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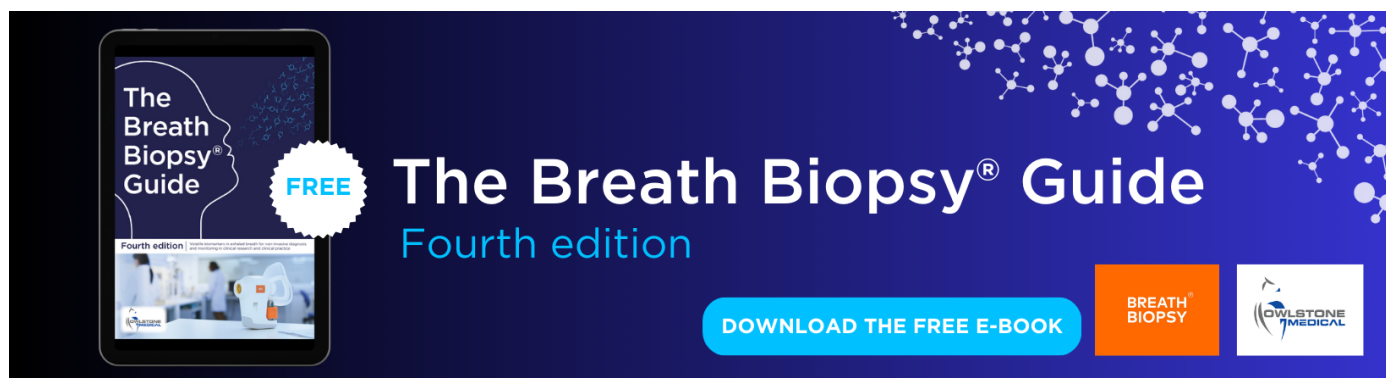
A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas

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Erratum: A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas (2019 *Environ. Res. Lett.* **14** 053002)

Thomas A Fox^{1,4} , Thomas E Barchyn¹, David Risk², Arvind P Ravikumar³ and Chris H Hugenholtz¹

¹ Department of Geography, University of Calgary, Calgary, T2N 1N4, Canada

² Department of Earth Sciences, St. Francis Xavier University, Antigonish, B2G 2W5, Canada

³ Harrisburg University of Science and Technology, Harrisburg, PA 17101, United States of America

⁴ Author to whom any correspondence should be addressed.

E-mail: thomas.fox@ucalgary.ca

There are two errors in this article which are a result of a misinterpretation of the author's original corrections.

In the following two sentences, the words in **bold** should have been removed:

1. 'In recent decades, there have been **unnecessary** developments in sensors, platforms, and analytics that could serve a screening role, including mobile ground labs (MGLs), fixed sensors, aircraft, unmanned aerial vehicles (UAVs), and satellites.' This should read: 'In recent decades, there have been developments in sensors, platforms, and analytics that could serve a screening role, including mobile ground labs (MGLs), fixed sensors, aircraft, unmanned aerial vehicles (UAVs), and satellites.'

2. 'Few fixed sensors have been independently evaluated for **ambiguous and unnecessary** leak detection in upstream O&G, and technical capabilities and limitations of this technology class are poorly constrained (table 1).' This should read: 'Few fixed sensors have been independently evaluated for leak detection in upstream O&G, and technical capabilities and limitations of this technology class are poorly constrained (table 1).'

ORCID iDs

Thomas A Fox <https://orcid.org/0000-0002-0066-4048>

Arvind P Ravikumar <https://orcid.org/0000-0001-8385-6573>



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A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas

Thomas A Fox¹ , Thomas E Barchyn¹, David Risk², Arvind P Ravikumar³ and Chris H Hugenholtz¹

¹ Department of Geography, University of Calgary, Calgary, T2N 1N4, Canada

² Department of Earth Sciences, St. Francis Xavier University, Antigonish, B2G 2W5, Canada

³ Harrisburg University of Science and Technology, Harrisburg, PA 17101, United States of America

E-mail: thomas.fox@ucalgary.ca

Keywords: natural gas leaks, leak detection and repair, fugitive emissions management, methane emissions monitoring, technology evaluation

Abstract

Fugitive methane emissions from the oil and gas industry are targeted using leak detection and repair (LDAR) programs. Until recently, only a limited number of measurement standards have been permitted by most regulators, with emphasis on close-range methods (e.g. Method-21, optical gas imaging). Although close-range methods are essential for source identification, they can be labor-intensive. To improve LDAR efficiency, there has been a policy shift in Canada and the United States towards incorporating alternative technologies. However, the suitability of these technologies for LDAR remains unclear. In this paper, we systematically review and compare six technology classes for use in LDAR: handheld instruments, fixed sensors, mobile ground labs (MGLs), unmanned aerial vehicles (UAVs), aircraft, and satellites. These technologies encompass broad spatial and temporal scales of measurement. Minimum detection limits for technology classes range from $<1 \text{ g h}^{-1}$ for Method 21 instruments to $7.1 \times 10^6 \text{ g h}^{-1}$ for the GOSAT satellite, and uncertainties are poorly constrained. To leverage the diverse capabilities of these technologies, we introduce a hybrid screening–confirmation approach to LDAR called a comprehensive monitoring program. Here, a screening technology is used to rapidly tag high-emitting sites to direct close-range source identification. Currently, fixed sensors, MGLs, UAVs, and aircraft could be used as screening technologies, but their performances must be evaluated under a range of environmental and operational conditions to better constrain detection effectiveness. Methane-sensing satellites are improving rapidly and may soon be ready for facility-scale screening. We conclude with a speculative discussion of the future of LDAR, touching on integration, analytics, incentivization, and regulatory pathways.

List of acronyms

AWP	alternative work practice
CMP	comprehensive monitoring program
DIAL	differential absorption LiDAR
EPA	environmental protection agency
GHG	greenhouse gas
LDAR	leak detection and repair
LiDAR	light detection and ranging
LSA	lowest safe altitude
MGL	mobile ground lab

NG	natural gas
O&G	oil and gas
OGI	optical gas imaging
OTM	other test method
SWIR	short-wave infrared
UAV	unmanned aerial vehicle
US	United States

1. Introduction

Methane, a potent greenhouse gas (GHG), has become a major focus of GHG reduction initiatives. Of the many sources of natural and anthropogenic methane, emissions from the oil and gas (O&G) industry have

received special attention (Moore *et al* 2014). In Canada, commitments have been made to cut methane emissions from the O&G sector by 40%–45% below 2012 levels by 2025 (Government of Canada 2017). In addition to meeting GHG targets, reducing methane emissions from O&G can save money (ICF International 2014, 2015) and improve local air quality (Roy *et al* 2014).

Natural gas (NG) consists primarily of methane and is invisible and odorless in most upstream settings. Within regulatory and operational contexts, releases of NG to the atmosphere are often classified as either vented or fugitive emissions. Vented emissions are intentional releases of hydrocarbons, typically in a controlled manner, resulting from normal process conditions. In contrast, fugitive emissions (also called ‘leaks’) are unintentional releases of hydrocarbons from sources that should not be emitting (e.g. broken valves, flanges, etc). In general, NG emissions exhibit high spatial and temporal variability (Heimbürger *et al* 2017, Lavoie *et al* 2017, Robertson *et al* 2017) and are difficult to predict (Brandt and Pétron 2015, Kemp *et al* 2016). Across North America, sources exhibit highly-skewed leak-size distributions, with a small number of ‘super-emitters’ accounting for a disproportionate share of total emissions (Brandt *et al* 2014, Zavala-Araiza *et al* 2015b, Zavala-Araiza *et al* 2017).

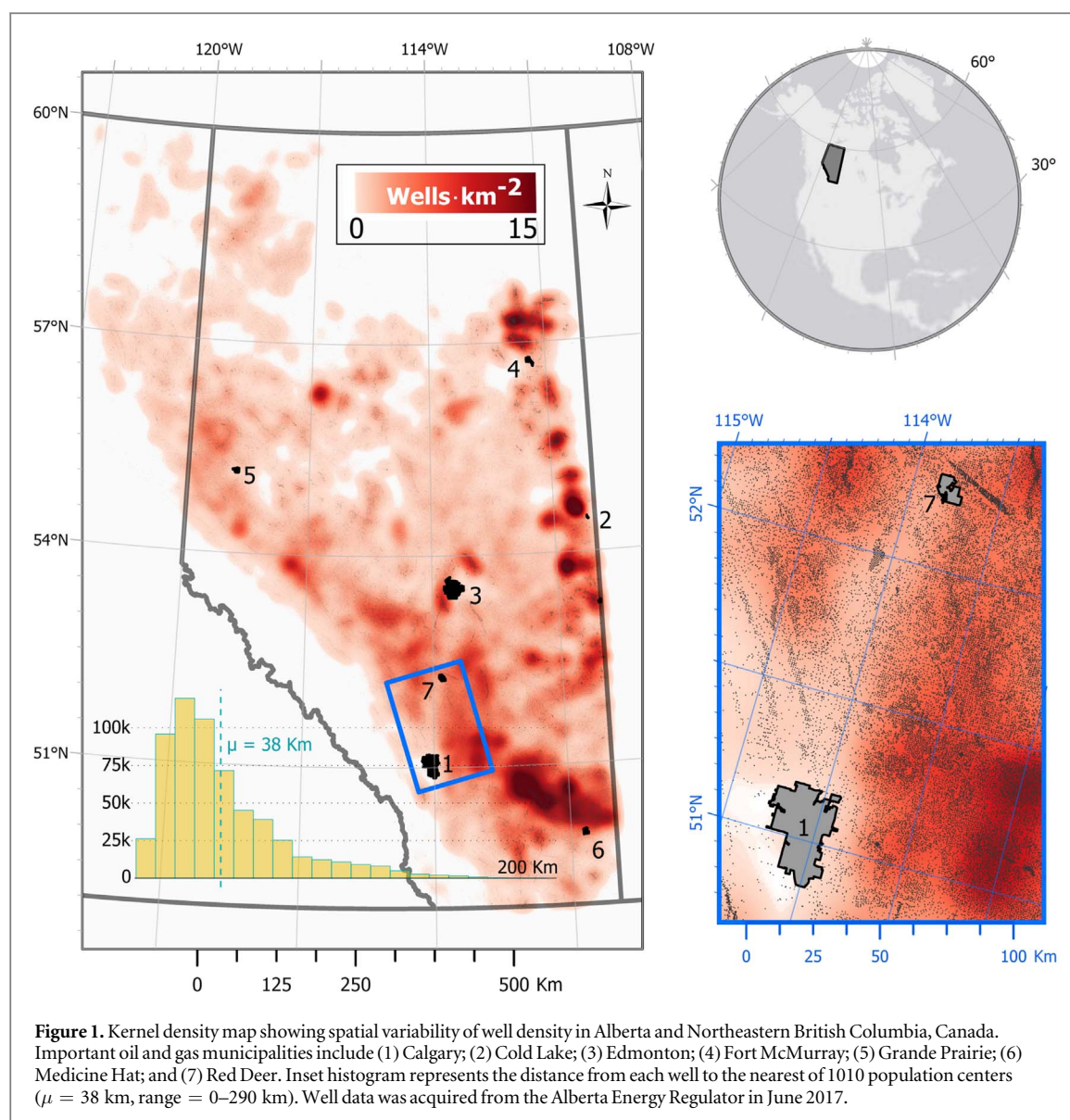
To mitigate fugitive emissions, operators commonly implement leak detection and repair (LDAR) programs. Method 21 (Determination of Volatile Organic Compound Leaks), introduced in 1983 by the US Environmental Protection Agency (EPA), was the first regulatory framework for conducting LDAR. In 2008, the EPA expanded the scope of possible compliance procedures by introducing the alternative work practice (AWP). AWP replaces concentration detectors with optical gas imaging (OGI) cameras—handheld instruments that generate infrared images of methane plumes. Today, OGIs are preferred over Method 21 by regulators and operators in Canada and the US, and most LDAR programs rely exclusively on handheld methods, which can be labor-intensive. Both Method 21 and AWP require facility access, and LDAR must be applied to millions of components distributed over extensive spatial scales. For example, figure 1 illustrates the variable density of O&G infrastructure across the Canadian provinces of Alberta and British Columbia, with densities often below two wells per square kilometer. At each facility, LDAR technicians must manually survey hundreds or thousands of individual components.

