNex campaign addressed many sectors and priority regions such as the SoCAB and SJV (Ryerson *et al.,* 2013). There has been an ongoing focus on SoCAB methane emissions and trends (Wennberg *et al.,* 2012; Wunch *et al*., 2016; Wong *et al.,* 2016), source attribution (Hopkins *et al.,* 2016), and characterization of individual sources such as the Aliso Canyon gas leak incident (Conley *et al.,* 2016; Thompson *et al*., 2016).

Recent years have also seen a dramatic improvement in the ability of passive remote-sensing methods to detect and locate large methane sources. Observations from polar orbiting satellites have detected strong, persistent enhancements of atmospheric methane in the Four Corners region and California's SJV (Kort *et al.,* 2014) and have produced spatially resolved estimates of United States methane emission trends (Turner *et al.,* 2016). The 2017 launch of the TROPOMI instrument on the Sentinel-5 Precursor satellite should further advance space-based methane detection for global studies (Butz *et al.,*2012). However, the ability of satellites to detect and quantify emissions from point sources is still limited to relatively coarse spatial scales (typically 25 km at best). Some surface measurement networks and models can resolve methane fluxes at resolutions as fine as a few kilometers but so far this is limited to a few urban testbeds (McKain *et al.,* 2015) and in most cases is insufficient to pinpoint and attribute point sources.

JPL and partners have devised a tiered observational strategy for efficiently surveying large areas for methane point sources, quantifying individual source emissions, and estimating their contributions to the net emissions of key regions and sectors. The strategy is flexible with regards to vantage points and measurement systems – enabling significant near-term progress using existing NASA remote sensing instrumentation that were developed as prototypes for next generation satellites. Over the past four years this strategy was tested with a series of exploratory airborne field campaigns over California's Central Valley and SoCAB (Thompson *et al.,* 2016) as well as the Four Corners region (Frankenberg *et al*., 2016).

Project Objectives

Based on the success of exploratory NASA airborne campaigns and in response to California policy needs the California Air Resources Board (CARB) and California Energy Commission (CEC) funded Jet Propulsion Laboratory (JPL) to conduct the first comprehensive airborne survey of methane point sources in the state.

In this study, a point source is defined as a condensed surface feature or infrastructure component (typically less than 10 meters across) that emits a plume of highly concentrated methane. This is in contrast to an "area source" or the combined effect of many small emitters distributed over a large area (typically 1 to 100 km across) that release methane in a more diffuse fashion including anaerobic decomposition occurring with rice cultivation and enteric fermentation from livestock, both of which are better addressed with other measurement methods and not included in this study.

The project technical objectives were as follows:

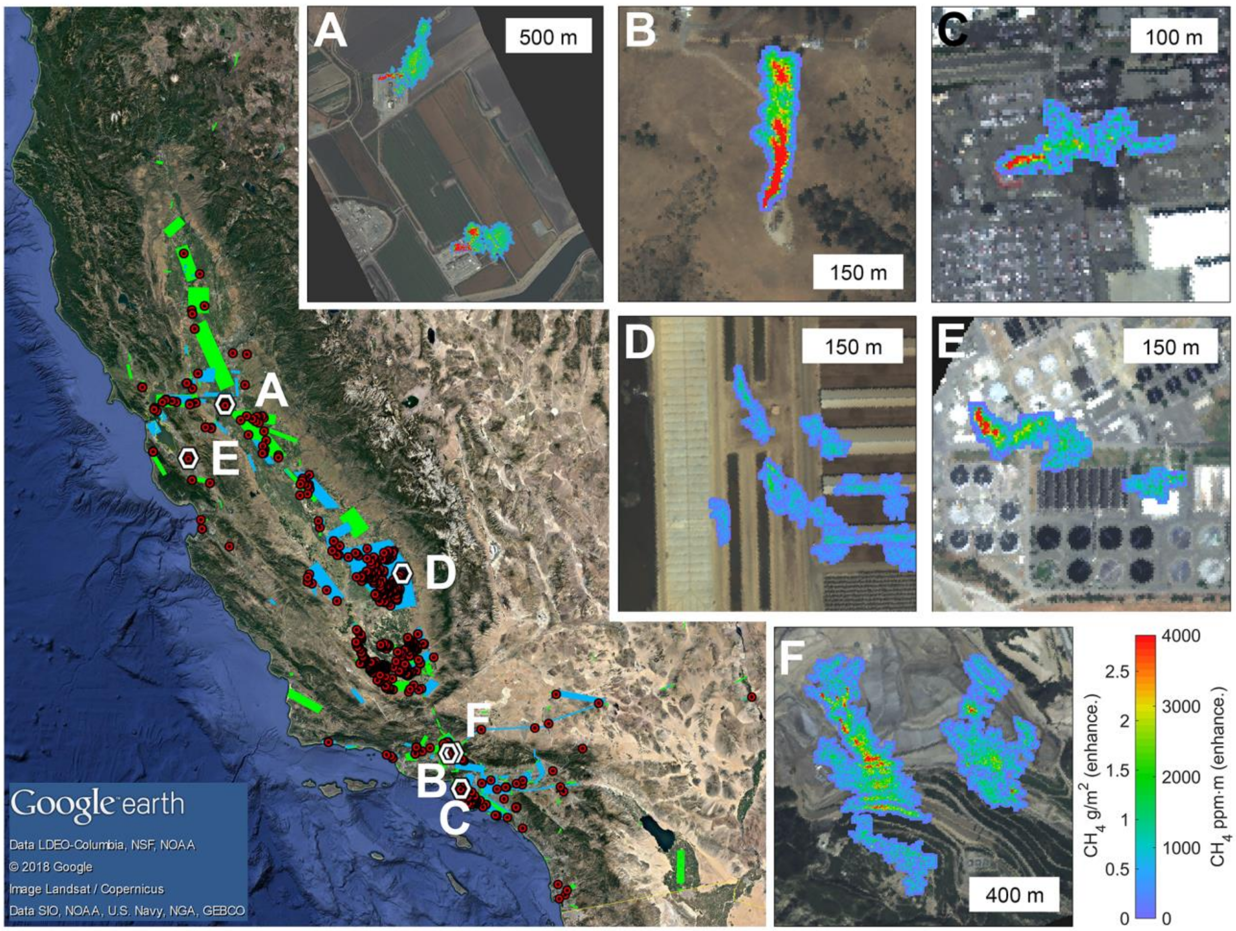
- Use state of the art airborne instruments and methane detection algorithms to conduct a California methane source survey over key regions that are major contributors to California's methane budget.
- Measurement data will be processed into maps of large source emitters detected within the areas flown.
- Provide the Energy Commission with the locations and plume characteristics of large fugitive emission sources located within the survey area for the natural gas system (CEC) and other relevant point source sectors (CARB).

CHAPTER 2: Project Approach

Observing Strategy for Methane Emissions

Data collection involved a broad airborne survey of methane point sources spanning key regions and sectors across the state by JPL's Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) in Figure 1.

Figure 1: Observing Strategy



Approximately 2000 individual AVIRIS-NG flight lines flown in 2016 (blue) and 2017 (green) covered over 272,000 individual facilities and infrastructure elements. Detected sources are indicated by red points with the densest clusters in the San Joaquin Valley (dairies and oil fields). The inset images show examples of representative methane plumes from different sectors: A. compressor stations at a natural gas storage facility, B. oil well, C. liquified natural gas tank, D. dairy manure management, E. wastewater treatment plant, F. landfill (Duren *et al.,* 2019). The color scales indicate the methane concentration-length enhancement in each pixel in units of parts per million-meter (ppm-m). Surface map images: Google Earth (basemap) and AVIRIS-NG (inset images).

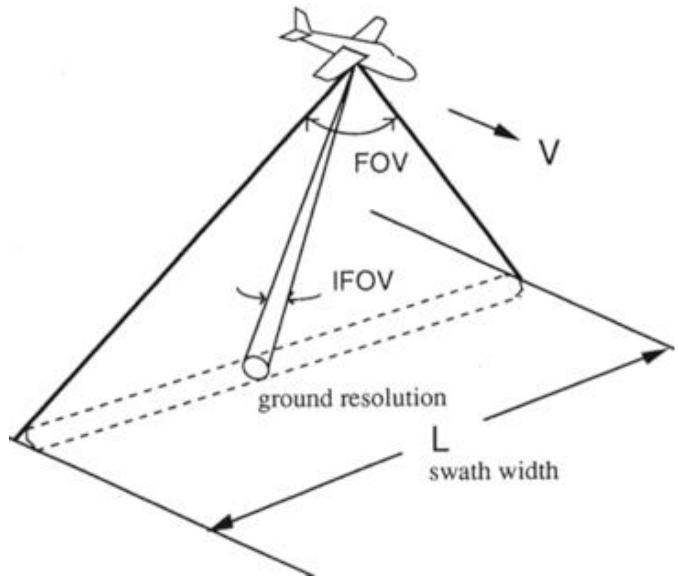
Source: Duren et al. 2019

The airborne remote sensing method applied is not optimized for detecting and quantifying area sources and hence methane emissions from area sources such as enteric fermentation, rice cultivation and wetlands are excluded from this study.

AVIRIS-NG Instrument and Methane Retrievals

The next generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) measures ground-reflected solar radiation from the visible to infrared spectral regions (350 to 2,500 nm). This push broom instrument has a 34° field of view and operates on high performance aircraft, allowing for efficient mapping of large regions. Increasing flight altitude affects the ground resolution, i.e., the size of each image pixel increases while the image swath increases (Figure 2, Table 1). For most of the California Methane Survey, AVIRIS-NG flew at 3 kilometer (km) above ground level, resulting in 3 meter (m) image pixels on average.

Figure 2: AVIRIS-NG Flight Parameters



L=image swath width, V=aircraft velocity, FOV=field of view, IFOV = instantaneous FOV.

Source: Murai, 1995.

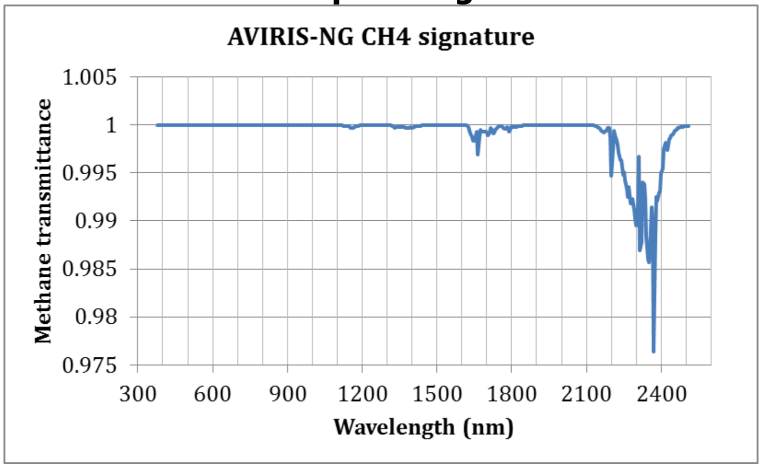
The methane retrieval is based on absorption spectroscopy (Figure 3) and has been used for a number of prior NASA research campaigns including Bakersfield area oil fields (Thompson et al., 2015), a campaign to the Four Corners region in Colorado and New Mexico (Frankenberg *et al.,* 2016), Aliso Canyon (Thompson *et al.,* 2016), and a study of California landfills (Krautwurst *et al.,* 2017). A methane controlled-release experiment indicated consistent detection of plumes for releases as low as 14.16 m^3/h (~10 $kgCH_4$/hr) at multiple AVIRIS-NG flight altitudes and variable wind speeds (Thorpe et al. 2016).

Table 1: AVIRIS-NG Image Parameters

Flight altitude (meters above ground level)	Image swath width (meters)	Ground resolution (meters)
1,000	611	1
2,000	1,223	2
3,000	1,834	3

Source: JPL

Figure 3: Methane Absorption Signature for AVIRIS-NG



Methane absorption signature (transmittance) plotted for the wavelength range measured by AVIRIS-NG. Strong absorptions are present between 2,200 and 2450 nm.

Source: JPL

The detected quantity is a mixing ratio length in units of ppm m representing the thickness and concentration within a volume of equivalent absorption. This is equivalent to an excess methane concentration in ppm if the layer is one meter thick (i.e. directly equivalent to ppb km). At a scale height of about 8 km, the total column averaged excess mixing ratio Xmethane would be about 0.000125 times the excess in ppm-m. For example, 1000 ppm-m is equivalent to an Xmethane enhancement of 125 ppb. Integrating over the physical area of the plume yields an Integrated Methane Enhancement (IME) in kg, as in Thompson *et al*. (2016) and Frankenberg *et al.* (2016), tantamount to the total observed mass of methane above the ambient background. This technique can be combined with simple steady state assumptions for a first-order estimate of a point source emission flux.

Methane retrievals are performed in real time onboard the aircraft (Figure 4), which permits the instrument operator to identify and geolocate plumes in real time.

Figure 4: Real Time Methane Mapping

Real time methane mapping onboard the aircraft. Red methane plumes are overlaid on raw AVIRIS-NG image.

Source: JPL

This information can be used for adaptive surveying and results communicated down to ground crews for rapid follow up. At the end of each flight day, methane quick-look data products (Figure 5) are generated and used to quickly assess results and plan future flights. After the AVIRIS-NG data is transported to JPL, scenes are reprocessed to generate methane retrievals for orthorectified scenes (planimetrically correct images with constant scale).

Figure 5: Methane Quick-Look Products

Methane quick-look products are generated at the end of each flight day. This example shows a plume from a leaking low-pressure gas pipeline that was confirmed and repaired by the gas company.

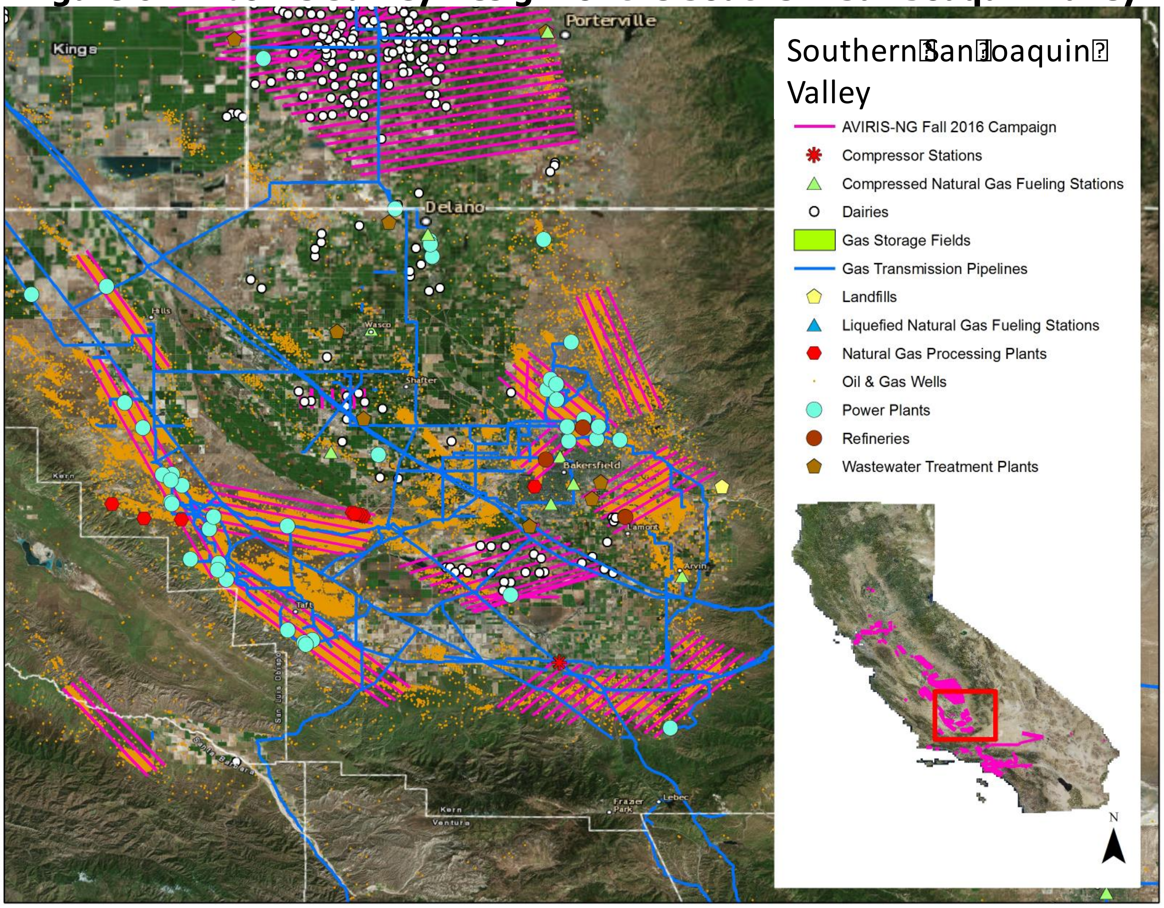
Source: JPL

Airborne Survey Design

Figures 6, 7 and 8 illustrates examples of AVIRIS-NG flight planning including the diversity of emission sectors and their spatial distributions. The flight planning was governed by two primary objectives: 1) spatial coverage sufficient to map the infrastructure in the state most likely responsible for >60 percent of methane point source emissions (with >80 coverage for key sectors) and 2) sufficient number of revisits to have a reasonable probability of detecting intermittent emission sources (for example for a source that is active 25 of the time, six visits should provide a detection probability of 0.82).

