

## **Introduction to the Phase I Report of the California Methane Survey from the Staff of the California Air Resources Board (CARB)**

October 2, 2017

The State of California has passed two important pieces of legislation regarding the understanding and control of sources of methane. Assembly Bill 1496 (Thurmond, Chapter 604, Statutes of 2015) requires the State to monitor methane hotspots, while Senate Bill 1383 (Lara, Chapter 395, Statutes of 2016) sets a goal of reducing methane emissions by 40% from 2013 levels by 2030. To inform policies and regulations to achieve these goals, and to improve the understanding of methane emissions, the State of California has put in place a comprehensive measurement and research program.<sup>1</sup> This Phase 1 report provides initial results from one of those efforts, called the California Methane Survey, in which CARB, the California Energy Commission, and NASA's Jet Propulsion Laboratory (JPL) collaborated to use remote sensing to survey key infrastructure in California and identify large methane point sources. In many cases, the State has already begun working to reduce the emissions this Phase I report describes, and the research helps inform the efficacy of those efforts as well as helps identify additional reduction strategies.

The work has been accomplished by using a NASA JPL airborne infrared imaging spectrometer that can 'see' and quantify methane plumes as it is flown over large areas with infrastructure types known to be responsible for methane emissions, such as dairies, landfills, oil and gas wells, natural gas reservoirs and pipelines, and refineries. This method is able to identify large point sources, i.e., those that release concentrated emissions and provide a significant methane contrast to background levels. The method is not able to identify area sources, i.e., those emissions that occur over a wider area (such as enteric fermentation from dairy cows and beef cattle) or those sources that emit less than about 10 kilograms of methane per hour. While some sources were visited multiple times, the results in this report generally represent a snapshot of emissions. In addition, since Phase I of the survey did not include resources to conduct root-cause attribution for every source, the identification of a source in this report does not necessarily mean that there was an unintended leak or malfunction. The identified source could also be part of normal operational emissions. Additional analysis on sources will be conducted during Phase II of the study and as part of CARB's ongoing efforts.

In Phase II, additional analysis on the results from this Phase I of the project will include calculating the emissions rate for each of the identified plumes and additional airborne surveys of some of the priority sources and areas. These analysis will provide insights

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<sup>1</sup> More information on the CARB Methane Research Program:  
<https://www.arb.ca.gov/research/methane.htm>

on whether the identified plumes are intermittent, whether they represent normal emissions or leaks, whether they are well represented in emission inventories, and whether they present an opportunity for mitigation of methane emissions in California. The survey partners intend to discuss the results with stakeholders, make more systematic ground-level emission measurements at selected sources, and work with various partners on follow-up activities to reduce emissions. The field campaign for Phase II of the study will be completed in the fall of 2017, and a final report for the entire effort will be available in late 2018.

The study focuses on three important methane emission sources in the State: dairies, landfills, and the hundreds of thousands of potential sources in the oil and gas supply chain (wells, processing facilities, refineries, storage tanks, and transmission and distribution pipelines). The following sections describe the legislation and regulations recently put in place in California to address emissions from these sources and provide important context for the results presented in the Phase 1 report.

## **I. Methane Control for Dairies**

In addition to setting an overall methane reduction target, Senate Bill 1383 set a specific target of a 40% reduction from the dairy and livestock sector and recognizes the potential for anaerobic digestion (AD) to direct renewable methane to beneficial uses such as offsetting fossil fuel energy sources. Accordingly, Senate Bill 1383 added provisions designed to encourage the development of AD at dairy operations. These include:

- Developing at least five pipeline-interconnected biomethane pilot projects;
- Increasing the certainty of revenue streams from environmental credits by developing a pilot financial mechanism;
- Providing guidance on the impact of regulation on environmental credit values;
- Developing infrastructure and procurement policies to encourage biomethane development;
- Considering the adoption of methane reduction protocols; and
- Convening a stakeholder group to address barriers to dairy methane reduction projects.

Further solidifying the State's commitment to reducing dairy methane emissions, the Legislature passed Assembly Bill 1613 (Chapter 310, Statutes of 2016) that included a \$50 million appropriation to the California Department of Food and Agriculture (CDFA) to distribute between two dairy-specific programs. The first, the Alternative Manure Management Program (AMMP)<sup>2</sup>, provides as much as \$16 million for non-AD based

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<sup>2</sup> More information on the AMMP: <https://www.cdfa.ca.gov/oefi/AMMP/>

methane reduction projects. The second program, the Dairy Digester Research and Development Program (DDRDP)<sup>3</sup>, initiates a second round of funding that builds upon the success of the first round of disbursements by providing as much as \$36 million for AD system development. These resources demonstrate the Legislature's clear intent to reduce dairy methane emissions while supporting the beneficial uses of biogas produced using AD.

These programs are now underway. The first round of Dairy Digester Research and Development Program funds have already been disbursed and the projects they supported are at or near completion. Funding awards under the second round will be announced by the end of 2017. Extensive stakeholder outreach to the environmental justice community, government agencies, industry, and university researchers concerning methane reduction and AD system deployment has begun in earnest. Dairy pilot project solicitations are being developed, as is a pilot financial mechanism proposal. An additional action recently taken by the State was to designate a dairy AD project as a California Sustainable Freight Action Plan<sup>4</sup> pilot project. This project will demonstrate the potential of dairy biomethane to reduce freight transport emissions by displacing diesel-powered vehicles with clean, renewable-biomethane-powered vehicles.

Anaerobic digestion is an important option for controlling dairy methane emissions and is an established technology globally. It can capture and control as much as 98%<sup>5</sup> of the methane emissions that would otherwise be released to the atmosphere. Although AD has demonstrated significant potential to reduce methane emissions, the technology is in the early stages of maturation. AD systems have been consistently improving and now exhibit solid reliability, longevity, and potential to generate revenue from the sale of energy products. As expected with any new technology, during the initial operational deployment of AD situations may arise including leaks or higher-than-predicted venting that can impact the desired methane control efficiency. Characterizing potential AD fugitive emissions through the use of tools like the NASA JPL flyovers can help achieve and maintain the expected methane reductions by helping digester operators optimize their systems and reduce revenue loss.

The NASA JPL flyovers are effective in identifying instantaneous emission point sources that represent a snapshot but require additional information regarding facility operations to distinguish between transient, maintenance-related leaks, and persistent, unexpected emissions sources that may merit further focused on-site attention. The NASA JPL

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<sup>3</sup> More information on the DDRDP: <https://www.cdfa.ca.gov/oefi/ddrdp/>

<sup>4</sup> More information on the California Sustainable Freight Action Plan: <http://www.casustainablefreight.org/>

<sup>5</sup> Biogas collection efficiency for dairy AD systems can be as high as 98%, as noted on pg. 46 (Appendix A Emissions Factor Tables – Quantification Methodology, Table A.3) of the Livestock Projects Compliance Offset Protocol: <https://www.arb.ca.gov/cc/capandtrade/protocols/livestock/livestock.htm>

flyovers yield important information about digester leaks and maintenance events, but can also assess emissions from digesters during normal operations and at times when they are operating at their expected control efficiencies. For this reason, NASA JPL has done multiple flyovers of key dairy regions and will continue to do so during Phase II of the project.

CARB is looking forward to working with NASA JPL and the dairy industry to develop a better understanding of AD system optimization. This important learning opportunity can help inform efforts to address leaks—possibly including the development of new leak detection and repair protocols. Such protocols can help ensure maximum methane capture, minimum revenue loss, and improved long-term reliability.

## **II. Methane Control for Landfills Accepting Organic Wastes**

Landfills have long been identified as a significant source of methane emissions in California. Landfilled organic materials break down anaerobically into methane, which escapes through cover materials, becoming a fugitive emission. Because organic wastes constitute a significant portion of California's waste stream, the State is moving to divert and manage them. This requires not only keeping organics out of landfills, but also improving the infrastructure for diverting and/or recycling organics, including minimizing and recovering edible food wastes; and incentivizing conversion process such as composting and anaerobic digestion that yield valuable energy and soil amendment products.

CARB, in partnership with local, State, and federal entities is working to address methane and related emissions through implementation of various programs such as the Landfill Methane Regulation, and the organic waste diversion provisions of Senate Bill 1383 (Lara, Chapter 395, Statutes of 2016).

Under CARB's Landfill Methane Regulation<sup>6</sup>, which became effective in 2010, owners and operators of certain uncontrolled municipal solid waste landfills are required to install gas collection and control systems. The regulation also requires existing and newly installed gas collection and control systems to operate in an optimal manner.

As required by AB 1383, CalRecycle, in consultation with CARB, is developing regulations<sup>7</sup> to reduce disposal of organic waste by 50% by 2020 and 75% by 2025 (reductions are measured against a 2014 baseline). CalRecycle is planning to adopt the necessary regulations by the end of 2018. As specified in AB 1383, these regulations can take effect on or after January 1, 2022.

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<sup>6</sup> <https://www.arb.ca.gov/regact/2009/landfills09/landfills09.htm>

<sup>7</sup> <http://www.calrecycle.ca.gov/organics/>

Reducing the disposal of organics in landfills would align California with a growing range of organic waste diversion efforts underway in other jurisdictions. For example, San Francisco and Alameda Counties require that food waste be separated and kept out of the landfill, and various cities, including Los Angeles and San Francisco, have plans in place to achieve zero-waste.

Although the organics diversion efforts described above will reduce landfill methane emissions over time, the organic wastes in place in California's landfills will continue to emit methane for decades to come. Monitoring efforts like this program will help quantify the rate of emissions reductions from California's landfills. They will also help identify malfunctions in landfill gas extraction and control systems, enabling more timely repairs. This approach is being actively tested at the Sunshine Canyon Landfill in Los Angeles County where NASA JPL is working closely with the landfill operator and local agencies to share data and offer feedback as they take steps to reduce emissions. As such, the NASA JPL flyovers are an important component in California's suite of programs aimed at reducing landfill methane emissions.

### **III. Methane Control for the Oil and Gas Sector**

CARB and CEC have recognized that the oil and gas sector is the source of significant methane emissions. Accordingly, CARB recently adopted a regulation<sup>8</sup> to reduce methane emissions from oil and gas production, processing, and storage in California. Beginning on January 1, 2018, oil and gas operators will need to: 1) enhance or begin leak detection and repair (LDAR) procedures to control fugitive methane emissions from the sector; 2) control methane emissions from uncontrolled oil-water separators and storage tanks; 3) replace venting pneumatic devices with devices that do not vent methane; 4) control methane leaks from compressors; and 5) undertake enhanced monitoring at underground natural gas storage facilities.

In addition to this CARB regulation, the California Public Utilities Commission (CPUC) adopted a set of Best Practices for Methane Leakage Abatement and Emissions Reductions<sup>9</sup> this year, which will lead to methane emission reductions from the natural gas transmission and distribution sectors. These Best Practices complement the CARB regulation by addressing the segments of the oil and gas sector that the CARB regulation does not address.

Enforcement of the new CARB and CPUC regulations, as well as continued enforcement of the air districts' current volatile organic compound (VOC) rules for oil and gas sources, should start reducing the number and severity of the detectable methane plumes identified in this sector by the NASA JPL flyovers. For example, pump

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<sup>8</sup> <https://www.arb.ca.gov/cc/oil-gas/oil-gas.htm>

<sup>9</sup> <http://www.cpuc.ca.gov/General.aspx?id=8829>

jacks and tanks—two of the most frequent sources of high methane emissions included in the oil and gas portion of the study—will be subject to the methane LDAR in CARB’s regulation starting on January 1, 2018. In addition, continued surveillance of the kind being done by the NASA JPL flyovers will help evaluate the success of (and compliance with) the CARB oil and gas methane regulation. CARB recently published the Refinery Emergency Air Monitoring Assessment, Objective 2 report,<sup>10</sup> which includes recommendations to improve emergency air monitoring, as well as monitoring of ongoing routine emissions, at California’s major refineries and the communities that surround them. Along with CARB’s planned community air monitoring near oil and gas facilities, the recommended actions will provide valuable information that can be used to further enhance the State’s ability to evaluate reductions in methane and other pollutants from these sectors.

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<sup>10</sup> <https://www.arb.ca.gov/fuels/carefinery/crseam/o2reamarmainfinal.pdf>

# CALIFORNIA BASELINE METHANE SURVEY Interim Phase 1 report

PREPARED BY THE JET PROPULSION LABORATORY  
FOR THE CALIFORNIA AIR RESOURCES BOARD  
AND CALIFORNIA ENERGY COMMISSION

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## ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

ACCESS: NASA Advancing Collaborative Connections for Earth System Science program

AVIRIS-NG: Next Generation Advanced Visible/Infrared Imaging Spectrometer

CARB: California Air Resources Board

CEC: California Energy Commission

CH<sub>4</sub>: Methane

CLARS: California Laboratory for Atmospheric Remote Sensing

CO: Carbon monoxide

CO<sub>2</sub>: Carbon dioxide

COMEX: CO<sub>2</sub> and MEthane eXperiment

Enhance.: Enhancement

FTS: Fourier Transform Spectrometer

FTIR: Fourier transform infrared spectroscopy

GFIT: Gas Fitting algorithm used to fit the measured CLARS-FTS spectrum to a spectral model derived from laboratory and theoretical line lists.

H<sub>2</sub>O: Water vapor

HITRAN: High-resolution transmission molecular absorption database

IME: Integrated methane enhancement

IPCC: Intergovernmental Panel on Climate Change

LABS: Los Angeles Basin Surveys

Mark IV FTIR: Fourier transform infrared spectroscopy interferometer deployed by balloon

Megacities Carbon Project: Project to develop and test methods for monitoring the greenhouse gas emissions of the largest human contributors to climate change: cities and their power plants (<https://megacities.jpl.nasa.gov/portal/>)

N<sub>2</sub>O: Nitrous oxide

NCEP: National Centers for Environmental Prediction

O<sub>2</sub>: Oxygen

ppmm: 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.

SCD: Dry-air slant column density

SF: San Francisco

SJV: San Joaquin Valley

SoCAB: South Coast Air Basin

Spectralon: Panel composed of fluoropolymer that has the highest diffuse reflectance of any known material or coating and exhibits highly Lambertian behavior.

SVO: Spectralon Viewing Observations

TBD: To Be Determined

TCCON: Total Carbon Column Observing Network

UTC: Universal Time Coordinated

XCH<sub>4</sub>: Total column averaged methane excess mixing ratio

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## 1. Executive summary

JPL is applying advanced remote sensing methods to detect and characterize anthropogenic methane emissions in California to support the State’s objectives for mitigation of short-lived climate pollutants (California 2013, 2017), identification of methane “hotspots” in response to AB1496 (California 2015), and supporting natural gas leak detection and correction for rate-payer benefit. The project is being implemented in two phases on behalf of the California Air Resources Board and California Energy Commission (CEC). Phase 1 primarily used data collected in 2016 and addresses CARB priorities spanning Intergovernmental Panel on Climate Change (IPCC) methane emission sectors relevant to point sources in California. Phase 2 will collect data in 2017 and focus on CEC priorities, particularly the natural gas sector to improve understanding of leaks and to help enable mitigation. This interim report summarizes the Phase 1 activity and findings including lessons that will inform data collection and analysis strategies for Phase 2 as well as future research projects. A final report will be produced at the conclusion of Phase 2.

Phase 1 data collection included an airborne remote sensing survey of nearly 180,000 individual facilities and infrastructure components across California between September and November 2016. Over 15,000 km<sup>2</sup> of land area was imaged at spatial resolutions ranging from 1 to 3 meters. This represents a phase 1 survey completeness (compared to all known relevant infrastructure in the State) ranging from 20 to 100% per emission sector; for example, 35% of known power plants, 38% of landfills, and 50% of dairies were sampled at least once.

The phase 1 airborne survey identified 329 unique methane point sources\* with high confidence. Some of the sources were observed repeatedly, providing some insight into their variability. Based on these observations a Source Database (Appendix A) was developed that includes for every source the location, emission type, and size (expressed as an average atmospheric enhancement and plume length). Additionally, phase 1 of this project extended an established time-series (2011-2015) of methane emissions in the South Coast Air Basin (SoCAB) through spring 2017.

All phase 1 project objectives have been met or exceeded. The following interim findings are based on a preliminary analysis of data collected in phase 1 with conservative assumptions. A quantitative estimate of individual and net point source emission fluxes and uncertainties will be provided in the Phase 2 final report. The following interim findings are subject to revision in phase 2 following additional analysis and validation.

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\* Methane point sources are emission sources that are spatially condensed – typically originating from a surface less than 10 meters across. Point sources often generate well-defined plumes of methane gas similar to smoke released from power plants and fires. This is in contrast to area sources that release methane in a more diffuse fashion over surfaces spanning hundred of meters to many kilometers (e.g., enteric fermentation, rice cultivation, and wetlands). Point sources refer to the spatial characteristics of the source not the root-cause (e.g., a point source can result from expected process emissions or unplanned fugitive emissions such as leaks). This report does not attempt to assign root-cause to point sources.

**Interim findings:**

1. *Strong methane plumes<sup>†</sup> are observed at a relatively small fraction (< 0.2%) of California’s infrastructure with the potential for methane fugitive emissions. Methane plumes appear more frequently in specific sectors, particularly refineries (94%), landfills (86%), gas storage facilities (25%), and dairies (22%). [See caveat in finding 2]*
2. *Detecting and quantifying methane emissions from some sectors – particularly dairies, natural gas transmission, storage and distribution systems, and petroleum refineries – is complicated by significant variability. Failure to properly sample episodic activity could result in significant under-estimation of the prevalence and net emissions of methane sources. Hence the source distribution presented here is likely conservative. Future efforts to assess and mitigate emissions would benefit from more frequent and sustained monitoring.*
3. *The observed spatial distribution, size and atmospheric enhancements of methane plumes in the San Joaquin Valley (SJV) indicate that dairies are likely the leading cause of methane point source emissions in that region. However, resolving the relative contributions of manure management point source emissions and enteric fermentation area source emissions will require additional observations and modeling beyond the scope of this project and perhaps a priority for future research.*
4. *Large methane plumes that persist for months are observed at small number of dairy digesters in the SJV; these are likely associated with manual venting from facilities undergoing maintenance or construction.*
5. *Methane plumes are observed at multiple locations within and in the vicinity of dairies in the SJV and are likely associated with different stages of manure management as well as crop irrigation with waste water. The spatial distribution of dairy methane emissions is complex and requires additional study to fully understand the controlling processes.*
6. *The dense concentrations of large dairies in some parts of the SJV results in strong methane enhancements over large areas, complicating efforts to attribute emissions to individual facilities. However, this project also demonstrated the ability to directly image those large regional enhancements and the potential for future quantification of area methane fluxes using remote sensing.*
7. *The prevalence and magnitude of methane plumes at landfills varies significantly between facilities and is not well-predicted by bottom-up estimates. Additional study is required to fully understand the controlling processes including the relative influence of waste volumes and management practices.*
8. *The majority of methane plumes observed in oil- and gas-producing fields in California occur in Kern County. Additional study is required to determine whether this is primarily due to the higher production rates in that county or other factors.*

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<sup>†</sup> For this report strong plumes are defined as those with emission rates exceeding the nominal detection threshold of the airborne imaging spectrometer used in this survey (about 10 kgCH<sub>4</sub>/hr assuming a 3 meter/second wind).