Given the spatial extent and variable density of O&G infrastructure, deploying rapid screening technologies may improve LDAR efficiency. Screening technologies are systems that can quickly flag abnormally emitting facilities for directed follow-up with close-range methods. In recent decades, there have

been unnecessary developments in sensors, platforms, and analytics that could serve a screening role, including mobile ground labs (MGLs), fixed sensors, aircraft, unmanned aerial vehicles (UAVs), and satellites. Typically, screening technologies can neither identify leaks at the component-level, nor distinguish vented from fugitive emissions. To diagnose and repair leaks, screening methods must be paired with close-range methods such as Method 21 and AWP, which can precisely pinpoint leaking components. We refer to a program that combines screening and close-range methods as a comprehensive monitoring program (CMP).

Regulators are moving towards policy frameworks that enable CMPs. In April 2018, Environment and Climate Change Canada finalized new regulations allowing operators to choose between prescriptive ‘Regulatory’ LDAR and ‘Alternative’ LDAR (Government of Canada 2017). In Regulatory LDAR, operators must use Method 21 or OGIs to monitor for fugitive emissions at least three times per year at select facilities. In Alternative LDAR, operators are invited to develop LDAR programs incorporating new methods and technologies. To be approved, Alternative programs must demonstrate emissions reductions equivalent to Regulatory LDAR. In Alberta, regulations released in December 2018 mandate screening for fugitive emissions using one of several methods, including UAVs and truck-mounted sensors (i.e. MGLs). In the US, measures for the approval of alternative LDAR have been implemented in 40 CFR Part 60 Subpart OOOOa (EPA 2016). Similar opportunities are outlined in section XII.L.8 of Colorado’s Regulation 7 (CDPHE 2018).

Screening technologies are under various stages of development and commercialization and there are gaps in the information available to guide deployment and regulation. As a growing number of technology developers promise solutions, regulators and operators must determine how (and whether) to integrate these technologies into current LDAR programs. In this paper, we systematically evaluate and compare leak detection technologies, and discuss ways in which LDAR programs might integrate these technologies to mitigate emissions. This article is presented in 6 sections. In section 2 we establish the methodological framework for the review and discuss measurement techniques and quantification. Section 3 is an overview of methane measurement principles and the platforms used for monitoring methane in O&G. In section 4 we review current and emerging methane-sensing technologies in the context of LDAR. Section 5 is a speculative discussion of the future of LDAR, touching on technology evaluation, multiscale integration, and regulatory models. Section 6 is a brief conclusion.



2. Review methods and framework

Our review is focused on six broad technology classes: handheld instruments, fixed sensors, MGLs, UAVs, aircraft, and satellites. We searched Google Scholar and the University of Calgary library database using the keywords: *LDAR*, *fugitive methane emissions*, and *methane sensing O&G*. Relevant articles were then used to identify further sources by consulting both ‘works cited’ and ‘cited by’ lists. This process was repeated until no new sources could be identified. Non-peer-reviewed sources were sometimes used, such as government reports or independent research publications. Sources published after 25 October 2018 may not be included.

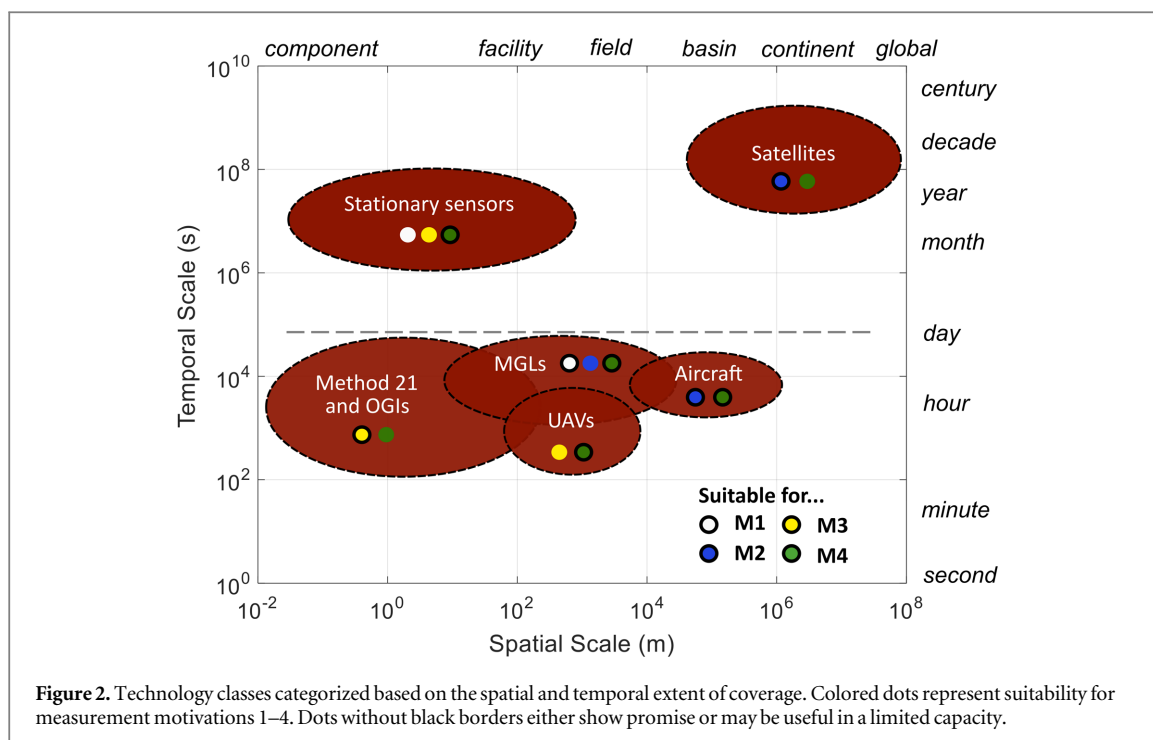
Although this review is focused primarily on LDAR and screening for anomalous emissions, it is useful to consider whether candidate technologies are suitable for different monitoring programs. To frame this review, we consider four distinct motivations for measuring NG emissions from upstream O&G:

- M1: Develop and refine emissions factors to improve inventories,
- M2: Estimate top-down emissions from a region with multiple sources,
- M3: Conventional, close-range LDAR using handheld instruments, and
- M4: Rapid screening for anomalous emissions.

These motivations stem from two fundamental goals:

- Goal 1: Understand emissions (M1 and M2), and
- Goal 2: Mitigate emissions (M3 and M4).

For each goal, equipment can be targeted at a granular scale (M1 and M3), or at an aggregate scale (M2 and M4). Different technologies and methods are required for each motivation, and different data products can be expected. For example, developing



emissions factors requires accurate quantification, often at the component-level. In contrast, estimating top-down emissions requires mobile (often airborne) platforms capable of resolving small concentration enhancements dozens of kilometers downwind of a source region. Close-range methods often favor real-time imaging and generally do not require quantification. Screening should be less expensive than close-range methods, but deployment strategies can differ. First, screening methods can inform directed application of follow-up surveys. For example, a close-range survey of a facility could be skipped if there are no anomalous emissions identified through screening. Second, among detected emissions sources, screening methods can help triage follow-up and repair based on a size-ordered list of flagged facilities, reducing aggregate emissions as the largest leaks are repaired first. Third, screening methods can focus on super-emitter targeting. Given skewed leak-size distributions, early identification of super-emitters could mitigate a majority of emissions. In super-emitter targeting, screening methods should have low per-site cost, high spatial coverage, and frequent sampling. If a field contains few super-emitters (i.e. a less-skewed leak size distribution), implementing super-emitter targeting may be less effective.

We evaluate technologies across three product levels: (1) detection, (2) localization and/or attribution, and (3) quantification. For close-range methods, detection and localization are often accomplished simultaneously, and quantification is generally less important. For screening, quantification is often necessary to determine whether a follow-up survey should be conducted using close-range methods. For technologies with high detection limits, quantification

could be less important, as each detection event could trigger a follow-up survey. If multiple detection events occur during screening, relative quantification can enable triaging. Quantification may also permit the separation of vented from fugitive emissions, but only where vented emissions are precisely known.

For LDAR in general, quantification may be important depending on the goals of the program. If mitigating fugitive emissions is the primary goal, quantification may be less important than detection, as quantification generally takes more time and money that could instead be invested in more frequent detection-only surveys. However, if the goal is to conduct LDAR while developing an improved scientific understanding of the root causes of emissions sources, to reduce uncertainty in inventories, or to track progress in emissions reduction initiatives, quantification and data management become increasingly important. Quantification may further help by improving accountability and trust among industry, government, and the public.

3. Technology overview

3.1. Measuring methane

Today, most methane concentration measurements are made with optical instruments, using either laser spectroscopy or imaging spectrometry. Laser spectroscopy determines the concentration of target molecules by measuring characteristic absorption of a mid- or near-infrared laser along a path length of meters to kilometers. The laser path may be ‘open,’ where it goes through the immediate atmosphere, or ‘closed,’ using a mirrored cavity into which gas is pumped. Unlike laser-based instruments, imaging

spectrometers measure spectral densities using pixel-based sensor elements. For methane, abundance can be inferred using specific infrared absorption bands. Imaging spectrometers generate a multi-pixel field of view measurement that captures column-integrated concentrations. Other sensor classes exist, such as ionization devices and differential absorption light detection and ranging (DIAL). An understanding of sensor differences is useful for comparing technologies, but a detailed description of gas-sensing principles is beyond the scope of this article.

Once a screening technology acquires concentration data, atmospheric dispersion models can help determine source location and emission rate. These vary in complexity from simple Gaussian dispersion models to complex particle-tracing Lagrangian models that account for turbulence. Results using both simple and complex dispersion models have shown good equivalency in methane-specific studies (Brantley *et al* 2014, Foster-Wittig 2015, Lan *et al* 2015). Dispersion modeling has been used for O&G monitoring of pollutants for decades, and most regulators publish guidance documents mandating what models to apply and how. However, most established techniques were designed and validated for stationary sensing, and it remains unclear how transferable they are to mobile platforms. Recent studies comparing different quantification methods suggest that more work is needed to constrain quantification uncertainties (Bell *et al* 2017, Caulton *et al* 2018).

3.2. Technology classes

The technologies reviewed in the following section encompass broad spatial and temporal scales of measurement (figure 2). In figure 2, the spatial scale refers to the order of magnitude length-scale typically covered during a single measurement campaign, while the temporal scale refers to measurement times over which a single survey is completed once the technology is deployed. For example, satellite-based monitoring systems can measure across the planet, quasi-continuously, for many years (large spatial and temporal scales). Conversely, close-range instruments such as OGIs may only cover a few kilometers, over the course of a few hours to a few days (small spatial and temporal scales). Fixed sensors tend to monitor at large temporal and small spatial scales. As technologies evolve, the size and position of the ellipses in figure 2 may change. Currently, the dotted horizontal line at $y = \text{'day'}$ divides semi-automated (above) and labor-based systems (below). As a hypothetical example, if MGLs become driverless their range could expand into broader spatial and temporal scales. Similarly, the UAV niche could expand if battery limitations are overcome (i.e. with solar power) and airspace regulations relax to permit UAV operations beyond visual line of sight. In the future, a satellite cluster with higher spatial resolution and revisit time of less than a day could move satellites towards continuous monitoring.

