CENTER FOR SPACE POLICY AND STRATEGY

JUNE 2020

MAPPING METHANE SUPER-EMITTERS IN OIL AND GAS FIELDS: A TIERED REMOTE SENSING STRATEGY

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Summary

Methane is a potent greenhouse gas (GHG) that is emitted from many anthropogenic sources, including livestock, landfills, agriculture, coal mining, and oil and gas activities. This paper focuses on the upstream petroleum sector, where U.S. current methane inventories vastly underestimate fugitive emissions. Understanding how emissions occur during oil and gas production can help industry and regulators consider new ways to find, prioritize, and recover escaping natural gas emissions of which the primary component is methane. A practical and tiered remote sensing approach using satellite, airborne, and ground-based sensors will improve local, regional, and international understanding of methane emission sources and rates.

California has an opportunity to lead and become the first state to control GHGs. California can start by gathering and fusing remote sensing data to provide actionable information on methane emissions, including mitigation, enforcement, and best policies and practices that could be extended to national and international scales. The natural gas industry also has an opportunity to further elevate its status as the cleanest burning fossil fuel by ensuring that its entire environmental lifecycle, which includes upstream production, is free from fugitive emissions.

Introduction

According to the Environmental Protection Agency (EPA), the San Joaquin Valley (SJV) has "some of the nation's worst air quality, failing to meet federal health standards for both ozone (smog) and particulate pollution."[1] The SJV Air District is federally classified as severe nonattainment, which means it does not meet the federal ground-level ozone and particulate matter standards.[*] For decades, numerous studies have underscored this point, proving that the SJV is one of the most polluted regions in the country. According to the California Department of Public Health statistics from 2013 to 2016, Kern County's death rate due to Chronic Lower Respiratory Disease (CLRD) is 12 times higher than that of California and 14 times higher than that of the United States.[2,3]

Multiple sources contribute to the air pollution problem, including agriculture, animal husbandry, landfills, transportation, and oil and gas extraction. Air quality problems, such as those facing California's Central Valley, will continue if the sources of air pollution are not mitigated. If the

[*] Less than 10 microns in diameter (PM10).

source is a *point source*†, such as an oil well, identifying exactly where the problem exists is a logical first step toward addressing that leak or fugitive emission. Despite many of the wells in the SJV region being over 90 years old, they continue to pump oil and emit high amounts of methane.[4]

This paper presents data from an airborne hyperspectral sensor survey that discovered a plethora of methane emitters in producing California oil fields. It also suggests that regulators should adopt a sustainable multi-platform remote sensing strategy for locating regional methane anomalies, imaging point source emissions, and mitigating leaks. Without an ongoing comprehensive methane monitoring program, California will not meet its statewide air regulation requirements to reduce smog, ozone, GHGs and associated asthma and other respiratory illnesses.‡ Moreover, the state will not be able to efficiently find and address new leaks, which could expose communities near upstream oil and gas facilities to unnecessary health and safety hazards.

Background: Economics, Environmental Liabilities, and Super-emitters

There is a pressing need to find leaking oil and gas infrastructure in California and the rest of the world. In March 2020, the COVID-19 pandemic drove crude oil prices to record 20-year lows after the global demand for energy plummeted due to reduced travel and industrial output. Historically, low oil prices have resulted in increased bankruptcies, as many domestic producers require a $40 per barrel threshold to break even for shale production. At today's oil prices§, we can expect to see increased bankruptcies for both large and small domestic producers, which could lead to a surge in the number of abandoned oil and gas assets or "orphan" wells. Even before the plunge in oil prices, the number of orphaned wells increased. Normally when oil or gas wells reach the end of their useful productive life, operators are required to decommission and plug their wells according to state plug and abandonment regulations. However, if an operator becomes insolvent, the state is often left with the responsibility to properly plug the well.[5]

According to a 2017 study by the California Council on Science and Technology,[6] there are approximately 229,000 oil and gas wells in the state of which about 122,000 have already been plugged. The 2017 report estimates that approximately 5,540 wells could already be at risk of becoming orphaned and an additional 69,425 wells, which are either "economically marginal or idle could become orphan wells in the future as their production declines and/or as they are acquired by financially weaker operators." This orphan well situation in California and other producing states underscores the need for a sustainable multi-platform remote sensing strategy for locating methane emitters and leaking wells. A combination of satellite sensors, airborne methane plume imaging, and in-situ sensors can help California find leaks, prioritize enforcement, and consider mitigation for those wells that were not properly decommissioned and plugged.

Surveys to detect extreme emitting sources are particularly valuable because a small share of the oil and gas producing infrastructure is responsible for a

† The United States Environmental Protection Agency (EPA) defines *point source pollution* as any contaminant that enters the environment from an easily identified and confined place.
‡ California's Clean Air Act waiver (2013) allows the state to introduce more stringent regulations than the federal Clean Air Act. The waiver is part of a larger package of policies the state has adopted in recent years to reduce smog and asthma rates and to lower CO_2 emissions.
§ As of June 8, 2020, West Texas Intermediate prices were $34 per barrel.