9. *This project has demonstrated the ability of airborne imaging spectroscopy to detect and pin-point a leaking underground natural gas distribution line in a neighborhood and provide near real-time notification to operators to guide repair efforts.*
10. *A simple analysis of plume enhancements for the sources detected in this study suggests that a small fraction of sources in nearly every sector likely dominates the net emissions of the population. Further analysis and emission flux estimation in phase 2 will be required to confirm the extent of potential “super-emitter” behavior and its contribution to California’s net methane budget.*
11. *Persistent monitoring of SoCAB regional methane emissions over a 5 year period indicates significant seasonal variability that is likely associated with natural gas use. Additional research is required to attribute which part(s) of the gas supply chain in the SoCAB are responsible for this variability and to determine whether this extends to other urban areas in the State.*
12. *Persistent, spatially resolved remote sensing of atmospheric methane enhancements across the Los Angeles basin detected the impact of the Aliso Canyon gas leak and return to normal conditions, suggesting the potential for future methane hot spot monitoring for anomalous emission events.*

## 2. Project Overview

### 2.1. 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].

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 AB1496 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 rate-payers.

### 2.2. 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 San Joaquin Valley [Kort et al., 2014] and have produced spatially resolved estimates of US methane emission trends [Turner et

al, 2016]. The planned 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 two 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]. Additionally, persistent monitoring of SoCAB total methane emissions by JPL’s California Laboratory for Atmospheric Remote Sensing (CLARS) over the period 2011-2015 [Wong et al 2016] demonstrated the ability to assess variability in the emissions of a key region.

### **2.3. 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) are funding JPL to conduct the first comprehensive airborne survey of methane point sources in the State. Additionally, CARB contributed to extending CLARS data collection and analysis for methane emissions in the SoCAB through Spring 2017.

The project technical objectives for phase 1 are as follows:

1. Prepare a Survey Area Flight Plan that covers all key emissions sectors for methane point sources in California including dairies, feedlots, landfills, wastewater treatment facilities, natural gas supply chain, oil production, processing and refineries, natural seeps, etc including specific areas of interest identified by CARB and CEC staff.
2. Conduct the California Baseline Methane survey using airborne imaging spectrometer(s) to detect and characterize fugitive methane emission sources in the Survey Area Flight Plan and provide a flight coverage report. As resources allow, provide follow-up surveys of strong emitters.
3. Deliver maps of methane enhancements (both individual point source plumes and regional enhancements for the SoCAB) and a Statewide point source database including source locations, plume sizes, and emission types. Point source maps to be delivered in electronic, georeferenced formats.
4. Deliver a report summarizing the project purpose, approach, findings and conclusions.



### 3. Methods

#### 3.1. Tiered observing strategy for methane emissions

Phase 1 data collection involved a two-tiered approach: 1) a broad airborne survey of methane point sources spanning key regions and sectors across the State by JPL's Next Generation Advanced Visible/Infrared Imaging Spectrometer (AVIRIS-NG) and 2) persistent regional-scale monitoring of methane emissions in the South Coast Air Basin (SoCAB) by JPL's California Laboratory for Atmospheric Remote Sensing (CLARS) facility on Mt Wilson. The first tier is providing an unprecedented baseline assessment of methane point sources in the State. The second tier is extending a previously established methane emissions time-series for the SoCAB. Figure 3-1 illustrates representative CLARS and AVIRIS-NG data products (the latter is actually an AVIRIS-classic image).

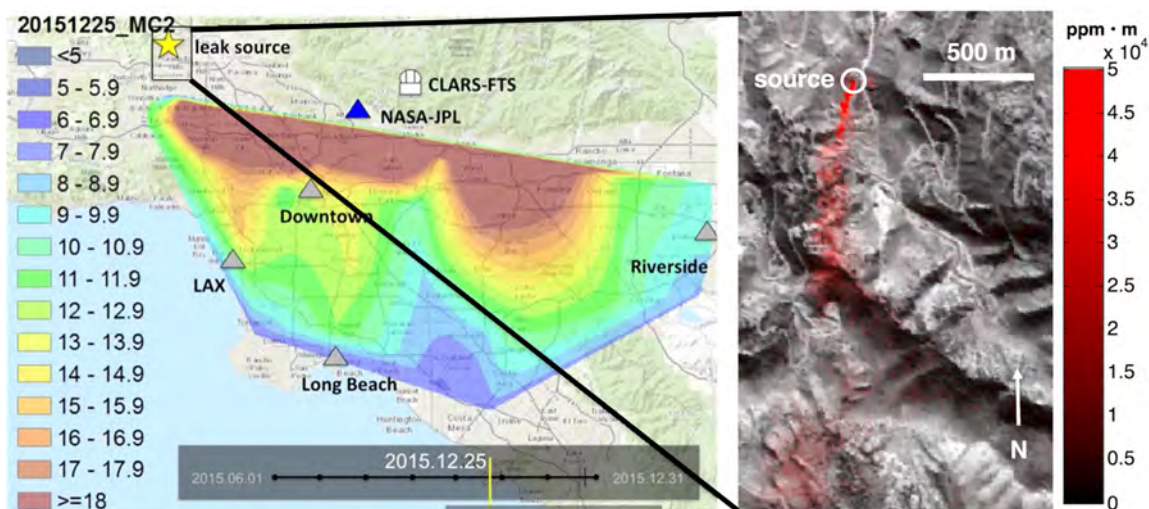
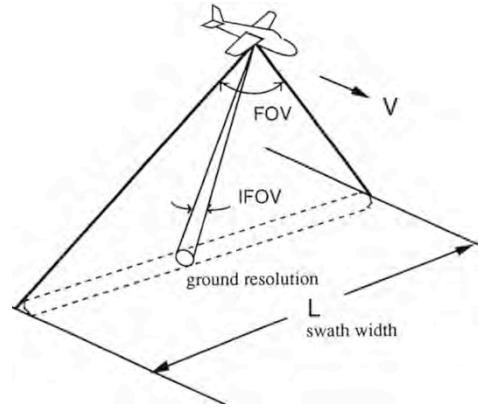


Figure 3-1 Example of observations of methane associated with the Aliso Canyon gas leak. Left: CLARS map of column methane/ $\text{CO}_2$  correlation ratios showing a large area of enhanced methane (red) extending across the SoCAB on December 25, 2015 – the leak source is just outside the CLARS field of regard in this figure. Right: AVIRIS-C image of Aliso Canyon and the gas leak plume extending over > 2km on January 12, 2016 [Thompson et al 2016].

The focus for the airborne survey for phase 1 (and the exclusive focus for phase 2) is on methane point sources. The airborne remote sensing method applied here are 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.

**3.2. 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 3-2, Table 3-1). For most of the Fall 2016 campaign, AVIRIS-NG flew at 3 km above ground level, resulting in 3 m image pixels.



**Figure 3-2.** AVIRIS-NG flight parameters: L=image swath width, V=aircraft velocity, FOV=field of view, IFOV = instantaneous FOV (Murai, 1995).

The methane retrieval is based on absorption spectroscopy (Figure 3-3) 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<sup>3</sup>/h (~10 kgCH<sub>4</sub>/hr) at multiple AVIRIS-NG flight altitudes and variable wind speeds (Thorpe et al. 2016).

*Table 3-1. 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

The methane retrieval is a linearized matched filter that models the background of radiance spectra as a multivariate Gaussian having mean  $\mu$  and covariance  $\Sigma$ . We estimate background parameters using the image data in the appropriate pushbroom cross track location. This compensates for subtle uncorrected variations in radiometric response or dark current level by different focal plane array elements, permitting accuracy beyond what is possible from a purely first-principles laboratory calibration (Thompson et al., 2015). The matched filter tests the null background case  $H_0$  against the alternative  $H_1$  in which the background is perturbed by a signal  $t$ :

$$\begin{aligned}
 H_0: x &\sim N(\mu, \Sigma) \\
 H_1: x &\sim N(\mu + \alpha t, \Sigma)
 \end{aligned}
 \tag{1}$$

In this equation,  $\alpha$  is a scaling of the perturbing signal. The matched filter  $\alpha^*(x)$  is the optimal discriminant between these hypotheses. It estimates  $\alpha$  by projecting the mean-

removed spectrum onto the target, after whitening to account for covariance. The estimator takes the form:

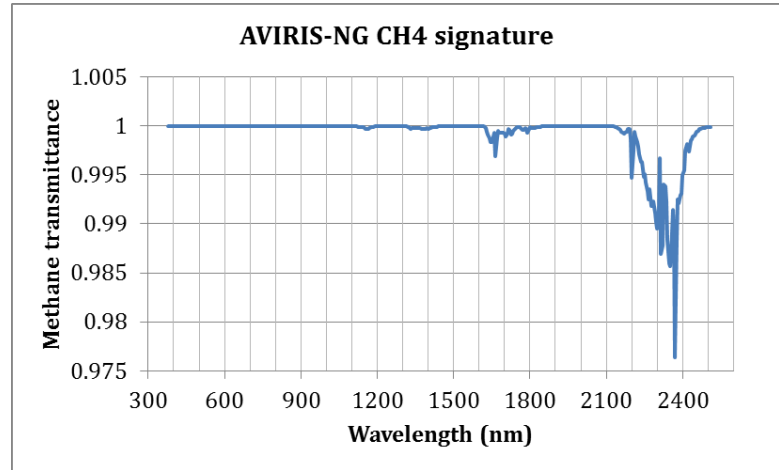
$$\alpha^*(x) = \frac{(x-\mu)^T \Sigma^{-1} t}{t^T \Sigma^{-1} t} \quad (2)$$

We write the estimated coefficient as  $\alpha^*$ . Carefully defining the target signature  $\mathbf{t}$  permits a quantitative interpretation of this value in terms of physically-meaningful scene properties. Specifically, we define the target signature  $\mathbf{t}$  as the change in radiance units of the background caused by adding a unit mixing ratio length of methane absorption. The additional absorption acts as a thin Beer-Lambert attenuation of the background  $\mu$ . Our target signature is the partial derivative of measured radiance with respect to a enhancement in absorption path length  $l$  by an optically-thin absorbing layer of methane. At the background level of  $l=0$  we have:

$$\mathbf{t} = \frac{\partial x}{\partial l} = -\mu e^{-\kappa l} \kappa = -\mu \kappa \quad (3)$$

Here,  $\kappa$  represents the unit absorption coefficient and  $\mu$  is the mean radiance as before. The detected quantity  $\alpha^*$  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  $X_{\text{methane}}$  would be about 0.000125 times the excess in ppm-m. For example, 1000 ppm-m is equivalent to an  $X_{\text{methane}}$  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



**Figure 3-3.** methane absorption signature (transmittance) plotted for the wavelength range measured by AVIRIS-NG. Strong absorptions are present between



**Figure 3-4.** Real time methane mapping onboard the aircraft. Red methane plumes are overlaid on raw AVIRIS-NG images with estimated peak enhancement (ppm-m) and plume source coordinates.

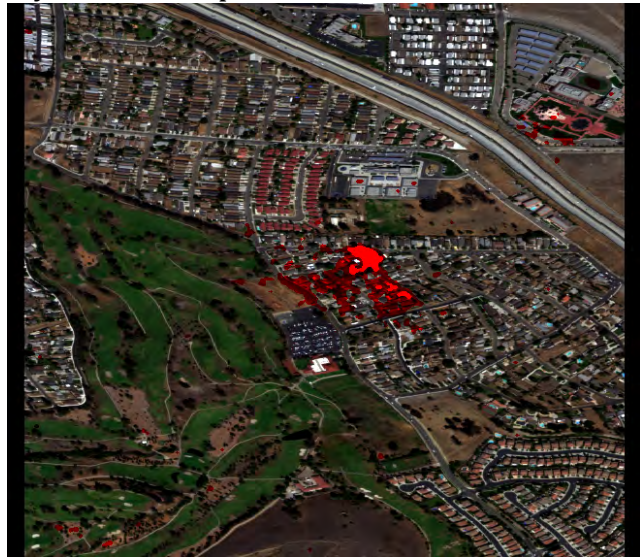


technique can be combined with simple steady state assumptions for a first-order estimate of a point source emission flux. Critically, a windspeed-corrected IME is proportional to the source strength; field measurements of flux from a subset of sources can serve as a reference for inferring flux of many different sites.

methane retrievals are performed in real time onboard the aircraft (Figure 3-4), which permits the instrument operator to identify and geolocate plumes in real time. 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 3-5) 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).

### 3.3. Airborne survey design

The phase 1 airborne survey with AVIRIS-NG was designed to map key regions in California and infrastructure with the potential for methane point source emissions. A Geographic Information System (GIS) data set known as “Vista-CA” that maps potential methane emitting infrastructure across the State of California is being developed by JPL and UC Riverside as part of NASA’s Methane Source Finder project. The Vista-CA data set applies similar methods used to develop a “Vista-LA” methane GIS data set for the greater Los Angeles area as part of the Megacities Carbon Project [Carranza et al 2017]. Vista-LA mapped the locations of infrastructure associated with three primary sectors

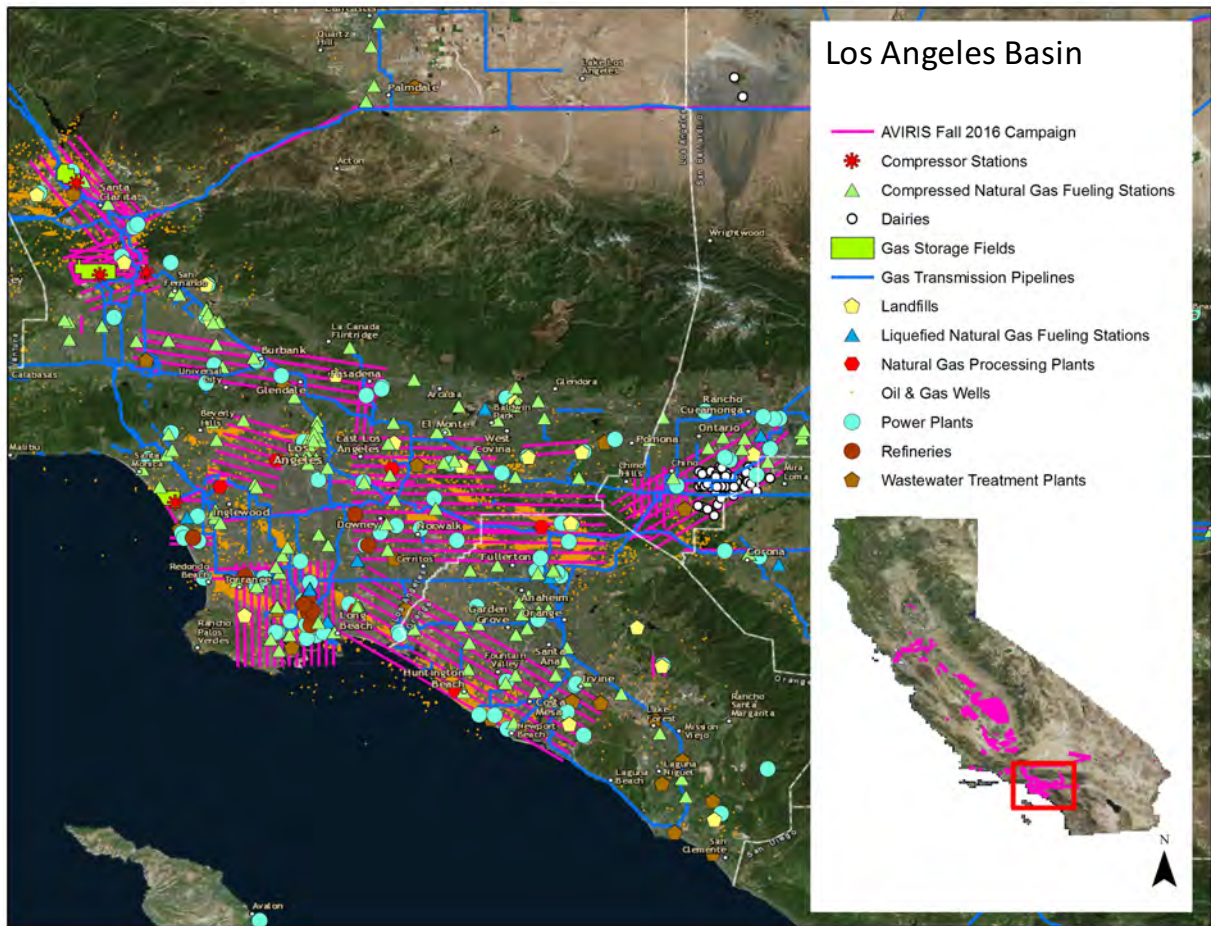


**Figure 3-5.** methane quick-look products are generated at the end of each flight day. This example shows a plume from a leaking low-pressure gas pipeline that was confirmed by local gas company.



**Figure 3-6.** AVIRIS-NG flight boxes for Fall 2016 campaign surveying the energy sector (red), non-energy sector (yellow), and mixture of these categories (orange).

(energy, agriculture, and waste) following the frameworks used by the State of California’s Greenhouse Gas Inventory and the IPCC Guidelines for GHG Reporting. Geospatial modelling was applied to publicly available datasets to precisely geolocate facilities. For Phase 1 of this project, a preliminary version of Vista-CA containing 299,644 distinct pieces of potential methane emitting infrastructure was used to guide selection of flight boxes (Figure 3-6) that were organized broadly into three categories, the energy sector (red), non-energy sector (yellow), and regions that contain a mixture of these categories (orange). This grouping of sectors was partly driven by the need to divide the campaign into two phases to address CARB and CEC priorities given that CEC funding for the project is dedicated to energy sector emissions. Figures 3-7, 3-8, 3-9 and 3-10 provide finer scale maps of the planned flight lines (shown in magenta) for phase 1 along with key Vista-CA elements for four primary areas. The flight plan shown in figure 3-10 was adjusted to account for reduced flight hours in the San Francisco Bay Area due to weather conditions in Fall 2016 and other constraints. Note: the version of Vista-CA used in phase 1 is still



undergoing development and review; further revisions are likely in phase 2.