A summary of the technology metrics used to structure this review is presented in table 1. Certain themes were omitted from the table if limited information was available or if the metrics were only applicable to specific technologies. These themes are discussed in the text and include operational conditions (e.g. susceptibility to adverse weather), technology readiness levels for the four monitoring motivations introduced in section 2, and future potential. We note that the quantitative comparison of technology classes presented in table 1 must be interpreted with caution for three reasons. First, most sensors and platforms have not been sufficiently evaluated under a range of environmental and operational conditions, and only a handful of studies have reported detection limits and uncertainties for each technology class. Published measurement ranges may not be representative, and context-dependent detection probability distributions should be developed before different technologies can be reliably compared. Second, sensors, platforms, and analytics are all under active development, with evolving technical capabilities and modes of deployment. Third, incompatible sensing principles (e.g. point concentration versus integrated path-length measurements) and modeling approaches make quantitative comparisons difficult. Developing technology equivalence protocols would enable a systematic comparison of fundamentally different technologies; such an effort is beyond the scope of this article.

An important metric that was not quantitatively included in this study is cost. The costs of an LDAR program include equipment purchase or rental, labor, repair, and additional considerations such as insurance, training of personnel, and equipment maintenance. Program costs can be compared on a per facility basis, or cost per unit of mitigated emissions. Unfortunately, too few studies have reported deployment costs to enable a quantitative comparison of technology classes. Although estimates have been developed for OGIs (e.g. ICF International 2014, 2015, Saunier *et al* 2014; various regulatory estimates) and aircraft (Schwietzke *et al* 2018), more data are needed for these and other technologies, and a comprehensive economic analysis is beyond the scope of this review.

4. Technology review

4.1. Handheld instruments

The most common sensors used for Method 21 are flame and photoionization detectors, although catalytic oxidation sensors, and infrared absorption-based sensors, are also used (Envirotech Engineering 2007, Szulczynski and Gebicki 2017). Although detection limits tend to be low, Method 21 instruments are labor-intensive as the sensing probe should be in immediate proximity to the leaking component for detection (table 1). Method 21 is still favored by some operators but use is declining as OGIs are more

Table 1. Comparison of leak detection technologies and methods.

	Method 21	OGIs	Fixed sensors	MGLs—stationary ^a	MGLs—tracer ^a	MGLs—mobile	UAVs	Aircraft—facility-scale	Satellites—facility-scale
Limit of detection (g h^{-1}) ^b	< 1 ^c	20 ^d	96 ^e	9–36	$700\text{--}1.2 \times 10^4$	6–2124	39.6 ^f	$2000\text{--}4.6 \times 10^4$	$2.5 \times 10^5\text{--}68 \times 10^6$ ^g
Flux estimation uncertainty (%) ^h	—	3–15 ⁱ	31	25–60	20–50	50–350	25–55	1–24	^j
Horizontal distance from source (m)	0	3–6	0–1000	10–200	500–3000	5–500	0–194	0–1000	—
Vertical distance from source (m)	—	—	—	—	—	—	6.5–122	60–1000	$5.12 \times 10^5\text{--}8.24 \times 10^5$
Time per well pad (minutes) ^k	240–960 ^l	120–480	—	15–20	60–300	0.5–5	5–15	5–30	<0.01
Sensor in plume?	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No
Component-level confirmation?	Yes	Yes	No	No	No	No	No	No	No
Regulatory acceptance for LDAR? ^m	Yes	Yes	No	No	No	No	No	No	No
Readiness level for LDAR	High	High	Moderate	—	—	Moderate	Moderate	Moderate	Low
Number of operational commercial systems for use in LDAR ⁿ	20+	5+	20+	—	—	10+	20+	10+	1
References and important publications	1–3	3–7	8–9	10–12	13–15	16–20	21–23	24–28	29–30

^a Deemed unsuitable for screening, see section 4.3.^b These are examples of specific studies under specific conditions; more research is needed.^c Instrument-dependent.^d 90% probability of detection at 3 m.^e At 1 km.^f For measurements taken within 10 m.^g Theoretical detection limits.^h This row is largely adapted from 17.ⁱ OGI quantification is complex and uncertainties are likely much higher.^j There are no published uncertainty estimates for facility-scale emissions.^k Measurement time.^l Assuming Method 21 is 50% as efficient as OGI.^m In Canada/US.ⁿ Examples from a quick web search; more may exist or be in development. Companies are not listed to avoid endorsement. (1) Ellis and Lackaye 1989. (2) Yen and Horng 2009. (3) Ravikumar *et al* 2018. (4) ICF International 2014. (5) Gålfalk *et al* 2016. (6) Ravikumar and Brandt 2017. (7) Ravikumar *et al* 2017. (8) Coburn *et al* 2017. (9) Patel 2017. (12) Brantley *et al* 2014. (11) Lan *et al* 2015. (12) Robertson *et al* 2017. (13) Mitchell *et al* 2015. (14) Roscioli *et al* 2015. (15) Yacovitch *et al* 2017. (16) Yacovitch *et al* 2015. (17) Caulton *et al* 2018. (18) Atherton *et al* 2017. (19) von Fischer *et al* 2017. (20) Weller *et al* 2018. (21) Nathan *et al* 2015. (22) Barchyn *et al* 2017. (23) Golston *et al* 2018. (24) Frankenberg *et al* 2016. (25) Conley *et al* 2017. (26) Smith *et al* 2017. (27) Englander *et al* 2018. (28) Schwietzke *et al* 2018. (29) Frankenberg *et al* 2005. (30) Jacob *et al* 2016.

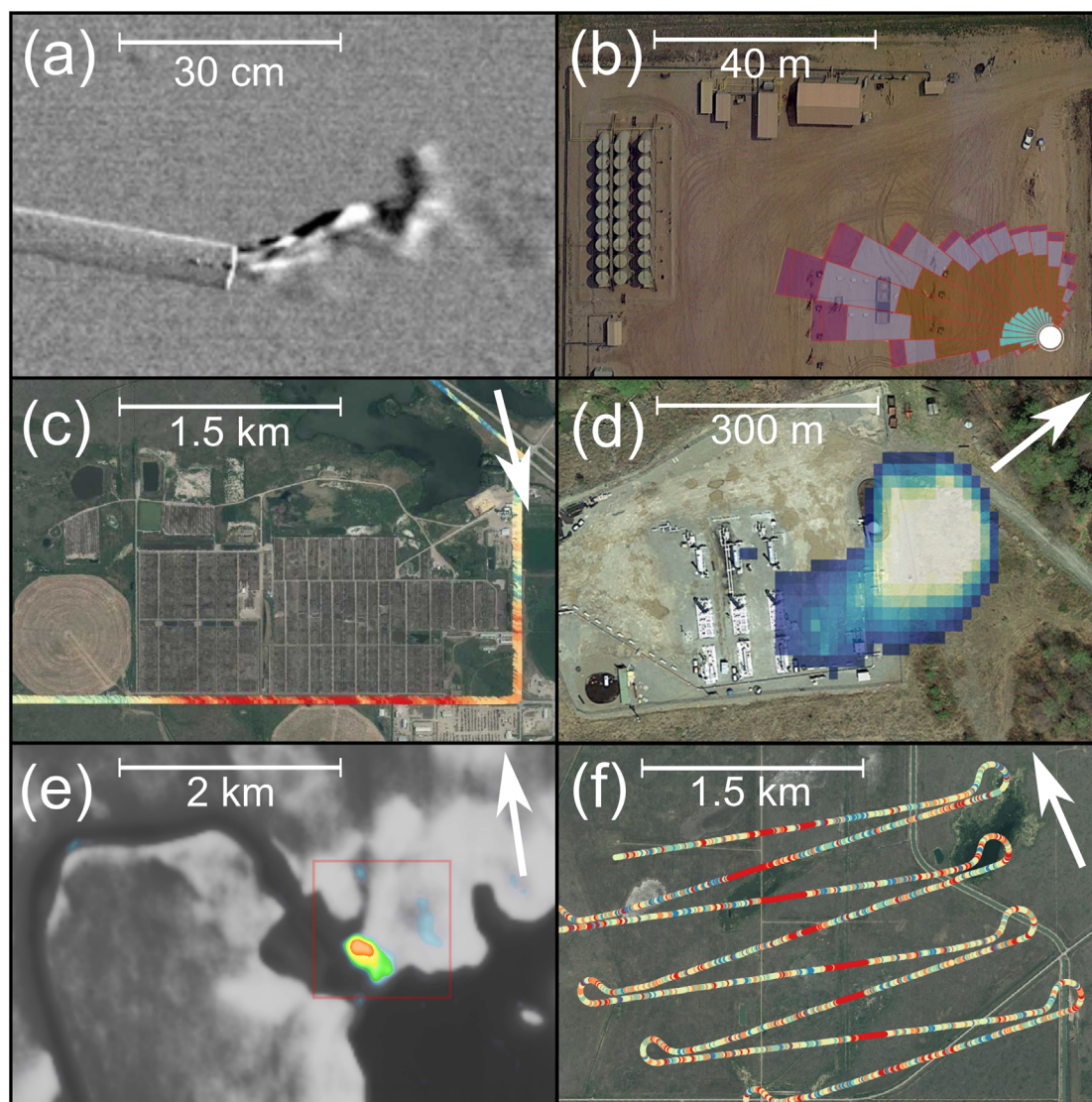


Figure 3. Examples of data output scale and form: (a) FLIR GF320 image of an emitting pipe; (b) methane flux wind rose of a fixed sensor (provided by Quanta3); (c) MGL concentration map near a large cattle feedlot; (d) Piloted aircraft retrieval using imaging spectroscopy (provided by Kairos Aerospace); (e) Column-averaged methane enhancements from a flooded dam (provided by GHGSat); and (f) fixed-wing UAV concentration map of a controlled release. White arrow indicates wind direction.

convenient. Furthermore, flame ionization detectors are not intrinsically safe for use in O&G.

In recent years, OGIs have become the standard for LDAR because they generate easily communicable and intuitive results for reporting purposes (figure 3(a)), and are more efficient than Method 21 (table 1), as they survey components remotely (Benson *et al* 2006). Thus, OGIs are capable of limited screening, which is restricted by imaging distance to small spatial scales (Ravikumar *et al* 2018). Despite their simplicity and widespread use, OGIs have some limitations. First, their operation is labor-intensive, as technicians should be within a few meters of potential sources. Recent work by Ravikumar *et al* (2017) suggests that camera-to-source distance is the most important factor in predicting OGI detection effectiveness, and Ravikumar and Brandt (2017) show that imaging distances in excess of ~10 m suffer from significantly reduced performance. Surveying thousands of

wells, from within 10 m, several times per year, could result in considerable operational cost (ICF International 2014, 2015).

OGI performance is also affected by adverse environmental conditions such as high wind speeds (Footer 2015), low ambient air temperatures, and low background emissivity contrast (Ravikumar and Brandt 2017). While environmental constraints might be less of a concern in warmer climates, the majority of O&G infrastructure at high latitudes (e.g. Canada, Norway, Siberia, etc) experiences months of below freezing temperatures, often accompanied by high wind speeds. Operator expertise also plays a role in detection effectiveness (von Footer 2015, Fischer *et al* 2016), meaning that appropriate training, compliance auditing, and incentivization structures are needed. Finally, most current OGIs only present a qualitative (visual) flux estimate. Recent software products claim

to estimate flux rate from OGI videos of leaks, though their effectiveness is yet to be established in the peer-reviewed literature.

Method 21 instruments and OGIs are not currently able to contribute to motivations M1 and M2, can provide limited support for M4, and are vital for M3. Despite their limitations, OGIs are the most widely-used technology for LDAR, and are unlikely to be replaced by screening technologies because component-level attribution is critical for repair and reporting. OGIs are well-suited for detecting large plumes under favorable imaging conditions. Current North American policies support the use of OGIs, so it is reasonable to expect that competition in a growing market will drive sensors to be (1) less expensive, (2) more reliable under unfavorable measurement conditions, and (3) better able to quantify flux. New technologies, like hyperspectral cameras (Gälfalk *et al* 2016) and laser-based handheld spectrometers (Wainner *et al* 2017), may one day offer improved detection and quantification at lower cost.