large share of total emissions, with this subset often referred to as *super-emitters*. During 2017, the Environmental Defense Fund (EDF) measured methane emissions, comparing top-down (airborne measurements of ambient concentrations) with bottom-up (ground-based emissions inventory) estimates. EDF found that "1% of natural gas production sites accounted for 44% of total emissions from all sites, and 10% of sites accounted for 80% of emissions; emission estimates were based on facility-wide (site-based) measurements."[7] The study further notes that the "***occurrence of abnormal process conditions***" causes additional emissions that "explain the gap between component based and site-based emissions."[8]

Environmental Health and Safety Impacts

Methane is the primary constituent of natural gas. Methane alone is not known to have any direct human health effects, although it is combustible and can pose a safety threat. However, it is the coproduced chemicals from natural gas production, such as hydrogen sulfide, toluene, xylene and benzene, that are also constituents of natural gas production and act as precursors to other hazardous pollutants such as tropospheric or ground-level ozone, which are known to cause asthma and other respiratory diseases that contribute to air pollution-related premature deaths.[**] Tropospheric ozone is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC). This can happen when VOCs from upstream oil and gas operations, as well as pollutants emitted by cars, power plants, refineries, and industrial plants, chemically mix and react together through processes facilitated by sunlight.[9]

The high and sustained methane emissions observed in this study also raise environmental justice issues. Kern County has a median household annual

Methane's Impact, Sources, and Estimates

Potency. Methane (CH_4) is a potent greenhouse gas (GHG) according to, among others, the EPA, U.N. Framework Convention on Climate Change (UNFCCC), and the Intergovernmental Panel on Climate Change (IPCC).[††] Each GHG is measured in terms of Global Warming Potential (GWP), which is calculated as a measure of how much energy the emissions of one ton of a gas will absorb over a given period of time, relative to the emissions of one ton of carbon dioxide (CO_2). CO_2 has a GWP of 1 and is the "reference gas." CH_4 is estimated to have a GWP of 28 to 36 over 100 years. Although CH_4 is 28 to 36 times as potent as CO_2 by these metrics, it is removed from the atmosphere more rapidly than CO_2 so that reducing the near-term rate of CH_4 emissions has a more immediate reduction rate of warming.[10,11]

Sources. The EPA also acknowledges that anthropogenic methane emissions are derived from the production and transport of coal, natural gas, oil, livestock, agricultural practices, and decay of organic waste in landfills. While this has long been understood by the commercial, regulatory, and environmental communities, it is the relative qualitative impact on ambient air pollution, or *source apportionment*, and nominal amounts contributed by these sources that continue to be investigated.

Measurements. There are two basic ways to estimate methane emissions:

1. **Bottom up (BU)** is based on inductive reasoning, whereby measurements from a representative sampling of targeted emitters of a given source type are scaled to the total number of emitters within that source type.
2. **Top down (TD)** is based on deductive reasoning. Measurements of ambient concentrations made by airborne sensors or sampling devices of a given region are used to estimate the per-well emissions required to produce those concentrations with a model.

There is sometimes a puzzling gap between these widely used methods for estimating methane emissions. For example, a recent study, supported by the National Science Foundation and designed to help inform strategies for targeted emission reductions, concluded that:

> [B]ottom-up inventories strongly underestimate CH_4 emissions from fossil fuel extraction, distribution and use. A study using both ground-based facility-scale measurements and verification from aircraft sampling found that US oil and natural-gas CH_4 emissions (largely from the production and gathering industry segments) are ~60% higher than those reported by the US Environmental Protection Agency, one of the primary data sources used in bottom-up inventories.[12]

[**] Ozone in the upper atmosphere, or stratosphere, forms a thin layer of "good" ozone, which absorbs most of the biologically damaging ultraviolet solar radiation and helps to control the earth's temperature.
[††] Methane is 34 times stronger a heat-trapping gas than CO_2 over a 100-year time scale according to the IPCC.

income of less than $50,000 and high rates of pollution-induced asthma as well as cardiovascular disease and chronic obstructive pulmonary disease, all of which can be exacerbated by pollution.[13] A 2006 study found that the health impacts of SJV's air pollution cost the southern section of the region an estimated $3 billion, or about $1,000 per person per year in a region where about a quarter of the population lives in poverty.[14] Such statistics underscore the business and environmental justice case for gathering actionable methane plume imagery on a routine basis to efficiently find and fix leaks.

California's Past Air Quality Successes and Moving Forward

The California Air Resources Board (CARB) has demonstrated significant success over the past few decades through a concerted statewide approach to improve air quality. More recently, CARB has demonstrated a greater interest in a bottom-up approach to address local problems and to locate specific point source emitters, which could contribute to disproportional impacts on certain areas, including vulnerable or low-income communities. CARB Chair Mary D. Nichols noted that "California is turning the top-down air quality planning approach on its head. We are committed to taking more actions as well as serving as technical and operational consultants for the communities that bear the brunt of air pollution."[15]

Recently CARB and the California Energy Commission (CEC) have championed methane research and are working with various research collaborators to implement a "tiered observation system" to conduct measurements at many different scales and identify emission sources. It is within this context that the findings from the current *Methane Super-emitters Case Study in Kern County, California*, which follows, should be considered.

INITIAL SURVEY DATA: Methane Super-emitters in Kern County, California

The SJV hyperspectral airborne collection study suggests that oil fields are leaking high levels of methane. Some steam injection wells are leaking at rates in excess of 200,000 percent above EPA estimates for the average leak rate for a gas well in the western United States.