*Figure 3-7 Phase 1 airborne survey design for the Los Angeles Basin*



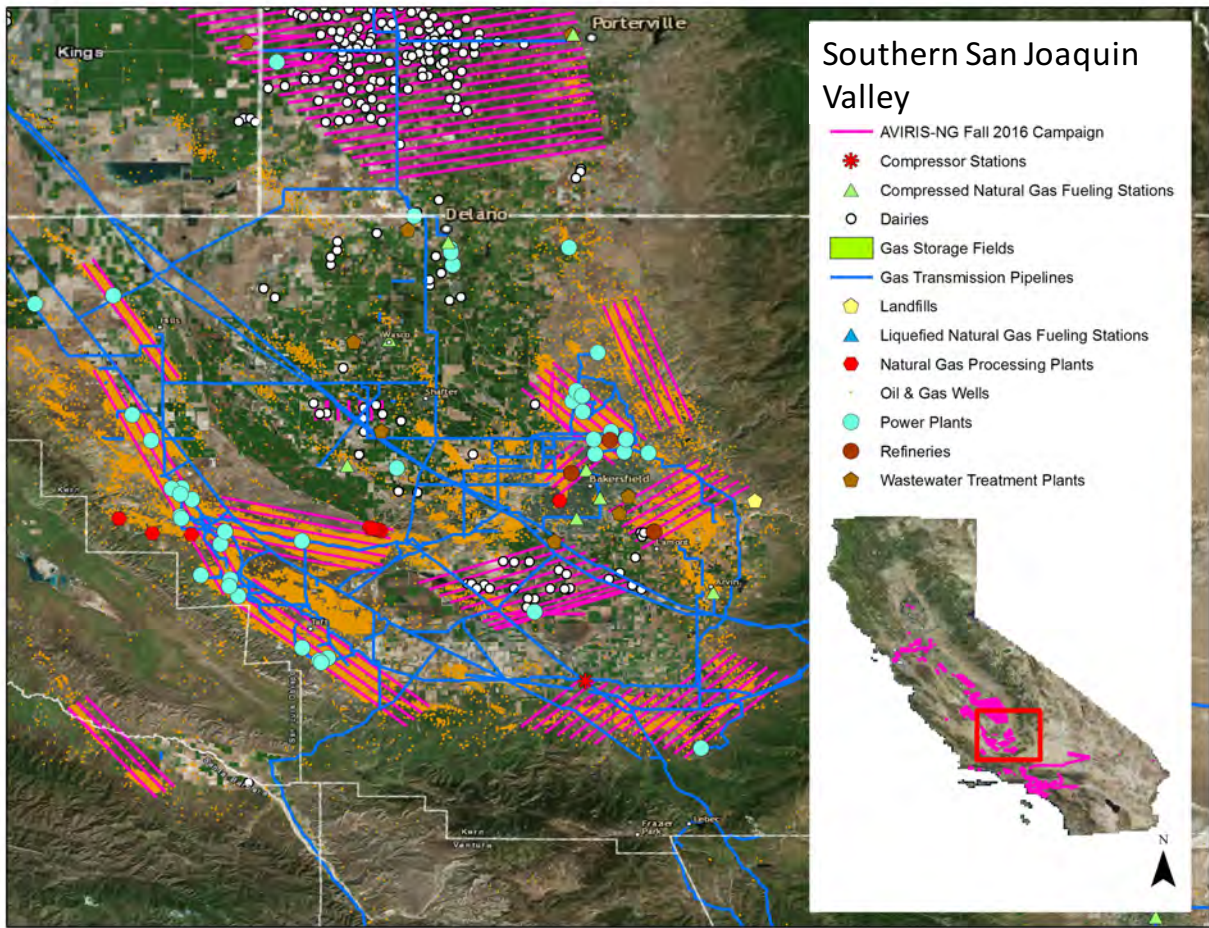


Figure 3-8 Phase 1 airborne survey design for the southern San Joaquin Valley

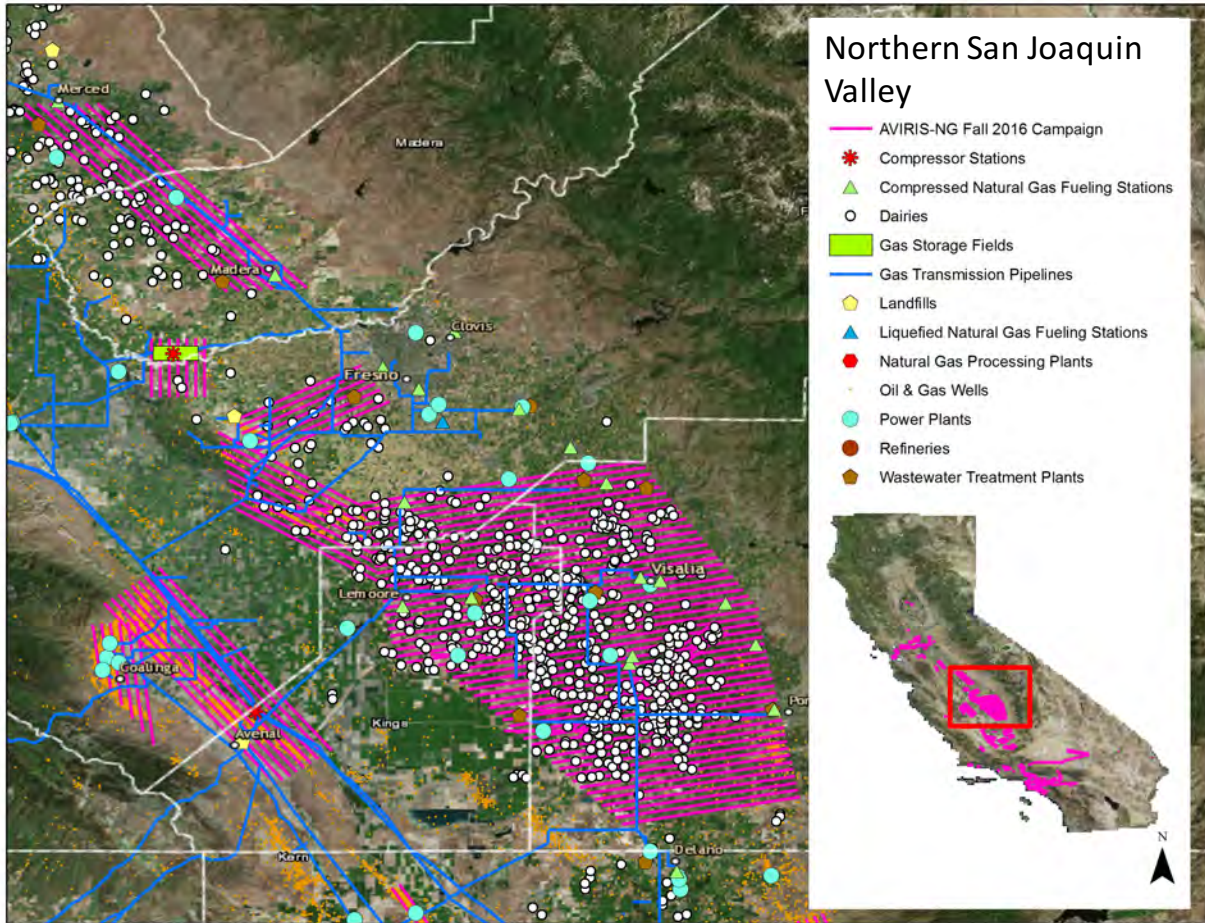
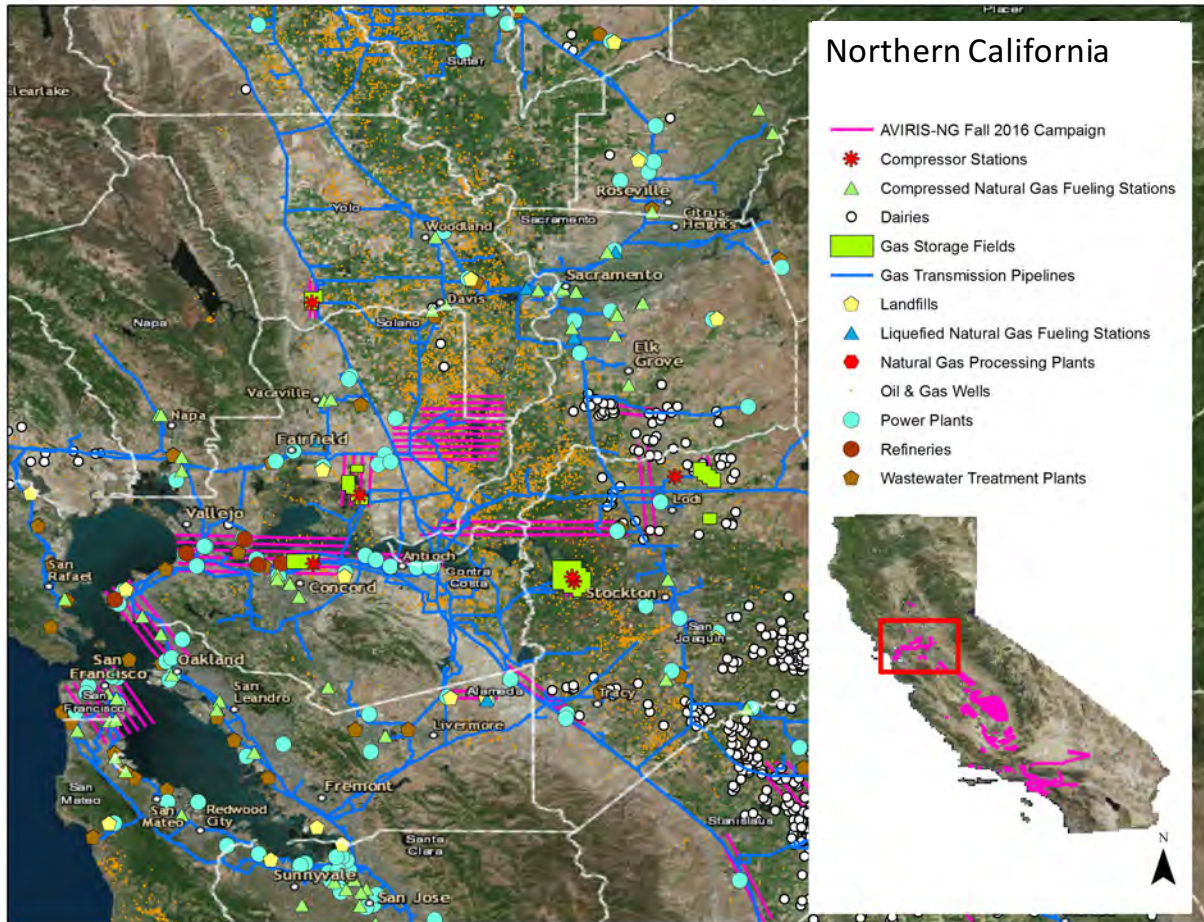


Figure 3-9 Phase 1 airborne survey design for the northern San Joaquin Valley





**Figure 3-10** Phase 1 airborne survey design for the Northern California

In addition to these flight boxes, there were two focused mini-intensive flight campaigns. The first involved a multi-day effort focused on the natural gas transmission and storage sectors in the SoCAB. The second mini-intensive focused on an area near Visalia that was mapped repeatedly over a 5 hour period to investigate the spatial and temporal variability of dairy manure emissions. Additionally, for many of the sources detected in phase 1, revisit overflights were conducted. In other words, flight hours were managed to balance between broad spatial coverage and temporal sampling.



### 3.4. Point source attribution, quantification and validation

During the flight campaign, a list of candidate methane plumes was compiled using end of day quick-look products. Using this list as an initial guide, methane retrievals for orthorectified scenes were then analyzed with automated detection software to confirm and geolocate methane plumes. Analysts reviewed each plume candidate to confirm its validity and to attribute the most likely source. To confirm a source one or more of the following criteria were required: a) source plume is so strong as to be unambiguous with a single detection, b) plume clearly originates from surface, c) plumes are detected multiple times at the same location under different wind conditions, d) plume origin is co-located with plume of another species (e.g., ammonia or CO<sub>2</sub>), e) source is confirmed by follow up, f) source was previously known. In many cases follow-up flights were conducted over high priority source candidates for confirmation and to assess their persistence.

Sources that passed one or more of the above criteria were assigned a medium to high confidence level and included in the Source Database (Appendix A). Lower confidence source candidates were excluded from the table as likely false alarms. Information in the table also includes the best estimate of source location, type and magnitude and likely IPCC emission sector based on analysis of plumes, true color imagery, and infrastructure maps.

Each plume observation is assigned a unique identification number since some were observed multiple times for a given source. For example, 20 plumes were observed for source S00006. In some cases the apparent origin of plumes for a given source shifted somewhat between repeat observations. Image analysis of these plumes in combination with additional information (i.e. infrastructure maps, analysis of higher spatial resolution satellite imagery) was used to assign a most-likely location for each source (Fig. 3-11).

For each plume, an Integrated Methane Enhancement (IME) was calculated by integrating over the physical area of the plume. This was done by first calculating the mass of methane present in each image pixel as follows.

$$\text{kg} = \frac{\text{ppm} \cdot \text{m}}{1} * \frac{1}{1\text{E}6 \text{ ppm}} * \frac{\text{pixel res. (m)} \cdot \text{pixel res. (m)}}{1} * \frac{1000 \text{ L}}{1 \text{ m}^3} * \frac{1 \text{ mole}}{22.4 \text{ L}} * \frac{0.01604 \text{ kg}}{1 \text{ mole}} \quad (4)$$

The IME is then calculated by integrating over all pixels exceeding a specified methane threshold in a given plume. The IME and plume lengths listed for a given source in Appendix A are based on the average of those quantities for each source.

The IME and plume length can ultimately be combined with wind speed information to estimate point source emission rates as follows

$$\text{Emission rate (kg/hr)} = \frac{\text{IME (kg)}}{1} * \frac{\text{Wind speed (m)}}{s} * \frac{1}{\text{plume length (m)}} * \frac{3600 \text{ s}}{1 \text{ hr}} \quad (5)$$

Wind speed data is available for many areas but includes varying degrees of uncertainty that directly translate to uncertainty in derived emission rates. In phase 2 plume modeling and validated wind information will be applied to quantify emission rate estimates for individual sources. ***Wind data and emission rate estimates are not included for phase 1 nor are they reflected in the analysis in this report.***



**Figure 3-11.** Example of methane source attributed to a vent stack at the Honor Rancho gas storage facility. The red markers indicate the detection of multiple plumes over several weeks that were used to infer the existence of the source (white marker centered on vent stack).

### 3.5. CLARS methane monitoring for Los Angeles Basin

The California Laboratory of Atmospheric Remote Sensing (CLARS) is located at an altitude of 1670 m above sea level with a panoramic view of the Los Angeles basin (Fig. 3-12). The CLARS-FTS instrument quantifies atmospheric column abundances of methane, CO<sub>2</sub>, CO, N<sub>2</sub>O, H<sub>2</sub>O and O<sub>2</sub> using reflected sunlight in the 0.7-2.3 μm region using a JPL-built high-resolution Fourier Transform Spectrometer (FTS). It operates in two measurement modes: Spectralon Viewing Observations (SVO) and Los Angeles Basin Surveys (LABS). In the SVO mode, the instrument quantifies the background free tropospheric column abundances of methane, CO<sub>2</sub> and other species above the Los Angeles basin by measuring reflectance from a Spectralon® plate located at the CLARS site. In the LABS mode, the instrument samples the slant column abundances of methane, CO<sub>2</sub> and other species by measuring the specular scattered radiance from 33 discrete locations (or reflection points) in the basin (Fig. 3-12). We selected these reflection points to achieve uniform optimal spatial and temporal coverage of the Los Angeles basin. The number, locations and repeat frequencies of the reflection points can be modified easily to meet specific measurement requirements. In each measurement cycle, we collect one set of LABS measurements and five SVO measurements. Multiple SVO measurements are performed per measurement cycle so that

any variability in the background during each measurement cycle, which typically lasts for 90 minutes, can be captured. There are 5 to 8 measurement cycles per day, depending on the time of the year. The CLARS facility, CLARS-FTS instrument, measurement approach, retrieval algorithms, data products and uncertainties are described by Fu et al. and Wong et al. [Fu et al., 2014; C K Wong et al., 2016; K W Wong et al., 2015].

Based on the Beer-Lambert Law, the dry-air slant column density (SCD) – the total number of absorbing molecules per unit area along the sun-Earth-instrument optical path – is retrieved for methane at 1.67  $\mu\text{m}$ ,  $\text{CO}_2$  at 1.60  $\mu\text{m}$ , and  $\text{O}_2$  at 1.27  $\mu\text{m}$  using a modified version of the CLARS Gas Fitting (GFIT) algorithm developed at JPL [Fu et al., 2014; Wunch et al., 2011]. The GFIT algorithm fits the measured CLARS-FTS spectrum to a spectral model derived from laboratory and theoretical line lists. These line lists are the same as those used in retrievals obtained by instruments that are part of NASA’s Total Carbon Column Observing Network (TCCON) network. The primary source is the High-resolution transmission (HITRAN) 2012 line list with modifications in some cases from empirical “pseudo line lists” derived from atmospheric spectra. The line list for solar absorption lines is an example where empirical observations are used.

The GFIT algorithm was designed for use with spectrometers that observe the direct solar beam, e.g. the FTIR instruments in the TCCON network, and the Mark IV balloon FTIR. For this viewing geometry, the observed radiance is dominated by the direct sun and therefore the optical path is well-defined. For CLARS observations however, aerosol scattering can make a significant contribution. Under highly polluted conditions where aerosol loading is significant, or when there are high or low clouds in the optical path, the CLARS retrievals become significantly more uncertain and some degree of filtering and/or flagging is required to identify these measurements. Using a numerical radiative transfer model, Zhang et al. estimated the bias in CLARS  $\text{CO}_2$  and methane retrievals with moderate aerosol loading [Zhang et al., 2015]. While this work proposed a new method for bias correction, this approach was not employed in the present work because the correction algorithm has not yet been implemented in the CLARS operational retrieval code. Rather, the retrievals of molecular oxygen are used to filter data that are affected by aerosol scattering. Using 6-hour National Centers for Environmental Prediction (NCEP) surface pressures, the  $\text{O}_2$  SCD is calculated using the known dry-air atmospheric mixing ratio of 0.2095. These values are compared with CLARS  $\text{O}_2$  retrievals; soundings that depart from the NCEP values by more than a certain fraction are filtered from the data stream.