In addition to the broader goal to map and revisit large areas the team also conducted several intensive studies focused on gaining insight into key emission processes. One intensive focused on an area near Visalia that was mapped repeatedly over a 5-hour period to investigate the temporal variability of manure emissions from more than 100 dairies with 60-minute revisit intervals. Others focused on natural gas infrastructure across southern California, gas-fired power plants during heat wave conditions and refineries in the LA basin and San Francisco Bay Area. In several cases coordinated, contemporaneous measurements were conducted with mobile on-road laboratories, fixed surface observations and other airborne systems to help validate source locations and emission estimates.

Figure 6: Airborne Survey Design for the Southern San Joaquin Valley

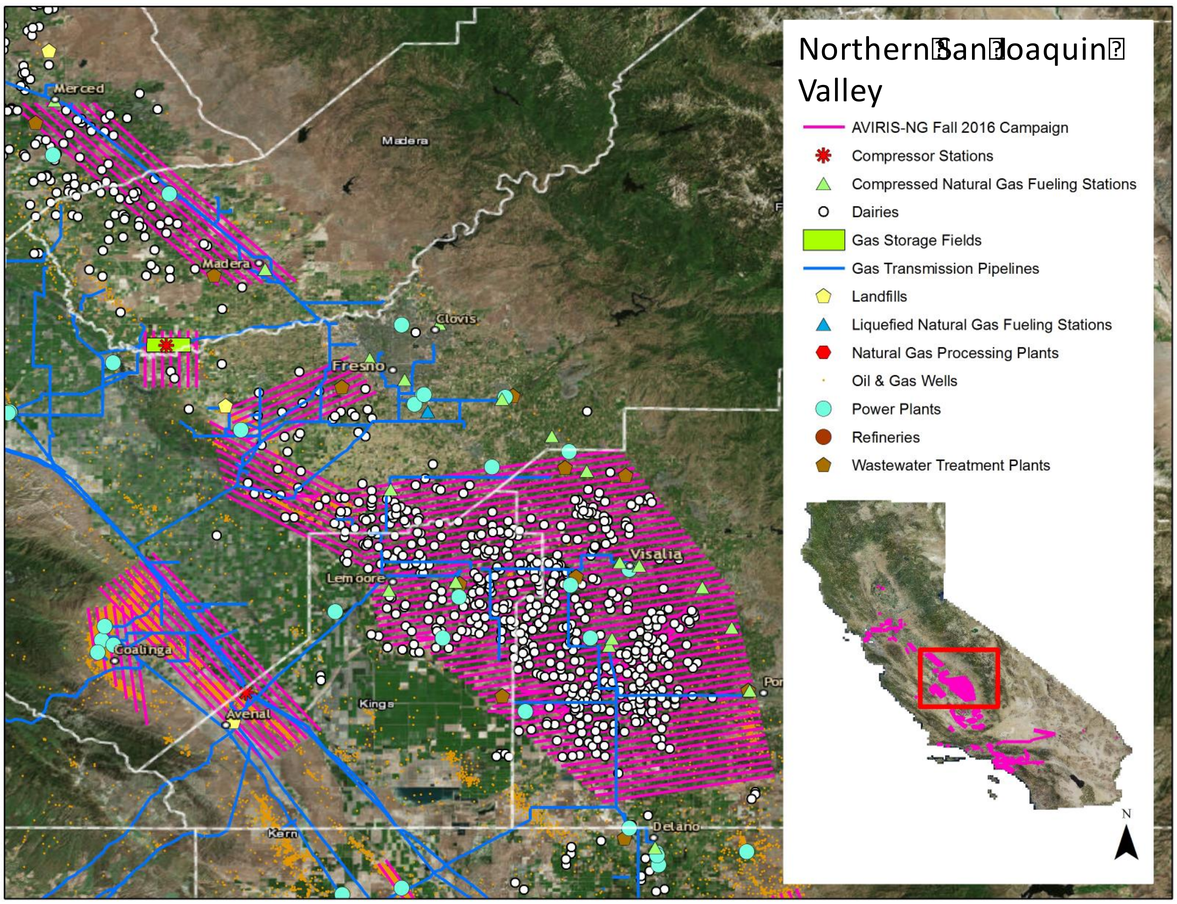


Source: JPL

A Geographic Information System (GIS) data set known as Vista-CA that maps potential methane emitting infrastructure across the State of California was developed by researchers at the University of California Riverside to assist with flight planning and for source attribution following detection of methane plumes (Duren *et al.,* 2019). The Vista-CA data set applies similar methods previously used to develop a Vista-LA methane GIS data set for the greater Los Angeles area (Carranza *et al*., 2017). Vista-CA mapped the locations of infrastructure associated with three primary sectors (energy, agriculture, and waste) following the frameworks used by the State of California's Greenhouse Gas Inventory and the IPCC Guidelines for GHG Reporting. Vista-CA contains 450,572 distinct pieces of potential methane emitting infrastructure and was used to guide selection of flight boxes (Duren *et al.,* 2019).

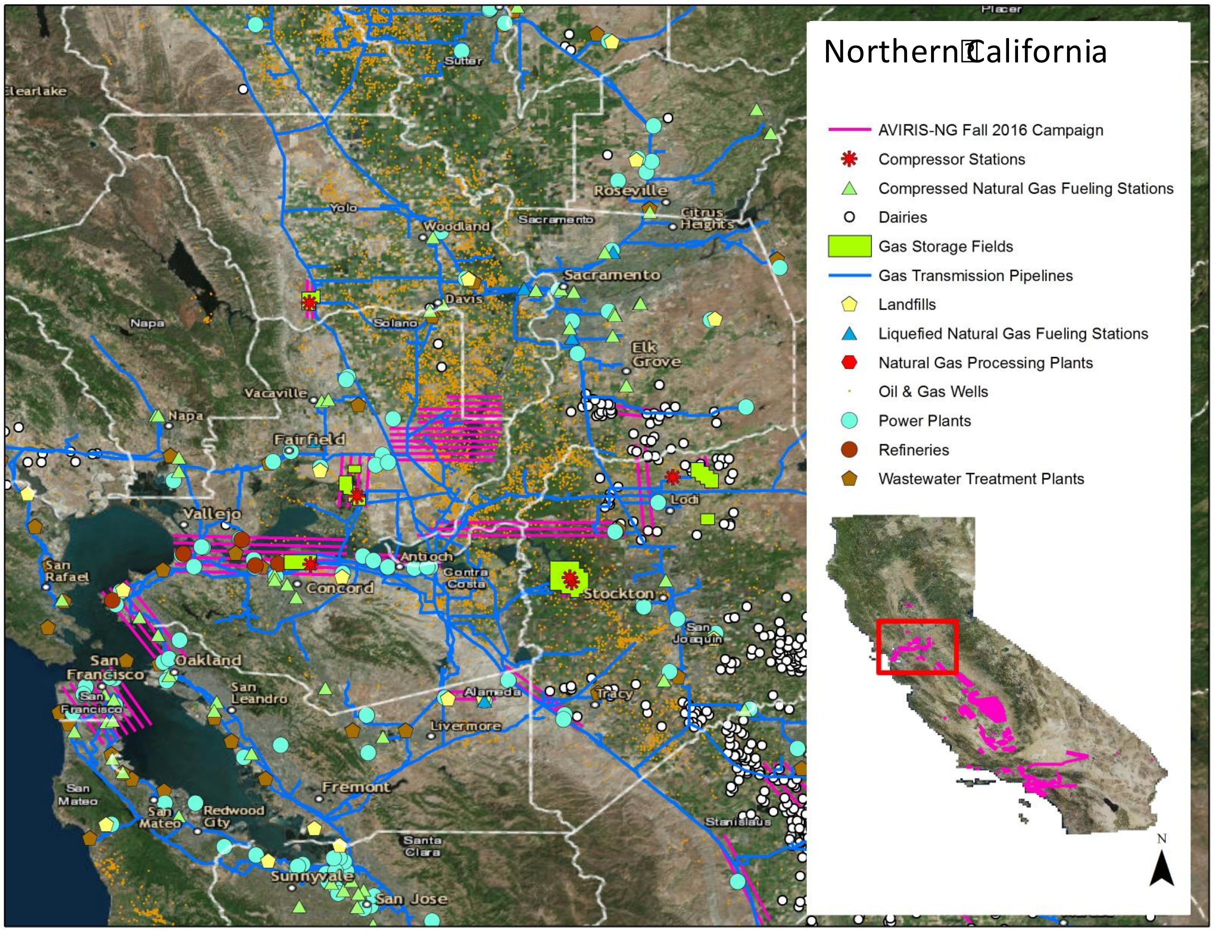
Many of the Vista-CA elements were readily derived from public data records but others were more challenging and required some new development. For example, the natural gas pipeline numbers in Vista-CA include transmission, distribution, gathering and "other" categories. The 4,599 km of gas transmission lines in California was derived from a combination of NMPS, CEC and EIA data but there is no publicly available map of distribution lines in urban areas. To address the latter gap a residential distribution line mask was constructed using parts of the California road network overlaid on raster cells classified as being 20-100 percent impervious in urban areas from the National Land Cover Dataset (NLCD; 53) and connected it to the existing NG Pipeline infrastructure using a 10km distance tolerance (Duren *et al.,* 2019). Survey coverage was computed by using the AVIRIS-NG flight path (1800m width) rectangular polygons as clip features to pull out overlapping pipelines and recalculate segment length within each AVIRIS-NG survey polygon. Oil and gas infrastructure is divided into two main categories: Production Sites (including well heads, pumpjacks, and other equipment immediately associated with extraction) and Other Production Equipment. Although the Vista-CA layers include 3,356 pieces of "other Production Equipment" such as condensate tanks and waste ponds that correlate well with satellite imagery of facility infrastructure this category should also include gathering lines for which the team had very limited information. For this reason (and that more than 80 percent of production fields in the state were surveyed) the emissions results from other production equipment are not up-scaled. Dairies are another special case given the number and magnitude of methane sources and complexity in identifying which facilities are more likely to be point source emitters (see Duren *et al.,* 2019 for details).

Figure 7: Airborne Survey Design for the Northern San Joaquin Valley



Source: JPL

Figure 8: Airborne Survey Design for Northern California

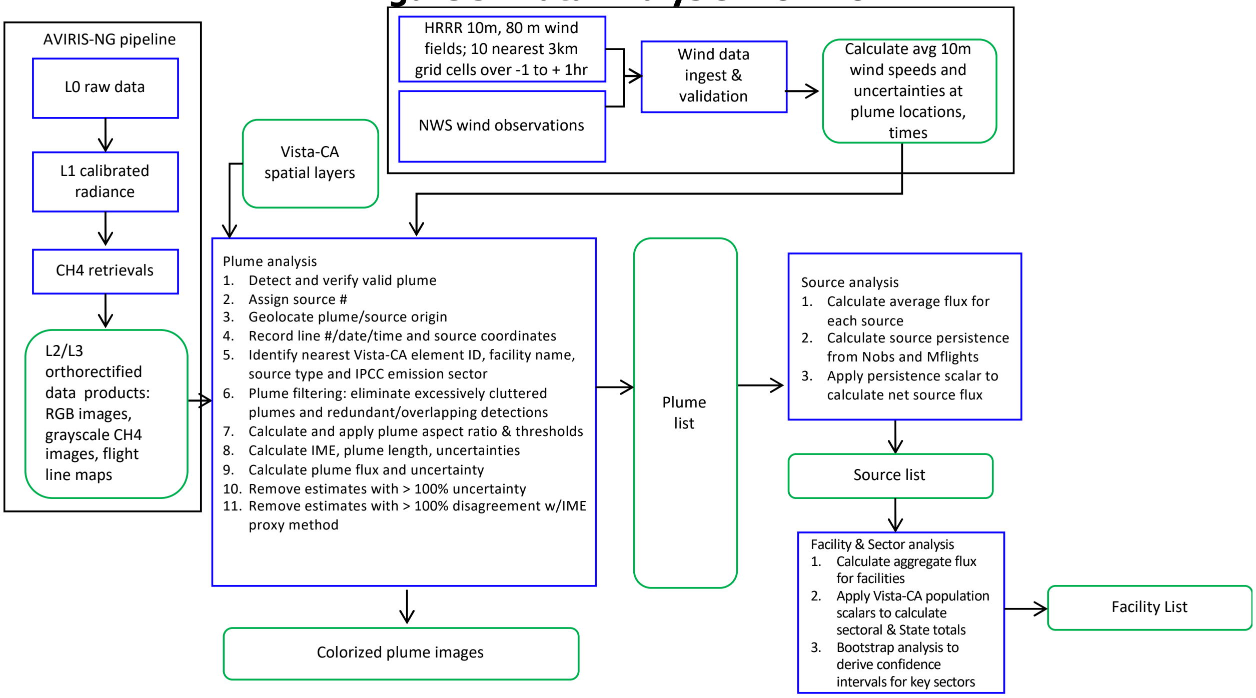


Source: JPL

Data Analysis

The analysis for this study (Figure 9) consists of a) standard processing including calibration and orthorectification of the AVIRIS-NG image cube data, b) retrieval of CH_4 column mixing ratio-lengths and generation of CH_4 plume maps, c) quality control and filtering of plumes, d) geolocation and attribution of CH_4 plumes to Vista-CA spatial layers, e) calculation of integrated methane enhancement (IME) and length for each plume, f) acquisition and processing of High Resolution Rapid Refresh (HRRR) reanalysis wind fields, g) emission flux estimation and uncertainty quantification for individual methane plumes, h) filtering and removal of plumes with sub-optimal shapes, are redundant/overlapping with others plumes or have excessive errors in IME and/or wind speed estimates, i) validating emission estimates with independent methods, j) averaging and scaling plume emission estimates with observed persistence to derive an annual net emission for each source, k) applying Vista-CA spatial layers to calculate net emission estimates for facilities and key sectors statewide, l) apply bootstrap analysis to determine confidence intervals for each sector and total population. Each of these steps is described in detail in Duren *et al*. (2019) with an overview below.

Figure 9: Data Analysis Workflow



Source: JPL

The AVIRIS-NG flights conducted during this survey detected 1,181 individual methane plumes that were each attributed to a Vista-CA infrastructure element (Tables 2 and 3). Plumes were identified manually for this study. An experimental machine learning system based on a convolutional neural network was trained on a subset of plumes from this and other field studies and then used to assess potential false positives and false negatives in the manual plume list. The observed presence or absence of a plume at each source was used to calculate its persistence (frequency of occurrence); e.g., the ratio of plume occurrences to the number of overflights of a given source. Many of the sources were highly intermittent – with a median persistence of 0.20 for the entire population (mean 0.33, range 0.02 – 1.0). The survey provided a median of nine samples per source (range 1-66) for the population, translating to a median probability of 0.75 that the persistence is at least as high as reported (mean 0.82).