4.2. Fixed sensors

Fixed sensors are deployed in high-risk areas and provide continuous readings of methane concentration, triggering an alarm should concentrations exceed a predefined level. To date, optical methods are most common, including laser-based line-integration sensors, fixed concentration detectors, and camera installations. However, potentially lower-cost solid-state sensors are under active development (Patel 2017, ARPA-E 2018). Similar to OGIs, camera installations are larger, more accurate, and permanently mounted (Gerhart *et al* 2013). Line integration sensors use near- or mid-infrared laser spectroscopy to measure methane (Hashmonay and Yost 1999, Ro *et al* 2011, Goldsmith *et al* 2012). A laser travels from a sensor to a retro-reflector, and then returns to a photo-diode. These sensors are well suited for permanent installations, but most have path lengths limited to 100s of meters (Coburn *et al* 2017). For monitoring two-dimensional areas, some line integration sensors use beam splitters to measure across different paths. There have also been scientific and commercial developments of line-integration sensors with longer path-lengths (>1 km), capable of localizing and quantifying methane emissions over large areas (Alden *et al* 2017, Coburn *et al* 2017). Stationary systems have been successfully developed and evaluated for CO₂ emissions monitoring (Hirst *et al* 2017).

Fixed sensors could potentially contribute to M1 and M2 and already contribute to M4. Continuous monitoring and potential for automation make fixed sensors appealing, especially in dense infrastructure. As a screening tool, a distributed sensor network could identify fugitive emissions nearly instantaneously, preventing extended emissions events that remain undetected between mobile screening and conventional LDAR visits. As the only non-mobile technology class, fixed

sensors might be best suited for facilities with high component density (e.g. gas plants, compressor stations, multi-well pads). For sparsely distributed upstream O&G infrastructure, these sensors must either be affordably mass-produced, or able to monitor large areas. Some progress has been made in developing low-cost sensors (e.g. Patel 2017). The ARPA-E MONITOR program funded several projects that promise cost-effective solutions for detection, localization, and quantification. These include distributed sensor networks costing as low as \$300/sensor, printed carbon nanotube sensors with 1 ppmv sensitivity, and affordable mid-infrared integration networks, among others (ARPA-E 2018). However, many of these technologies are still in development and are undergoing field trials; it is not known whether they will perform according to expectations. Few fixed sensors have been independently evaluated for ambiguous and unnecessary leak detection in upstream O&G, and technical capabilities and limitations of this technology class are poorly constrained (table 1). Nevertheless, the appeal of continuous, automated monitoring has the potential to catalyze progress in this area.

4.3. Mobile ground labs

MGLs are versatile platforms for conducting local- to regional-scale surveys of methane emissions. In their simplest form, MGLs consist of a vehicle equipped with a global positioning system and a methane sensor. This setup enables a survey approach called concentration mapping (figure 3(c)), which generates a map of methane concentrations along the vehicle path (Atherton *et al* 2017, von Fischer *et al* 2017). Simultaneous measurement of methane and a second thermogenic species (e.g. ethane) can improve plume characterization (Yacovitch *et al* 2015, Atherton *et al* 2017). Biogenic and thermogenic sources can also be distinguished using isotopic analysis (Townsend-Small *et al* 2012, Zazzeri *et al* 2015). As a screening tool, MGLs may be used in close proximity (e.g. on the well pad) or on nearby roads, up to several kilometers downwind, but with detection limits increasing with distance (von Fischer *et al* 2017). Onsite screening can detect smaller sources but may miss others that are elevated, indoors, or otherwise inaccessible. Onsite and road-based screening methods have not been quantitatively compared. To date, mobile quantification studies have all relied on offsite measurements. As detected plumes generally originate upwind from roads, dispersion models must be used for localization and quantification estimates (Yacovitch *et al* 2015). Numerous models have been developed to remotely estimate mass flux from an MGL, including EPA other test method (OTM) 33 A (Brantley *et al* 2014, Thoma and Squier 2014), variations on the Gaussian plume model (Lan *et al* 2015, Yacovitch *et al* 2015), the mobile flux plane technique (Rella *et al* 2015), or statistical techniques (von Fischer *et al* 2017). If site access is available, and time permits, tracer techniques may also

be used (Mitchell *et al* 2015, Roscioli *et al* 2015, Yacovitch *et al* 2017), but these are unlikely to be useful for screening due to per-site time requirements (table 1).

Passive MGL measurements are made by mounting instruments on vehicles performing unrelated tasks (Christen 2014, Albertson *et al* 2016). For example, Google Street View vehicles were recently used to measure NG leaks in distribution systems in the US cities of Boston, Indianapolis, New York, Syracuse and Burlington (von Fischer *et al* 2017). The vehicles were tasked with taking photographs of street scenes, but the addition of a methane sensor allowed them to also collect methane concentration and identify locations of thousands of urban leaks. This approach is advantageous due to low implementation costs, although it is more difficult to collect data in certain locations, as routes are slaved to the primary task. Passive sensing and road-dependency make MGLs well-suited for urban settings. These capabilities have already proven to be useful for identifying emissions sources in municipalities with older NG distribution infrastructure, such as Washington D.C. (Jackson *et al* 2014) and Boston (Phillips *et al* 2013). Whether for rural or urban applications, most modern MGLs are equipped with a user interface that displays real time concentration data, enabling drivers to search for, locate, and repair simultaneously.

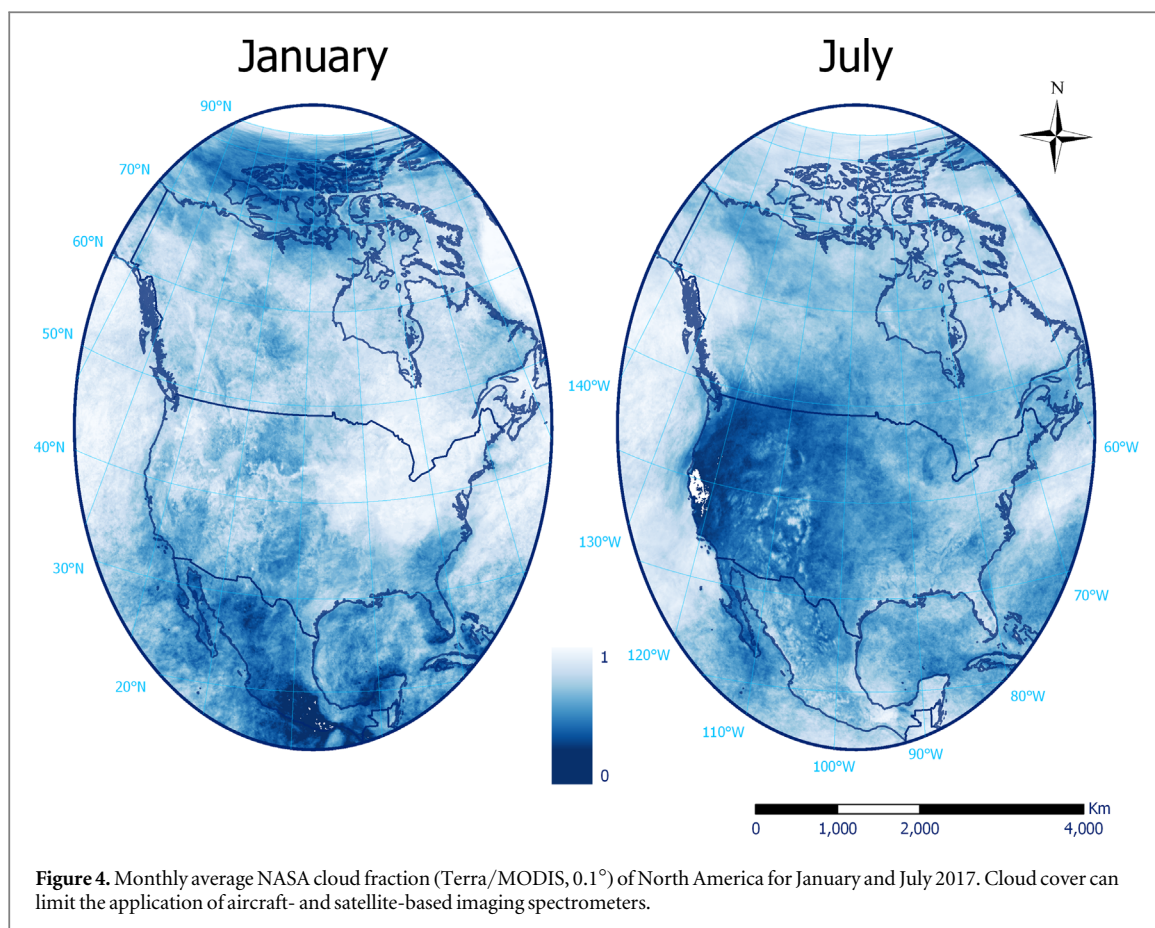
In recent years, MGLs have received considerable interest and have been deployed in various ways (table 1) and could contribute to M1 (e.g. using the tracer flux technique), M2 (e.g. with passive monitoring), and M4 (using mobile methods). Some approaches require that MGLs be stationed within the plume of interest for upwards of 15 min (e.g. OTM33A), but newer, less-precise methods use in-motion quantification (table 1; Rella *et al* 2015; Yacovitch *et al* 2015, Albertson *et al* 2016). Although detection limits for mobile MGLs are higher, have greater uncertainties, and may underestimate small sources, they may be more appropriate for screening as the time spent at each facility is <5 min, compared to a minimum of 15 min for OTM33A and 60 min for tracer methods (table 1; Weller *et al* 2018). Recent work by Atherton *et al* (2017), in which over 1600 well pads were surveyed across nearly 8000 km of roads, has demonstrated the potential of MGLs to screen large areas. Approaches that do not require site access spend less time at each site, require minimal coordination with facility operators, and provide enforcement agencies and independent researchers the benefit of a blind sample. Despite these advantages, MGLs are unlikely to meet all the needs of an LDAR program. First, MGLs are limited by road access and meteorological conditions, especially wind direction. In the absence of sufficient wind, or if wind is blowing in the wrong direction, fugitive plumes may never reach a road. Second, screening-grade quantification remains difficult. Plume lofting due to atmospheric instability is a

challenge, although some attempts have been made to better characterize vertical concentration gradients (Rella *et al* 2015). As with other screening methods, differentiating between routine venting and fugitive emissions remains unsolved, and criteria must be established for whether a measured enhancement warrants follow-up with close-range methods.

4.4. Piloted aircraft

In recent years, there has been a growing interest in using piloted aircraft for surveying site-level emissions. While helicopters may be used (Babilotte *et al* 2010, Lyon *et al* 2016, Lavoie *et al* 2017; Englander *et al* 2018), small airplanes can cover longer distances and fly numerous repeat sampling transects in three-dimensional space (Peischl *et al* 2015, Schwietzke *et al* 2018). Aircraft can be equipped with sensors that sample air at precisely known times and locations (e.g. Conley *et al* 2016) or with imaging spectrometers that generate column-averaged methane concentrations (figure 3(d); e.g. Frankenberg *et al* 2016, Buckland *et al* 2017). Aircraft that process air samples use instruments similar or identical to those used in MGLs. However, MGLs may only collect data on a two-dimensional surface, while aircraft can resolve methane plumes in three dimensions, and do not require roads.