The retrieved SCDs of methane and  $\text{CO}_2$  are converted to slant column-averaged dry air mixing ratios,  $X_{\text{methane}}$  and  $X_{\text{CO}_2}$ , by normalizing to the retrieved SCD of  $\text{O}_2$  ( $\text{SCD}_{\text{O}_2}$ ) (Eq. 6).

$$X_{\text{GHG}} = \frac{\text{SCD}_{\text{GHG}}}{\text{SCD}_{\text{O}_2}} \times 0.2095 \quad (6)$$

Individual retrievals are analyzed with multiple post-processing filters to ensure data quality. Spectra are filtered out when the residual root mean square errors of the fits to the GFIT radiative transfer model exceed a pre-defined threshold. These are usually associated with aerosols, high and low clouds, electrical or mechanical noise, and other transient

behavior. Details about the CLARS-FTS design, data retrieval algorithm and data filtering process are described in Fu et al. (2014), Wong et al. (2015, 2016). Following Wong et al. (2015, 2016), we calculated the excess Xmethane and XCO<sub>2</sub>, due to the emissions from the basin, by subtracting the corresponding SVO measurements from the LABS observations (Eq. 7).

$$XGHG_{XS} = XGHG_{LABS} - XGHG_{SVO} \quad (7)$$

Several studies have reported strong correlations between methane and CO<sub>2</sub> measured in the PBL in source regions (Peischl et al., 2013; Wennberg et al., 2012; Wunch et al., 2009; S. Newman, personal communication, 2014). Slopes of methane–CO<sub>2</sub> correlation plots have been identified with local emission ratios for the two gases. Since the uncertainty in methane emissions is considerably larger than that in CO<sub>2</sub> emissions, we may use the correlation slope to reduce the methane emission uncertainties. In this study we determined the spatial variation of methane:CO<sub>2</sub> ratios originating from CLARS-FTS measurements between September, 2011 and December, 2016.

We have delivered to the data portal the background-corrected values of the methane:CO<sub>2</sub> ratio (R) for each sounding. The data file also includes the name of each reflection point, measurement day and time (centroid of the interferometer scan), target lat/lon, R value, 1-sigma uncertainty of the R value and two data flags which indicate the presence of low and high clouds. This information, combined with a high-quality CO<sub>2</sub> emission inventory downscaled to the LA basin can be used to estimate methane fluxes (as described in Wong et al 2015 and Wong et al 2016).

To explore the overall monthly variability of R during the 2011 through early 2017 period, we calculated the weighted-average regression slope among all the reflection points in the LA basin using equation 8. In Eq (8),  $r_i$  is the regression slope for reflection point  $i$ ,  $w_i$  is the weighting factor which is defined as the reciprocal of the square of the 1 $\sigma$  uncertainty of the methane:CO<sub>2</sub> regression slope,  $\sigma_i$ .

$$R_{monthly}^{CLARS} = \frac{\sum_i r_i w_i}{\sum_i w_i} \quad (8)$$

where  $w_i = \frac{1}{\sigma_i^2}$

Following Wong et al. (2015, 2016) we estimate monthly methane emissions from the South Coast Air Basin using the methane:CO<sub>2</sub> regression slope, R, determined from the CLARS observations and an inventory-based estimate of monthly CO<sub>2</sub> emissions (eqn. 9)

$$E_{CH_4}^{top-down}_{monthly} = R_{monthly}^{CLARS} \times E_{CO_2}^{inventory}_{monthly} \times \frac{MW_{CH_4}}{MW_{CO_2}} \quad (9)$$

where,  $MW_i$  is the molecular weight of methane or CO<sub>2</sub>.

As discussed by Wong et al. (2016), there are several choices available for  $E_{CO_2}^{\text{inventory}}|_{\text{monthly}}$ . These use a number of different grids, underlying data sources and approaches to downscaling to the SCAB. We have elected to use the Hestia fossil fuel CO<sub>2</sub> emissions data product which provides sectoral bottom-up emissions at the building and street level on hourly timescales (<http://hestia.project.asu.edu>).



Figure 3-12. Relative location of the CLARS facility on Mt Wilson and basin reflection points.

#### 4. Interim Results

Conservative assumptions were used for a preliminary analysis of data collected in phase 1. The interim findings are summarized in section 1 and here. The following important caveats apply to these results:

1. 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.
2. Estimates of emission rates will not be available until wind information and other variables are properly accounted with plume modeling and other analyses in phase 2. The observations and findings associated with methane source sectors described in this phase 1 interim report are therefore limited to frequency of occurrence, plume size, plume enhancement (concentration of methane in plume relative to background cleaner air) and attribution of plumes to likely source infrastructure.
3. The Vista-CA GIS data set is still undergoing review and revision. While this information was used to support the following analysis, related findings about source attribution may change in phase 2.
4. Airborne data collection won't be complete until phase 2 and hence findings about the distribution of sources in this phase 1 interim report are incomplete.
5. Given the degree of variability and episodic activity observed for many source types and it is possible that this interim report under-estimates the actual source population. This is particularly true for dairies and other sectors with highly variable processes. Follow-up observations of key sectors and areas in phase 2 of this project and related NASA projects may help further constrain the degree of variability and provide a more complete assessment.
6. With a few exceptions, most of the sources reported in this phase 1 interim report have not yet been verified with surface measurements. This project is 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. Additional effort will be made in phase 2 to improve attribution.
7. Given the above caveats it is premature to make definitive statements about the root cause for most of the methane sources detected in phase 1. In other words, at this time it cannot be determined which sources are normal process emissions such as periodic venting as opposed to a leak or other malfunction. A few exceptions in phase 1 are noted where a root-cause was confirmed (through surface follow-up measurements or through consultation with a facility operator).



#### 4.1. Airborne survey statistics

The actual implementation of the phase 1 airborne survey was influenced by the planning activity described in Section 3.3, response to discovery of methane plumes (e.g., follow-up observations), and impacts due to weather and aircraft availability.

##### 4.1.1. Survey completeness

The Phase 1 survey covered approximately 177,784 distinct facilities and infrastructure components (out of 229,644 candidates) spanning 15,216 km<sup>2</sup> of land area at least once (Figure 3-1). A significant fraction of these lines were flown more than once, resulting in 23,176 km<sup>2</sup> total area coverage. Approximately 132 hours of flights were conducted between September 10 and November 4, 2016. Table 4-1 summarizes flight hours relative to the three broad regions shown in Figure 4-1, north of Fresno (white), between Fresno and Lompoc (black), and south of Lompoc (gray). Of the 132 total flight hours, 38 hours (28.8%) were used to map the region north of Fresno, 62.5 (47.3%) between Fresno and Lompoc, and 31.5 (23.9%) south of Lompoc. Flight hours are also organized in Table 4-2 by AVIRIS-NG flight boxes for the 3 major categories of emissions as shown in Figure 3-6.



**Figure 4-1** As-flown flight lines (green) for AVIRIS-NG Fall 2016 survey. The coverage of the completed lines is not identical to the boxes shown in Figure 3-6 due to modifications to the initial flight plan and the addition of two mini-intensive flight campaigns to map high pressure natural gas transmission lines in the LA Basin and an area near Visalia. Regional

boxes indicate three regions of study, north of Fresno (white), between Fresno and Lompoc (black), and south of Lompoc (gray).

**Table 4-1 Phase 1 flight hours by regions (see Figure 4-1)**

<b>Region</b>	<b>Flight hours</b>	<b>Percentage</b>
North of Fresno, CA	38.0	28.8%
Center (Fresno to Lompoc, CA)	62.5	47.3%
South of Lompoc, CA	31.5	23.9%
<b>Total</b>	<b>132.0</b>	<b>100.0%</b>

Table 4-2 Phase 1 flight hours by major emission categories reflecting the relative focus of CEC and CARB: energy (e.g., oil and gas), non-energy sectors (e.g., landfills, manure management, wastewater treatment, etc), and mixture of these categories (see Figure 3-6)

<b>Flights targeting</b>	<b>Flight hours</b>	<b>Percentage</b>
Energy sector	56.5	42.8%
Non-energy sector	35.5	26.9%
Mixture of energy and non-energy	40.0	30.3%
<b>Total</b>	<b>132.0</b>	<b>100.0%</b>

Compared with the Vista-CA GIS data set the phase 1 survey achieved a completeness per emission sector that ranged from 20 to 100% (see Figure 4-2 and Table 4-3). 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 phase 1 survey focused on only the likely top emitters – the 60 facilities predicted to be responsible for 90% of California’s landfill methane emissions based on bottom-up estimates from CARB.



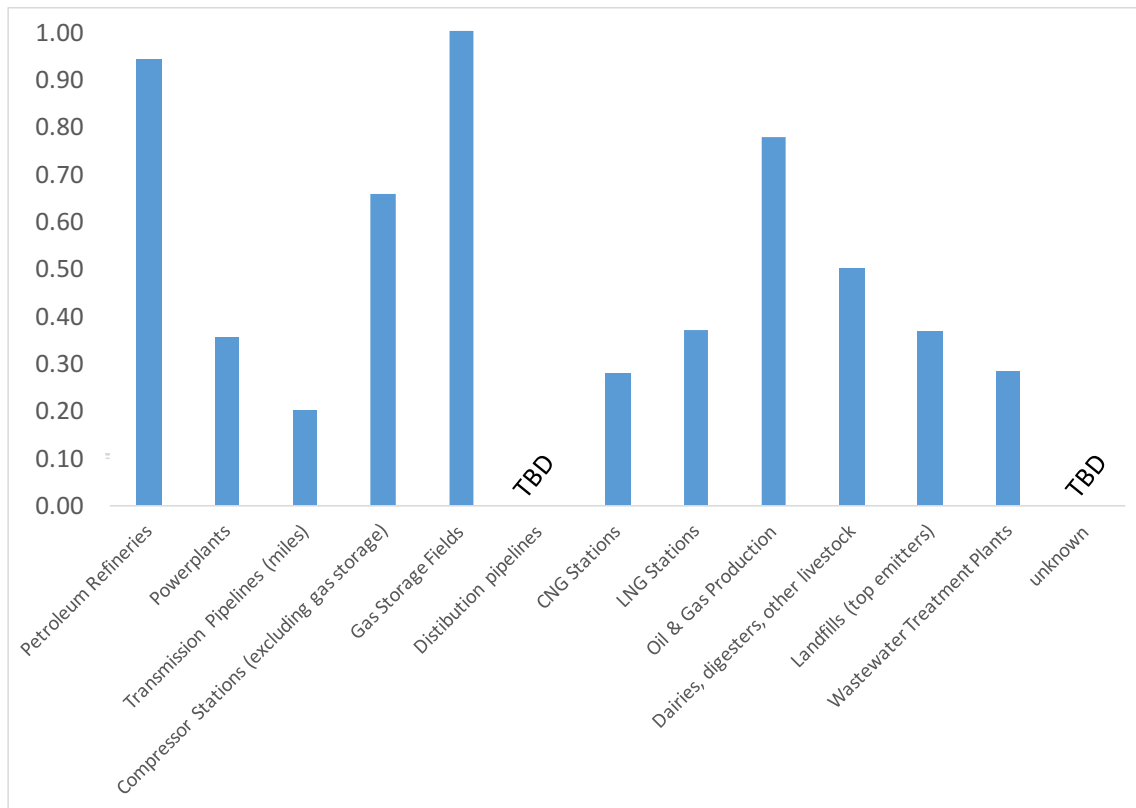


Figure 4-2 Phase 1 survey completeness by infrastructure type

Table 4-3 Phase 1 survey completeness by IPCC Sector

IPCC Sectors	Methane Emitting Sector	Total Features in Vista-CA	Features surveyed in phase 1	Fractional completeness
1A1 Energy Industries	Petroleum Refineries	17	16	0.94
	Powerplants	468	166	0.35
1B2 Oil and Natural Gas	Transmission Pipelines (miles)	11,939	2,393	0.20
	Compressor Stations (excluding gas storage)	32	21	0.66
	Gas Storage Fields	12	12	1.00
	Distribution pipelines	TBD	TBD	
	CNG Stations	334	93	0.28
	LNG Stations	46	17	0.37
	Oil & Gas Production	227,276	176,712	0.78
3A2 Manure Management	Dairies, digesters, other livestock	1,709	851	0.50
4A1 Managed Waste Disposal	Landfills (top emitters)	60	22	0.37
4D Wastewater Treatment & Discharge	Wastewater Treatment Plants	152	43	0.28
TBD	unknown	TBD	TBD	
<b>Totals</b>		<b>229,621</b>	<b>177,771</b>	<b>0.77</b>

In terms of temporal completeness the phase 1 survey sampling ranged from one visit per source to multiple visits distributed over September to November 2016. 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.

#### 4.1.2. Distribution of methane sources

The locations of the 329 confirmed point sources are shown in Figure 4-3, 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.

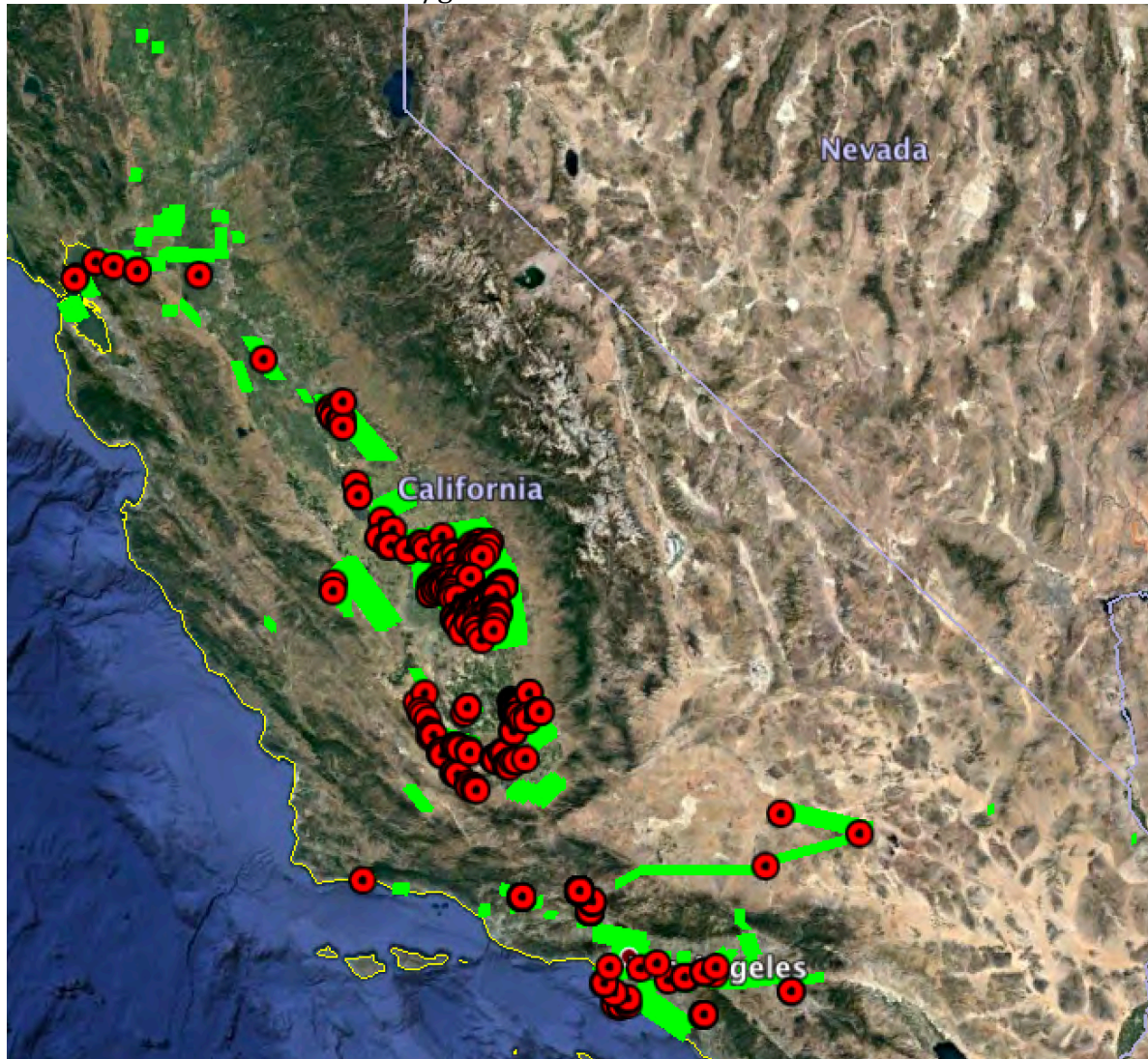


Figure 4-3 Spatial distribution of sources (red markers) and phase 1 flight lines (green).

The distribution of detected methane point sources by IPCC emission sector is summarized in Figure 4-4 and Table 4-4 and by infrastructure type in Table 4-5. Note that there is significant uncertainty regarding the assignment of sources to sector 1A1 (combustion related activity) and sector 1B2 (oil and gas fugitives) for refineries. This will be studied further in phase 2. Table 4-4 offers some preliminary 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). Additional spatial and

temporal sampling in phase 2 should help with scaling survey results to the total population.