Filtering criteria were used to eliminate plumes with noisy retrieval results and complex shapes from the overall emissions analysis. An integrated methane enhancement (IME) and plume length for each plume were computed using methods that build on those demonstrated in previous studies (Thompson *et al.,* 2016; Frankenberg *et al.,* 2016). Near surface wind speeds were calculated for each plume location and overflight time using NOAA's HRRR data set (3km, hourly resolution) with validation from surface weather observations. Methane emissions and uncertainties were calculated using the IME, plume length and wind speed data for every plume. Additional filtering was then applied using the aforementioned IME proxy method to calculate emissions. Plumes emission estimates that differed by > 100 percent between the two methods were eliminated from the source emissions analysis. The net result of the filtering steps left 1050 plume emission estimates for the analysis. An average emission rate was then calculated for each source using the plume emission estimates and the observed source frequency or persistence. This process resulted in emission estimates and 1sigma (σ) uncertainties for 564 sources at 230 facilities and infrastructure elements.

For most sectors, the extent of the observed methane plume was small compared to the full spatial extent of the associated facility and generally appeared in a repeatable fashion from the source to which it was attributed. For most sectors emissions for individual sources are reported, with larger facilities often including multiple sources. However, a different accounting scheme is used for landfills given the complexity of emission processes. For landfills where plumes were detected, large plumes spanning the spatial extent of the facility were observed. Additionally, in most cases the location of each landfill plume evolved significantly over time in response to daily changes in waste deposition and surface cover. The team defined each landfill with observed methane plumes as a composite source. All plume observations at a given landfill, within a single flight line, were summed to get the total facility emissions per flight line for that sample interval. This process is defined in more detail in Duren *et al.,* 2019, SI section S2.8.

CHAPTER 3: Project Results

The following caveats apply to these results:

- The remote sensing methods applied in this project were not optimized for detecting and quantifying area sources and hence methane emissions from area sources such as enteric fermentation, rice cultivation and wetlands are excluded from this study.
- With the exception of approximately 100 sources, most of the sources reported in this report have not yet been verified with surface measurements. This project was limited to remote sensing methods and was not funded to conduct follow-up surface verification.[†] This means that there are some residual uncertainties about source attribution that could result in misidentification of facilities and/or incorrect assignment of a source to a given emission sector.
- This project was also not funded to determine which sources are normal process emissions such as periodic venting as opposed to a leak or other malfunction. A few exceptions are noted where a root-cause was confirmed (through surface follow-up measurements or through consultation with a facility operator).

Airborne Survey Statistics

The actual implementation of the airborne survey was influenced by the planning activity described in Section 2, response to discovery of methane plumes (e.g., follow-up observations), and impacts due to weather and aircraft availability.

Survey Completeness

The survey covered approximately 271,556 distinct facilities and infrastructure components (out of 449,648 candidates) spanning 21,699 km^2 of land area at least once (Figure 10). A significant fraction of these flight lines were flown more than once, resulting in 54,817 km^2 total area coverage (Duren *et al.,* 2019).

[†] See https://ww2.arb.ca.gov/our-work/programs/methane/ab1496-research for CARB Methane Hotspots Research website including follow up measurements of some sources detected by this and other studies.

Figure 10: Spatial Coverage for Survey

As-flown AVIRIS-NG flight lines (cyan) showing area covered during the California Methane Survey.

Source: JPL

Compared with the Vista-CA GIS data set the survey achieved a completeness per emission sector that ranged from 32 to 100 percent (Table 2; Duren *et al.,* 2019). Note that most of the categories shown here represent facilities or other discrete infrastructure features with the exception of transmission pipelines – as linear features the latter are reported as fraction of total length. Also, for landfills the survey focused on only the likely top emitters – the 60 facilities predicted to be responsible for 90 percent of California's landfill methane emissions based on bottom-up estimates from CARB.

Table 2: Survey Completeness by Emission Sector

IPCC Emission Sector	Vista-CA Infrastructure Elements		Vista-CA Infrastructure Elements Data Sources	Number of Features Surveyed by AVIRIS (2016-2017)	Total Number of Vista-CA Infrastructure Elements	Percentage of Vista-CA Infrastructure Elements Surveyed	Percentage of IPCC Emission Sector Surveyed
1A1 Energy Sectors	Gas-fired Power Plants		CARB Inventory (2014) EIA (2016) EPA FLIGHT (2016)	238	435	54.7%	57.3%
	Refineries		CARB Inventory (2014) EIA (2016) EPA FLIGHT (2016)	26	26	100.0%	
	sub-totals			*264*	*461*		
1B2 Oil and Natural Gas	CNG Fueling Stations		AFDC (2017)	107	162	66.0%	60.4%
	LNG Fueling Stations		AFDC (2017)	25	46	54.3%	
	Natural Gas Stations (non-storage compressor, dehydration, metering, odor, etc)		CEC (2017) EPA FLIGHT (2016)	538	1,131	47.6%	
	Natural Gas Pipelines (length in km)		CEC (2012) EIA (2017) NLCD (2011) NPMS (2013) U.S. Census Bureau (2017)	68,548	216,774	31.6%	
	Natural Gas Processing Plants		EIA (2014)	23	26	88.5%	
	Natural Gas Storage Fields		DOGGR (2016) EIA (2016)	12	12	100.0%	
	Oil and Gas: Other production equipment		DOGGR (2018)	2,872	3,356	85.6%	
	Oil and Gas: Wells		DOGGR (2018)	198,231	225,766	87.8%	
	sub-totals			*270,356*	*447,273*		
3A2 Manure Management	Dairies	All dairies	CIWQS (2018) CARB (2015) RWSCB - Region 5 (2017) SJVAPCD (2017)	890	1,544	57.6%	64.5%
		CAFOs with >1000 head		443	620	71.5%	
4A1 Solid Waste Disposal Sites	Landfills	Composting Sites	CalRecycle (2015) CARB (2015) EPA FLIGHT (2016)	166	430	38.6%	38.2%
		Solid Waste Disposal Sites (landfills)	CalRecycle (2015) CARB (2015) EPA FLIGHT (2016)	270	716	37.7%	
4D1 & 4D2 Wastewater Treatment	Wastewater Treatment Plants	Domestic Wastewater treatment & discharge	CARB (2016) EPA FLIGHT (2016)	57	148	38.5%	38.5%
		Industrial Wastewater treatment & discharge	other (satellite imagery)	1	n/a	n/a	
	TOTALS			***272,447***	***451,192***	***60.4%***	

Source: Duren et al., 2019

In terms of temporal completeness the survey sampling ranged from one visit per source to multiple visits distributed over the project time span. In some cases (e.g., intensive study of dairies near Visalia and some studies of underground gas storage fields) revisit intervals as short as a few minutes were obtained over the course of a day, providing insight into diurnal variability. Most of the overflights occurred between the hours of 10 am and 3 pm local time.

Spatial, Temporal and Sectoral Distribution of Emissions

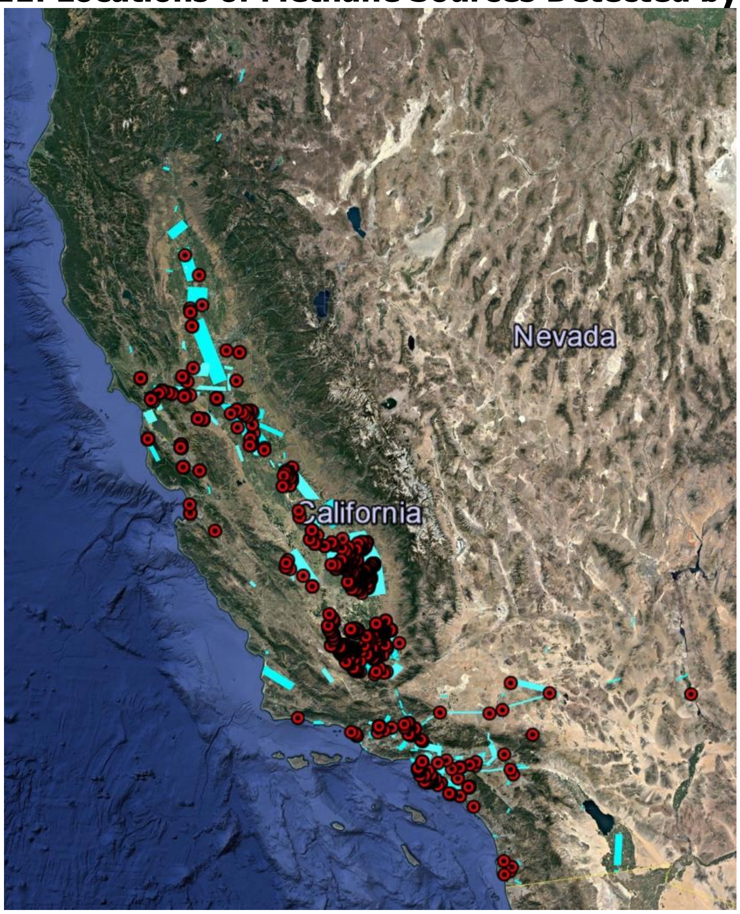
Our analysis provided emission estimates and 1sigma (σ) uncertainties for 564 sources at 230 facilities and infrastructure elements. The locations of the 564 confirmed point sources are shown in Figure 11, indicating that most of the strong point sources detected in this survey are concentrated in the southern half of the state- particularly the SoCAB and areas in the SJV with the largest concentrations of dairies and oil/gas fields. The point source population has a heavy-tail distribution indicating that 10 percent of the point sources are responsible for 60 percent of the point source emissions (Figure 12). This is generally consistent with previous studies of the US oil and gas supply chain (Alvarez *et al.,* 2018, Zavala-Araiza *et al.,* 2015, Brandt *et al.,* 2015), but here the team also observed the super-emitter behavior in every surveyed emission sector including manure management, landfills, wastewater treatment plants and refineries. The sum of the measured source emissions is 0.511 Tg CH_4/yr and a non-parametric bootstrap analysis was applied to the population of observed sources to calculate a 95 percent confidence interval of 0.433 - 0.601 Tg CH_4/yr (Duren *et al.,* 2019).

The repetitive, high spatial resolution plume imagery from the California Methane Survey allowed us to characterize point source behavior and controlling processes, particularly for sectors that have not been as well studied as the oil and gas production sector. Many of these point sources are highly intermittent. In some cases, the intermittent emissions can be explained by normal operations (e.g., periodic waste flushing at large dairies) albeit with higher than expected emission rates. In other cases, more persistent activity is apparently due to sustained venting at a small number of anaerobic digesters at dairies and wastewater treatment plants or leaking bypass valves at natural gas compressor stations. A similar distribution of source persistence/frequency (20-35 percent on average) was found and emissions in the manure management, wastewater treatment and oil and gas sectors. The methods used to estimate source persistence are described in Duren et al., 2019 SI section 2.9. However, it should be noted that this survey was primarily intended to provide completely spatial sampling rather than a comprehensive assessment of source persistence. It is recommended that future studies be designed to provide frequent and uniform temporal sampling of intermittent emissions to provide more robust statistics.

Solid waste management is the largest methane point source emission sector in California (Table 3) with persistent plumes only observed at 32 of 436 surveyed landfills and composting facilities. The imagery of landfills identified methane plumes associated with construction, gaps in intermediate cover and leaking gas capture wells – indicating a sub-population of anomalous emitters. The team did not detect a larger population of smaller methane point sources across the landfill sector, which suggests the majority of those facilities emit methane as area sources that are not detectable with this method.

Since a significant fraction (32-100 percent) of every point source emission sector in California was surveyed, the team can upscale their measurements to estimate statewide point source emissions. Table 3 gives coverage scalars for each sector derived by combining the Vista-CA infrastructure data with the AVIRIS-NG flight coverage. For most sectors the scalar is simply the number of Vista-CA elements divided by the number of elements surveyed at least once during this study – with three exceptions where additional constraints were applied to reduce or eliminate scaling. This results in 0.618 (95 percent confidence 0.523-0.725) TgCH4 yr-1, equivalent to 34 - 46 percent of the California Air Resources Board (CARB) methane inventory for 2016 (Duren *et al.,* 2019). Solid waste management contributes 41 percent of observed point source emissions followed by 26 percent from manure management and 26 percent from oil and gas (in contrast to 32 percent, 39 percent and 25 percent of total methane emissions for those sectors according to the CARB the inventory). The rest of California's methane budget is likely due to area sources such as enteric fermentation, rice cultivation and non-super-emitter landfills as well as a large number of low emission sources in the downstream natural gas supply chain that fall below the detection threshold of this survey (Ellis *et al.,* 2010, Fitzgerald *et al.,* 2000, Wennberg *et al.,* 2012). Any under-estimates in the CARB inventory (Wecht *et al.,* 2014, Turner *et al.,* 2015, Jeong *et al.,* 2014, Cui *et al.,* 2019) will reduce the relative contribution of point sources to California's total budget.

Figure 11: Locations of Methane Sources Detected by Survey

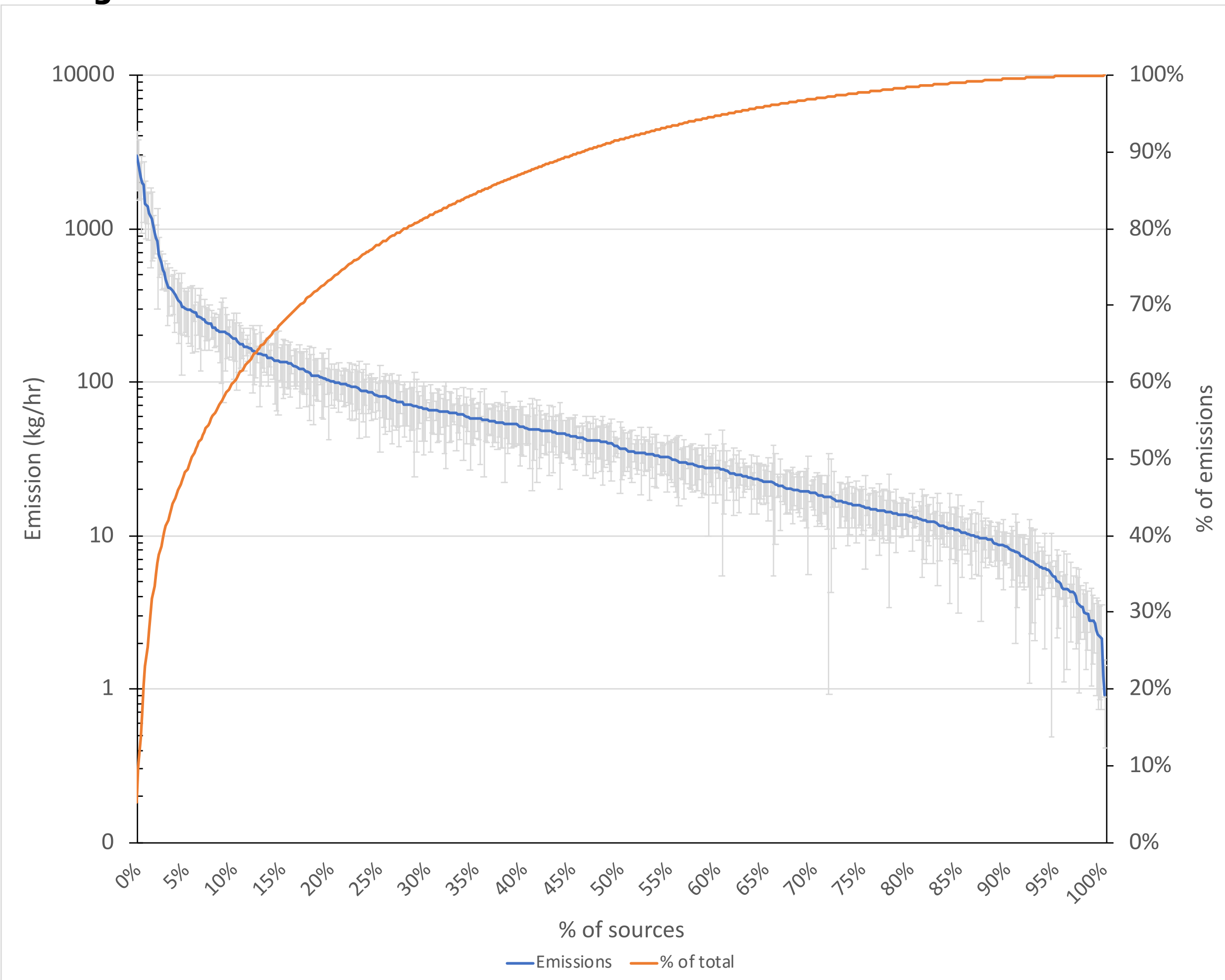


AVIRIS-NG flight lines (cyan) and methane sources (red points).