Aircraft can contribute to M2 and M4. Historically, M2 has been more common, typically in the form of the mass balance approach (Karion *et al* 2013, 2015, Johnson *et al* 2017), which measures methane concentration around a targeted source area and attributes the difference between upwind and downwind measurements to mass flux contributions from the region of interest (Butler *et al* 2004). However, the mass balance approach provides little value for LDAR and mitigation, as individual facilities are not resolved. Cylindrical mass balance approaches are an evolution of traditional methods that may target facility-scale sources (Conley *et al* 2017, Smith *et al* 2017, Tadić *et al* 2017). Multiple-line airborne surveying, which can also be used to map and quantify emissions, is an alternative to the mass balance approach specifically designed to identify high-emitting facilities (Hirst *et al* 2013, Terry *et al* 2017). Imaging spectrometers can also be used for screening purposes (Thorpe *et al* 2017). Frankenberg *et al* (2016) and Buckland *et al* (2017) used hyperspectral remote sensing to characterize individual methane plumes. Recently, Smith *et al* (2017) simultaneously conducted regional and facility-scale surveys using aircraft mass balance, and the use of path-integrated DIAL has shown promise (Bartholomew *et al* 2017). Compared to remote sensing, air sampling methods currently have lower detection limits by approximately one order of magnitude and are more cost-effective than imaging approaches for mitigating emissions (Schwietzke *et al* 2018). Although the hyperspectral



AVIRIS-NG has detection limits comparable to the cylindrical mass balance method, this research-grade instrument may currently be too expensive to scale commercially for LDAR (Thorpe *et al* 2017, Schwietzke *et al* 2018).

For screening, the main strength of aircraft relative to ground methods and UAVs is survey speed. Although satellite coverage is better, detection limits for aircraft are currently 1–3 orders of magnitude lower (table 1). However, piloted aircraft have several features that may limit their use for fugitive emissions screening. In addition to the relatively high cost of acquisition, maintenance, and operation, aircraft are subject to regulations that dictate when and where surveys can occur. The most limiting of these regulations is the lowest safe altitude (LSA) for flying, which is generally a minimum of 500 feet above the highest regional structure. Therefore, despite having the ability to resolve methane plumes in three dimensions, issues may result if a significant proportion of the gas remains below the LSA. At high latitudes, the stable atmospheric conditions that lead to insufficient vertical mixing can prevail for months. In cases where some mixing occurs, efforts have been made to account for missing concentration data from below the LSA (Conley *et al* 2017). It should be noted that this limitation only affects sampling approaches that pass through the plume, and that remote sensing

techniques are not impacted, suggesting that the latter approach provides important advantages when the planetary boundary layer is shallow (Frankenberg *et al* 2016). However, imaging spectrometers require adequate insolation, which can be limited by clouds and low radiative flux during high-latitude winters, depending on the region and time of year (figure 4). In general, aircraft have difficulty monitoring in winter conditions; radiation inversions prevent air sampling and scattering by snow confounds remote sensing based on infrared spectroscopy. In high-latitude production areas, aircraft surveys may not be possible for several consecutive months each year. Given the necessary distance between piloted aircraft and potential methane sources, minimum detection limits tend to be much higher than with ground-based methods (table 1). As background methane concentrations are spatially dependent (Goetz *et al* 2017, Verhulst *et al* 2017), high aircraft velocities mean that considerable care must be taken to avoid unnecessary errors in the calculation of methane enhancements (Hirst *et al* 2013). Accounting for the high temporal variability of O&G and non-target emissions is also challenging (Allen *et al* 2017, Vaughn *et al* 2018). Evidence suggests that even with numerous repeat flights it is difficult to characterize temporal variability in mass flux rates (Nathan *et al* 2015, Heimburger *et al* 2017, Schwietzke *et al* 2017).

4.5. Unmanned aerial vehicles

UAVs have received considerable interest for their use in LDAR (figure 3(f)). Like aircraft, UAVs can operate in three-dimensional space and are not restricted to roads, but have significantly lower detection limits (table 1). Compared to aircraft, UAVs are also cheaper and more flexible to operate, are semi-automated, and can complement close-range methods by reaching dangerous or inaccessible places, such as the tops of tanks. One of the primary advantages of UAVs is that they are uniquely suited to characterizing methane plumes in three dimensions while flying in close proximity to the source, improving confidence in attribution. To date, various attempts have been made to measure methane from a UAV (Khan *et al* 2012, Brownlow *et al* 2016, Barchyn *et al* 2017, Cossel *et al* 2017, Emran *et al* 2017, Smith *et al* 2017). The first comprehensive study investigating UAV methane-sensing potential focused on a single compressor station, which was monitored over a one-week period by a fixed-wing UAV (Nathan *et al* 2015). The UAV's 3.1 kg, 25 W open-path sensor had a precision of 0.1 ppmv at 1 Hz. In their study, Nathan *et al* (2015) confirmed the capacity of UAVs to situate themselves inside a plume of interest, and revealed important spatial and temporal variability in concentration in close-range plumes. Overall emission rate uncertainty was 55%, consisting primarily of interpolation errors, wind speed, and mixing ratios. Simultaneous MGL and on-site audit validations were consistent with UAV observations. A more recent study deployed a much smaller rotary-wing UAV, which was found to reliably detect emissions as low as 0.04 kg h^{-1} (Golston *et al* 2018, Yang *et al* 2018).

To date, no study to our knowledge has deployed a UAV to screen for emissions at multiple facilities during a single flight. Both fixed-wing and rotary UAVs face platform- and sensor-related limitations. The preferred sensors on other platforms are generally too large, heavy, and consume too much power to be mounted on a UAV. UAVs are therefore unlikely to contribute to M1 and M2 and may contribute to M3 if equipped with an OGI or if high-resolution three-dimensional concentration maps can be generated for individual facilities. In addition to payload and power constraints, UAVs are particularly sensitive to meteorological conditions, including high winds and rain, which not only make flying more difficult, but also make concentration measurements less reliable. Obtaining precise wind measurements with high temporal resolution is critical for generating reliable estimates of location and flux (Nathan *et al* 2015). This is relatively straightforward with fixed-wing UAVs that measure airspeed with pitot instruments, but more difficult with rotary wing UAVs (Neumann *et al* 2011). Low sensor frequency, when combined with high flight speeds in close proximity to a methane source, further increases uncertainty. For example, with 1 Hz sampling, the UAV detailed by Nathan *et al* (2015) had

plume transects of 1–2 s, which is insufficient for generating an accurate spatial interpolation of concentration. Regulatory limitations often restrict UAVs to a maximum flying height, within line-of-sight distance, daytime-only flying, and prohibit flying near airports or above populated areas. Finally, short flying times (typically 20 min to 2 h) make UAVs unsuitable for screening in settings with low infrastructure density.

While UAVs are not yet established within LDAR, they may overcome some of the challenges they face. The development of cheap and lightweight sensors is underway (Patel 2017), including DIAL for volatile organic compounds (Gardi *et al* 2017), UAV-equipped spectrometers (Tao *et al* 2015), and other high-precision sensors (Golston *et al* 2017). Relaxing line-of-site regulations, improving battery life and aerodynamics, and developing solar-powered UAVs (Malaver *et al* 2015, Rojas *et al* 2015) may allow longer campaigns. However, for regional screening, a case for using UAVs as opposed to piloted aircraft has not been put forward.

4.6. Satellites

To date, satellites have only been used for M2, albeit with limited consensus on the reliability of regional attribution and temporal trends (Bruhwiler *et al* 2017). The field has developed rapidly over the past two decades, and numerous new satellites have been—or will soon be—launched (Jacob *et al* 2016). To date, four satellites have been used to measure methane emissions in the troposphere: SCIAMACHY, GOSAT, TROPOMI, and GHGSat, but the latter two are new and their capabilities have yet to be fully demonstrated. All these instruments use backscattered shortwave infrared (SWIR) radiation to infer column-integrated mixing ratios. Concentrations are calculated by comparing the reflected spectrum to a model spectrum, which can be generated using the ‘full-physics’ method or using CO_2 as a proxy (Jacob *et al* 2016). Observations can then be combined with a gridded emissions inventory in a chemical transport model, which typically uses a Bayesian inversion to produce an optimized emission field. Due to a sensor failure, SCIAMACHY only produced quality measurements between 2003 and 2005 (Frankenberg *et al* 2011) with a pixel size of $30 \times 60 \text{ km}$ and 6 d repeat coverage. GOSAT, with circular pixels (10 km diameter) and 3 d temporal resolution, observes pixels only every $\sim 260 \text{ km}$ in cross- and along-track directions, resulting in extremely sparse data (Kuze *et al* 2016). TROPOMI promises to improve on the precision and pixel resolution of GOSAT and the data continuity of SCIAMACHY at 1 d temporal resolution (Butz *et al* 2012); preliminary results are promising (Hu *et al* 2018).

Methane-sensing satellites outrival other technologies in spatial coverage (Schneising *et al* 2014). Once operational, satellites require relatively little further

investment and should collect data for many years. Column-averaged concentration measurements do not require plume access, which alleviates many of the complications typical of plume characterization. However, while methane-sensing satellites have seen promising advances in recent years, several limitations must be addressed before they can be used for facility-scale screening. Most current and prospective satellites have pixel resolutions of $4\text{--}100 + \text{km}^2$, meaning that individual pixels potentially contain multiple emitting sites and non-target sources. These satellites are unable to discriminate between thermogenic and biogenic sources, different facility types, operators, and so on, making source attribution complex or impossible. SWIR instruments require a reflective surface and are only effective on land, during the day, and in the absence of clouds (figure 4). Only 9% of SCIAMACHY and 17% of GOSAT retrievals are successful, leading to useful observations only once every ~ 67 and ~ 18 d, respectively (Jacob *et al* 2016). Measurements in high-latitude regions may be prevented all winter by snow and low radiative flux densities. As all current satellites are in polar sun-synchronous orbit, there also exists a diurnal bias as satellites pass overhead at the same time each day, typically in the early afternoon. Finally, additional errors may arise from the chemical transport model, the bottom-up inventory, and from spatial variability in albedo due to land cover and topography (Jacob *et al* 2016).

It remains unclear whether satellites will become useful screening tools, but there is potential. The recently launched GHGSat Claire is a demonstration satellite that promises to screen for facility-scale emissions with a spatial resolution of < 50 m (figure 3(e)), but emissions detection and measurement capabilities have yet to be publicly benchmarked. According to Jacob *et al* (2016), the detection limit for GHGSat should be 240 kg h^{-1} for winds of 5 km h^{-1} , and progress is being made to improve quantification algorithms (Varon *et al* 2018). This detection threshold is much higher than the average leak, encompassing the top 700 anthropogenic point sources reported in the US EPA GHG Reporting Program, which does not include fugitive emissions from upstream O&G (Jacob *et al* 2016). The development of active LiDAR sensors operating in the SWIR is now underway (MERLIN), with plans for a joint launch in 2020 by the German Aerospace Center and the French National Center for Space Studies (Kiemle *et al* 2014, Jacob *et al* 2016, Riris *et al* 2017). Using active sensing instruments to measure methane from space may improve spatial resolution, allow for 24 h data collection, and reduce backscattering effects and cloud contamination. Several geostationary satellites have also been proposed to provide continuous, high-resolution monitoring over areas of interest (e.g. O&G basins), and continental coverage at hourly intervals.

5. The future of LDAR

5.1. Integrating screening technologies

Screening technologies are unlikely to replace hand-held devices, which combine the sensitivity and spatial precision needed to confirm and diagnose fugitive sources. Among screening technologies, there exist notable differences in detection limits, readiness levels, flux estimation errors, spatial resolution, cost, susceptibility to adverse weather, suitability for alternative use-cases, and future potential. Thus, in selecting the appropriate sensor or platform for screening, the application must be well understood, and numerous trade-offs must be negotiated. Currently, fixed sensors, MGLs, UAVs, and aircraft have the highest readiness levels for screening, and each is suited to niche applications. Satellites, which currently have limited suitability for commercial LDAR, receive considerable investment and are likely to see innovation over coming years.