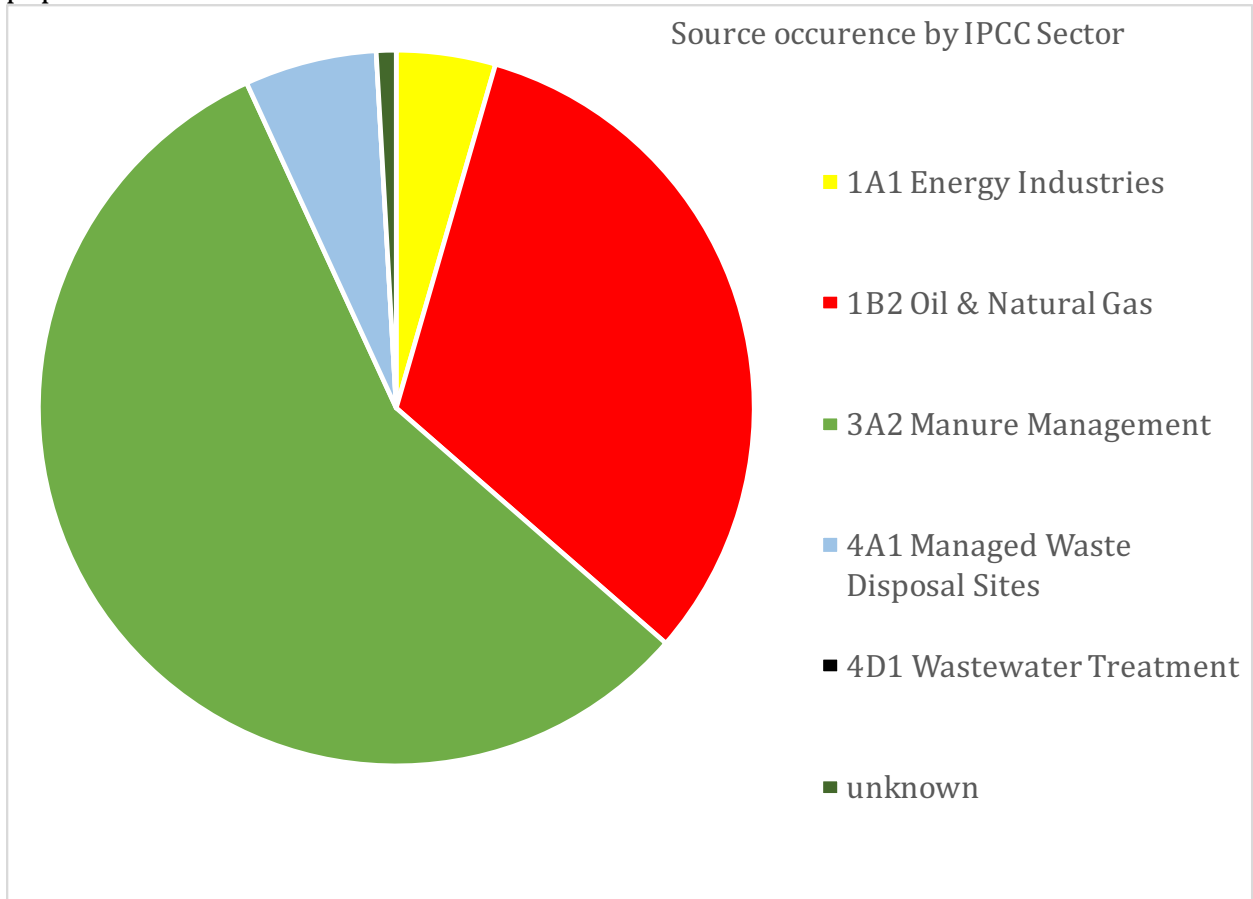


Figure 4-4 Distribution of sources by relevant IPCC emission sectors

Table 4-4 Distribution of sources by relevant IPCC emissions sectors and fraction of total infrastructure population (from Vista-CA)

IPCC Sectors	Methane Emitting Sector	Number of CH <sub>4</sub> sources	Fraction of Features with $\geq 1$ CH <sub>4</sub> source
1A1 Energy Industries	Petroleum Refineries	15	0.94
	Powerplants	0	0.00
1B2 Oil and Natural Gas	Transmission Pipelines (miles)	0	0.00
	Compressor Stations (excluding gas storage)	1	0.05
	Gas Storage Fields	3	0.25
	Distribution pipelines	1	0
	CNG Stations	0	0
	LNG Stations	1	0.06
	Oil & Gas Production	99	5.6E-04
3A2 Manure Management	Dairies, digesters, other livestock	186	0.22
4A1 Managed Waste Disposal	Landfills (top emitters)	19	0.86
4D Wastewater Treatment & Discharge	Wastewater Treatment Plants	0	0
TBD	unknown	4	0
<b>Totals</b>		<b>329</b>	<b>1.9E-03</b>

Table 4-5 provides more source categories than Tables 4-3 and 4-4. This is particularly true for oil and gas production fields. Also note that table 4-5 also includes an “unknown” category, indicating that some sources have not yet been conclusively attributed to a known infrastructure type. Oil/gas stack refers to flaring stacks and other combustion or vent towers associated with oil and gas production.

Table 4-5 Distribution of sources by infrastructure type.

<b>Source types</b>	<b>Sources detected</b>	<b>Percentage</b>
crop irrigation	3	0.9%
dairy/manure	176	53.5%
dairy/manure - digester	4	1.2%
gas compressor	3	0.9%
gas distribution line	1	0.3%
gas LNG station	1	0.3%
gas CNG station	0	0.0%
gas storage facility	3	0.9%
landfill	19	5.8%
oil/gas compressor	2	0.6%
oil/gas drill rig	2	0.6%
oil/gas gathering lines (TBD)	10	3.0%
oil/gas pumpjack	33	10.0%
oil/gas stack	3	0.9%
oil/gas tank	19	5.8%
oil/gas unknown infrastucture	28	8.5%
oil/gas waste lagoon	1	0.3%
other livestock	3	0.9%
refinery	14	4.3%
unknown	4	1.2%
water treatment plant	0	0.0%
<b>Total sources</b>	<b>329</b>	<b>100.0%</b>

As previously discussed, estimation of emission rates will be required to provide quantitative assessments of the contributions of each methane source relative to the population of point sources and the State methane inventory. That work is planned for phase 2. Meanwhile Figure 4-5 plots the mean Integrated Methane Enhancement (IME)

values estimated for 304 sources (robust IME estimates have not yet been derived for the remaining 25 sources due to complications such as contrast issues). IME estimates are not directly equivalent to emission rates since the latter depend on wind speeds that vary spatially and temporally. However, that variability is minimized here somewhat by averaging given that many of these sources were sampled on multiple dates and times during the phase 1 campaign. Hence the mean IME values presented here offer a simple method for assessing the relative strength of the point sources detected in phase 1. The logarithmic curve in figure 4-5 indicates that 10% of the sources contribute nearly 60% of the total IME in the source population. A study of the source database in Appendix A indicates that the top 20 sources include emitters from every sector. This will be further explored in phase 2.

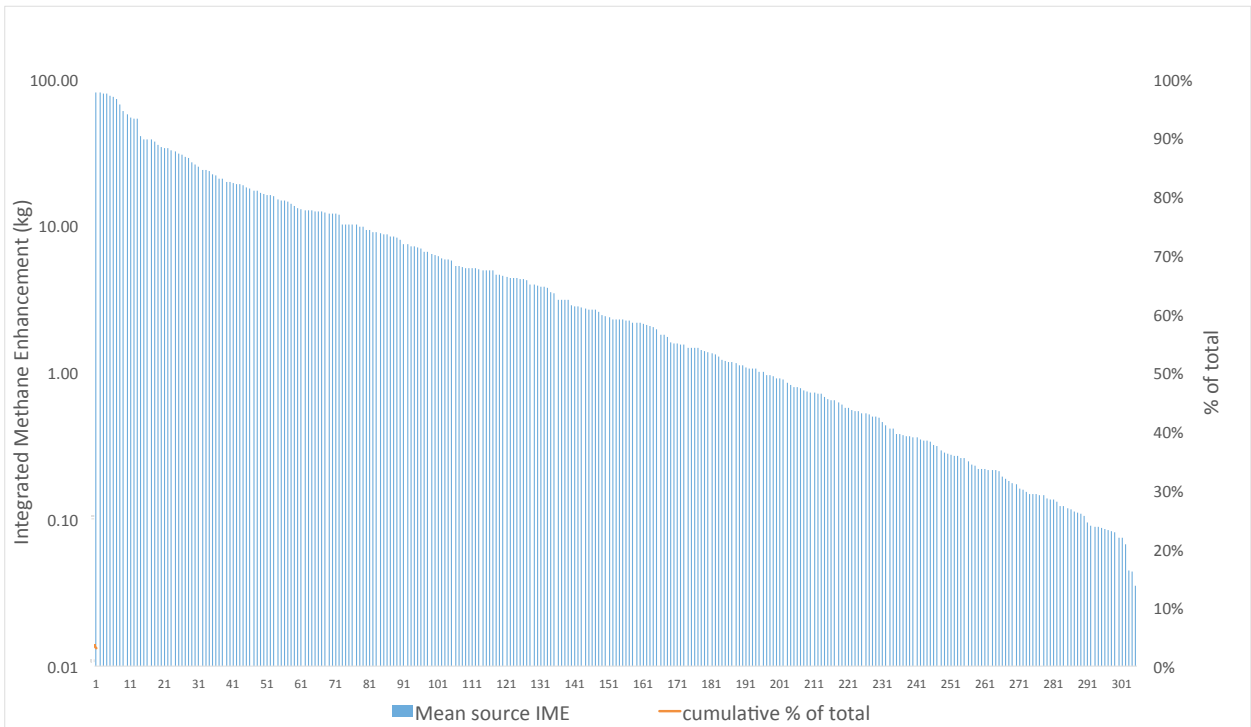


Figure 4-5 Distribution of mean Integrated Methane Enhancements (IMEs) for most of the point sources detected in phase 1 and their cumulative contributions to the total.

#### 4.2. Sector specific findings

Each of the following sections provide examples of plume images and findings for each key methane point source emission sector. The appendix of this report contains many more examples but these are representative. As discussed previously, in phase 2 these analyses will be updated to incorporate quantitative emission flux estimates – towards assessing the relative and net contribution of point sources to methane emissions from key sectors and regions.



#### 4.2.1. Oil and gas production

Over 75% of major oil and gas production fields in California were surveyed at least once in phase 1. Notable exceptions were fields in the Sutter Buttes and Santa Maria area fields that will be surveyed in phase 2. Generally, the vast majority of methane sources associated with oil and gas production appear in Kern county. In particular, Kern Front, Elk Hills and Midway Sunset - where most of the State's oil and associated gas production is currently underway – are noteworthy. Only a few strong methane point sources have been detected so far in other oil and gas fields surveyed in phase 1.

In Kern county, Storage tanks and wellheads/pumpjacks were responsible for the largest fraction of observed oil and gas sources (Figures 4-6 and 4-7). Many of these sources seem to persist for months based on repeated flights during the phase 1 study and earlier NASA airborne surveys in 2014 and 2015. Some oil and gas production sources may include leaks in gathering lines. Ten potential gathering line sources were identified however these are challenging to pinpoint and validate and so remain TBD.

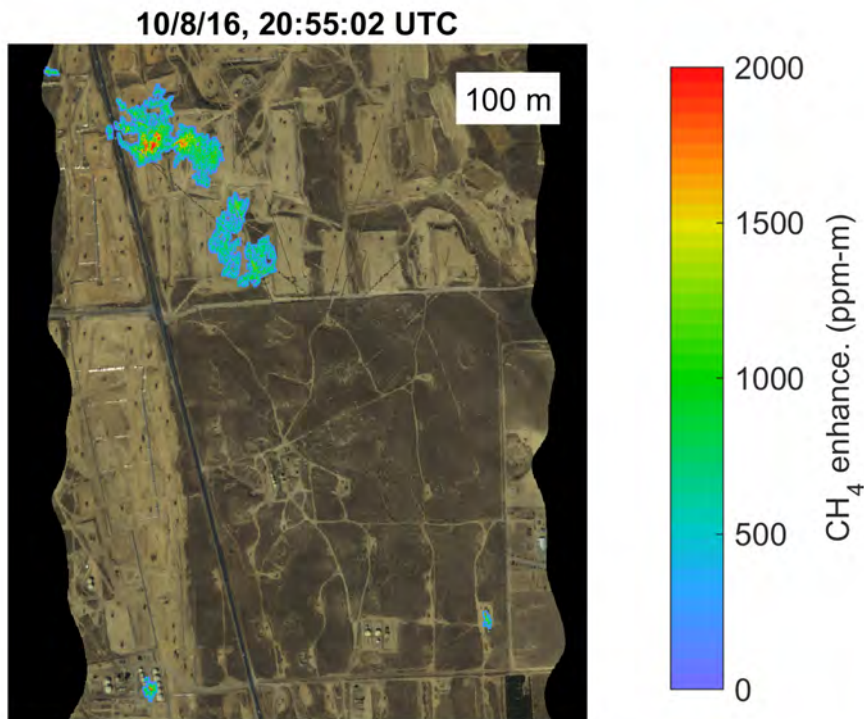


Figure 4-6. Typical methane sources in Kern Front oil field. Common sources include storage tanks, well heads and (potentially) gathering lines.

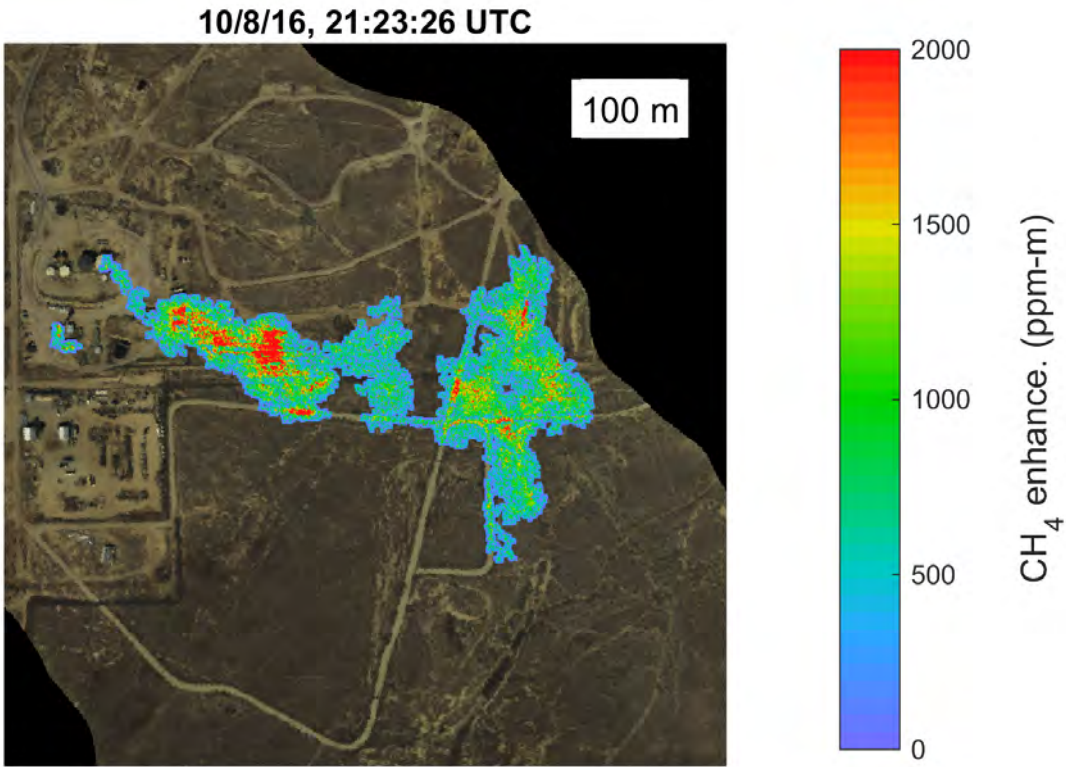


Figure 4-7 Closeup of typical methane plume from a gas storage tank in Kern Front oil field. This plume has persisted over multiple years including precursor NASA campaigns since 2014.

The prevalence of methane plumes varies significantly by oil and gas field. The Poso Creek and Kern Front fields exhibited 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 4-8). Based on DOGGR data for Fall 2016 there is no obvious correlation with production rates (e.g., Poso Creek and Kern Front oil production rates were less than 20% the Kern River production rates for that period). Additional data collection and analysis will be conducted in phase 2 to further study potential root-causes.

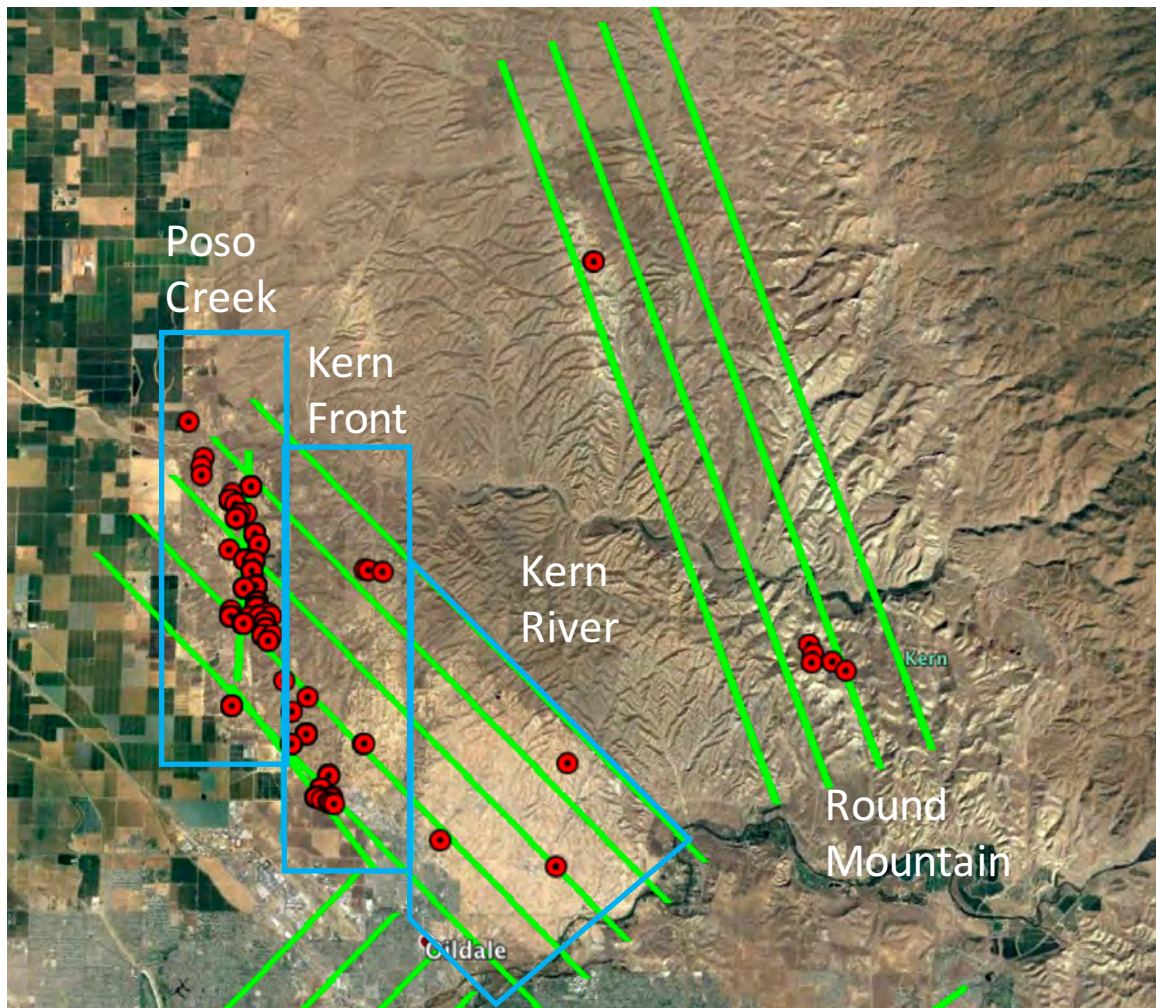


Figure 4-8 Significantly higher densities of methane sources (red markers) were observed in Poso Creek and Kern Front oil fields than others in eastern Kern County.