The Aerospace Corporation (Aerospace) conducted four airborne surveys between April 2015 and September 2018 in Kern County, California. The airborne surveys included:

- **Kern River Oil Field** – Discovered in 1899, its current principal operator is Chevron.
- **Poso Creek Field** – Discovered in 1919 by Standard Oil, its principal operator is E&B.
- **Kern Front Field** – Discovered in 1912, it has several operators.

Figure 1: San Joaquin Valley (SJV) and airborne survey area.

Hyperspectral Airborne Survey

Aerospace used the Mako hyperspectral instrument to conduct the surveys over the three Kern County oil fields (see Figure 2). Details of each survey are given in Table 1. The Mako instrument can detect almost 700 gases and 4,000 solids that have diagnostic spectral features in the longwave-infrared,[‡‡] one of which is methane. Wellhead natural gas may contain water vapor and nonhydrocarbon gases such as sulfur, helium, nitrogen, hydrogen sulfide, and carbon dioxide, which are typically removed from natural gas before it is sold to consumers.[16] Given that other gases and water vapor could exist within an emissions plume, it is important to be able to distinguish between these gases. The spectral resolution of Mako enables positive discrimination of methane from water vapor and other nonhydrocarbon gases. Specifically, water vapor interference in the 7.6 µm to 8.3 µm spectral range is reduced sufficiently for effective methane spectroscopy.

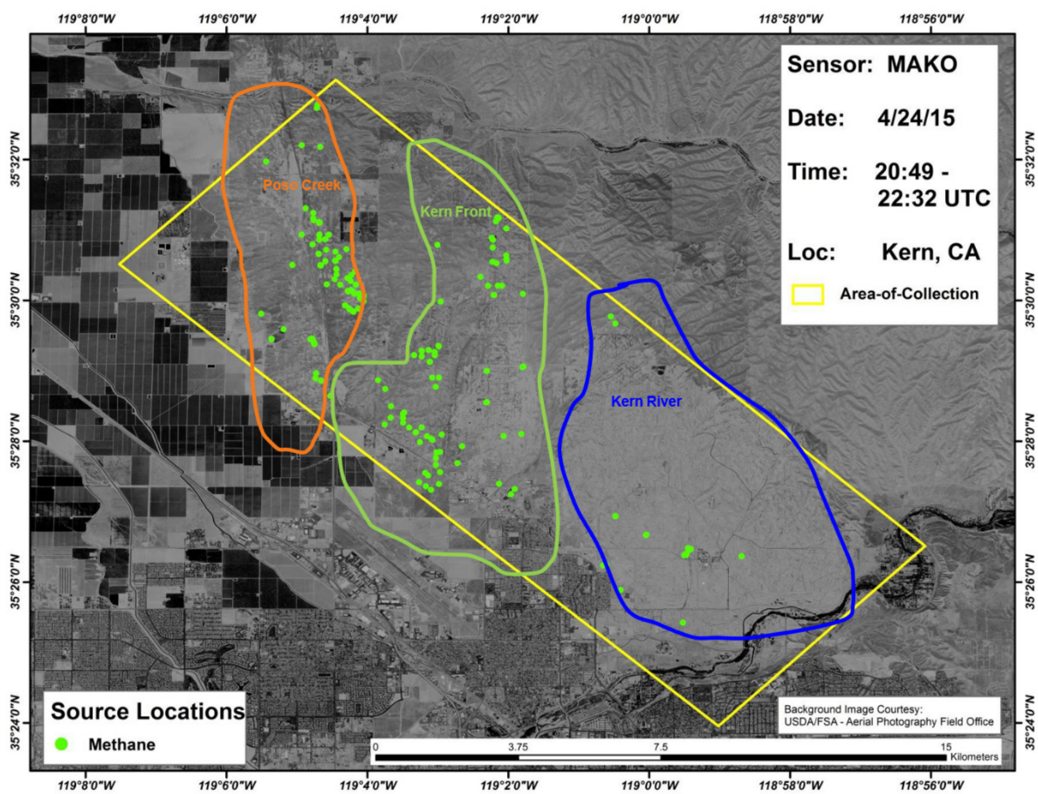


Figure 2: Kern County, California – April 2015 hyperspectral airborne survey. *Green markers represent nearby methane emitters (this survey detected more than 150 point sources) in Poso Creek (orange outline), Kern Front (green outline), and Kern River (blue outline) oil fields.*

‡‡ Mako is a hyperspectral thermal infrared whiskbroom imaging spectrometer designed and built by The Aerospace Corporation and operated from a Twin Otter aircraft. It operates in the 7.8 µm to 13.4 µm spectral range.

Table 1: Mako Sensor Airborne Surveys in Kern County, California, Between July 2014 and September 2018. This table measures gas volumes using petroleum industry terms of "MCF," or one thousand cubic feet, which is the standard for metering natural gas in the United States.[a] One MCF per day (MCFD) is sufficient natural gas to meet the needs of four average homes. The last column calculates the total detectable methane daily flow amounts (MCFD) from the fields assessed, assuming that all leaks were at the minimum detectable limit. Many leaks exceeded that limit and some exceeded 80 MCFD.