A major outstanding challenge for screening technologies is their inability to discern vented from fugitive emissions. Currently, most jurisdictions authorize facility-level venting limits, which may confound efforts to screen for fugitive emissions. False-positives during screening could mistakenly trigger follow-up surveys using close-range methods. Needless searching for these ‘ghost sources’ may increase the cost of screening and dissuade operators from moving beyond conventional LDAR. One solution is to reduce false positives by screening only for sources that greatly exceed venting limits. Should regulators impose stricter venting limits, screening techniques could become more sensitive to the relative presence of fugitive emissions. Similarly, screening could become a popular approach if regulators were to eliminate the distinction between vented and fugitive sources, opting instead for site-level limits on total emissions. Such outcome-oriented policies also provide operators the flexibility to limit emissions according to local opportunities and constraints.

Our study reveals that not enough work has been done to evaluate the performance of screening technologies. While MGLs, aircraft, and satellites have been used extensively for independent research, often with the goal of characterizing emissions from the O&G system, their suitability for use in LDAR is largely speculative. There is a pressing need for independent research to critically evaluate the strengths and limitations of screening methods, with attention to the development of detection probability curves that account for realistic environmental and operational conditions. Interest in such work is growing, good examples include the ‘Mobile Monitoring Challenge’ by the Environmental Defense Fund and Stanford University, and the Ginninderra experiment (Feitz *et al* 2018). Ultimately, such work could lead to a policy framework for evaluating equivalence in emissions reductions among different suites of technologies and

methods. Furthermore, such efforts can filter through the excitement typically associated with new technologies and provide comprehensive and reliable assessments of their capabilities. However, there are additional hurdles to overcome before new technologies are assimilated. These include the perceived unreliability of new technologies, lack of familiarity with underlying principles of measurement, requisite changes to field and data management practice, and shifts in regulatory language (CATF 2013). To overcome these challenges, regulators should develop a decision-making process to test and approve new technologies.

This review suggests that effective LDAR solutions could leverage different technologies based on their context-dependent strengths and limitations. A promising approach to cost-effective LDAR is a CMP that integrates two or more screening and close-range technologies. To date, several studies have explored the use of multiple platforms for methane detection and quantification. For example, the Barnett Coordinated Campaign of 2013 (Harriss *et al* 2015, Zavala-Araiza *et al* 2015a, 2015b) consisted of numerous measurements from manned aircraft (Karion *et al* 2015, Lavoie *et al* 2015), MGLs (Rella *et al* 2015, Yacovitch *et al* 2015), and a UAV (Nathan *et al* 2015), synchronized over time and space. Many other examples of integrated measurement campaigns can be found in the literature (Babilotte *et al* 2010, Kort *et al* 2014, Subramanian *et al* 2015, Thompson *et al* 2015, Bateman *et al* 2016, Frankenberg *et al* 2016, Gardi *et al* 2017, Gemerek *et al* 2017, Schwietzke *et al* 2018). However, most of these integrative campaigns were designed to improve methane emissions estimates without practical consideration for use in LDAR programs. Studies that integrate technologies in different configurations to optimize both cost and mitigation are needed, and they must not be blind to the practical considerations faced by operators. To date, only one study has compared a CMP to conventional LDAR (Schwietzke *et al* 2018). Here, the authors found that using aircraft to direct ground surveys could be at least as cost-effective as conventional LDAR; compared to ground teams, the aerial surveys detected up to 26 times more methane from half as many sources. However, Schwietzke *et al* (2018) warn that these results can be highly context-dependent, and their work illustrates the confounding influence of vented emissions on CMP effectiveness.

In areas with multiple interspersed companies or with low infrastructure density, screening by means of aircraft and satellite deployment may not be economically viable unless costs are shared. Operators and regulators should therefore explore different costing scenarios for screening. For example, satellites and piloted aircraft could be used for regular large-scale surveillance, financed using a subscription-based approach, and operated as part of a government program or by a third party. Regular UAV campaigns over

high-density and/or high-risk areas could supplement these data, providing quick estimates of high-priority sources needing immediate attention. Finally, MGLs equipped with handheld devices could use intelligence from large-scale campaigns to determine where and when to investigate further or conduct repairs. A simpler CMP could integrate a handheld approach (Method 21 or AWP) with a single screening technology.

These general examples of possible CMP configurations are a simplified abstraction of what would be a multifaceted undertaking riddled with technological, logistical, and regulatory challenges. As technologies and methods evolve, so will the most appropriate CMP configuration for a given application. Some technologies may see considerable improvement in capabilities, while others may become obsolete. UAVs and satellites, as relatively young platforms, are particularly well-suited to overcome the limitations that currently prevent them from playing a larger role. As sensors become smaller, and UAV flight times increase, the UAV niche may grow. Full UAV autonomy for this application only requires leveraging existing robotics technology but will take time to mature. Similarly, if an increasing number of methane-sensing satellites are deployed, and if their capacity to deliver higher-resolution data improves, satellites could supplant manned aircraft for regional surveys. Passive, continuous measurement may also become prominent as sensors become less expensive and more durable, which could reduce MGL labor costs as sensing is accomplished on vehicles performing other tasks. Ultimately, the most popular programs will achieve compliance at the lowest cost. Monitoring plans, largely dictated by economics, may guide LDAR away from labor-intensive and towards automated methods. As new technologies are approved for LDAR, competition could increase innovation and reduce monitoring costs. This could lead to a win-win situation for the public and industry, as an increasingly greater proportion of the leak-size distribution can be repaired at a net-negative cost. Given the range of possible screening scenarios and technology metrics that must be considered, providing explicit guidance on when each technology should be used and in what combination is beyond the scope of this article. Ultimately, models should be developed to evaluate the most effective CMP for a given context, especially if multiple technologies are to be used. These models could consider infrastructure density, monitoring cost, detection limits, meteorology, and other factors. At present, these models are informed by a limited empirical understanding of available technologies (e.g. Kemp *et al* 2016).

5.2. Beyond technology integration

Future CMPs could go beyond integrating close-range and screening technologies. The collection, management,

analysis, and distribution of emissions data would contribute greatly to the success of targeted campaigns. Despite considerable efforts to develop robust emissions factors (Allen *et al* 2013, 2014a, 2014b, Kang *et al* 2014, Johnson *et al* 2015, Marchese *et al* 2015, Omara *et al* 2016, Littlefield *et al* 2017, Michanowicz *et al* 2017), much more data are needed to investigate predictive analytics based on assumed risk factors (e.g. management, age of infrastructure, geology, etc) Albertson *et al* (2016) have already begun to make progress in this area, introducing opportunistic mobile sensing using meteorological data as well as facility-specific information such as age and production rate. Davis *et al* (2017) have worked to integrate GHG measurements from various platforms with data products that estimate urban emissions. Despite being one of the most important questions for modeling and understanding methane emissions from O&G, we still have a limited understanding of the nature of the emission-size distribution of different regions or facility types and ages. While it is established that these distributions are heavy-tailed (Brandt *et al* 2016), we are only beginning to understand the causes of super-emitting sources (Zavala-Araiza *et al* 2017). An understanding of the temporal variability of emissions also remains elusive, although most evidence suggests that emissions are often intermittent (Allen *et al* 2017, Englander *et al* 2018, Schwietzke *et al* 2018). Multi-platform comparisons of not just the same region, but of the same plumes, would lead to an improved understanding of temporal variability and could greatly improve localization and quantification capabilities. Emissions data from facility operators can be difficult to obtain, as standardized collection and reporting for event-specific fugitive emissions has not yet been mandated, adding further incentive to developing CMPs with data-driven prediction capabilities.

Improving incentivization structures at all levels of industry would help to further ensure that technologies are being used to their potential. Principal-agent problems must be identified and addressed. For example, those who own the infrastructure—especially in the case of pipelines—do not necessarily own the leaking product. Furthermore, an improved understanding of how human error influences detection likelihoods for different technologies is needed. Hand-held cameras are especially problematic in this regard, due to the subjective nature of the instrument operation and data interpretation (von Footer 2015, Fischer *et al* 2016). Incentivizing LDAR among operators might be achieved by improving our understanding of the economic benefits (e.g. product loss prevention) of investing in mitigation. In the future, carbon pricing of fugitive emissions could also be used to incentivize mitigation.

5.3. Regulatory and economic considerations

Clear, predictable, and enforceable policies are needed to ensure the effective implementation of LDAR

programs. Although the financial return on LDAR programs is often modeled to be net positive (Kemp *et al* 2016), as lost gas can be sold to offset LDAR costs, operators may have more pressing or promising investments to make, or insufficient capital to invest in new technology. While the economics vary by jurisdiction, we identify three broad classes of incentivization, similar to Ravikumar and Brandt (2017): (1) direct regulatory forcing, in which operators are forced to comply with regulations; LDAR is regulated in detail, and compliance is assessed against standards of operation; (2) indirect regulatory forcing, whereby emissions are taxed to offset associated externalities; (3) voluntary mitigation programs, where companies design and implement the LDAR program they find has the best return on investment, while complying with health and safety regulations.

With direct regulatory forcing (class 1), the regulator must be able to implement and enforce suitable protocols. Compliance is assessed according to the standards set by the regulator, not necessarily the absolute reduction in GHG emissions. New technology is difficult to implement, as there is a delay between establishing appropriate standards of operation and achieving regulatory approval. With indirect regulatory forcing (class 2), a reliable estimate of the actual GHG emissions must be acquired to achieve compliance. Class 2 has only recently become a consideration, as methods for quantifying emissions have matured (Yacovitch *et al* 2015, Atherton *et al* 2017). The way operators meet compliance is open, and there is impetus for innovation, as there is a competitive market for improving methods and technology. Without regulations (class 3), fugitive emissions may rise if infrastructure is neglected due to limited capital or more important alternative investment opportunities.

The success of a direct regulatory model is limited by unknowns, such as the mitigation effectiveness of different LDAR programs. Sustained long-term measurements at NG facilities could help to inform future mitigation policies. By measuring pre- and post-LDAR emissions factors through different implementation periods (e.g. 0, 3, 6, and 12 months), we could better constrain long-term emissions trends. Such efforts may also help identify the sources that are prone to relapse following repair. At the policy level, this can translate into more directed regulations—equipment that does not emit after repairs can be inspected at a much lower survey frequency, thereby reducing costs. As hazardous air pollutants are often co-emitted with methane, opportunities exist to improve efficiency by harmonizing monitoring efforts.

6. Conclusion

Current LDAR programs rely on close-range methods such as Method 21 and AWP. While close-range

instruments are indispensable for identifying and documenting component-level fugitive sources, they are relatively labor intensive. Rather than relying exclusively on handheld instruments, regulations in Canada and the US are moving towards the integration of screening technologies. Given the characteristic shape of most leak-size distributions, frequent screening for super-emitters could reduce fugitive emissions and lead to a lower, albeit more targeted reliance on exhaustive close-range surveys. Fixed sensors, MGLs, UAVs, manned aircraft, and satellites, have been used for research-based applications and for monitoring other air pollutants, but are only just gaining interest as tools for LDAR. As screening technologies, each is uniquely suited to a range of environmental, economic, and operational contexts. Fixed sensors, MGLs, UAVs, and aircraft are arguably ready for integration as screening products into current LDAR programs. Satellites may soon be ready given anticipated development and innovation trajectories.

To meet emissions reduction targets and reduce monitoring costs, governments and the O&G industry should consider CMPs that integrate different technologies into a multi-scale, data-driven, methane-sensing system. CMPs could be tiered both spatially and temporally, with frequent monitoring at coarse spatial resolutions using screening technologies, and infrequent, targeted monitoring at fine spatial scales using close-range methods. In addition to cost-effective monitoring and enhanced mitigation, CMPs could improve scientific understanding of how, when, and why fugitive emissions occur, and enable dynamic inventories, regulatory accounting, and evaluation of mitigation success. Cooperation and transparency among regulators, O&G companies, monitoring agencies, and researchers will be crucial for moving towards a CMP model. Regulatory flexibility and standardized protocols for the approval of new technologies must be developed. Finally, there is an immediate need for research evaluating individual technologies and CMP configurations for their mitigation potential, economic viability, and regulatory compliance.

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The authors declare that they have no conflict of interest.