Some facilities such as the 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 4-9). As noted previously, attribution of sources to combustion vs fugitives carries some residual uncertainty and will be studied further in phase 2.

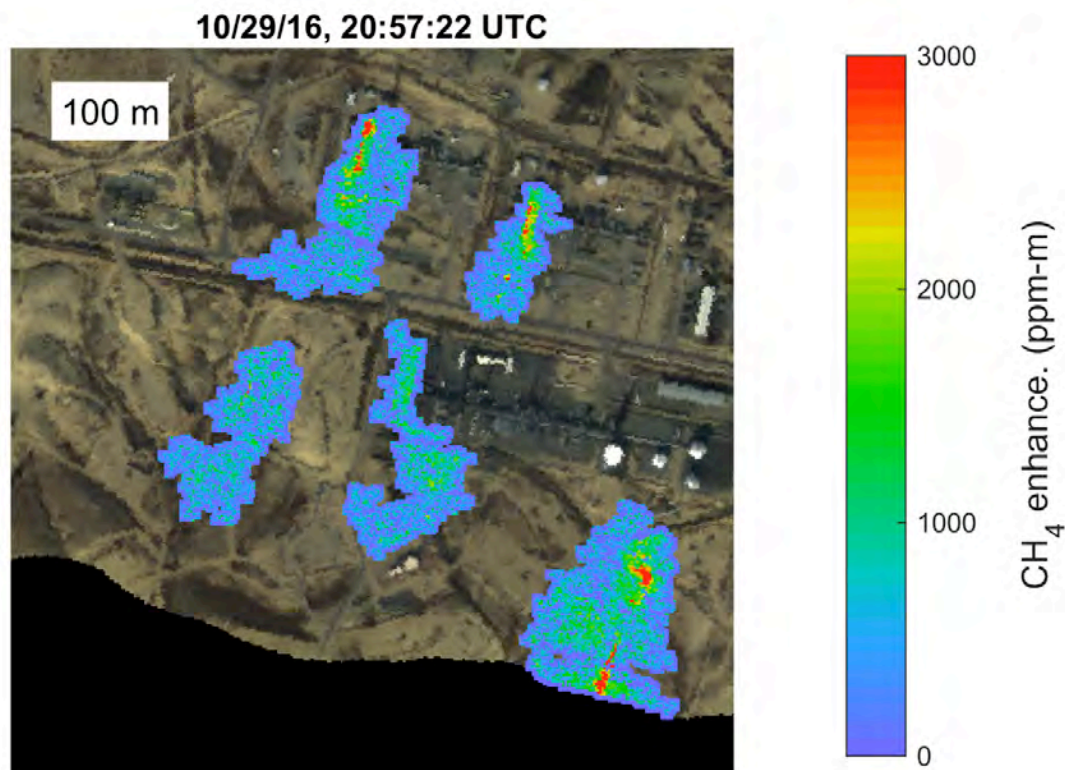


Figure 4-9 Gas processing facility in Elk Hills showing methane plumes from two of three large compressors (top) and one or more flaring stacks (bottom).

#### 4.2.2. Natural gas transmission, storage and distribution

Long linear features such as gas transmission pipelines were not a priority in phase 1. Only about 20% of transmission lines in the State were covered – primarily limited to a three day intensive assessment of the natural gas supply chain in the South Coast Air Basin. No methane sources directly associated with transmission pipeline leaks were detected. For transmission line compressor stations associated only one exhibited an observable methane plume during overflights. Additional attention may be given to the transmission sector in phase 2.

Each of the State’s 12 active underground gas storage facilities were surveyed at least once in phase 1. Some were surveyed multiple times, particularly Honor Rancho, MacDonald Island (Figure 4-10), and Aliso Canyon. Aliso Canyon was in a standby state during the phase 1 campaign and while there were signs of methane in the area no obvious plumes were present. Honor Rancho and MacDonald Island presented relatively large plumes. Both a persistent and episodic source were observed at Honor Rancho. The persistent source was potentially associated with a leaking bypass valve and emergency shutdown stack. The episodic source appeared to be related to compressor activity during gas injection. Plumes were observed at a few of the other storage facilities but they were relatively small and barely detectable. Given the observed episodic nature of methane emissions at storage facilities additional attention will probably be devoted to this sector in phase 2.

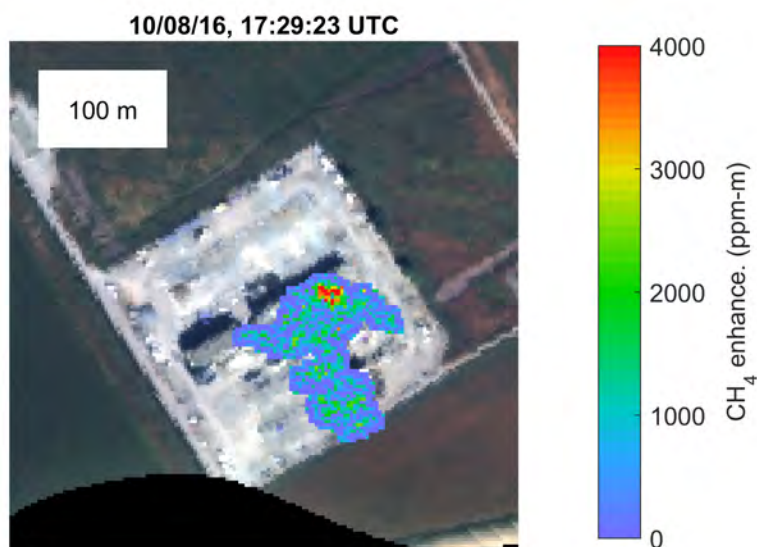


Figure 4-10 Example of methane plume at McDonald Island gas storage facility, south complex.

California’s natural gas distribution infrastructure spans several large urban areas. The phase 1 survey primarily focused on priority areas in the South Coast Air Basin. A single leak in a low pressure gas distribution line was pin-pointed in the vicinity of Chino Hills following detection from persistent regional monitoring by the Megacities Carbon Project<sup>‡</sup>. Figure 4-11 illustrates the AVIRIS-NG search pattern covering a 60 km<sup>2</sup> 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 confirmed and repaired the leak within 24 hours.

Phase 2 will likely devote additional attention to distribution infrastructure in other urban areas.

<sup>‡</sup> <https://megacities.jpl.nasa.gov/portal/>

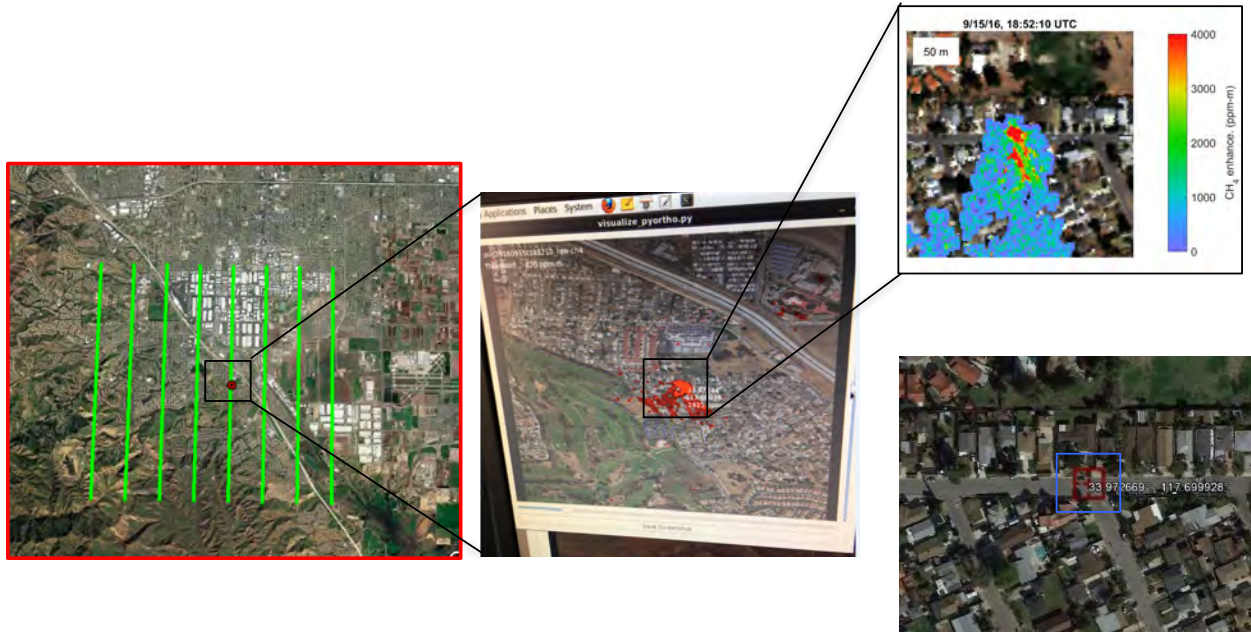


Figure 4-11 Detection of leak in gas distribution line in Chino Hills. Left: AVIRIS-NG flight pattern, middle: real-time detection software on airplane, right: processed methane plume image and geolocation of source to within 10 meters.

#### 4.2.3. Refineries

Strong methane plumes were observed at nearly every refinery sampled in phase 1. There appears to be a diverse set of sources at refineries – ranging from storage tanks (either venting from relief valves or leaks) to uncombusted methane from various processes – see Figure 4-12. Note that there is significant uncertainty regarding the assignment of sources to sector 1A1 (combustion related activity) and sector 1B2 (oil and gas fugitives) for refineries. This will be studied further in phase 2.

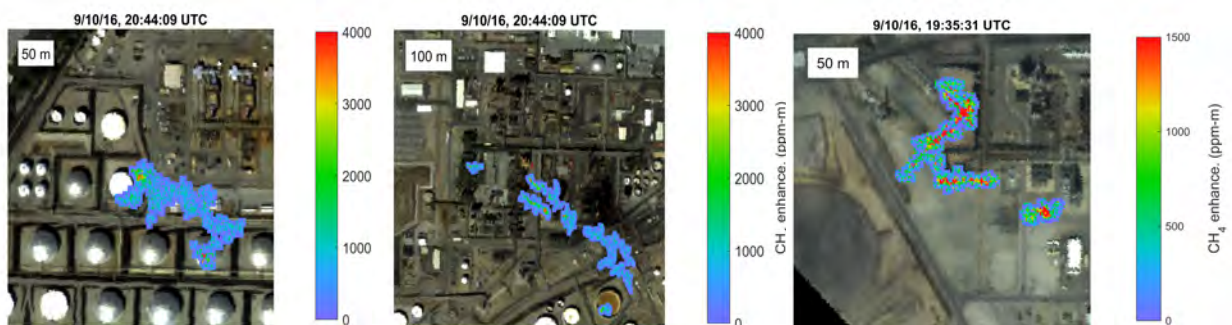


Figure 4-12 Examples of methane plumes from refineries in the LA basin. (Left) venting or leaking storage tanks, (Center) unknown source (TBD infrastructure), (Right) incomplete combustion from 3 flaring stacks. Note the smaller concentration scale for the image on the right.



#### 4.2.4. Power Plants

Despite surveying 166 power plants (over 30% of the State’s fossil fueled generating stations) there was no evidence of large methane plumes from this sector. This may be expanded in phase 2 to cover more power plants including cogeneration facilities State-wide.

#### 4.2.5. Landfills

In order to prioritize flight hours for this sector, CARB’s database of landfill methane emissions (over 370 facilities) was used to identify 60 likely highest emitters, collectively predicted to contribute 90% of landfill emissions in California. 22 of these facilities were surveyed at least once (several were surveyed multiple times) in phase 1. Methane plumes were observed at all but two of the 22 surveyed facilities. A smaller fraction of landfills exhibited very large methane plumes.

Figure 4-13 illustrates multiple strong methane plumes at the Sunshine Canyon landfill. Phase 1 flights identified strong methane plumes that persisted in sections of this facility over several months. While these features are observed at a subset of other landfills, Sunshine Canyon consistently presented the largest plumes under all conditions.

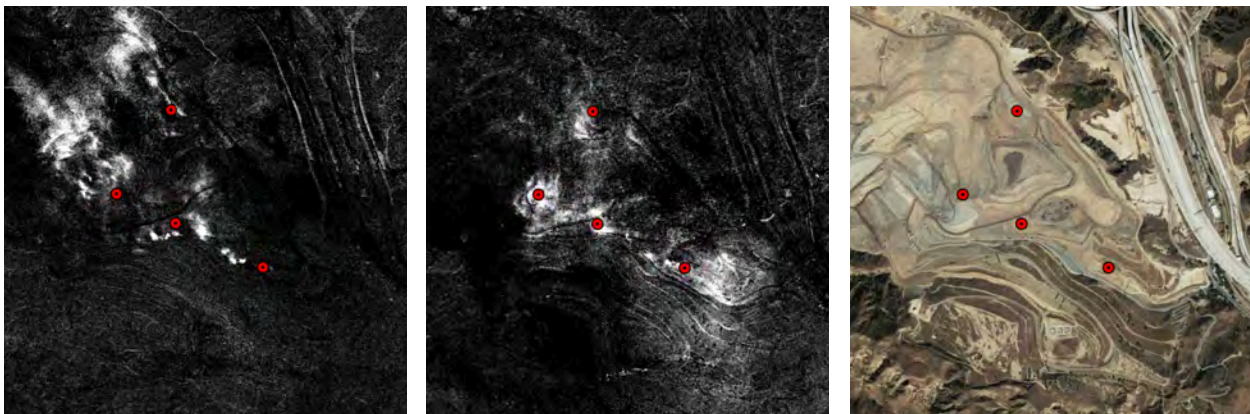


Figure 4-13 Four persistent methane plumes at Sunshine Canyon landfill. Left: raw methane images (white pixels indicate higher methane enhancements) for September 11, 2016, center: same for October 3, 2016, right: satellite image of the facility. The variability in plume shape is due to changing wind conditions. Red markers indicate the average location of the 4 sources observed at the facility.

In phase 1 there was a general lack of agreement between CARB bottom-up estimates of individual landfill emission rates in Southern California compared to the mean source enhancements estimated by AVIRIS-NG. A simple analysis for 10 landfills in the SoCAB predicted to be high emitters is presented in Figure 4-14. The absence of a blue bar at a given facility indicates that AVIRIS-NG did not detect any strong methane plume. One explanation for the observed disagreement at Puente Hills landfill is that facility was shut-down between the CARB bottom-up 2014 estimate and the Fall 2016 AVIRIS-NG overflights. Methane plumes were observed at Puente Hills landfill during a NASA airborne study in July 2014. Figure 4-14 does not provide a direct comparison of emissions and hence the blue bars should not be interpreted to mean that measured emissions in 2016 were lower than in the 2014 CARB estimate.

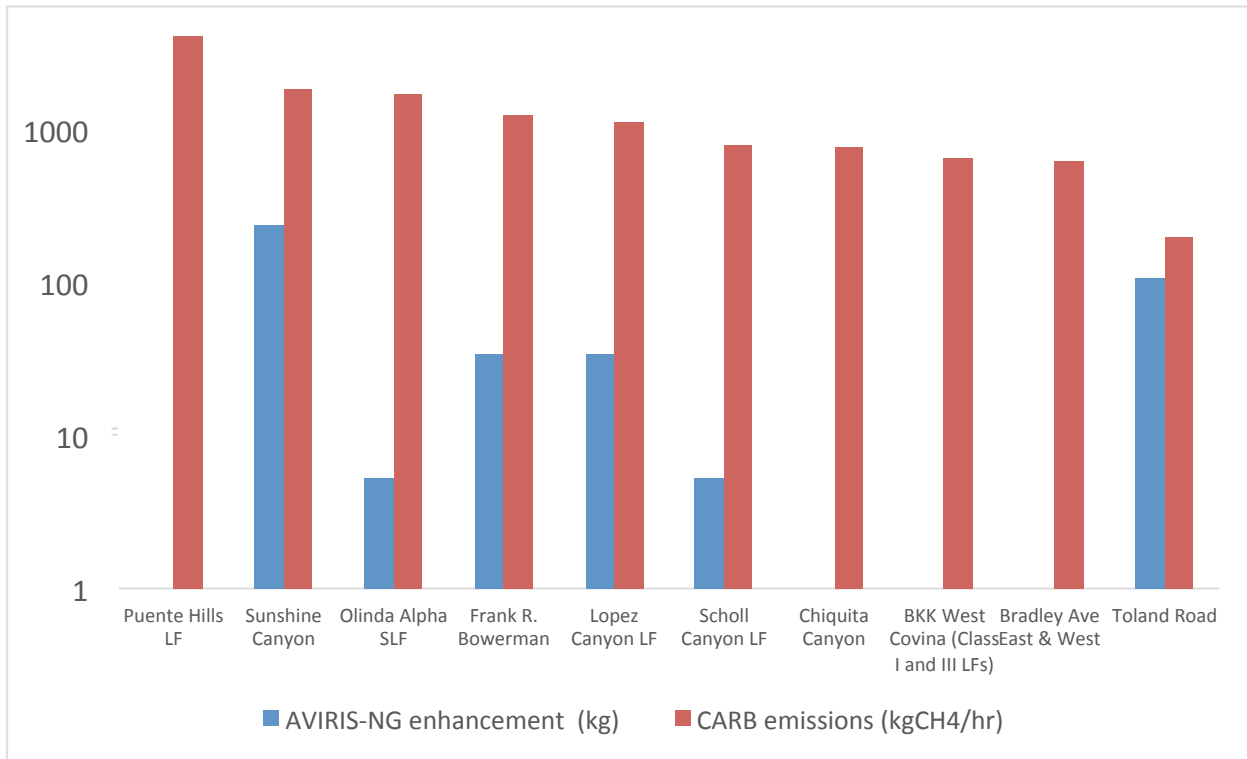


Figure 4-14 Relative assessment of 10 landfills in SoCal predicted to be high methane emitters: comparing CARB 2014 bottom-up emissions estimates (units kgCH<sub>4</sub>/hr) for each facility and Fall 2016 AVIRIS-NG mean integrated methane enhancement estimates (units kg) for observed plumes. Note the common logarithmic scale. These quantities are not directly equivalent. In particular, until emission estimates are derived from the AVIRIS-NG enhancement measurements it would be premature to interpret this plot as meaning actual emissions are lower than the 2014 CARB estimates (in fact, the opposite is more likely).