Survey Date	Altitude Above Ground (ft)[b]	GSD (m)[c]	Methane Source Count	Lowest Estimate of Methane Leak Rates for Three Oil Fields[d]
September 14, 2018	9,000	1.5	91	1,820 MCFD
May 12, 2016	6,000	1	227	4,540 MCFD
September 28, 2015	6,000	1	119	2,380 MCFD
April 24, 2015	4,500	0.75	210	4,200 MCFD

[a] In terms of energy output, one thousand cubic feet (MCF) of gas is equal to approximately 1,000,000 British Thermal Units (BTU).
[b] Twin Otter airborne platform
[c] Pixel size
[d] Assumes methane flow is at minimal detection limit 20 MCFD.

Actual sensor measurement sensitivity depends upon several factors, including:

- Distance to target (flying altitude)
- Thermal contrast (temperature difference) between the ground and overlying airmass
- Wind velocity, which may impact the accuracy of emission rate estimation

The studied fields comprise shallow oil reservoirs with "heavy" or high gravity oil,[§§] and very high well density, and they are producing using various types of enhanced recovery with steam injection (e.g., "huff & puff").[***,17] Images generated from Aerospace's airborne hyperspectral imaging (HSI) sensor indicate that several operating wells in Kern County, many of which were undergoing steam injection, were leaking at flux rates at *over* 200,000 percent above the EPA average estimate for western U.S. gas wells. Typically, oil reservoirs bleed off their gas early during their early production years, and Kern River, Poso Creek, and Kern Front oil fields have been producing for over a century. It is therefore surprising to observe this amount of gas escaping from a heavy oil well. This raises the question: What *abnormal process conditions* are responsible for turning this well into a super-emitter and where is the gas originating? It is possible that abnormal conditions exist as a result of steam injection that is causing *thermal cracking*, a process by which the heavy crude oil is subjected to high heat that breaks the bonds of long-chained hydrocarbon molecules into shorter-chained hydrocarbons such as methane. Once free, the methane quickly finds the path of least resistance and escapes upwards and into the atmosphere.

[§§] American Petroleum Institute (API) gravity 10° to 15°.
[***] API Gravity is the American Petroleum Institute standard, an inverse measure of a petroleum liquid's density. For instance, lighter oil is typically above 30 degrees and heavy oil is below 20 degrees.

It is also possible that old cement to secure the well casing has failed and is now creating a vertical path from the reservoir to the surface. This could be due to the advanced age of the wells or tectonic activity within the region (several active faults[†††] occur within the production areas). Certainly, understanding *why* these wells are leaking is important. More importantly, finding *where* the leaks are occurring and plugging or fixing them is necessary to protect the environment, health, and safety of the region, and to reduce economic loss from releasing gas that could be collected and sold. Finally, a program to conduct routine regional surveys to find new leaks will be essential.

Large and Sustained Methane Leaks Exceed Reported Gas Production

Despite differing field conditions, observed fugitive emissions from the three Kern County oil fields (Poso Creek, Kern River and Kern Front) were significant. The Mako sensor can detect methane gas leak rates at approximately 20 MCFD and higher under the conditions prevailing during the Kern surveys. However, many of the fugitive methane emissions occurred at much higher rates. For instance, the Cauley Lease in Poso Creek field appeared to be leaking at 82 MCFD. In the same year, however, the operator reported *production* (not leaks) of only 115 MCF for the year (363 production days). This means that for every reported 1 MCF produced, 259 MCF leaked or escaped, assuming that fugitive emissions were continuous during production. [‡‡‡]

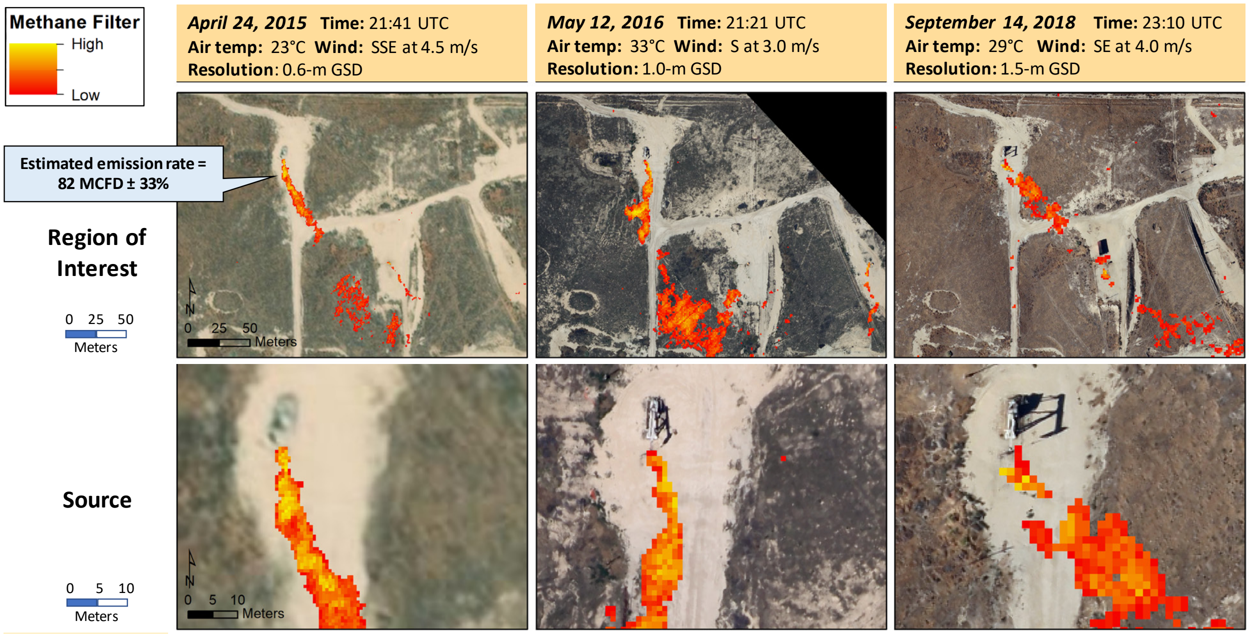
The EPA estimates that the average gas well in the western United States leaks approximately 13.3 MCF[18] per year, yet our airborne survey found many wells leaking at rates equivalent to more than 10,000 MCF per year. The minimum detectable methane flow rate observed during this survey was estimated to be approximately 20 MCFD, meaning that the sensor was detecting only sources that were more than 500 times higher than EPA's average per-well estimate. The observed aggregate leak rates across the Kern complex for the four survey datasets range between 1,820 and 4,200 MCFD (see Table 1).