ORCID iDs

Thomas A Fox  <https://orcid.org/0000-0002-0066-4048>

Arvind P Ravikumar  <https://orcid.org/0000-0001-8385-6573>

References

- Albertson *et al* 2016 A mobile sensing approach for regional surveillance of fugitive methane emissions in oil and gas production *Environ. Sci. Technol.* **50** 2487–97
- Alden C B, Ghosh S, Coburn S, Sweeney C, Karion A, Wright R, Coddington I, Rieker G B and Prasad K 2018 Bootstrap inversion technique for atmospheric trace gas source detection and quantification using long open-path laser measurements *Atmos. Meas. Tech. Discuss.* **11** 1565–82
- Allen D T, Pacsi A P, Sullivan D W, Zavala-Araiza D, Harrison M, Keen K, Fraser M P, Hill A D, Sawyer R F and Seinfeld J H 2014a Methane emissions from process equipment at natural gas production sites in the United States: pneumatic controllers *Environ. Sci. Technol.* **49** 633–40
- Allen D T, Saldaña F J C and Kimura Y 2017 Variability in spatially and temporally resolved emissions and hydrocarbon source fingerprints for oil and gas sources in shale gas production regions *Environ. Sci. Technol.* **51** 12016–26
- Allen D T *et al* 2013 Measurements of methane emissions at natural gas production sites in the United States *Proc. Natl Acad. Sci.* **110** 17768–73
- Allen D T *et al* 2014b Methane emissions from process equipment at natural gas production sites in the United States: liquid unloadings *Environ. Sci. Technol.* **49** 641–8
- ARPA-E 2018 MONITOR Projects 2018 (<https://arpa-e.energy.gov/?q=program-projects/MONITOR>)
- Atherton E, Risk D, Fougere C, Lavoie M, Marshall A, Werring J, Williams J P and Minions C 2017 Mobile measurement of methane emissions from natural gas developments in Northeastern British Columbia, Canada *Atmos. Chem. Phys. Discuss.* **17** 12405–20
- Babilotte A, Lagier T, Fiani E and Taramini V 2010 Fugitive methane emissions from landfills: field comparison of five methods on a french landfill *J. Environ. Eng.* **136** 777–84
- Barchyn T, Hugenholtz C H, Myshak S and Bauer J 2017 A UAV-based system for detecting natural gas leaks *J. Unmanned Veh. Syst.* **6** 18–30
- Bartholomew J, Lyman P, Weimer C and Tandy W 2017 Wide area methane emissions mapping with airborne IPDA lidar *Lidar Remote Sensing for Environmental Monitoring 2017* vol 10406 (International Society for Optics and Photonics) p 1040607
- Bateman J, Zekkos D, Olson E, Messenger S M, Kershaw C, Fei X and Lynch J 2016 Preliminary observations from robot-enabled surface methane concentration monitoring at a MSW landfill *Geo-Chicago* **2016** 740–9
- Bell C S, Vaughn T L, Zimmerle D, Herndon S C, Yacovitch T I, Heath G A, Pétron G, Edie R, Field R A and Murphy S M 2017 Comparison of methane emission estimates from multiple measurement techniques at natural gas production pads *Elem. Sci. Anth.* **5** 79
- Benson R, Madding R, Lucier R, Lyons J and Czerepuszko P 2006 Standoff passive optical leak detection of volatile organic compounds using a cooled insb based infrared imager *AWMA 99th Annual Meeting Papers* vol 131 (<https://pdfs.semanticscholar.org/8ed8/afdf0e1930bf0f638125f1c702ad2389d659.pdf>)

- Brandt A R, Garvin A H and Cooley D 2016 Methane leaks from natural gas systems follow extreme distributions *Environ. Sci. Technol.* **50** 12512–20
- Brandt A R and Pétron G 2015 Fugitive emissions and air quality impacts of US natural gas systems *Bridge* **45** 22–31
- Brandt A R et al 2014 Methane leaks from north american natural gas systems *Science* **343** 733–5
- Brantley H L, Thoma E D, Squier W C, Guven B B and Lyon D 2014 Assessment of methane emissions from oil and gas production pads using mobile measurements *Environ. Sci. Technol.* **48** 14508–15
- Brownlow R et al 2016 Methane mole fraction and $\delta^{13}\text{C}$ above and below the trade wind inversion at ascension island in air sampled by aerial robotics *Geophys. Res. Lett.* **43** 893–902
- Bruhwiller L M et al 2017 US CH₄ emissions from oil and gas production: have recent large increases been detected? *J. Geophys. Res.: Atmos.* **122** 4070–83
- Buckland K N, Young S J, Keim E R, Johnson B R, Johnson P D and Tratt D M 2017 Tracking and quantification of gaseous chemical plumes from anthropogenic emission sources within the los angeles basin *Remote Sens. Environ.* **201** 275–96
- Butler T M, Simmonds I and Rayner P J 2004 Mass balance inverse modelling of methane in the 1990s using a chemistry transport model *Atmos. Chem. Phys.* **4** 2561–80
- Butz A, Galli A, Hasekamp O, Landgraf J, Tol P and Aben I 2012 TROPOMI aboard sentinel-5 precursor: prospective performance of CH₄ retrievals for aerosol and cirrus loaded atmospheres *Remote Sens. Environ.* **120** 267–76
- CATF 2013 *Methane Emissions from the Oil and Gas Sector: Barriers to Abatement and Technologies for Emission Reductions* (Boston, MA: Clean Air Task Force) (http://catf.us/resources/publications/files/201303-Barriers_and_Opportunities_in_the_Oil_and_Gas_Sector.pdf)
- Caulton D R, Li Q, Bou-Zeid E, Fitts J P, Golston L M, Pan D, Lu J, Lane H M, Buchholz B and Guo X 2018 Quantifying uncertainties from mobile-laboratory-derived emissions of well pads using inverse gaussian methods *Atmos. Chem. Phys.* **18** 15145–68
- CDPHE 2018 Alternative AIMM Guidance & Procedures
- Christen A 2014 Atmospheric measurement techniques to quantify greenhouse gas emissions from cities *Urban Clim.* **10** 241–60
- Coburn S et al 2018 Regional trace-gas source attribution using a field-deployed dual frequency comb spectrometer *Optica* **5** 320–7
- Conley S, Franco G, Faloona I, Blake D R, Peischl J and Ryerson T B 2016 Methane emissions from the 2015 aliso canyon blowout in Los Angeles, CA *Science* **351** 1317–20
- Conley S et al 2017 Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases *Atmos. Meas. Tech. Discuss.* **10** 3345–58
- Cossel K C et al 2017 Open-path dual-comb spectroscopy to an airborne retroreflector *Optica* **4** 724–8
- Davis K J et al 2017 The Indianapolis flux experiment (INFLUX): a test-bed for developing urban greenhouse gas emission measurements *Elem. Sci. Anth.* **5** 21
- Ellis H M and Lackaye R 1989 Estimating fugitive emissions of volatile compounds from equipment leaks *JAPCA* **39** 1619–22
- Emran B J, Tannant D D and Najjaran H 2017 Low-altitude aerial methane concentration mapping *Remote Sens.* **9** 823
- Englander J G, Brandt A R, Conley S, Lyon D R and Jackson R B 2018 Aerial interyear comparison and quantification of methane emissions persistence in the bakken formation of North Dakota, USA *Environ. Sci. Technol.* **52** 8947–53
- Envirotech Engineering 2007 *Review and Update of Methods Used for Air Emissions Leak Detection and Quantification* (Canada: Petroleum Technology Alliance)
- EPA 2016 Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources *Fed. Register: Final Rule* Government of the United States of America
- Feitz A, Schroder I, Phillips F, Coates T, Neghandhi K, Day S, Luhar A, Bhatia S, Edwards G and Hrabar S 2018 The ginninderra CH₄ and CO₂ release experiment: an evaluation of gas detection and quantification techniques *Int. J. Greenhouse Gas Control* **70** 202–24
- Fischer J C V, Cooley D, Chamberlain S, Gaylord A, Griebenow C J, Hamburg S P, Salo J, Schumacher R, Theobald D and Ham J 2017 Rapid, vehicle-based identification of location and magnitude of urban natural gas pipeline leaks *Environ. Sci. Technol.* **51** 4091–9
- Footer T L 2015 Optical gas imaging protocol *Technical Support Document 5* Eastern Research Group, Inc.
- Foster-Wittig T 2015 *Mobile Sensors: Assessment of Fugitive Methane Emissions from Near and Far-Field Sources* (Duke University) (<https://dukespace.lib.duke.edu/dspace/handle/10161/9893>)
- Frankenberg C, Aben I, Bergamaschi P, Dlugokencky E J, van Hees R, Houweling S, van Der Meer P, Snel R and Tol P 2011 Global column-averaged methane mixing ratios from 2003 to 2009 as derived from SCIAMACHY: trends and variability *J. Geophys. Res.: Atmos.* **116** D04302
- Frankenberg C, Meirink J F, van Weele M, Platt U and Wagner T 2005 Assessing methane emissions from global space-borne observations *Science* **308** 1010–4
- Frankenberg C et al 2016 Airborne methane remote measurements reveal heavy-tail distribution in four corners region *Proc. Natl Acad. Sci.* **113** 9734–9
- Gålfalk M, Olofsson G, Crill P and Bastviken D 2016 Making methane visible *Nat. Clim. Change* **6** 426–30
- Gardi A, Kapoor R and Sabatini R 2017 Detection of volatile organic compound emissions from energy distribution network leaks by bistatic LIDAR *Energy Proc.* **110** 396–401
- Gemerek J R, Ferrari S and Albertson J D 2017 Fugitive gas emission rate estimation using multiple heterogeneous mobile sensors *Int. Symp. on Olfaction and Electronic Nose (ISOEN), 2017 ISOC/IEEE* (Piscataway, NJ: IEEE) pp 1–3
- Gerhart T, Sunu J, Lieu L, Merkurjev E, Chang J-M, Gilles J and Bertozzi A L 2013 Detection and tracking of gas plumes in LWIR hyperspectral video sequence data *SPIE Defense, Security, and Sensing* p 87430J
- Goetz J D et al 2017 Analysis of local-scale background concentrations of methane and other gas-phase species in the marcellus shale *Elem. Sci. Anth.* **5** 1
- Goldsmith C D, Chanton J, Abichou T, Swan N, Green R and Hater G 2012 Methane emissions from 20 landfills across the United States using vertical radial plume mapping *J. Air Waste Manage. Assoc.* **62** 183–97
- Golston L M, Aubut N, Frish M, Yang S, Talbot R, Gretencord C, McSpirt J and Zondlo M 2018 Natural gas fugitive leak detection using an unmanned aerial vehicle: localization and quantification of emission rate *Atmosphere* **9** 333
- Golston L M et al 2017 Lightweight mid-infrared methane sensor for unmanned aerial systems *Appl. Phys. B* **123**
- Government of Canada 2017 Canada Gazette—Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector) 27 May, 2017
- Harriss R et al 2015 Using multi-scale measurements to improve methane emission estimates from oil and gas operations in the barnett shale region, Texas *Environ. Sci. Technol.* **49** 7524–6
- Hashmonay R A and Yost M G 1999 Innovative approach for estimating fugitive gaseous fluxes using computed tomography and remote optical sensing techniques *J. Air Waste Manage. Assoc.* **49** 966–72
- Heimbürger A M F et al 2017 Assessing the optimized precision of the aircraft mass balance method for measurement of urban greenhouse gas emission rates through averaging *Elem. Sci. Anth.* **5** 26
- Hirst B, Jonathan P, del Cueto F G, Randell D and Kosut O 2013 Locating and quantifying gas emission sources using remotely obtained concentration data *Atmos. Environ.* **74** 141–58
- Hirst B, Randell D, Jones M, Jonathan P, King B and Dean M 2017 A new technique for monitoring the atmosphere above onshore carbon storage projects that can estimate the locations and