Source: JPL

The distribution of detected methane point sources by Intergovernmental Panel on Climate Change (IPCC) emission sector is summarized in Figure 13 and Table 3. This offers some insight into the potential total population of point sources in the state (e.g., fraction of sampled infrastructure where at least one methane source was detected).

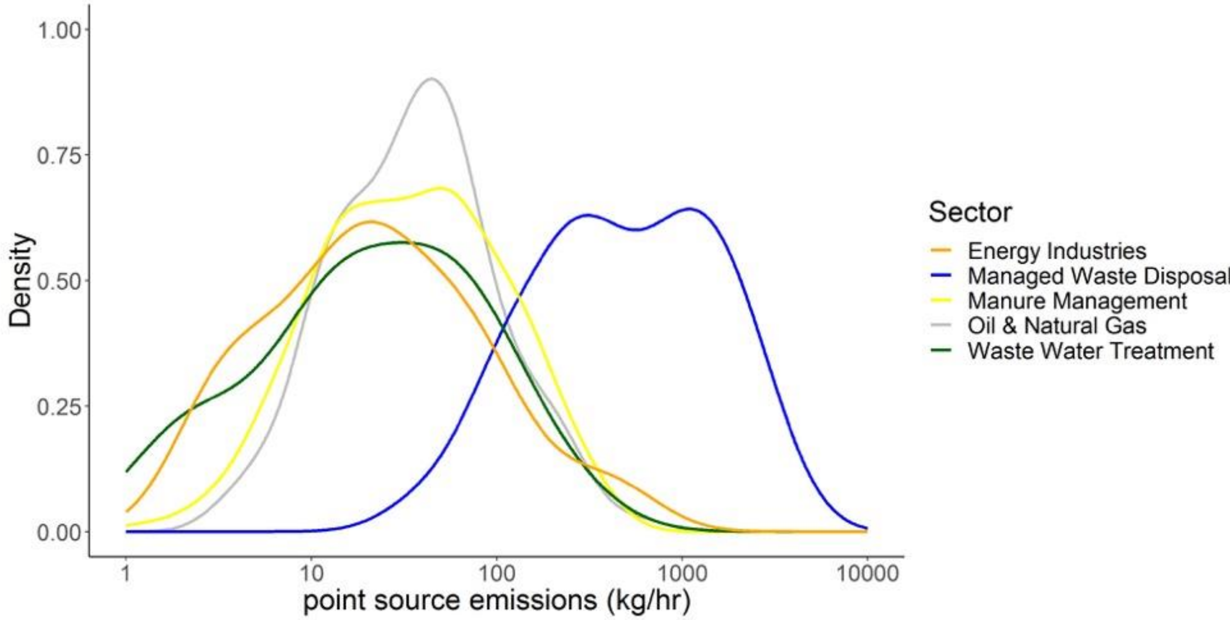
Figure 12: Distribution of Methane Emissions from Individual Sources



Distribution of average methane emissions and 1σ uncertainties for the 564 point sources detected in the survey, adjusted for source persistence (frequency) in units kgCH4/hr. The heavy tail indicates that 10 percent of detected point sources contribute 60 percent of the population total emissions.

Source: Duren *et al.,* 2019

Figure 13: Emission Histograms for Key Sectors



Histograms indicating the density of measured methane point source emissions (adjusted for persistence) for each of the key sectors in California (kgCH4/hr). Managed waste disposal exhibits qualitatively different behavior than the other sectors, with point sources only appearing at 32 persistent, high emitting landfills – likely constituting a distinct sub-population within that sector.

Source: Duren et al., 2019

Table 3: Summary of Total Emissions by Sector

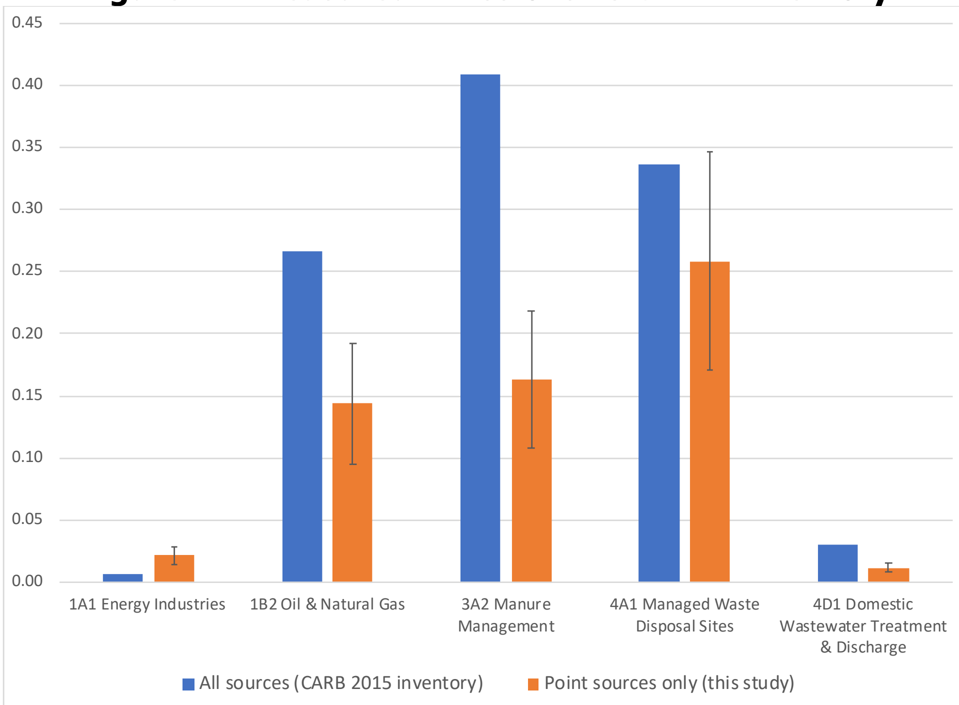
IPCC Source Category	Vista-CA infrastructure element	# of Vista-CA infrastructure elements	# of surveyed elements	% surveyed	Sectoral Scalar	N sources detected	Measured emissions (TgCH$_4$ y^{-1})	State Total Emissions (TgCH$_4$ y^{-1})	State total 95% confidence intervals (TgCH$_4$ y^{-1})	% of total emissions
1A1 Energy Industries	Gas fired power plants	435	238	55	1.83	7	0.007	0.013	0.007, 0.021	2.1%
	Refineries	26	26	100	1.00	37	0.015	0.015	0.008, 0.023	2.4%
	sub-totals	*461*	*264*	*57*	*1.27*	*44*	*0.022*	*0.028*	*0.015, 0.044*	*4.6%*
1B2 Oil and Natural Gas	CNG/LNG Fueling Stations	208	132	63	1.58	6	0.002	0.003	0.003, 0.004	0.5%
	NG Stations (non-storage compressor, metering, etc)	1,131	538	48	2.10	5	0.005	0.010	0.009, 0.012	1.6%
	NG Pipeline (transmission, distribution)	216,774	68,548	32	3.16	5	0.004	0.012	0.010, 0.014	1.9%
	NG Processing Plants	26	23	88	1.13	5	0.004	0.004	0.004, 0.005	0.7%
	NG Storage Fields	12	12	100	1.00	11	0.009	0.009	0.008, 0.010	1.4%
	Oil & Gas: Wells	225,766	198,231	88	1.14	107	0.048	0.054	0.046, 0.063	8.8%
	Oil & Gas: Other Production Equipment	3,356	2,872	86	1.00	120	0.066	0.066	0.056, 0.076	10.7%

IPCC Source Category	Vista-CA infrastructure element	# of Vista-CA infrastructure elements	# of surveyed elements	% surveyed	Sectoral Scalar	N sources detected	Measured emissions ($TgCH_4\ y^{-1}$)	State Total Emissions ($TgCH_4\ y^{-1}$)	State total 95% confidence intervals ($TgCH_4\ y^{-1}$)	% of total emissions
	sub-totals	*447,273*	*270,356*	*60*	*1.16*	*259*	*0.137*	*0.158*	*0.135, 0.184*	*25.6%*
3A2 Manure Management	Dairy Confined Animal Feeding Operations	620	443	71	1.40	215	0.115	0.161	0.137, 0.187	26.1%
4A1 Managed Waste Disposal	Landfills & composting facilities	1,146	436	38	1.11	32	0.229	0.255	0.175, 0.345	41.3%
4D1, 4D2 Wastewater Treatment & Discharge	Domestic & industrial wastewater treatment	148	57	39	2.60	12	0.004	0.012	0.005, 0.020	1.9%
	Industrial wastewater treatment: beef processing	n/a	n/a	n/a	1.00	2	0.004	0.004	0.004, 0.005	0.6%
	Totals	*449,648*	*271,556*	*60*	*1.21*	*564*	*0.511*	*0.618*	*0.523, 0.725*	*100.0 %*

Summary of persistence (frequency) adjusted point source emissions by IPCC sector from this study and estimated total emissions derived with population scalars. Most of the scalars are simply the ratio of the number Vista-CA infrastructure elements to the number of surveyed elements with three exceptions highlighted in blue font (other oil and gas production equipment, landfills and industrial wastewater treatment) where scaling is further constrained or eliminated.

Source: Duren *et al.,* 2019

Figure 14: Measured Emissions vs CARB Inventory



Comparing statewide methane point source emission estimates from this study and the relevant sectors in the 2016 CARB inventory that are likely to include point sources (11). The whiskers indicate the 95 percent confidence intervals from this study.

Source: Duren et al., 2019

The following sections provide additional findings for methane point source emission sector.

Sector Specific Findings

Oil and Gas Production and Processing

Approximately 79 percent of the oil and gas sector emissions in the study are attributed to production in California. Spatially, 85 percent of point source emissions from production are concentrated in the southern San Joaquin Valley (the highest oil- and associated-gas producing region in the State), 14 percent in Los Angeles and Ventura counties, and 1 percent in the Sacramento Valley. There is no compelling evidence of strong methane emissions from abandoned oil or gas wells or specific to fracking operations although more detailed analysis is recommended to confirm that.

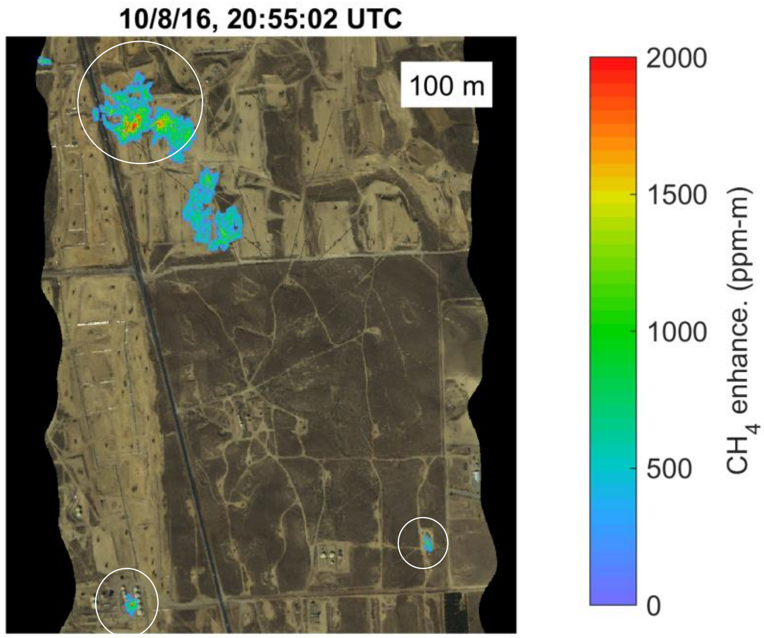
The Vista-CA "Oil and Gas: Wells" category (Table 2) includes active well heads, pumpjacks, and other equipment immediately associated with extraction and also inactive wells. "Oil and Gas: Other Production Equipment" is derived the "California Statewide Oil and Gas Production or Injection Facility Boundary" data set from DOGGR https://maps.conservation.ca.gov/doggr/metadata/FacilityBoundaries.html. To the team's knowledge that is the best publicly available database on locations of oil and gas production infrastructure in California that may emit methane including permanent tanks, flowlines, headers, gathering lines, wellheads, heater treaters, pumps, valves, compressors, injection equipment, production safety systems, separators, manifolds, and pipelines. However, that database does not likely cover all such equipment statewide, and also excludes production equipment known to emit methane, such as separators, water tanks, acid gas removal units, and dehydrators. The team had limited information about the spatial distribution of some components such as gathering lines. For these reasons, and the fact that more than 80 percent of production fields in the state were surveyed, no attempt was made to upscale the emissions results from other production equipment.

Production-normalized emissions for the largest associated-gas producing ‡ oil and gas fields in the SJV covered by this survey were estimated by dividing the net methane emission estimates for each facility by reported gas production numbers (DOGGR 2016), using a methane content for associated gas derived from composition measurements (USGS 2007). For 15 of the top associated gas producing fields in the SJV the team found a mean production-normalized emission rate of 4.2 percent (range 1.5 – 82.9 percent, Table 4). Recall that the plume imagery only detects point sources greater than the detection limit, so these estimates for those fields are likely conservative. Fields with lower production tend to have higher production-normalized emission rates. For the fields in Table 4 the seven with lowest gas production are responsible for 2 percent of the associated gas but 41 percent of the methane point source emissions. Both of these findings are in good agreement with another recent study that modeled oil and gas production emissions across the US using sparse measurements from major oil and gas basins, predicting higher production-normalized emissions from lower producing fields and a production-normalized emissions rate of 4.8 percent for gas production in the SJV that is significantly higher than the 1.5 percent mean rate for the entire US (Omara *et al.,* 2018).

The prevalence of methane plumes varies significantly by oil and gas field. The Poso Creek and Kern Front fields exhibited some of the highest density of methane plumes in the state – both dramatically higher than other nearby oil fields such as Kern River and Round Mountain (Figure 17). There is no apparently correlation with oil and gas produc-tion in this case. All of these fields are relatively low gas producers whereas Kern River produced nearly six times as much oil in October 2016 as each of the other three fields. A recently released whitepaper based on an independent airborne study of the same three oil fields reported a similar spatial distribution of methane sources (Jones et al., 2020).

‡ This refers to associated gas production as reported by DOGGR, not oil production.

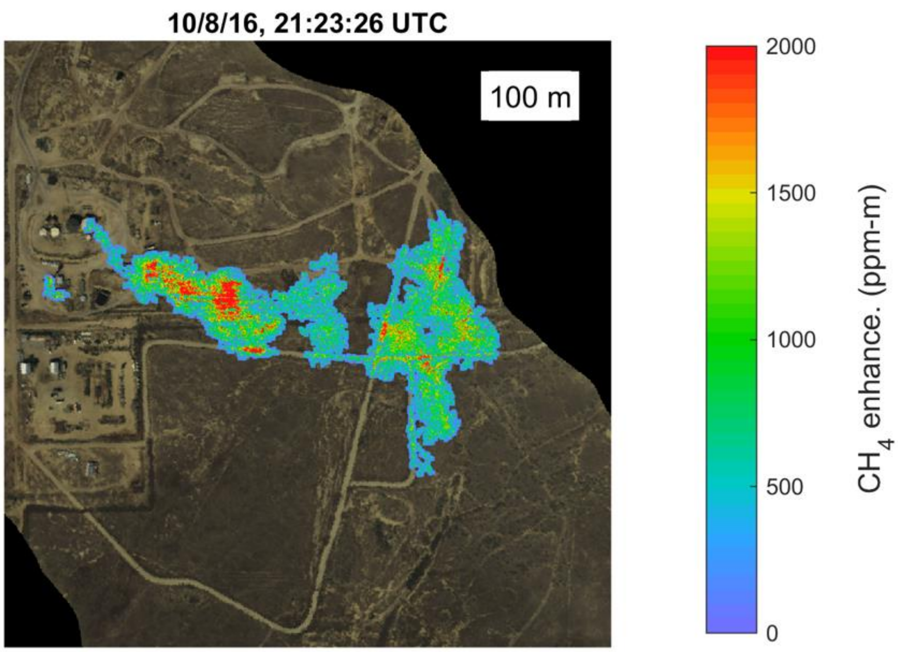
Figure 15: Typical Methane Plumes in SJV Oil and Gas Fields



Commonly observed methane point sources in oil and gas fields include storage tanks, well heads and (potentially) gathering lines. Example shown is in Kern Front.