Figure 3 shows a well on the Cauley lease in Poso Creek Field during three different airborne surveys on April 24, 2015; May 12, 2016; and September 14, 2018. During April 2015, this well was leaking at a rate of 30,000 MCF per year, or 2,250 times greater than the EPA estimate for an average western gas well. This well continued to leak at high rates throughout the two-hour duration of the airborne survey on April 24, 2015. During repeat airborne surveys in May 2016 and September 2018, this well continued to show evidence of significant fugitive methane emissions. Without persistent monitoring it is difficult to determine whether the fugitive emissions are continuous. However, it is conceivable that fugitive emissions were coincidental with the well's almost continuous production for 363 days during 2015.

These observations suggest that the EPA per-well estimate, which calculates and aggregates average emissions factors for various components to provide average well emission estimates, vastly underestimates methane emissions in upstream oil production because a small subset of wells have emissions far in excess of the assumed average for gas wells. Moreover, given that these wells are producing heavy crude, many oil industry practitioners might not expect that high levels of

[†††] Including the Kern Front Fault and Premier Fault, which are actively creeping faults due to fluid withdrawal according to the California Geological Survey.

[‡‡‡] Upstream oil and gas methane emissions can be sporadic, particularly for crude oil storage tanks where gases vaporize and collect under the tank roof and periodically "flash out." However, many of the wellhead leaks in the Kern County fields appeared to be continuously leaking during the two-hour airborne surveys and from year to year during the four airborne surveys from 2015 through 2018.



API #: 029-1653 **Current Operator:** E&B Resources **Well Name:** Cauley #56 **Field:** Poso Creek **Area:** Premier **Total Depth:** 2,473 feet
SUMMARY: Completed drilling Jan. 17, 1946; Originally produced from the Chanac sand (2,405 – 2,443 ft), starting at around 100 BOPD and 33 BWPD, 12.5° API gravity. By December 2008 the well was producing 5 BOPD and 411 BWPD.
2009 rework to an upper pay zone – Etchegoin sand (perforated from 2,350 – 2,330) and prepared for steam stimulation.
2013 rework again and prepared for steam stimulation.
PRODUCTION: ***Yr 2015*** - 866 BO, 115 MCF, 363 days; ***Yr 2016*** 662 BO, 80 MCF, 366 days ***Yr 2017***- 588 BO, 216 MCF, 355 days; first report of gas production January 2015. *(BO: barrels of oil, BWPD: barrels of water per day)*

Figure 3: Poso Creek Field, Kern County. *Large persistent methane leak (false color plume images in orange) observed from a single well between 2015 and 2018. Neighboring wells are seen emitting smaller leaks, denoted by the small orange "streamers" visible in the upper "Region of Interest" image panels.*

natural gas (of which methane is a dominant constituent) exist in these fields, which typically produce heavy oil between 10° to 15° American Petroleum Institute (API) gravity. Gas shales that have undergone fracking are more often the target of methane emission surveys.

Beyond environmental concerns, there are viable economic interests in capturing and selling natural gas (which is composed of 87 percent to 97 percent methane[19]). As an example, the well in Figure 3 has an estimated emission rate of 82 MCF per day. Applying a wellhead gas price of 2.12 per MCF[§§§] translates to a yield of $174 per day or $63,510 per year in gas sales for this one well.

Regularly scheduled airborne surveys to identify the super-emitting subset of producing wells and related infrastructure along with follow-up for operator mitigation and regulatory enforcement would dramatically reduce gas leaks and drive production facilities toward greater efficiency and cleaner production. Another approach for reducing fugitive emissions involves California's recent regulatory scrutiny of steam injection wells. According to a Notice to Operators (January 7, 2020), "Moratorium on New Approvals of Cyclic Steam above Fracture Pressure," the California Department of Conservation Geologic Energy Management Division (CalGEM) expressly prohibits surface expression resulting from injection operations.[20] A

[§§§] Energy Information Agency forecasts that natural gas spot prices will average $2.21 pe MCF during 2020. https://www.eia.gov/outlooks/steo/report/natgas.php.

surface expression is defined in CalGEM's regulations as a "flow, movement, or release from the subsurface to the surface of fluid or other material such as oil, water, steam, **gas**…that is outside of a wellbore and that appears to be caused by injection operations" (Cal. Code Regs., tit. 14, $1720.1, subd. (n)). Imagery of methane plumes emitting from gas wells undergoing steam injection provides evidence of surface expressions.