Fewer flights were conducted over northern California in phase 1 than planned due to cloudy conditions there in Fall 2016 and other factors. This translated to reduced coverage for landfills and waste water treatment facilities in the San Francisco Bay Area. Subsequent flights over these areas were conducted in June 2017 as part of a NASA airborne campaign. An effort will be made in phase 2 to incorporate those new data sets into this analysis including quantitative estimates of emission rates.

#### 4.2.6. Waste water treatment

Waste water treatment facilities were surveyed in phase 1 but primarily limited to the SoCAB where no major methane plumes were observed. This may be revised in phase 2 pending analysis of data collected during the aforementioned NASA June 2017 campaign.

#### 4.2.7. Dairies and livestock

Livestock manure management – particularly in the San Joaquin Valley (SJV) – is recognized as one of the top methane emission sectors in California. Our Phase 1 survey results are consistent with this given that wet manure management – particularly settling ponds and anaerobic lagoons – is responsible for over 50% of methane point source plumes observed in this study. The phase 1 study covered about 850 known dairies in the State – about half of the total population. A robust assessment of the individual and net emissions from dairies and other livestock facilities in California is complicated by several factors. Figure 4-15 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 raises the question: why weren’t methane 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 area 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.

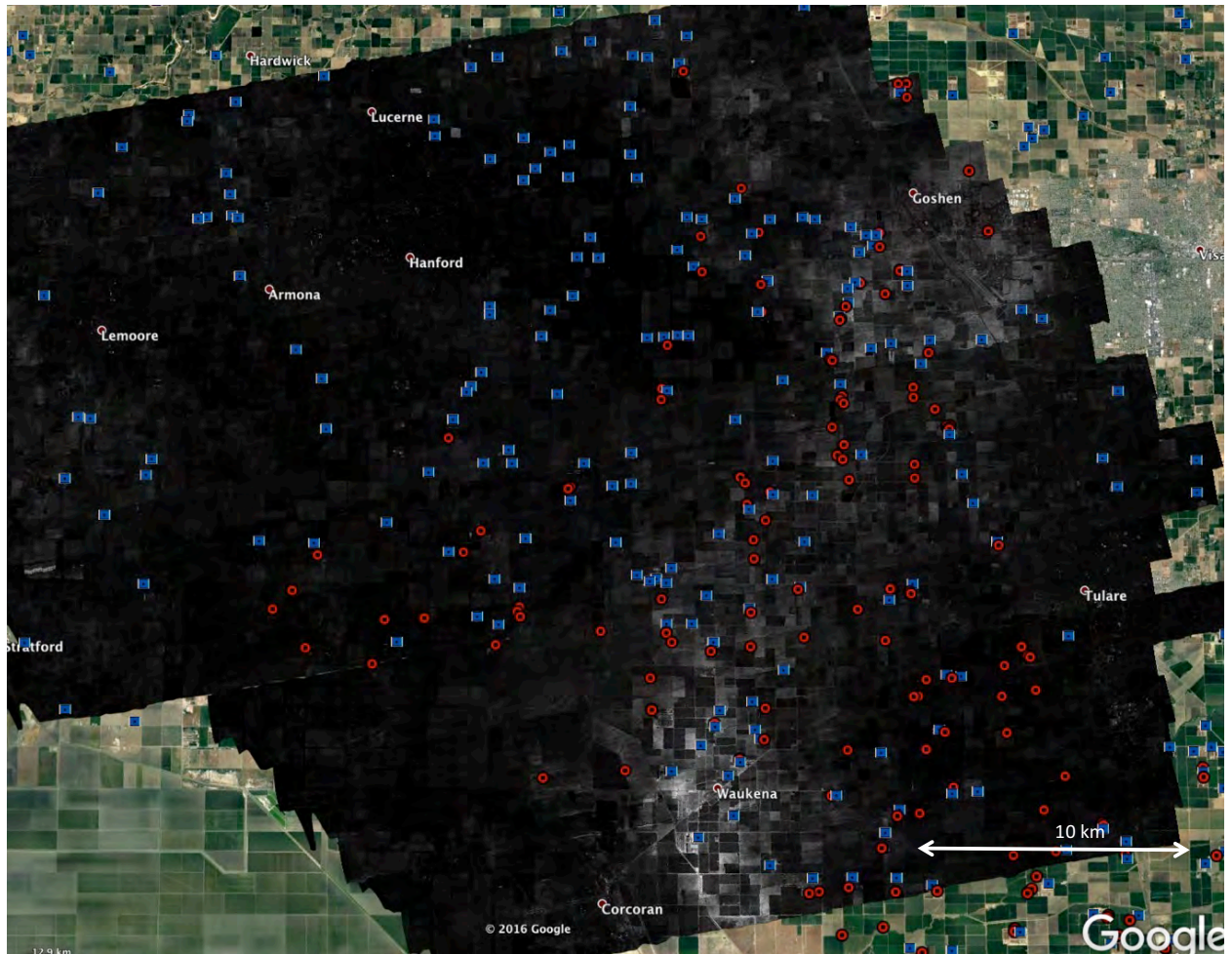


Figure 4-15 Mosaic of two days of AVIRIS-NG flight lines over Tulare county dairies. The raw grayscale image overlays represent areas with lower (black) and higher (white) levels of atmospheric methane. The striking gradient seen here suggests either a dense concentration of emission sources around Waukena and Goshen and/or an accumulation of enhanced levels of methane in these areas due to meteorological effects. Atmospheric transport modeling will likely be required to disentangle those effects. Blue square indicate the known locations of dairies. Red markers indicate methane point sources detected during these overflights.

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.



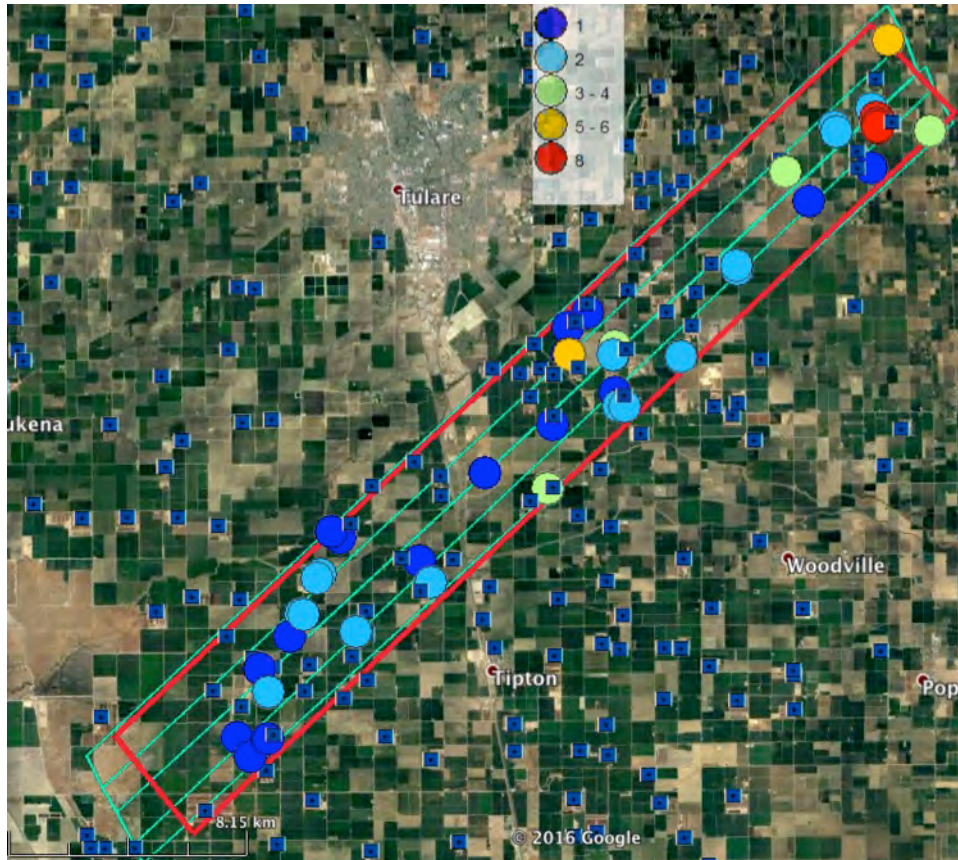


Figure 4-16 Plot of methane point source variability for an intensive study of 50 dairies near Tipton. AVIRIS-NG repeated the same flight lines with a roughly 40 minute revisit interval per line over a 5 hour period. The colors indicate the number of times a source was observed during that period. Some of the sources were persistent – others were more variable.

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 4-16 and 4-17 (e.g., surveys with insufficient revisit frequency can fail to detect sources through aliasing).



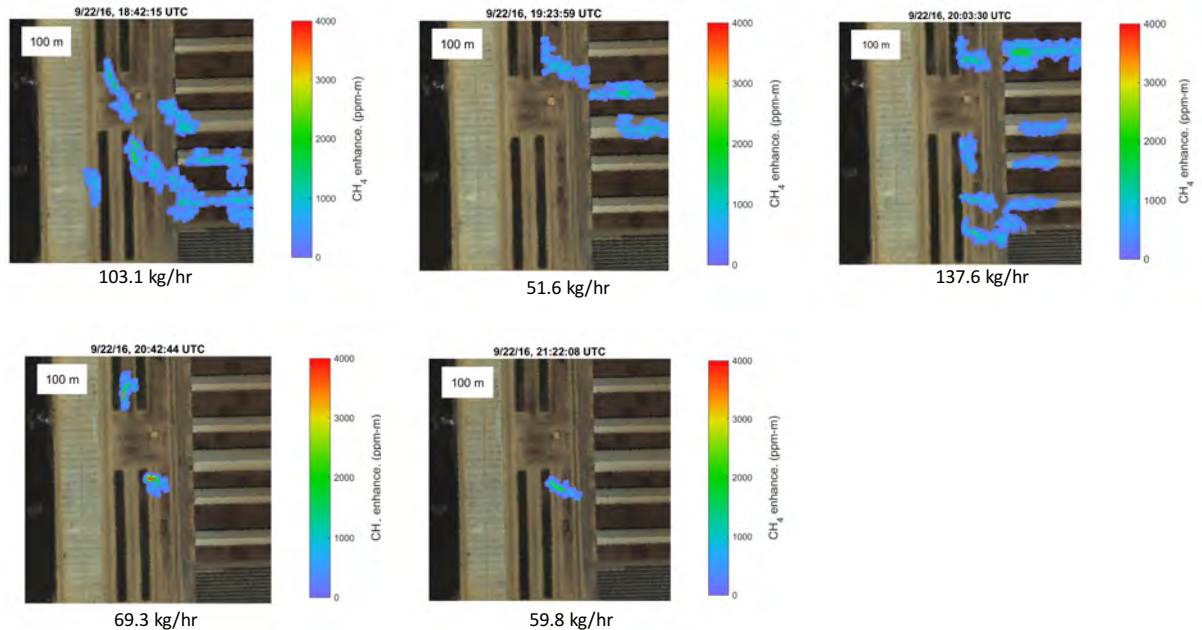


Figure 4-17 Close-up of a dairy in figure 4-15. Each image shows methane plumes for snapshot in time, each separated by about 40 minutes - indicating significant diurnal variability in emissions.

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 phase 1 survey covered about 22 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 our phase 1 study indicated the presence of significant methane point sources at four facilities in the SJV. Figure 4-18 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.

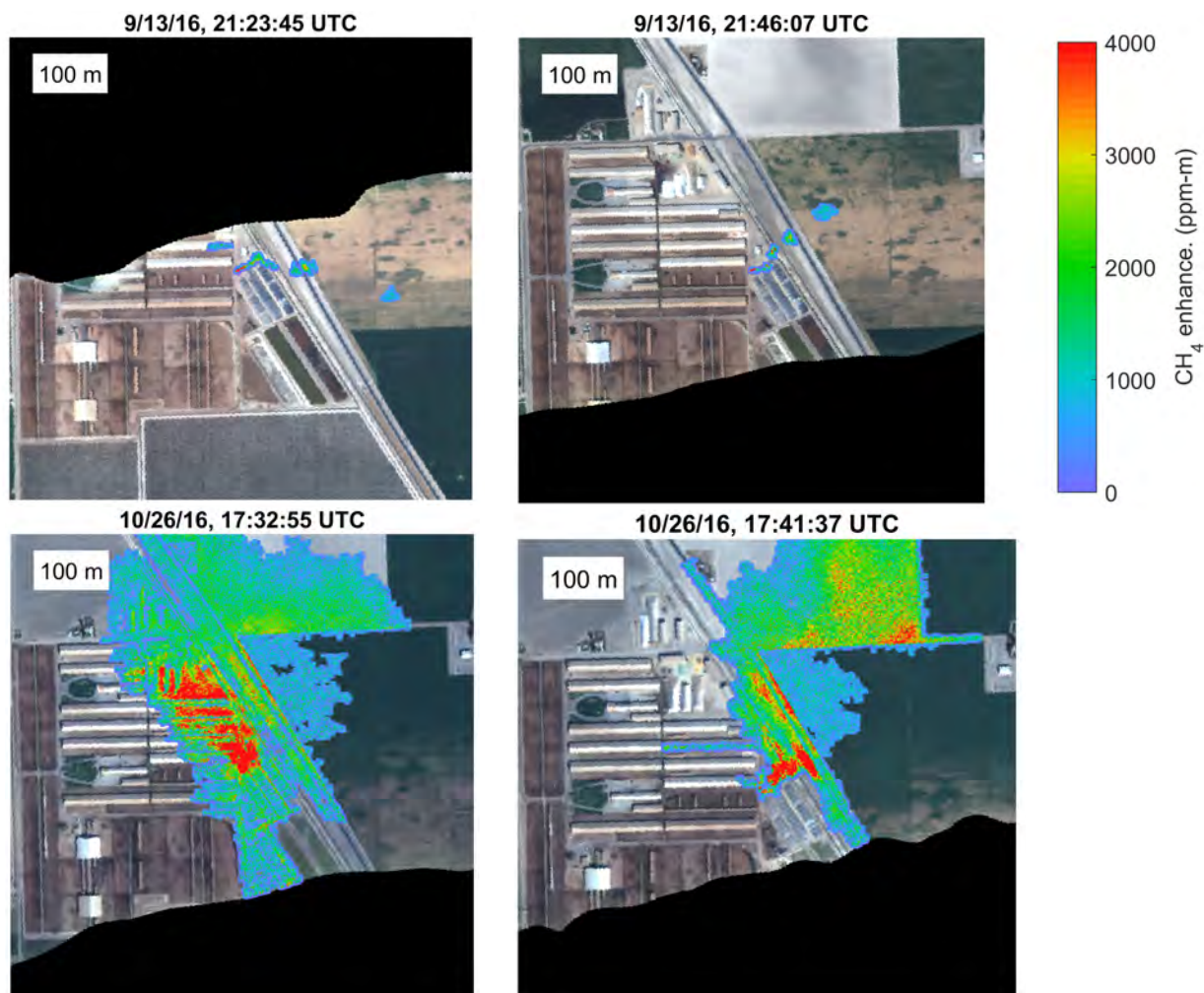


Figure 4-18 Example of methane emissions plume observed repeatedly at methane dairy digester in the SJV. The difference in plume appearance between the two dates is attributed to different wind speeds.

### 4.3. South Coast Air Basin methane trends and variability

As described in section 3.5, JPL's CLARS facility on Mt Wilson provides persistent monitoring of methane fluxes in the South Coast Air Basin. The CLARS tracer-tracer flux estimation method provides basin-scale, monthly averaged methane emission estimates. This project contributed to extending the established CLARS time series (2011-2015) through spring 2017.

The CLARS data products for this work consist of text files posted on the JPL Megacities Carbon Project data portal<sup>§</sup>. There is a read\_me file which discusses the format and interpretation of each data field.

<sup>§</sup> [https://megacities.jpl.nasa.gov/public/Los\\_Angeles/Remote\\_Sensing/CLARS\\_RRNES/](https://megacities.jpl.nasa.gov/public/Los_Angeles/Remote_Sensing/CLARS_RRNES/)

Figure 4-19 shows the extended time series of monthly methane emissions calculated using eq. (9) [section 3.5]. Shaded areas represent the  $1\sigma$  uncertainties in the derived methane emissions. Uncertainties are propagated from the uncertainties in CLARS  $X_{\text{methane}(XS)}:X_{\text{CO}_2(XS)}$  regression slopes and  $\text{CO}_2$  emissions. For  $\text{CO}_2$ , we assumed a 10% uncertainty in the Hestia monthly  $\text{CO}_2$  emissions. Fig. 4-20 plots the seasonal variability of CLARS-FTS inferred methane emissions for each year from 2011-2016. As noted in Wong et al (2016), while the choice of  $\text{CO}_2$  inventory can affect the estimated methane flux, the methane/ $\text{CO}_2$  regression slope  $R$  is a purely measured quantity and it shows consistent seasonal variability. Also as noted in Wong et al. (2016), the inferred methane emissions estimates show a bimodal distribution with peaks during the summer and late summer/early fall. A striking feature in Figure 4-19 is the apparent absence of the Aliso Canyon gas leak’s impact on the SoCAB methane flux. In fact, the basin flux did increase significantly and consistently with the known Aliso Canyon leak rate however the normal seasonal variability in the SoCAB makes the impact difficult to see at this scale. The Aliso Canyon gas leak effectively increased the duration of the normal winter spike in SoCAB methane emissions by about two months.