Source: JPL

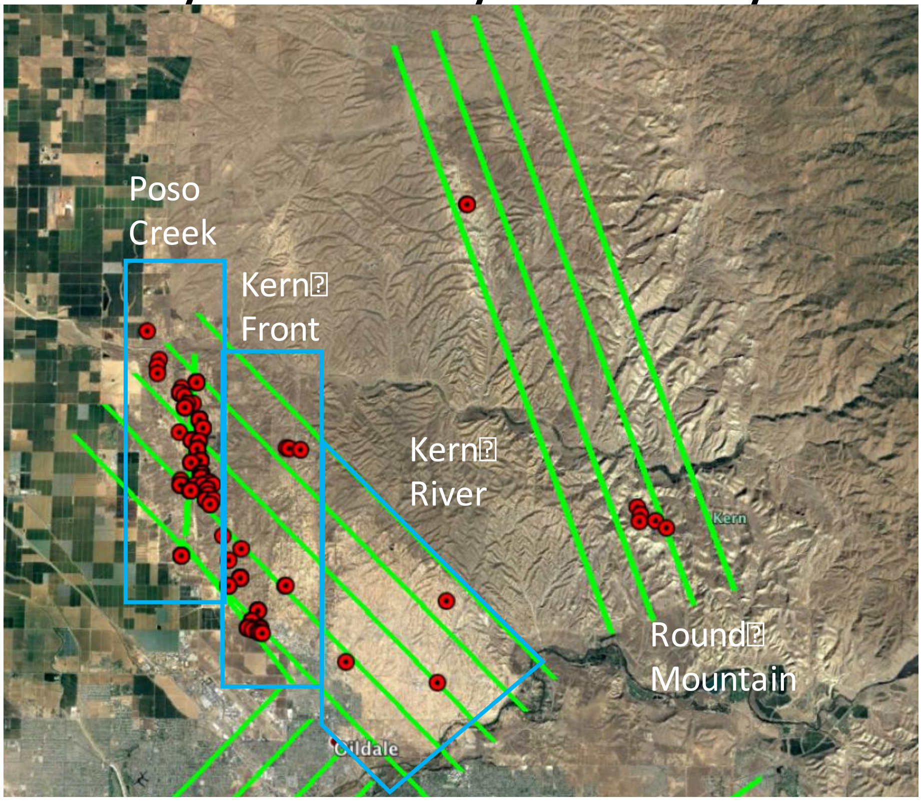
Figure 16: Closeup of a Methane Plume from a Condensate Storage Tank



Example of a typical storage tank (from Kern Front oil field). This plume was consistently through at least September 2017 after initial detection from NASA airborne campaigns since 2014, suggesting a mechanism other than normal intermittent pressure relief valve actuation.

Source: JPL

Figure 17: Variability in Source Density Between Nearby Oil and Gas Fields



Significantly higher densities of methane sources (red markers) were observed in Poso Creek and Kern Front oil fields than others in eastern Kern County.

Source: JPL

Table 4: Production-Normalized Emission Rates for Associated Gas Producing Fields in the SJV

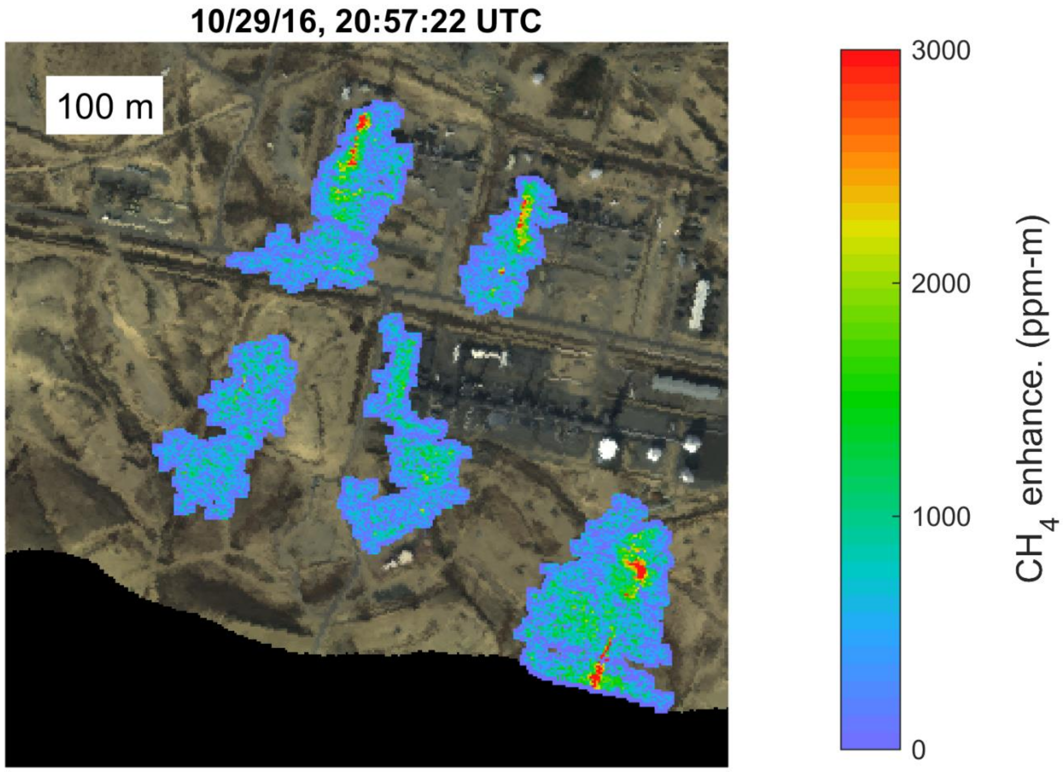
facility	2015 Net Gas Production (BCF)	Total methane production TgCH4/yr	Methane production kgCH4/hr	Methane emissions kgCH4/hr	production normalized emission rate	CH4 mole fraction of associated gas
Field 1	56.2	0.9142	104360	1569	1.5%	0.86
Field 2	13.3	0.1975	22543	88	0.4%	0.79
Field 3	10.3	0.1714	19571	294	1.5%	0.88
Field 4	8.1	0.1046	11937	485	3.9%	0.68
Field 5	4.5	0.0698	7968	341	4.1%	0.82
Field 6	4.5	0.0749	8551	1446	14.5%	0.88
Field 7	4.0	0.0605	6910	200	2.8%	0.80
Field 8	2.8	0.0466	5320	570	9.7%	0.88
Field 10	0.8	0.0126	1442	1302	47.4%	0.88
Field 9	0.7	0.0113	1294	202	13.5%	0.80
Field 11	0.36	0.0054	621	578	48.2%	0.79
Field 12	0.27	0.0040	455	283	38.3%	0.79
Field 13	0.26	0.0040	461	312	40.4%	0.83
Field 14	0.15	0.0024	273	450	62.2%	0.86
Field 15	0.12	0.0019	221	202	47.7%	0.84
		totals	*191926*	*8321*	*4.2%*	0.83
	totals for fields producing < 1 BCF		*4767*	*3328*	*41.1%*	

Estimated leakage rates for the largest associated gas producing fields in the southern San Joaquin Valley. The equivalent average methane production is derived from 2016 reported annual production in billion cubic feet or BCF (DOGGR 2016) and CH4 mole fraction measurements from another study (USGS 2007). The 7 lowest producing fields in this table are responsible for 2 percent of associated gas production and 41 percent of methane emissions.

Source: JPL

Some facilities such as the sour gas production plant and gas injection facility in Elk Hills oil field presented unique combinations of methane plumes associated with compressor operation and flaring stacks (Figure 18).

Figure 18: Gas Processing Facility in Elk Hills



Gas processing facility in Elk Hills showing methane plumes from two of three large compressors (top) and one or more flaring stacks (bottom). These are all highly intermittent sources.

Source: JPL

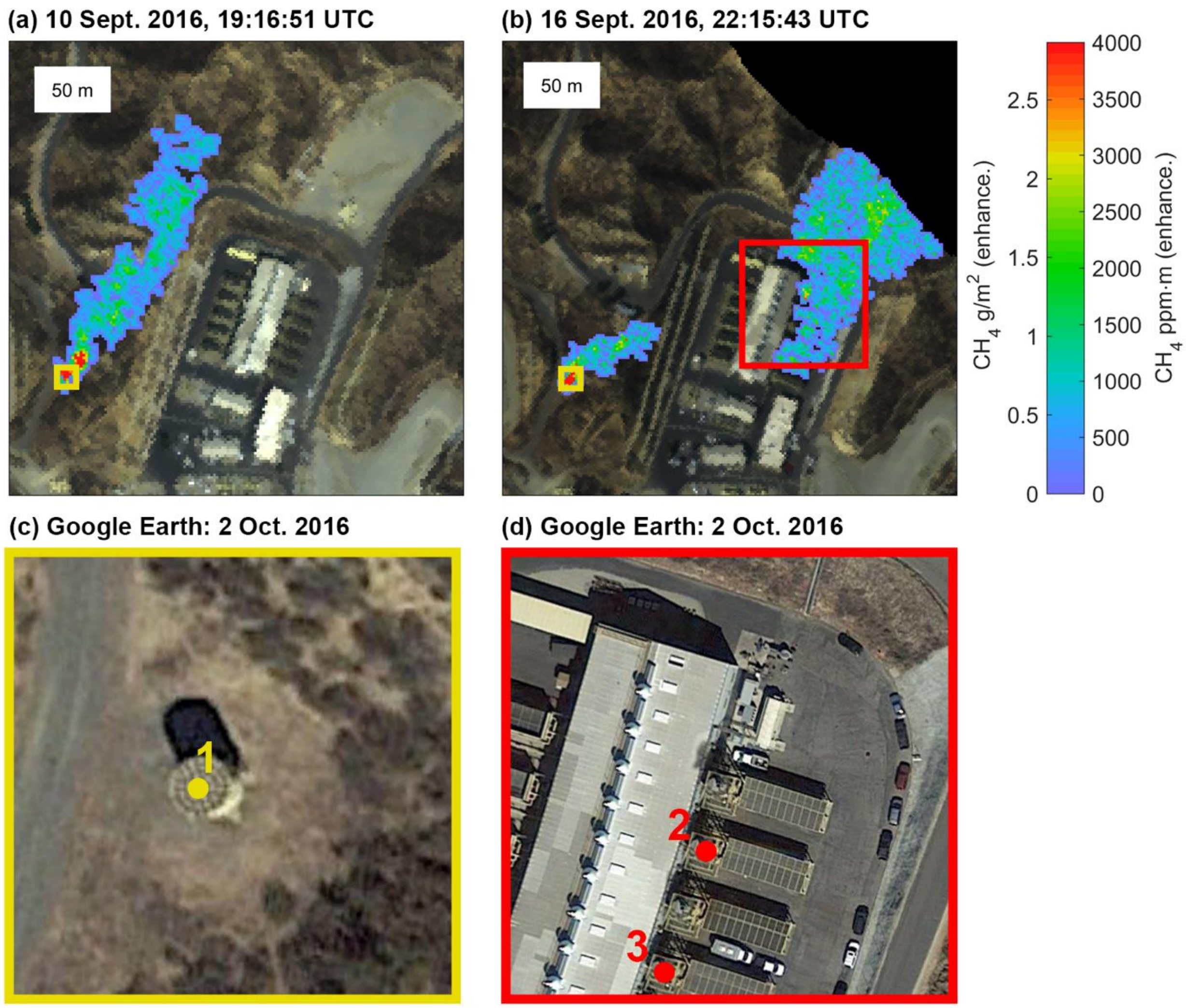
Natural Gas Transmission, Storage and Distribution

- The team estimated that 4.9 percent of the point source emissions observed in this study can be attributed to these sectors (1.9 percent for transmission and distribution pipelines, 1.4 percent for storage and 1.6 percent for non-storage gas stations). The Vista-CA data set used for source attribution for this study derived spatial maps of gas transmission lines in California from a combination of NMPS, CEC and EIA data. However, there is no publicly available map of distribution lines in urban areas. To address this issue the team constructed a residential distribution line mask using parts of the California road network overlaid on raster cells classified as being 20-100 percent impervious in urban areas from the National Land Cover Dataset and connected it to the existing NG Pipeline infrastructure using a 10km distance tolerance (Duren *et al.,* 2019). "Natural Gas Stations" in Table 2 include 158 non-storage compressor stations as well as dehydration stations, metering stations, odor stations, pressure limiting stations, regulation stations, storage stations, taps, and valves; 48 percent of these natural gas stations were surveyed.
- Approximately 32 percent of transmission and distribution pipelines in the state were surveyed at least once. For the transmission sector a small number of plumes were observed at compressor stations including at least one persistent source at a shutdown

stack (suggesting a possible leaking bypass valve). No leaks in transmission pipelines were observed.

All of California's 12 active underground gas storage facilities were surveyed multiple times (Thorpe et al 2019). Some were surveyed extensively, particularly Honor Rancho (Figure 19), Aliso Canyon (Figure 20) and MacDonald Island (Figure 21c, d).

Figure 19: Multiple Emission Sources at Honor Rancho Storage Facility



Attribution of multiple methane emission sources detected at Honor Rancho gas storage facility. (a) AVIRIS-NG result shows a persistent methane plume for source 1 (yellow box in (a) and (b)). (b) Source 2 and/or source 3 appeared intermittently (red box). (c) Close-up of source 1 with high-resolution satellite imagery (Google Earth). The facility operator confirmed that source 1 is the facility's emergency shut down stack – likely due to a leaking isolation valve. (d) Close-up of sources 2 and 3 - likely from the rod pack vents for reciprocating compressor units 2 and 4.

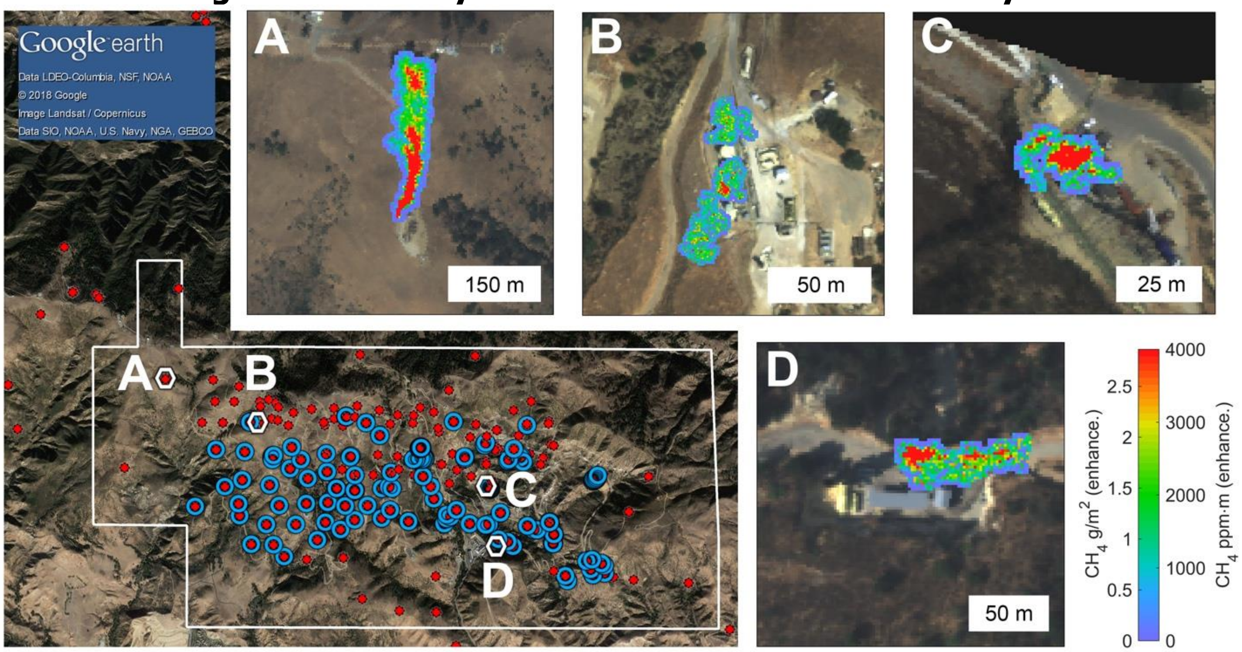
Source: Thorpe *et al,* 2019

In 2016, Aliso Canyon was in a standby state and no obvious plumes were present. In August 2017 injection operations resumed at Aliso Canyon and plumes were regularly observed at the compressor station's shutdown stack in addition to intermittent plumes observed at other infrastructure in the area that are most likely associated with oil production rather than gas storage operations (Figure 20).