Meeting California GHG Regulations Through Best Available Technology

New State Regulations for Addressing Methane Leaks

Contrary to national efforts seeking to deregulate and propose relaxed standards for methane leak detection and repair for the upstream oil and gas sector, California is moving toward more stringent regulations. Moreover, CARB has now enacted regulations such as *Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities* that would curtail methane emissions at crude oil and natural gas production facilities by as much as 45 percent over the next 9 years. [21] To this end, the methane emissions identified through satellite imaging and higher resolution airborne surveys would need to be mitigated according to these proposed rules.[****]

A multi-tiered approach (satellite, airborne, and in-situ sensors) allows for better mapping, targeting, and mitigating fugitive methane emissions. Starting with satellite data, airborne remote sensing campaigns can further refine methane plume imagery as well as provide more accurate leak locations and leak rate calculations. Methane plume imagery provides actionable intelligence by pointing to the emission source, which allows operators and regulators to mitigate expeditiously.

The EPA regulatory framework often favors *best available technology* (BAT), a term which recognizes that techniques and technologies change as society or industry advances knowledge, practices, and technologies. Hence, EPA relies upon "reasonably achievable," "best practicable," and "best available" and looks to state environmental agencies to apply BAT across their state. The current ground-based "in-situ" method for measuring methane leaks is labor intensive because the in-situ sensor must be situated inside the plume to detect it, meaning likely locations for leaks must be known in advance to properly position the sensor to "find" and measure the leak. More flexible scanning capabilities could be offered by mobile ground-based remote sensing methods, but this approach still lacks the ability to survey large areas in a timely manner. By contrast, an airborne imaging sensor can play a lead role in monitoring petroleum fields and other areas for a range of airborne pollutants.

Both Aerospace and the Jet Propulsion Laboratory (JPL) have tested optical imaging sensors during methane leak hunting campaigns.[22,23,24] Airborne optical gas imaging sensors offer a combination of spatial resolution and a real acquisition rate to provide the petroleum production and pipeline communities a powerful surveillance capability. Relative capabilities of these sensors should be considered against various survey targets and performance requirements (see Table 2).

[****] On September 24, 2019, the EPA proposed a rule to amend its 2012 and 2016 rules affecting the New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants. The potential actions would rescind methane requirements of the NSPS applicable to sources in the production and processing segments. This rule is expected to be an E.O. 13771 deregulatory action.

Table 2: Airborne Spectral Imagers *(nonexhaustive list of sensors with published methane detection capabilities)*	
Existing Longwave-Infrared (LWIR) Sensors	
Mako The Aerospace Corporation (California, USA)	Mako hyperspectral sensor, operating at 7.6–13.2 microns in long-wavelength infrared (LWIR), rapidly surveys large areas at 21 km^2 per minute for 1.6 m ground resolution, while flying at 3 km above ground level.
HyTES Hyperspectral Thermal Emission Spectrometer Jet Propulsion Lab (California, USA)	HyTES measures scene self-emission at 7.5–12.0 microns in the LWIR with a 2.8 km field of view and 6 m ground resolution at 3 km survey altitude.
Fixed Gas Find IR Camera FLIR Systems (Oregon, USA)	FLIR's range of optical gas imaging (OGI) cameras includes GF77a, a methane imaging LWIR camera using uncooled detector technology. A methane-specific spectral filter enables visualization of gas leaks against the background infrared scene.
HyperCam Telops (Québec, Canada)	Telops markets a compact commercial LWIR hyperspectral imager that is configurable for airborne or ground-based operation and has been used for methane leak surveying.
Existing Shortwave-Infrared (SWIR) Sensors	
AVIRIS-NG Airborne Visible/ Infrared Imaging Spectrometer – Next Generation Jet Propulsion Lab (California, USA)	AVIRIS-NG measures ground-reflected solar radiation at wavelengths from 380 nm to 2,510 nm shortwave-infrared (SWIR) with a 1.8 km field of view and 3 m ground resolution at typical survey altitudes of 3 km. JPL has also proposed an airborne spectrometer based on the AVIRIS-NG design that would be specifically targeted toward methane measurement.
LeakSurveyor Kairos Aerospace (California, USA)	LeakSurveyor, a proprietary solar-reflection (SWIR) spectrometer system, delivers 30 percent or greater probability of detection at leak rates of 4 MCFD per mph of wind. 130 km^2 daily area coverage capability from 0.9 km survey altitude.
Future Sensors	
Increasing spectral imaging sensors are emerging and operating in both the SWIR and LWIR wavebands.	Future sensors will target methane and other high-visibility pollutants, including some that use variants of the systems listed above. Technological proficiency will be the key for commercial success drivers in the imaging sensor market based on cost, product quality, responsiveness, scalability of operations, and the demonstrated ability to innovate.

Best Available Technology Fused with Remote Sensing Hierarchy

What is the best way to monitor the nation's progress (and that of other nations) toward methane reduction? This is a daunting task because airborne and other types of field campaigns provide only a snapshot of a highly dynamic petroleum industry.