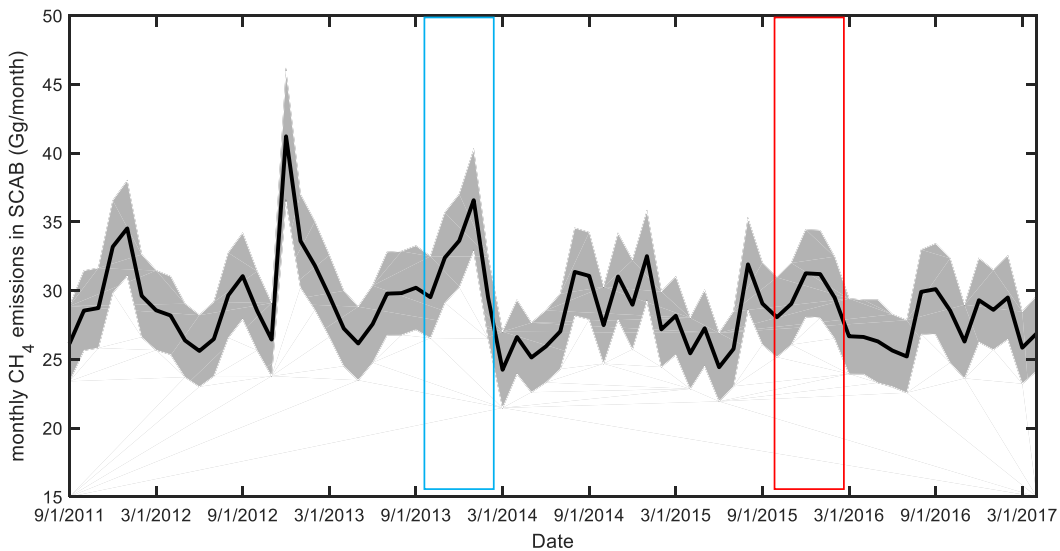


Figure 4-19 CLARS time-series of SoCAB monthly average methane emissions from 9/2011-3/2017. The gray shading indicates uncertainty bounds. The red box covers the period of the Aliso Canyon gas leak in fall 2015-winter 2016. The blue box provides a reference for comparing the Aliso Canyon incident with the fall/winter spike in 2013-2014.

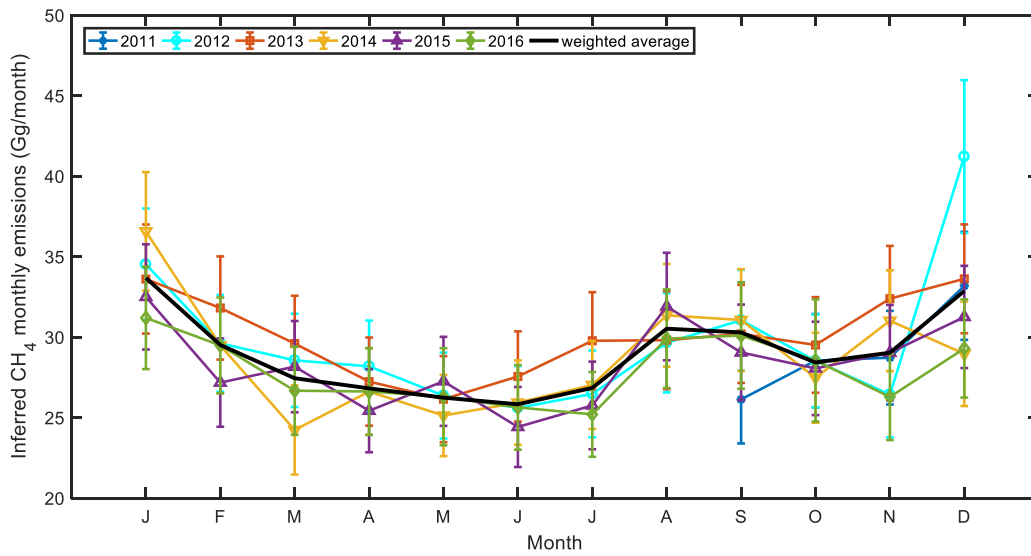


Figure 4-19 Comparison of SoCAB methane seasonal variability by year.

Fig. 4-20 shows the annual SoCAB methane emissions from 2011-2016. The central values for each year show a small decreasing slope beginning in 2013 but the trend is not statistically significant within the uncertainties of the emissions estimation method.

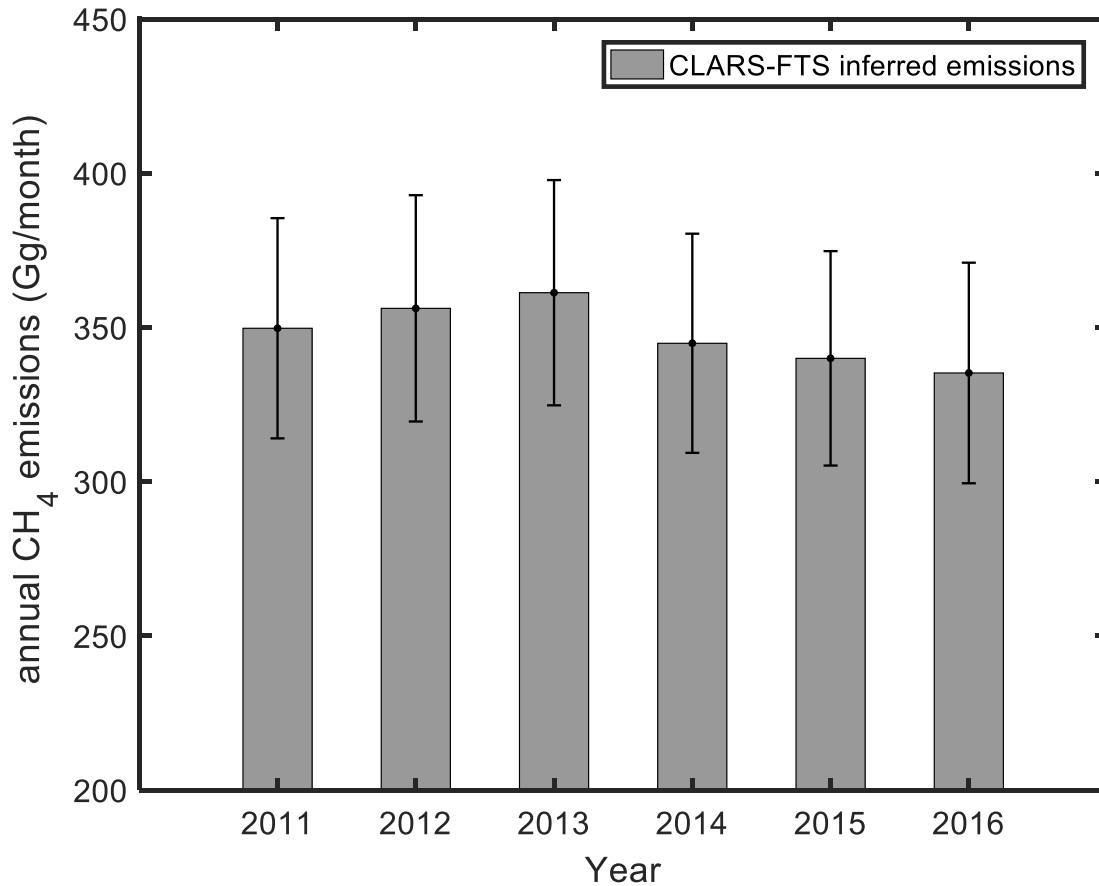


Figure 4-21 CLARS time-series of SoCAB annual methane emissions.

Additionally, CLARS's daily, spatially resolved scans of Xmethane/XCO<sub>2</sub> correlation ratios across much of the SoCAB demonstrated the ability to directly detect the atmospheric impact of large anomalous methane emission sources such as the Aliso Canyon gas leak. Figures 4-22 and 4-23 provide examples of CLARS methane maps during and following that incident. Future improvements in CLARS data processing and analysis frameworks could enable the ability to rapidly detect and locate large methane hot spots in the SoCAB. Such a capability, if combined with rapid-response airborne imaging spectroscopy such as AVIRIS-*ng* to precisely geolocate sources, could be important in cases where sudden leak onset occurs in remote or unmonitored locations (and/or in cases involving methane that has not been treated with an odorizing agent).



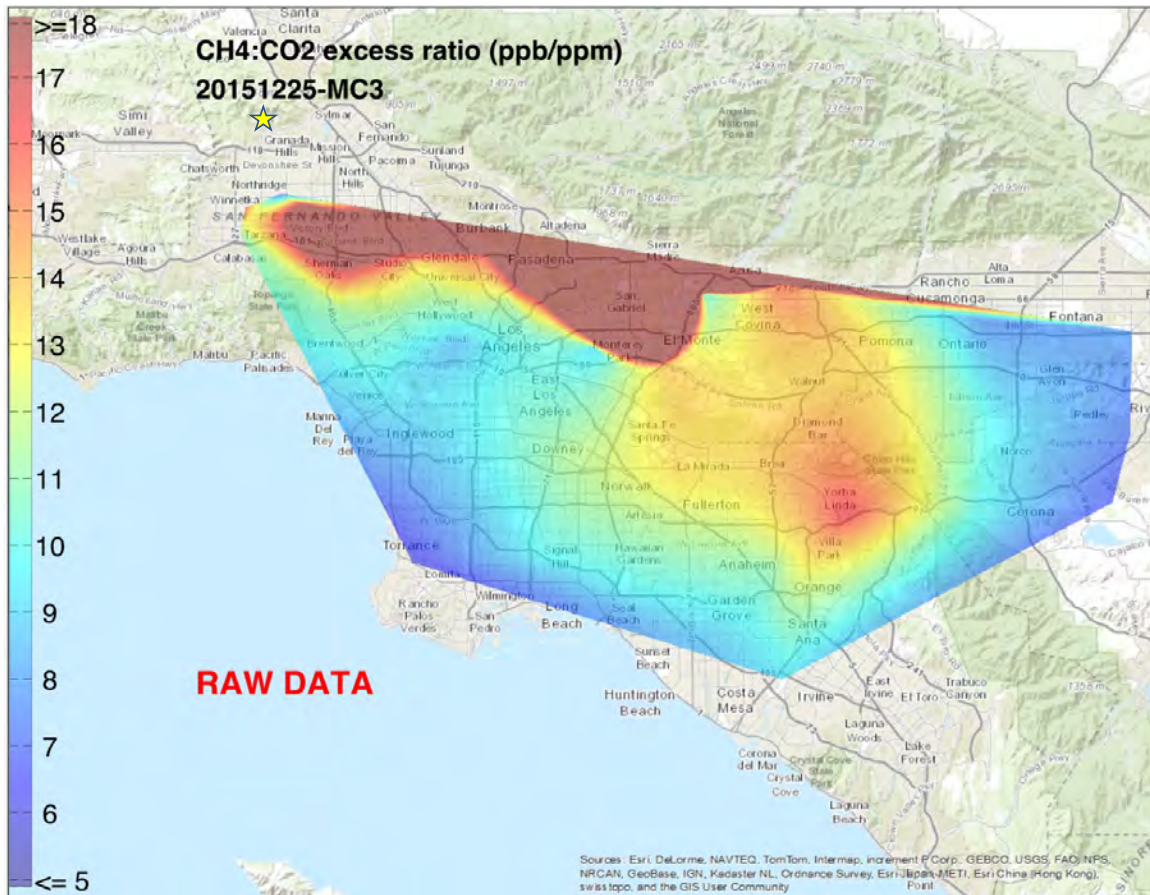


Figure 4-22 CLARS map of Xmethane/XCO<sub>2</sub> correlation ratios for measurement cycle 3 (early afternoon) on December 25, 2015. The high (red) values indicate a plume of methane extending from the San Fernando Valley across the LA basin. The yellow star indicates the location of the Aliso Canyon gas leak (well SS25) source.

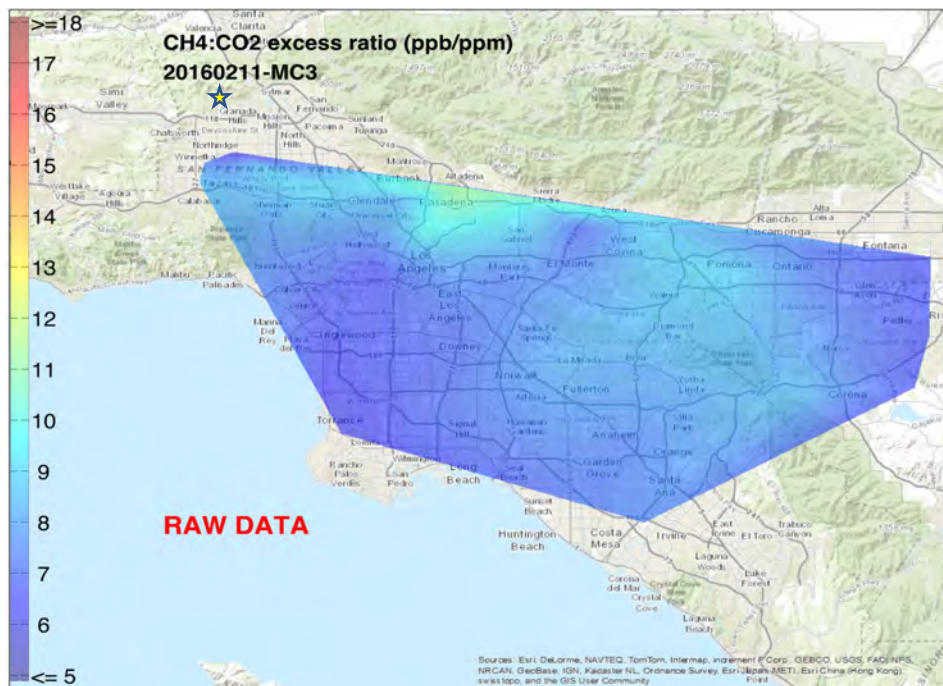
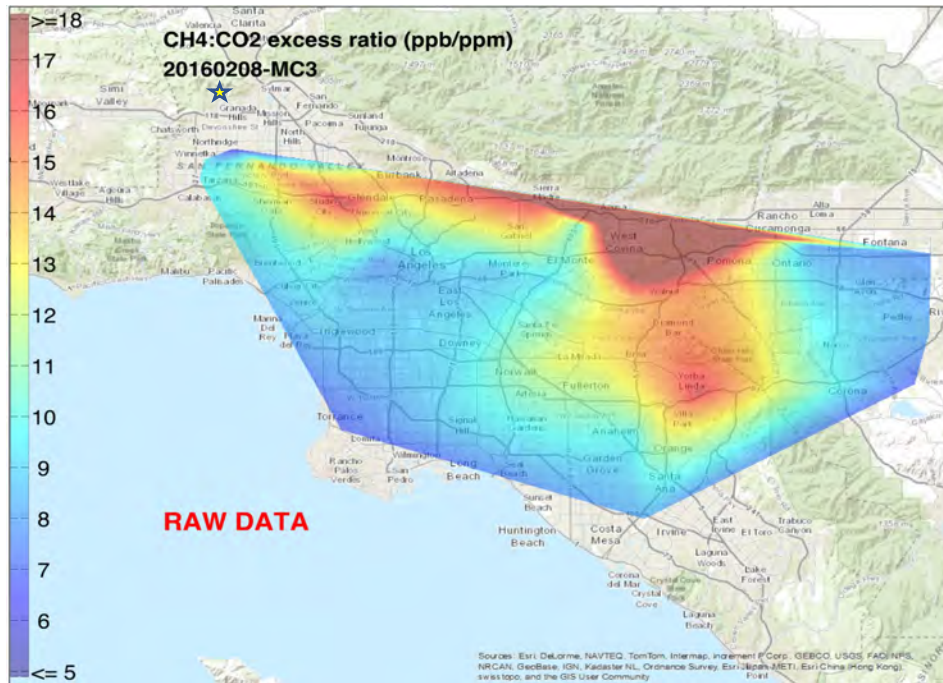


Figure 4-23 Same as figure 4-18 but for early afternoon on February 8, 2016 (top) and February 11, 2016 (bottom). The Aliso Canyon leak was plugged on the morning of the 11<sup>th</sup>.

## 5. Conclusions

JPL is applying advanced remote sensing methods to detect and characterize anthropogenic methane (methane) emissions in California to support the State’s objectives for mitigation of short-lived climate pollutants (California 2013, 2017), identification of methane “hotspots” in response to AB1496 (California 2015), and supporting natural gas leak detection and correction for rate-payer benefit.

Phase 1 of the first comprehensive survey of methane point sources in California has been completed. All objectives for phase 1 have been met. Phase 1 primarily used data collected in 2016 and addresses CARB priorities spanning IPCC methane emission sectors relevant to point sources in California. Phase 2 will collect data in 2017 and focus on CEC priorities, particularly the natural gas sector, to improve understanding of leaks and to help enable mitigation. This interim report summarizes the Phase 1 activity and findings including lessons that will inform data collection and analysis strategies for Phase 2 as well as future research projects. A final report will be produced at the conclusion of Phase 2.

Significant, preliminary insights have been gained in phase 1 regarding the distribution of methane point sources and some of the controlling processes. In addition to the findings summarized in the Executive Summary some major lessons-learned include:

1. More attention is required to address the challenge of episodic activity in key methane emission sections including repeated airborne remote-sensing surveys and persistent regional-scale monitoring. This is particularly true for dairy emissions and will likely require additional research beyond the scope of this project to answer key questions about relative and total emission fluxes and controlling processes.
2. Future advances in imaging spectroscopy have the potential address area sources (e.g., enteric fermentation, rice cultivation, and wetlands) as well as the point sources described here. In particular, improving the spectral resolution of an AVIRIS-NG class imaging spectrometer from the current 5 nm to 1 nm could enable such advances [Thorpe et al 2016b].
3. 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 relatively small leaks in natural gas infrastructure. Future improvements in measurement and analysis frameworks could support operational, rapid-response versions of such systems.

As planned, additional data collection and analysis in phase 2 of the project will be performed to validate the interim findings and address the open questions reported here. That phase 2 activity is planned to include another 6-8 week airborne campaign in Fall 2017 followed by analysis and interpretation. It may also incorporate data and findings from recent NASA funded research campaigns in California. A key new element for the phase 2 report will be inclusion of emission/flux estimates.

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