Honor Rancho presented a persistent methane plume at an emergency shutdown stack, due to a leaking isolation valve (Figure 19a, c). The operator confirmed this mechanism and subsequently mitigated it. An intermittent source was also observed from the compressor units – likely from the rod pack vents for one or two reciprocating compressors when those units were operated (Figure 19b, d).

MacDonald Island presented relatively large plumes on multiple occasions associated with venting from shutdown stacks and one compressor (Figure 20 c, d). Plumes were also observed at Gill Ranch (Figure 20a, venting from shutdown stack), Lodi (Figure 20b, likely dehydrator venting, Kirby Hills (Figure 20, venting from shutdown stack) and Wild Goose (Figure 20f, compressor loss).

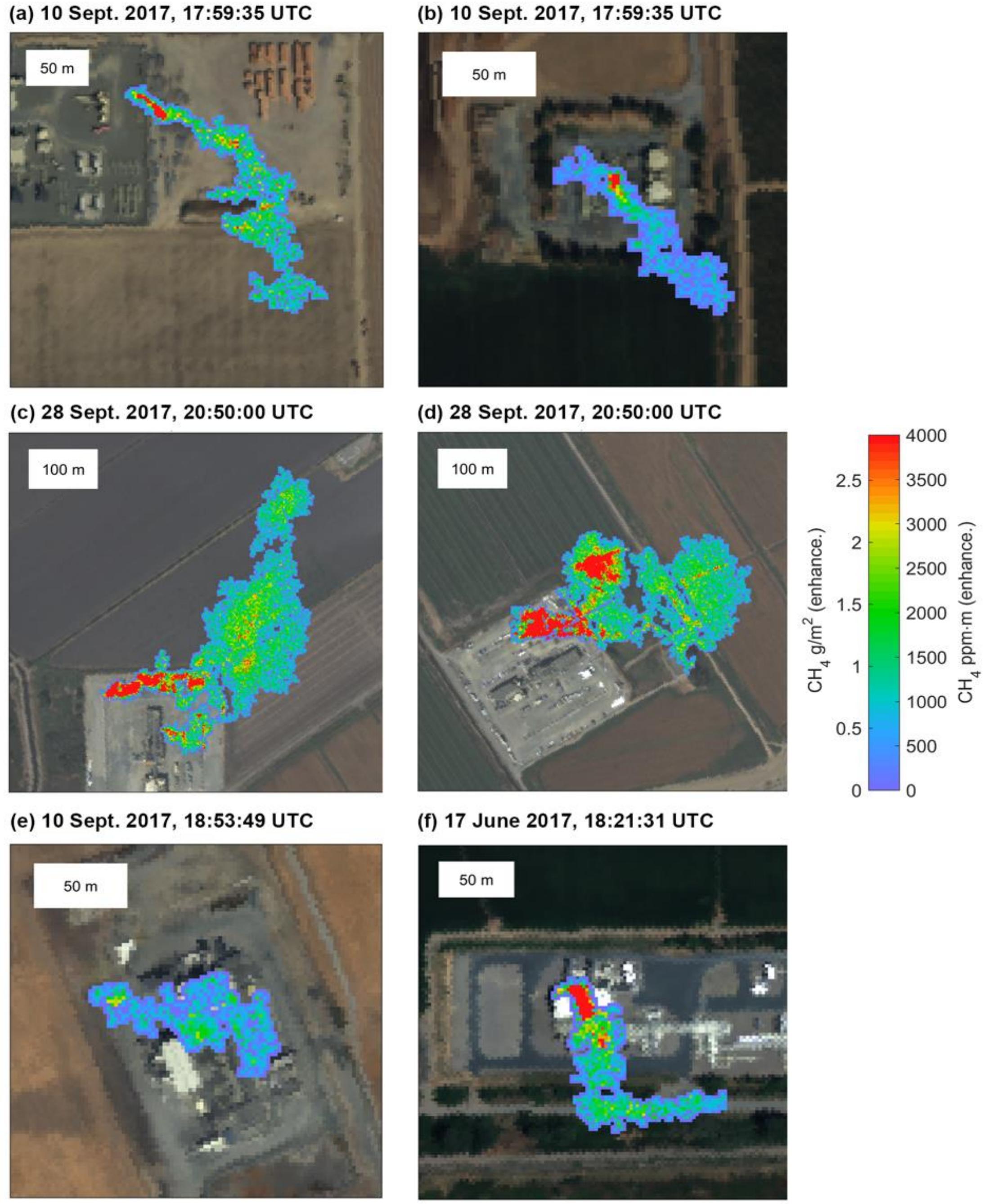
Figure 20: Variety of Emission Sources at Aliso Canyon



Characterizing methane emissions from diverse activities in Aliso Canyon. Aliso Canyon field spans roughly 14 km^2 and DOGGR records indicate 251 wells (red dots) - 115 of which are linked to the deeper gas storage reservoir (blue circles) and the rest connected to shallower oil-producing formation (combination of active, idle and plugged wells). Subpanels (a) through (d) indicate methane plumes observed with AVIRIS-NG overlaid on true color imagery that correspond to the locations shown in the map of the Aliso Canyon field from a pumpjack (a), tank (b), drill rig (c), and blowdown stack at the storage facility's compressor station (d).

Source: Thorpe *et al.,* 2019

Figure 21: Examples of Different Emission Modes at Gas Storage Facilities



(a) Gill Ranch venting from shutdown stack, (b) Lodi –likely dehydrator venting, (c) and (d) McDonald Island south and north platforms - venting from shutdown stacks and one compressor, (e) Kirby Hills – venting from shutdown stack, (f) Wild Goose compressor loss.

Source: Thorpe *et al.,* 2019

California's natural gas distribution infrastructure spans several large urban areas. Four leaks in distribution lines were detected (two each in the LA basin and Bakersfield area) and shared the data with the gas company to guide repairs. In each case follow-up AVIRIS-NG flights verified the repairs were successful.

Figure 22: Detection of Leak in Low Pressure Gas Distribution Line

Example of gas leak detection and repair in Chino Hills. Left: AVIRIS-NG flight pattern, middle: real-time detection software on airplane, right: processed methane plume image and geolocation of source to within 10 meters.

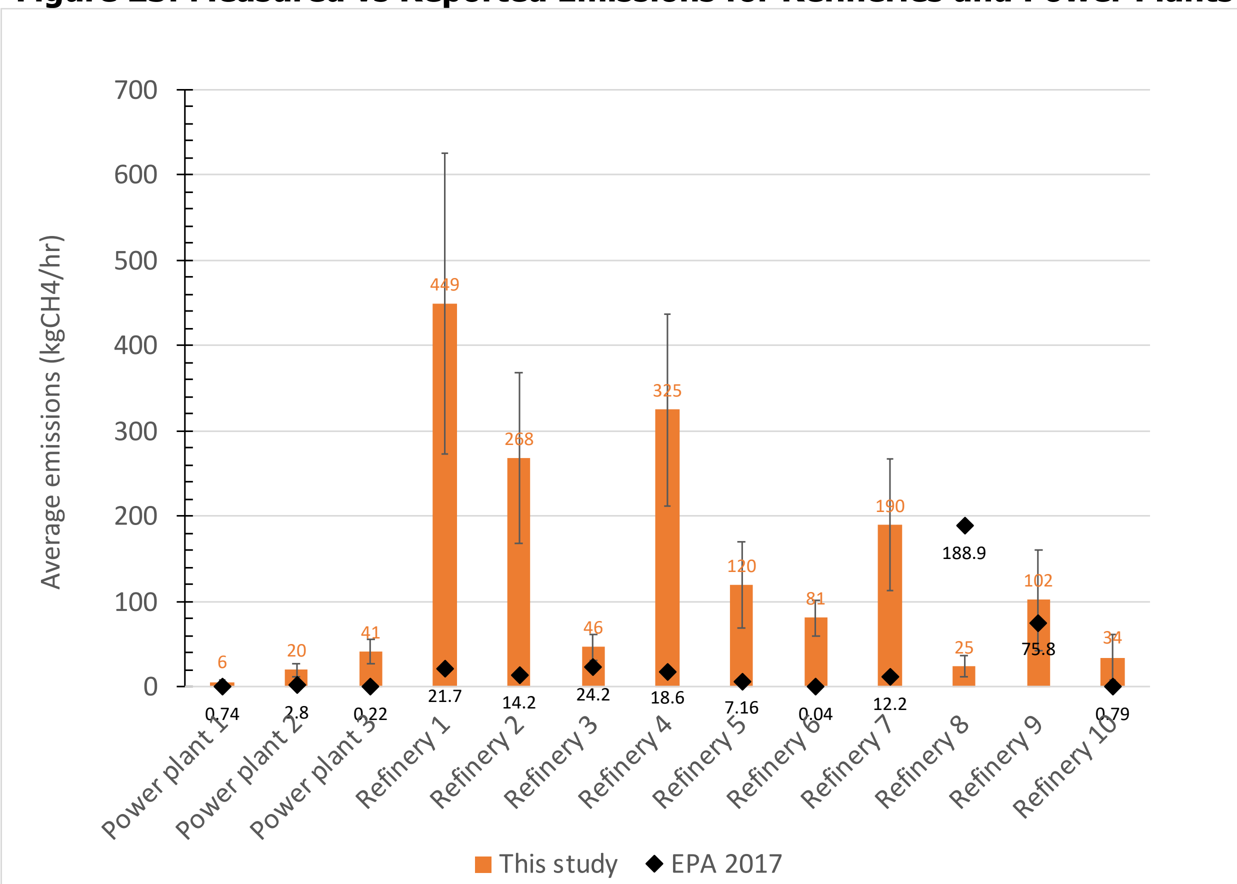
Source: JPL, see https://photojournal.jpl.nasa.gov/catalog/PIA22467

Figure 22 illustrates the AVIRIS-NG search pattern covering a 60 km^2 area in 30 minutes, real-time detection with the onboard software, and determination of the source location to within 10 meters. The gas company was notified and dispatched technicians to the site who promptly confirmed and repaired the leak.

Refineries

Methane emissions from the Energy Industries sector in California are significantly higher than reported by the CARB inventory (Fig. 14) and appear to be strongly influenced by refineries although this sector is only responsible for 2.4 percent of the estimated total for statewide point source emissions. This was attributed to intermittent strong sources that translate to average emissions that with one exception are significantly higher than reported to the EPA (Fig.23). Strong methane plumes were observed at nearly every refinery sampled in this study. There appears to be a diverse set of sources at refineries, ranging from storage tanks (either venting from relief valves or leaks) to unknown sources (Figure 24).

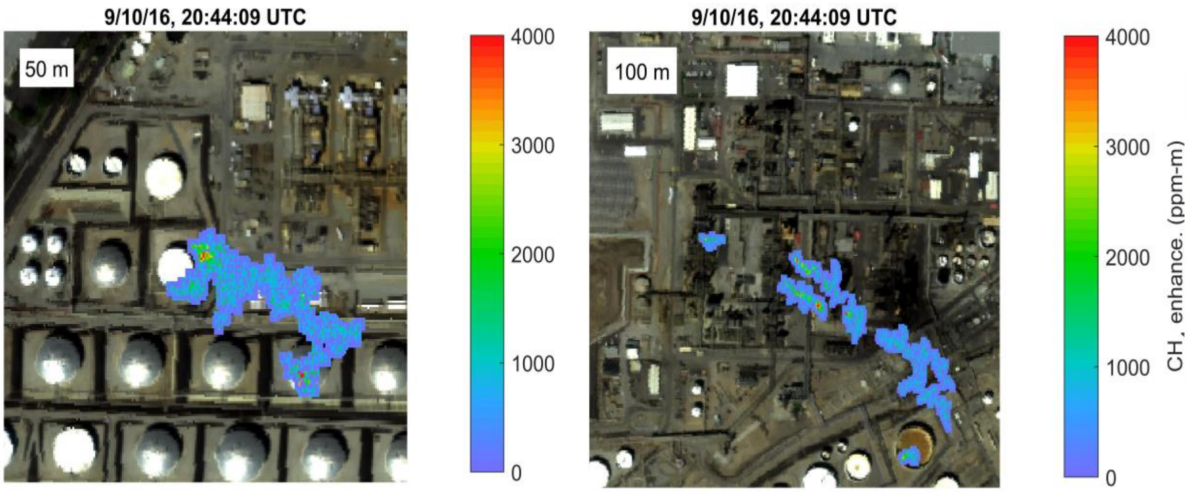
Figure 23: Measured vs Reported Emissions for Refineries and Power Plants



Comparing hourly average emissions derived from annual total emissions in EPA's Greenhouse Gas Reporting Program (GHGRP) for facilities participating in that program in 2017 (EPA 2018) with persistence adjusted average emission estimates from this study for facilities with at least 6 overflights. With two exceptions the GHGRP emissions are significantly lower than observed by AVIRIS-NG.

Source: Duren *et al.,* 2019

Figure 24: Examples of Methane Plumes from Refineries in the LA Basin



(Left) venting or leaking storage tanks, (Right) methane from combustion sources.

Source: JPL

Power Plants

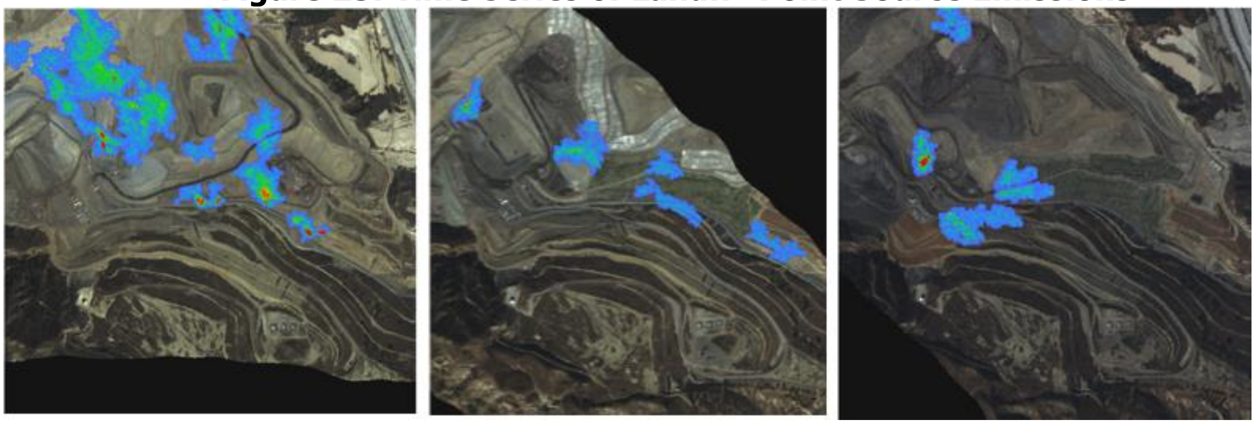
The team surveyed 238 natural gas-fired power plants in the state – an estimated 55 percent of all such facilities – including an intensive campaign during a heat wave in Los Angeles to assess the potential for additional fugitives during peak demand periods. Plumes at only seven such facilities were observed. While some of the observed emissions are larger than those reported to the EPA (Figure 23), the team concluded that this is not a major methane emitting sector for California – collectively responsible for about 2.1 percent of total emissions from the population of point sources. The research team acknowledges the possibility that a few cogeneration facilities located within the oil and gas fields currently attributed to the oil and gas sector may be appropriately classified under the power generation sector. However, study results would not significantly change were this reclassification made.