From a space perspective, the National Oceanic and Atmospheric Administration's (NOAA) network of observing satellites remains sparse even in the United States.[25] However, the space sector has grown significantly over the past decade and there are new satellite assets to consider, both existing and planned.

Currently, the data from the European Space Agency's (ESA) Sentinel-5P, the precursor satellite known as TROPOMI (TROPOspheric Monitoring Instrument), was launched on October 13, 2017, and provides free open source data.[††††] This data could help U.S. planners prioritize regions and industrial processes needing further survey and study.

TROPOMI is not the only satellite focused on finding methane. GHGSat (Montreal, Canada) has adopted a commercial approach to data sales. Table 3 provides a summary of currently operating and planned satellites that target GHGs, including methane.

Imagery derived from TROPOMI's dataset (see Figure 4), based upon the average concentration of the vertical column rather than surface or near surface measurements, shows various methane anomalies over the United States. The SJV region shows a relatively high methane column-averaged concentration (dark orange). TROPOMI uses a spectrometer measuring reflected sunlight in the ultraviolet (UV), very near infrared (VNIR), and shortwave infrared (SWIR) spectral ranges and builds images using total column mixing ratio measurements. This type of observation can provide complementary measurements and can display regional anomalies. However, it cannot attribute point source emissions to their sources on the ground.

While TROPOMI and future generations of satellites will provide a temporal record of large-scale emissions and a basis for The President's Climate Action Plan[26], they could miss the finer details needed for action at the local level. Such information could be acquired by fusing satellite data with airborne imagery and subsequent validation through local in-situ sampling and optical imaging. This broader dataset could be used to:

- Improve the local and national GHG inventories that form the basis for regulation
- Monitor the progress of the Climate Action Plan
- Support enforcement of the Clean Air Act (which often relies on facility self-reporting)
- Encourage compliance at (and even beyond) regulatory levels
- Improve the global GHG inventories used for treaty validation[‡‡‡‡]

[††††] TROPOMI is the sole instrument on the EU Copernicus Sentinel 5 Precursor satellite, which was launched in October 2017; therefore, "Sentinel-5P" or TROPOMI are often used interchangeably.

[‡‡‡‡] EPA helps developing countries assess national GHG inventories; therefore, improved EPA methodologies and metrics will improve assessment from other countries using similar methodologies/analyses.

Table 3: Methane Hunters in Space	
Spectral Data Product: Source-Resolved Imagery	
GHGSat Sponsor: Canadian commercial company	♦ **Closed Data** – availability restricted to subscribers. ♦ **Status** – currently operating as a demonstration satellite in polar orbit, launched June 2016. Orbits the earth 15x per day. ♦ **Imaging Sensor** – a wide-angle imaging spectrometer (SWIR at 1600–1700 nm) and a cloud and aerosols sensor (VNIR at 400–1000 nm). A second satellite will enter service during spring 2020. ♦ **Swath/Resolution** – 12 km/25x25 m^2.
Gaofen-5 Sponsor: China Aerospace Science and Technology Corp.	♦ **Data** – availability restricted. ♦ **Status** – operational, launched during 2018. ♦ **Imaging Sensors** – according to press release, equipped with six observation payloads, full spectrum from UV to LWIR.
MethaneSAT Sponsor: non-profit, Environmental Defense Fund	♦ **Free and Open Data** – available to the public. ♦ **Status** – plans to launch in 2022. ♦ **Imaging Sensor** – Ball Aerospace is designing the SWIR spectrometer methane sensor; single satellite with a 200 km field-of-view. Polar orbiting with agile targeting. ♦ **Planned Swath/Resolution** – 200 km/400x130 m^2.
Bluefield Sponsor: U.S./Canadian commercial company	♦ **Planning Phase** – developing a "backpack-sized" satellite. Eight satellites are planned for daily revisit and global coverage. ♦ **Closed Data** – availability restricted to subscribers. Subset for academics and public. ♦ **Swath/Resolution** – 12 km/20x20 m^2.
Spectral Data Product: Atmospheric Column Measurements	
Greenhouse Gas Observing Satellite (GOSAT-2) "IBUKI-2" Sponsor: Japan Aerospace Exploration Agency (JAXA)	♦ **Open Data** – targets CO_2, CH_4, CO. ♦ **Status** – replaces GOSAT-1 (2009), sun-synchronous orbit at 666 km; GOSAT-2 launched October 2018, orbit at 613 km. ♦ **Non-imaging Sensor** – 4-band Fourier transform spectrometer with pointing capability. Column-averaged mole-fraction measurements. ♦ **Swath/Resolution** – 920 km/10 km dia.
TROPOspheric Monitoring Instrument (TROPOMI) Sponsor: European Space Agency (ESA)	♦ **Free and Open Data** – seeks to understand methane super-emitters globally as part of ESA's Copernicus program. Other targets: tropospheric ozone column (trop. O_3), SO_2, OCHO, O_3, NO_2, CO, and aerosols. ♦ **Status** – operating prototype instrument. ♦ **Non-imaging Sensor** – 8-band spectrometer measuring reflected sunlight in the UV/VNIR/SWIR spectral ranges. Total column mixing ratio measurements. Looking at a larger swath and with lower spatial resolution and higher detection limit than MethaneSAT. ♦ **Swath/Resolution** – 2,600 km/7 x 7 km^2.