Landfills

To prioritize flight hours for this sector, CARB's database of landfill methane emissions and the Vista-CA data set were used to identify 436 likely highest emitters, collectively predicted to contribute 90 percent of managed waste disposal emissions in California. The observed point sources at 30 landfills and two composting facilities include some of the largest outliers in the overall source population and collectively are the highest emitting point source sector in California – representing about 43 percent of the total (Figure 14). The high-resolution images suggest that some of the strong methane plumes at these landfills may be associated with gaps in intermediate cover, delays in construction projects and/or leaking gas capture wells – all indicating a significant mitigation opportunity; however follow up study is recommended to confirm this. Figure 25 provides an example of a reduction in the number and size of methane point source plumes over time at a large landfill in Southern California due to mitigation efforts from the operator that were in part informed by the data from this study (Cusworth *et al.*, 2020).

The varying degrees of agreement and disagreement between our measurements and bottom-up accounting for the landfills illustrated in Figure 26 is representative of the total population of landfills that exhibit point sources. The fact that the team did not detect a larger population of smaller methane point sources across the landfill sector suggests the majority of those facilities emit methane as area sources and/or point sources below the detection limit. They concluded that the landfills exhibiting point sources in California are a unique sub-population.

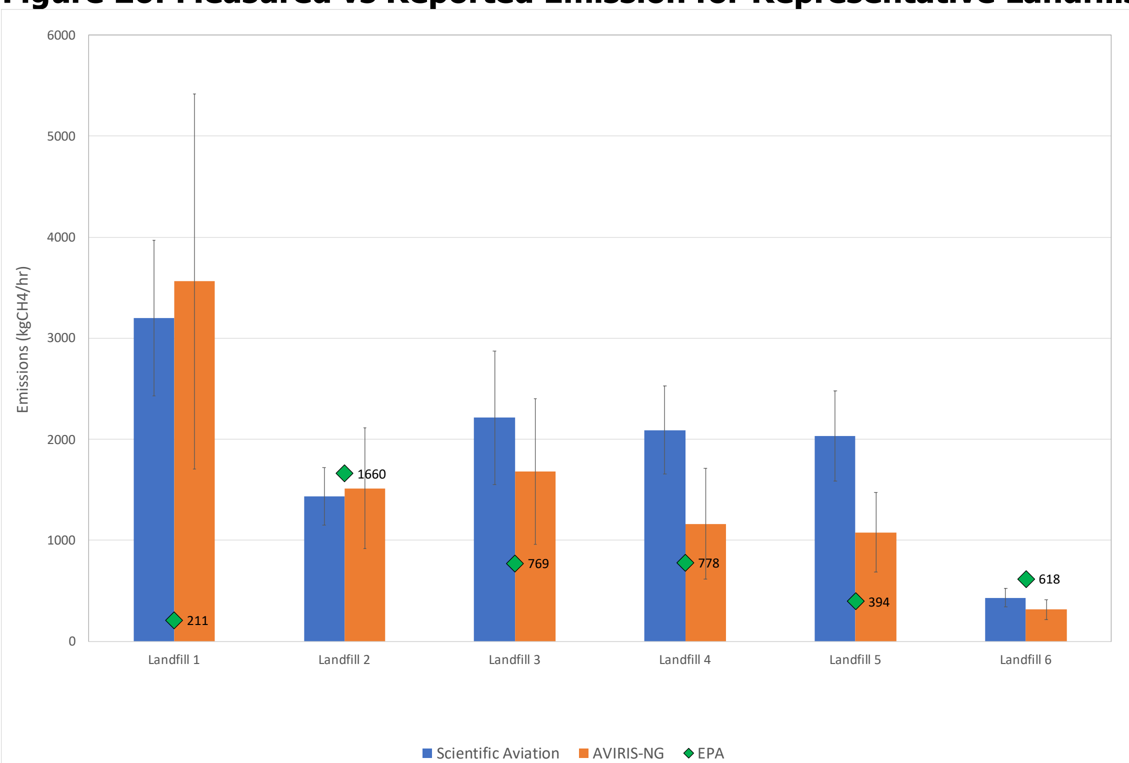
Figure 25: Time Series of Landfill Point Source Emissions



Example of tracking trends in methane point source emissions over time at a large landfill in southern California. Left: September 2016, Center: October 2017, Right: October 2018.

Source: JPL

Figure 26: Measured vs Reported Emission for Representative Landfills



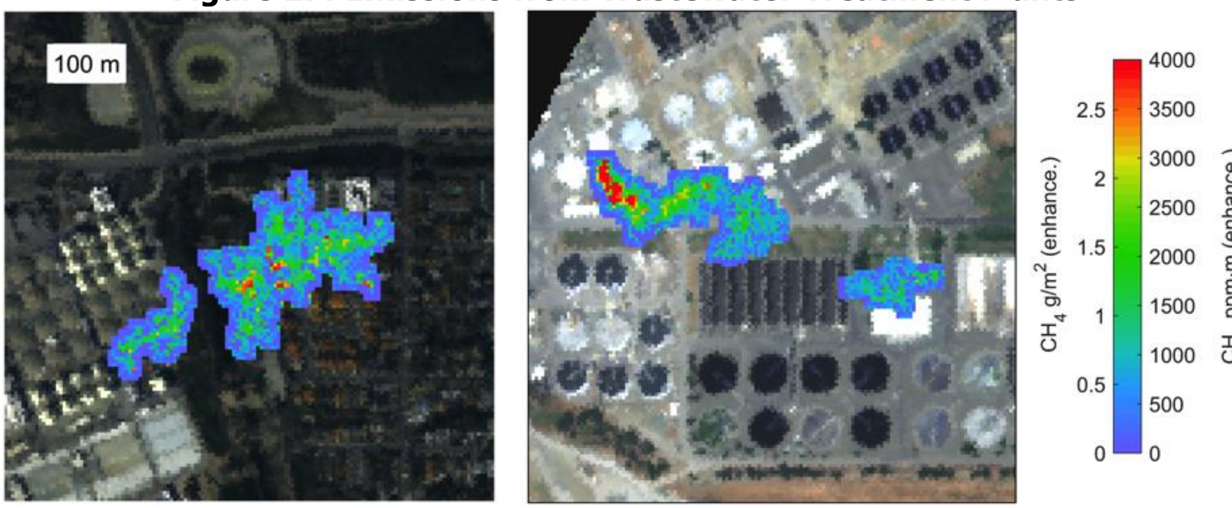
Comparing landfill emissions reported to the EPA for 2017 (EPA 2018) with persistence adjusted average emission estimates from this study and mean values from a series of coordinated Scientific Aviation flights (CARB 2018b) – the last 4 of which were not contemporaneous with AVIRIS-NG flights. Since Scientific Aviation measures the net facility emissions (area + point sources) and AVIRIS-NG only measures point sources, the latter will be lower than the former in many cases

Source: Duren *et al.,* 2019

Wastewater Treatment

We estimate that this sector is responsible for about 2.6 percent of total methane point source emissions in California. A total of 57 domestic wastewater treatment facilities were surveyed. Only 12 exhibited methane point source plumes - three of which were persistent, suggesting potentially anomalous activity (see Figure 26 for examples). While the team did not explicitly include industrial wastewater treatment and discharge in the Vista-CA data set or flight planning, a large beef processing facility with methane plumes emanating from on-site pits was detected. After confirming the latter were not associated with dairies or other nearby infrastructure (using satellite imagery) this single facility was allocated to emission sector 4D2 "Industrial Wastewater > Production processed - Red meat".

Figure 27: Emissions from Wastewater Treatment Plants



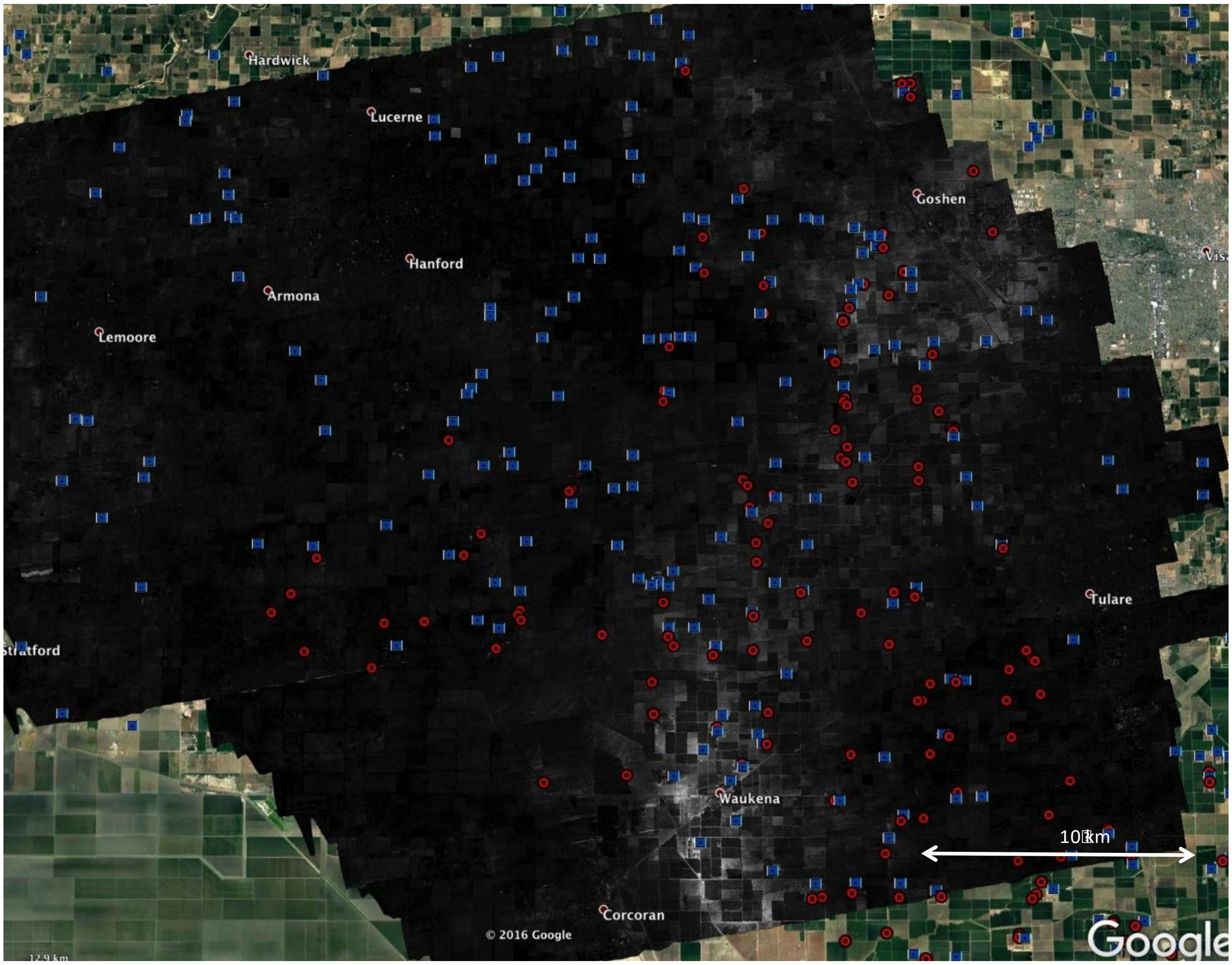
Examples of persistent methane point sources at a small number of wastewater treatment facilities. Left: Hyperion treatment plant, Right: Santa Clara/San Jose plant.

Source: JPL

Dairies and Livestock

The team surveyed 443 Confined Animal Feeding Operations (CAFOs) in California – an estimated 71 percent of all such facilities in the State. CAFO manure management – particularly at large dairies in the San Joaquin Valley (SJV) – is recognized as one of the top methane emission sectors in California. The survey results are consistent with this given that wet manure management – particularly settling ponds and anaerobic lagoons – is responsible for about 26 percent of methane total methane emission from point sources in California. A robust assessment of the individual and net emissions from dairies and other livestock facilities in California is complicated by several factors. Figure 28 indicates one such factor: the complex spatial gradients of near-surface atmospheric methane that manifests in portions of the SJV in response to the dense concentration of emission sources (large dairies) and/or the effects of "pooling" from wind and other meteorological variables. This figure also raises the question: why weren't methane point sources detected at more dairies? Detecting and attributing methane plumes to individual point sources can be challenging in the presence of strong methane enhancements over large areas – essentially a "contrast" problem. In such areas there is a risk both of over-estimating the emissions of individual dairies (by convolving the flux with nearby facilities) and also under-estimate the net emissions of the area. This represents an active area of measurement science and is a priority for future attention.

Figure 28: Mosaic of Two Days of AVIRIS-NG Flights Over Tulare Area Dairies

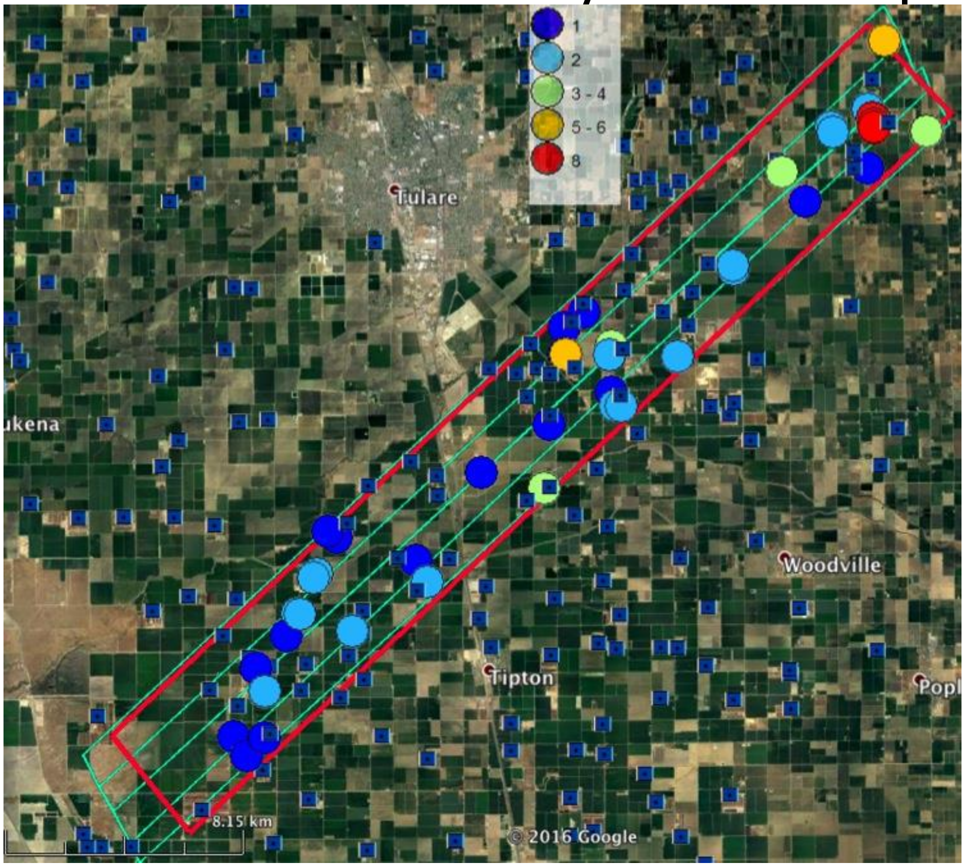


The raw grayscale image overlays represent areas with lower (black) and higher (white) levels of atmospheric methane. The striking gradient seen here suggests accumulation of enhanced levels of methane in these areas due to the combination of many strong emitters and low wind conditions. Atmospheric transport modeling will likely be required to disentangle those two effects. Blue squares indicate the known locations of dairies from the Vista-CA data set. Red markers indicate methane point sources detected during these overflights.

Source: JPL

Another complexity involves the inherent variability of dairy methane emission processes. The primary driver for methane point source emissions from manure management involves the use of water and anaerobic conditions that promote methanogenesis. Dairies are dynamic facilities in that water and wastes are moved around each facility over the course of the day on a given duty-cycle, translating to methane point sources that can vary significantly on time-scales of hours – as anaerobic layers in lagoons are disturbed and as methane laden water is transported around the facility including irrigation for adjacent fields.

Figure 29: Methane Point Source Variability for Dairies Near Tipton

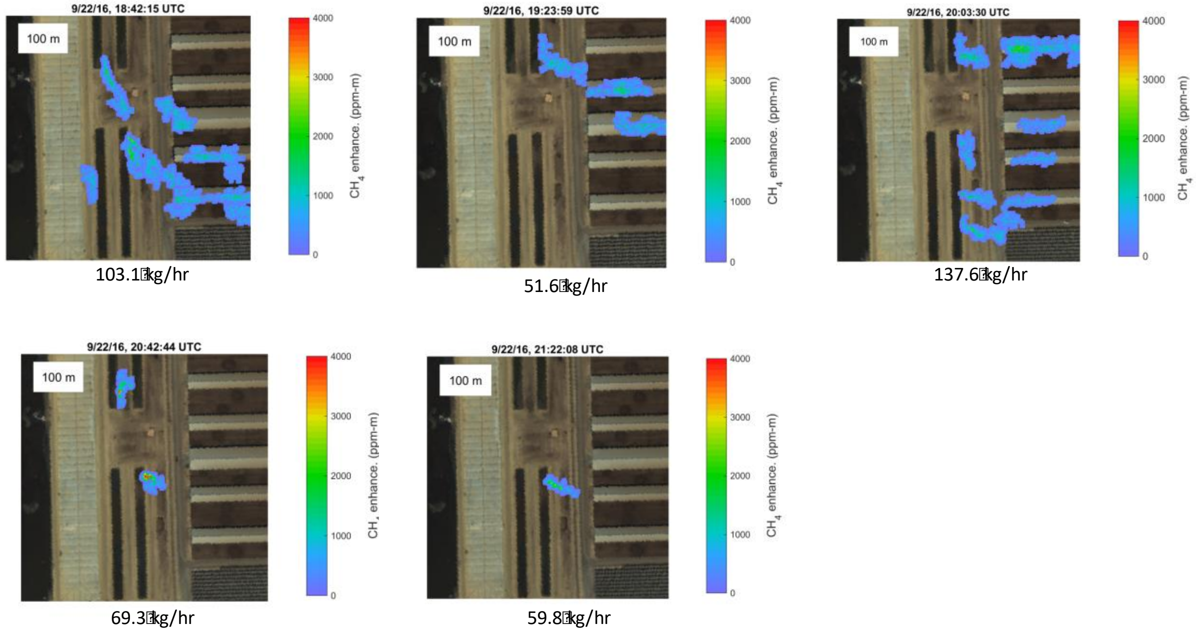


AVIRIS-NG repeatedly flew the same flight lines over an area with about 100 large dairies near Tipton with a roughly 45-minute revisit interval per facility over a 5-hour period. The colors indicate the number of times a source was observed during that period. Some of the sources (red circles) were persistent – others were highly variable. This variability is common in many emission sectors and illustrates the need for frequent sampling.

Source: JPL

This diurnal, management-driven variability is likely somewhat independent of seasonal variability in emission fluxes driven by changing temperatures. This short-term variability can have an impact on detectability as illustrated in Figure 29 and 30 (e.g., surveys with insufficient revisit frequency can fail to detect sources through aliasing).

Figure 30: Close-Up of a Dairy from the Intensive Study

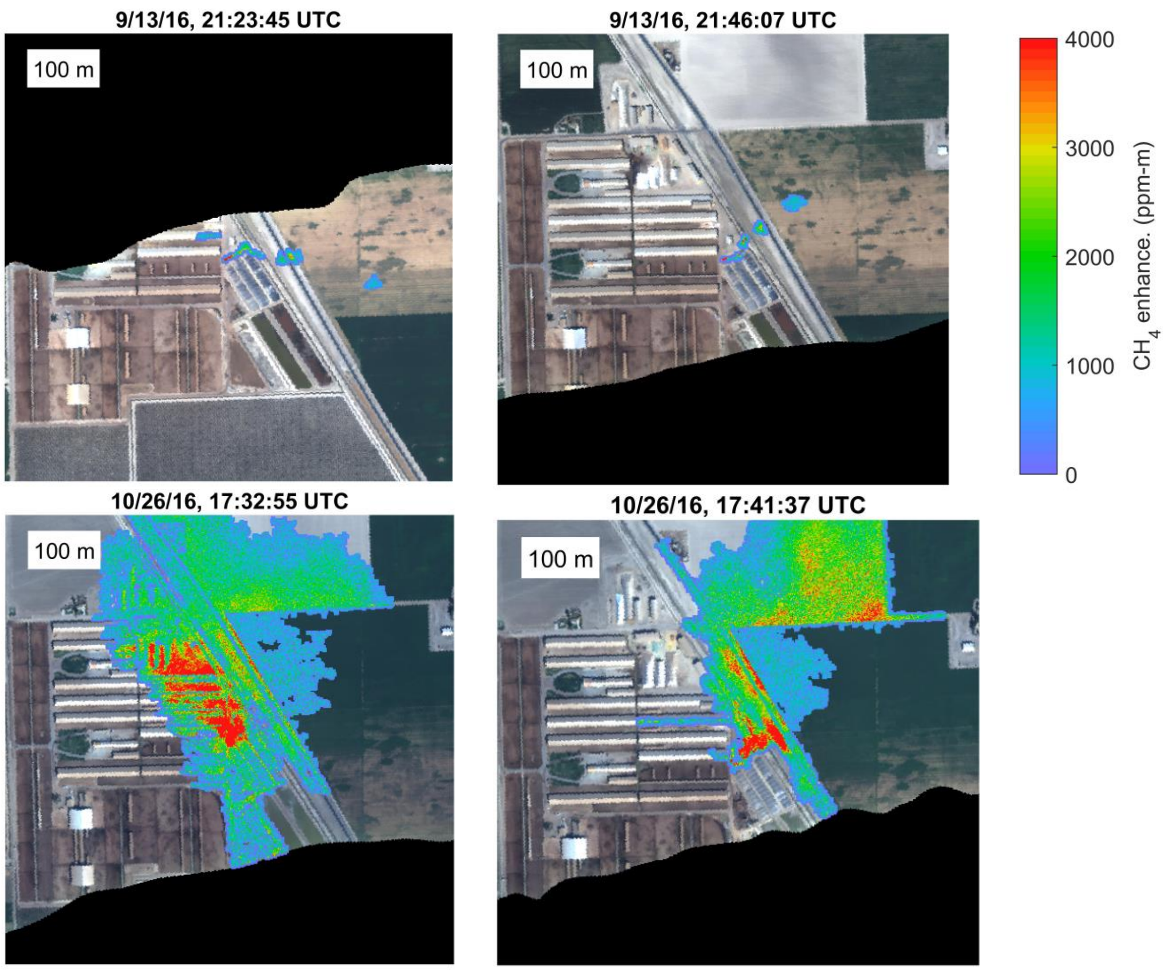


Each image shows methane plumes for snapshot in time, each separated by about 45 minutes - indicating significant temporal variability in emissions. In this case the variability is attributed to water flushing manure from feedlots on the right side of each image through settling ponds in the middle.

Source: JPL

Methane digesters are increasingly being deployed at California dairies in an effort to reduce the net greenhouse gas impact of each facility while offering additional revenue opportunities such as biogas for energy production. The survey covered about 25 known dairy digesters in the state including a combination of facilities in operation and still undergoing construction. In principle a well-functioning digester should capture methane from manure management however the study indicated the presence of significant methane point sources at four facilities in the SJV. Figure 31 shows an example of a persistent methane plumes at a dairy digester. The biogas operator for this facility indicated that the cause was likely manual venting during maintenance activity. This suggests that future monitoring for atmospheric methane around these facilities before and after digester construction could prove useful for assessing their efficacy in meeting mitigation objectives while helping operators avoid unintentional biogas product loss.

Figure 31: Methane Plume Observed Persistently at Dairy Methane Digester



The difference in plume appearance between the two dates is attributed primarily to different wind speeds.

Source: JPL

CHAPTER 4: Knowledge Transfer

Much of the new data analysis system used in this study was developed under parallel NASA programs. All data on methane plumes detected in this study (following quality control filtering), as well as the new GIS methane data set (*Vista-CA*), are now available through a prototype *Methane Source Finder* web-based methane data portal (https://methane.jpl.nasa.gov). That portal and those data sets are designed to improve their accessibility and relevance to a diverse set of stakeholders. The team is exploring options to transfer sustained operation of the methane data portal to the California Air Resources Board in the future.

Additionally, during this study, the project team organized multiple meetings and briefings to share and discuss interim findings with stakeholders, including staff from the CEC, CARB, CalRecycle, Bay Area Air Quality Management District, South Coast Air Quality Management District, Southern California Gas company, Pacific Gas and Electric company, Milk Producer's Council, City of Los Angeles Department of Sanitation, Sunshine Canyon Landfill Local Enforcement Agency, and several operators of individual facilities. These interactions resulted in two-way knowledge transfer, including feedback on the utility of the methane data sets as well as ground truthing and explanations about potential causes for the observed emissions. Another source of knowledge transfer was the publication of a paper in the journal *Nature* (Duren *et al*., 2019).

CHAPTER 5: Recommendations

The team found that methane point sources across all sectors are significant contributors to California's methane budget. The prevalence of methane super-emitter activity observed in key sectors also suggests significant mitigation potential for California – particularly for landfills, dairies, and oil and gas production. With these lessons in mind, the team makes the following recommendations for future attention by the State of California and other stakeholders.

- Detecting, quantifying, and attributing point source emissions to specific infrastructure elements on an ongoing basis can improve the scientific understanding of regional methane budgets and inform policy and planning activities that reduce methane emissions.
- The highly intermittent and stochastic nature of many point sources underscores the need for persistent, wide area monitoring systems (Duren *et al.,* 2019). The most effective approach will likely involve a tiered observing system with components for detecting strong point source emissions such as those described here, as well as other components optimized for monitoring area emissions below the detection limit of AVIRIS-NG (Duren *et al*., 2012; Cusworth *et al*., 2020b). The combination of methods that collectively provide high spatial resolution and high frequency sampling over large areas could also help disentangle the relative contributions of point and area sources to regional methane budgets.
- Future developments in high performance imaging spectroscopy have the potential to address area sources (e.g., from enteric fermentation, rice cultivation, and wetlands) and reduce the detection limits for point sources by a factor of 10 or more. In particular, improving the spectral resolution of an AVIRIS-NG class imaging spectrometer from the current 5 nm to 1 nm in the 2100-2400 nm range, without sacrificing other aspects of instrument performance, would enable dramatic advances (Thorpe *et al.,* 2016b).
- One of the largest sources of uncertainty in emission estimates for individual methane point sources is the general coarse space-time resolution of near surface wind speed data at most locations. Improvements in wind speed data, either through simultaneous remote sensing or denser surface observations and/or higher resolution weather reanalysis products, could reduce emission uncertainties by 20-50 percent or more.
- This project has demonstrated the ability of regional scale monitoring systems to detect the footprint of large anomalous methane emissions and of airborne imaging spectrometers to find and pinpoint leaks in natural gas infrastructure. However, the data analysis is complex and time-consuming. Future improvements in measurement and analysis frameworks could support operational, rapid-response versions of such systems, which would be particularly valuable for hazardous leak detection.
- The mitigation examples in this study were primarily limited to natural gas transmission, storage, and distribution infrastructure and a single landfill. Opportunities abound to further evaluate and apply these methods in other key sectors, particularly anaerobic

digesters at dairies and wastewater treatment plants, as well as key infrastructure within oil and gas fields. Establishing pilot projects to further facilitate data sharing and collaborative mitigation could provide scientists and technologists with the feedback necessary to make these systems more relevant and effective (Hopkins *et al.*, 2016).

- A concerted effort to diagnose and mitigate some of the point source emissions observed at 32 landfills and composting facilities could provide a significant advance towards meeting the State's target of reducing methane emissions. It could also help address related priorities, including air-quality, environmental justice, and the potential economic potential of biogas as an alternative energy source.

CHAPTER 6: Benefits to Ratepayers

This project has provided new insights into California's methane budget. Specifically, the team conducted the first systematic assessment of the relative contributions of methane point sources, including their distribution by space, time, and emission sector. These findings may lead to improvements in California's greenhouse gas inventory and to efforts by state and local agencies and businesses to both prioritize future investments in methane emissions mitigation and to assess overall progress towards emission reduction goals.

This work also highlights the potential for efficient point source monitoring techniques to directly enable mitigation of a broad class of methane super-emitters, representing a significant contribution to California's climate stabilization targets. The researchers estimated 0.158 (95 percent confidence 0.135-0.184) $TgCH_4$/yr in point source emissions for the oil and gas sector in California (Duren *et al.,* 2019). If translated to natural gas equivalent, this represents approximately $28-$39 million in annual product loss at July 2018 US city-gate gas prices. This indicates the potential value of mitigation for California ratepayers, additional to climate benefits.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ACCESS	NASA Advancing Collaborative Connections for Earth System Science program
AVIRIS-NG	Next Generation Airborne Visible/Infrared Imaging Spectrometer
CARB	California Air Resources Board
CEC	California Energy Commission
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
EPA	United States Environmental Protection Agency
Enhance	Enhancement
GIS	Geographic Information System
H2O	Water vapor
HITRAN	High-resolution transmission molecular absorption database
HRRR	High resolution rapid refresh reanalysis
IME	Integrated methane enhancement
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
N_2O	Nitrous oxide
NCEP	National Centers for Environmental Prediction
O_2	Oxygen
Ppm-m	Parts per million meter. Representing the thickness and concentration within a volume of equivalent absorption that is equivalent to an excess methane concentration in ppm if the layer is one meter thick.
SF	San Francisco
SJV	San Joaquin Valley
SoCAB	South Coast Air Basin
TBD	To Be Determined
UTC	Universal Time Coordinated
XCH_4	Total column averaged methane excess mixing ratio

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APPENDIX A:
Data Availability

Methane plumes images, Vista-CA layers, and regional scale methane emission products for California can be viewed at the Methane Source Finder prototype data portal at https://methane.jpl.nasa.gov/

AVIRIS-NG calibrated radiance and reflectance products can be ordered from the AVIRIS-NG data portal https://avirisng.jpl.nasa.gov/alt_locator/

Retrieved methane images from flight lines in this study are available for download at https://doi.org/10.3334/ORNLDAAC/1727

Vista-CA infrastructure spatial layers are available for download at https://doi.org/10.3334/ORNLDAAC/1726

An electronic archive of the following products has also been delivered to CARB and CEC.

1. Georeferenced image files (GeoTIFF format) for the 1349 methane plumes detected during this study that passed quality control checks
2. Plume list: source ID, latitude, longitude, detection date, detection time (UTC), source type, IPCC sector, IME/r (kg m^{-1}), $\sigma_{IME/r}$ (kg m^{-1}), U_{10} (m s^{-1}), σ_{U10}(m s^{-1}), Q_{plume}(kg h^{-1}), σ_Q (kg h^{-1}) [last two fields intentionally blank for those plumes lacking emission estimates due to quality control and filtering]
3. Sources list: source ID, latitude, longitude, source type, IPCC sector, number of overflights, persistence, confidence in persistence estimate, persistence adjusted average source emissions Q_{source}(kg h^{-1}), σ_Q (kg h^{-1})

where

IME = integrated methane enhancement (total mass of methane in plume)

r = plume length

$\sigma_{IME/r}$ = uncertainty (standard deviation) in IME/r estimate

U_{10} = total (vector) wind speed at 10 meters above ground level

σ_{U10} = uncertainty in wind speed at 10meters above ground level

Q_{plume} = instantaneous plume emission rate (single observation)

Q_{source}= average, persistence adjusted source emission rate

σ_Q = total uncertainty in emission rate