Operational phase (light blue) — Planning phase (beige)

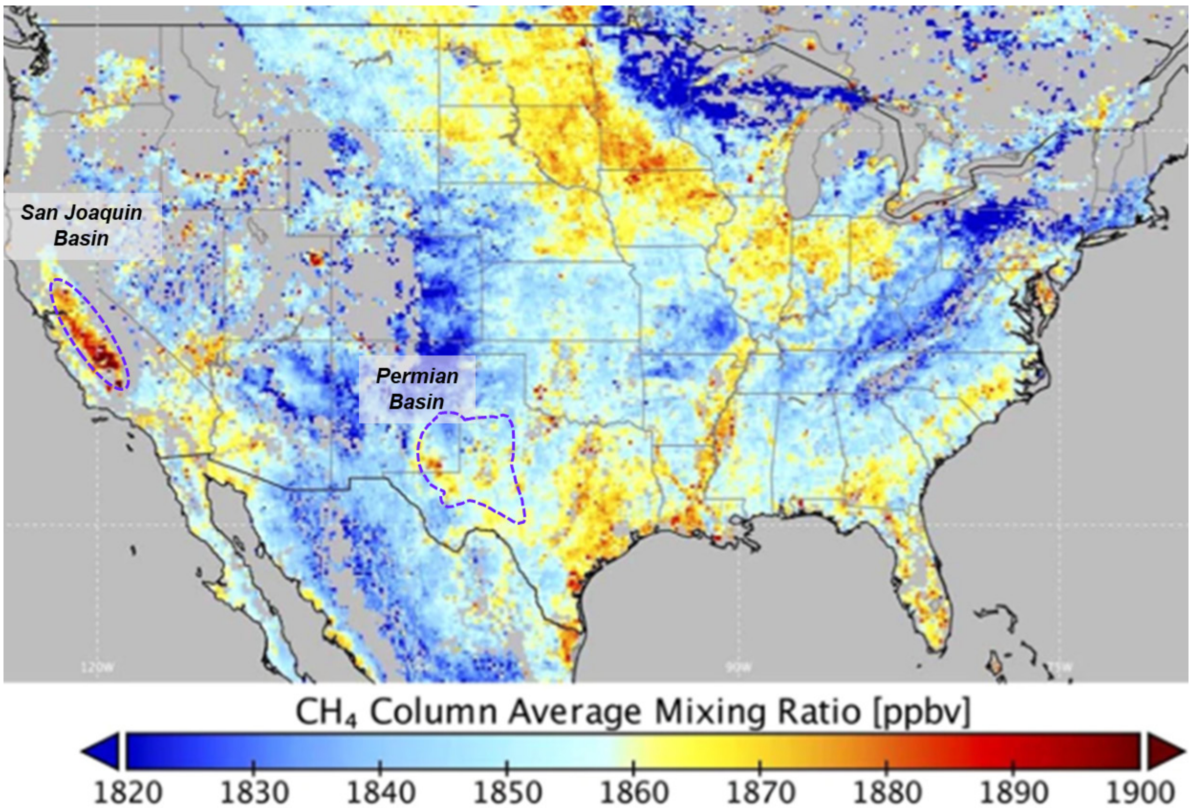


Figure 4: Daily satellite observations of methane from oil and gas production regions – average TROPOMI columns for methane over the United States between December 1, 2018, and March 31, 2019. *Source: De Gouw, J.A.; Veefkind, J.P.; Roosenbrand, E. et al.;* Scientific Reports *10, 1379 (2020).*

Conclusion: Moving Toward Action

The SJV case study suggests that our knowledge of methane inventories is vastly underestimated. Accurate methane inventories can have a profound impact on existing and future regulations and how specific industries operate and control emissions. Measurements must be defensible to foster broad acceptance of regulation and effective mitigation strategies. Increasing the confidence in satellite, airborne, and ground-based sensors will help move the needle toward a more accurate local, regional, and international understanding of methane emission sources and rates.

A practical approach would be to establish routine data collection across multiple platforms to fuse airborne and ground-based data[§§§§] with space-based information and fill gaps related to fine-scale processes not characterizable from space observations. Over time a long-term sustainable framework would emerge from the integration of mobile in-situ assets, airborne surveys, and ground-based networks.

California has an opportunity to lead and become the first state to control GHGs. It can start by gathering, fusing, and sharing actionable information on methane emissions and propose best policies and practices that could be extended to national and international scales. This opportunity will support efforts to measure results and immediately mitigate point source emissions, as regulators, industry, and the citizenry pursue methane reduction to meet climate change goals and improve air quality for all citizens.

Acknowledgments

The authors would like to thank Oliver Weatherbee of SpecTIR Hyperspectral & Remote Sensing Solutions and Shanti Rao of the Jet Propulsion Laboratory for their insight and comments. We also appreciate the helpful review and contributions from Aerospace colleagues: Dr. Angie Bukley; Dr. Jamie Morin, Dr. Katherine Saad; and Patrick Johnson.

[§§§§] Global Monitoring for Environment and Security (GMES) In-situ Coordination (GISC) emphasizes collection from terrestrial sources, including ground-based, airborne, and ship/buoy-based observations and measurements that are needed to implement and operate the Copernicus services.

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