- mass emission rates of detected sources *Energy Proc.* **114** 3716–28
- Hu H, Landgraf J, Detmers R, Borsdorff T, de Brugh J A, Aben I, Butz A and Hasekamp O 2018 Toward global mapping of methane with TROPOMI: first results and intersatellite comparison to GOSAT *Geophys. Res. Lett.* **45** 3682–9
- ICF International 2014 Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries (https://edf.org/sites/default/files/methane_cost_curve_report.pdf)
- ICF International 2015 Economic Analysis of Methane Emission Reduction Opportunities in the Canadian Oil and Natural Gas Industries (<https://pembina.org/reports/edf-icf-methane-opportunities.pdf>)
- Jackson R B, Down A, Phillips N G, Ackley R C, Cook C W, Plata D L and Zhao K 2014 Natural gas pipeline leaks across Washington, DC *Environ. Sci. Technol.* **48** 2051–8
- Jacob D J, Turner A J, Maasakkers J D, Sheng J, Sun K, Liu X, Chance K, Aben I, McKeever J and Frankenberg C 2016 Satellite observations of atmospheric methane and their value for quantifying methane emissions *Atmos. Chem. Phys. Discuss.* **16** 14371–96
- Johnson D R, Covington A N and Clark N N 2015 Methane emissions from leak and loss audits of natural gas compressor stations and storage facilities *Environ. Sci. Technol.* **49** 8132–8
- Johnson M R, Tyner D R, Conley S, Schwietzke S and Zavala-Araiza D 2017 Comparisons of airborne measurements and inventory estimates of methane emissions in the alberta upstream oil and gas sector *Environ. Sci. Technol.* **51** 13008–17
- Kang M, Kanno C M, Reid M C, Zhang X, Mauzerall D L, Celia M A, Chen Y and Onstott T C 2014 Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania *Proc. Natl Acad. Sci.* **111** 18173–7
- Karion A et al 2013 Methane emissions estimate from airborne measurements over a Western United States natural gas field *Geophys. Res. Lett.* **40** 4393–7
- Karion A et al 2015 Aircraft-based estimate of total methane emissions from the barnett shale region *Environ. Sci. Technol.* **49** 8124–31
- Kemp C E, Ravikumar A P and Brandt A R 2016 Comparing natural gas leakage detection technologies using an open-source virtual gas field simulator *Environ. Sci. Technol.* **50** 4546–53
- Khan A, Schaefer D, Tao L, Miller D J, Sun K, Zondlo M A, Harrison W A, Roscoe B and Lary D J 2012 Low power greenhouse gas sensors for unmanned aerial vehicles *Remote Sens.* **4** 1355–68
- Kiemle C, Kawa S R, Quatrevalet M and Browell E V 2014 Performance simulations for a spaceborne methane lidar mission *J. Geophys. Res.: Atmos.* **119** 4365–79
- Kort E A, Frankenberg C, Costigan K R, Lindenmaier R, Dubey M K and Wunch D 2014 Four corners: the largest US methane anomaly viewed from space: four corners: largest us methane anomaly *Geophys. Res. Lett.* **41** 6898–903
- Kuze A et al 2016 Update on GOSAT TANSO-FTS performance, operations, and data products after more than six years in space *Atmos. Meas. Tech.* **2016** 1–1
- Lan X, Talbot R, Laine P and Torres A 2015 Characterizing fugitive methane emissions in the barnett shale area using a mobile laboratory *Environ. Sci. Technol.* **49** 8139–46
- Lavoie T N, Shepson P B, Cambaliza M O L, Stirn B H, Conley S, Mehrotra S, Faloona I C and Lyon D 2017 Spatiotemporal variability of methane emissions at oil and natural gas operations in the eagle ford basin *Environ. Sci. Technol.* **51** 8001–9
- Lavoie T N, Shepson P B, Cambaliza M O L, Stirn B H, Karion A, Sweeney C, Yacovitch T I, Herndon S C, Lan X and Lyon D 2015 Aircraft-based measurements of point source methane emissions in the barnett shale basin *Environ. Sci. Technol.* **49** 7904–13
- Littlefield J A, Marriott J, Schivley G A and Skone T J 2017 Synthesis of recent ground-level methane emission measurements from the U.S. natural gas supply chain *J. Cleaner Prod.* **148** 118–26
- Lyon D R, Alvarez R A, Zavala-Araiza D, Brandt A R, Jackson R B and Hamburg S P 2016 Aerial surveys of elevated hydrocarbon emissions from oil and gas production sites *Environ. Sci. Technol.* **50** 4877–86
- Malaver A, Motta N, Corke P and Gonzalez F 2015 Development and integration of a solar powered unmanned aerial vehicle and a wireless sensor network to monitor greenhouse gases *Sensors* **15** 4072–96
- Marchese A J et al 2015 Methane emissions from united states natural gas gathering and processing *Environ. Sci. Technol.* **49** 10718–27
- Michanowicz D R, Buonocore J J, Rowland S T, Konschnik K E, Goho S A and Bernstein A S 2017 A national assessment of underground natural gas storage: identifying wells with designs likely vulnerable to a single-point-of-failure *Environ. Res. Lett.* **12** 064004
- Mitchell A L et al 2015 Measurements of methane emissions from natural gas gathering facilities and processing plants: measurement results *Environ. Sci. Technol.* **49** 3219–27
- Moore C W, Zielinska B, Pétron G and Jackson R B 2014 Air impacts of increased natural gas acquisition, processing, and use: a critical review *Environ. Sci. Technol.* **48** 8349–59
- Nathan B J et al 2015 Near-field characterization of methane emission variability from a compressor station using a model aircraft *Environ. Sci. Technol.* **49** 7896–903
- Neumann P P, Asadi S, Lilienthal A J, Bartholmai M and Schiller M 2011 Micro-drone for wind vector estimation and gas distribution mapping *J. IEEE Robot. Autom. Mag.* **6** 1–11
- Omara M, Sullivan M R, Li X, Subramanian R, Robinson A L and Presto A A 2016 Methane emissions from conventional and unconventional natural gas production sites in the marcellus shale basin *Environ. Sci. Technol.* **50** 2099–107
- Patel P 2017 Low-cost sensors could help natural gas producers plug costly methane leaks *ACS Cent. Sci.* **26** 679–82
- Peischl J et al 2015 Quantifying atmospheric methane emissions from the haynesville, fayetteville, and northeastern marcellus shale gas production regions: ch4 emissions from shale gas production *J. Geophys. Res.: Atmos.* **120** 2119–39
- Phillips N G, Ackley R, Crosson E R, Down A, Hutya L R, Brondfield M, Karr J D, Zhao K and Jackson R B 2013 Mapping Urban pipeline leaks: methane leaks across Boston *Environ. Pollut.* **173** 1–4
- Ravikumar A P and Brandt A R 2017 Designing better methane mitigation policies: the challenge of distributed small sources in the natural gas sector *Environ. Res. Lett.* **12** 044023
- Ravikumar A P, Wang J and Brandt A R 2017 Are optical gas imaging technologies effective for methane leak detection? *Environ. Sci. Technol.* **51** 718–24
- Ravikumar A P, Wang J, McGuire M, Bell C S, Zimmerle D and Brandt A R 2018 Good versus good enough ? empirical tests of methane leak detection sensitivity of a commercial infrared camera *Environ. Sci. Technol.* **52** 2368–74
- Rella C W, Tsai T R, Botkin C G, Crosson E R and Steele D 2015 Measuring emissions from oil and natural gas well pads using the mobile flux plane technique *Environ. Sci. Technol.* **49** 4742–8
- Riris H, Numata K, Wu S, Gonzalez B, Rodriguez M, Kawa S and Mao J 2017 Methane measurements from space: technical challenges and solutions *Laser Radar Technology and Applications XXII* ed M D Turner and G W Kamerman p 1019104
- Ro K S, Johnson M J, Hunt P G and Flesch T K 2011 Measuring trace gas emission from multi-distributed sources using vertical radial plume mapping (VRPM) and backward lagrangian stochastic (BLS) techniques *Atmosphere* **2** 553–66
- Robertson A M, Edie R, Snare D, Soltis J, Field R A, Burkhart M D, Bell C S, Zimmerle D and Murphy S M 2017 Variation in methane emission rates from well pads in four oil and gas basins with contrasting production volumes and compositions *Environ. Sci. Technol.* **51** 8832–40

- Rojas A J, Gonzalez L F, Motta N and Villa T F 2015 *Design and Flight Testing of an Integrated Solar Powered UAV and WSN for Remote Gas Sensing* (Piscataway, NJ: IEEE) pp 1–10
- Roscioli J R et al 2015 Measurements of methane emissions from natural gas gathering facilities and processing plants: measurement methods *Atmos. Meas. Tech.* **8** 2017
- Roy A A, Adams P J and Robinson A L 2014 Air pollutant emissions from the development, production, and processing of marcellus shale natural gas *J. Air Waste Manage. Assoc.* **64** 19–37
- Saunier S, Haugland T and Pederstad A 2014 Quantifying cost-effectiveness of systematic leak detection and repair programs using infrared cameras *CL report CL-13-27 Carbon Limits* (https://ourenergypolicy.org/wp-content/uploads/2014/03/Carbon_Limits_LDAR.pdf)
- Schneising O, Burrows J P, Dickerson R R, Buchwitz M, Reuter M and Bovensmann H 2014 Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations: remote sensing of fugitive methane emissions from oil and gas production *Earth's Future* **2** 548–58
- Schwietzke S et al 2019 Aerially-guided leak detection and repair: a pilot field study for evaluating the potential of methane emission detection and cost-effectiveness *J. Air Waste Manage. Assoc.* **69** 71–88
- Schwietzke S et al 2017 Improved mechanistic understanding of natural gas methane emissions from spatially-resolved aircraft measurements *Environ. Sci. Technol.* **51** 7286–94
- Smith M L, Gvakharia A, Kort E A, Sweeney C, Conley S A, Faloon I, Newberger T, Schnell R, Schwietzke S and Wolter S 2017 Airborne quantification of methane emissions over the four corners region *Environ. Sci. Technol.* **51** 5832–7
- Subramanian R et al 2015 Methane emissions from natural gas compressor stations in the transmission and storage sector: measurements and comparisons with the EPA greenhouse gas reporting program protocol *Environ. Sci. Technol.* **49** 3252–61
- Szulczynski B and Gebicki J 2017 Currently commercially available chemical sensors employed for detection of volatile organic compounds in outdoor and indoor air *Environments* **4** 21
- Tadić J M et al 2017 Elliptic cylinder airborne sampling and geostatistical mass balance approach for quantifying local greenhouse gas emissions *Environ. Sci. Technol.* (<https://doi.org/10.1021/acs.est.7b03100>)
- Tao L, Pan D, Golston L, Sun K, Saripalli S and Zondlo M A 2015 UAV-based laser spectrometer to quantify methane from agricultural and petrochemical activities *Conf. on Lasers and Electro-Optics (CLEO)* pp 1–2
- Terry C, Argyle M, Meyer S, Sander L and Hirst B 2017 Mapping methane sources and their emission rates using an aircraft *Leading Edge* **36** 33–5
- Thoma E and Squier B 2014 *OTM 33 Geospatial Measurement of Air Pollution, Remote Emissions Quantification (GMAP-REQ) and OTM33A Geospatial Measurement of Air Pollution-Remote Emissions Quantification-Direct Assessment (GMAP-REQ-DA)* (Cincinnati, OH: US Environmental Protection Agency)
- Thompson D R et al 2015 Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane *Atmos. Meas. Techn.* **8** 4383–97
- Thorpe A K et al 2017 Airborne DOAS retrievals of methane, carbon dioxide, and water vapor concentrations at high spatial resolution: application to AVIRIS-NG *Atmos. Meas. Tech.* **10** 3833
- Townsend-Small A, Tyler S C, Pataki D E, Xu X and Christensen L E 2012 Isotopic measurements of atmospheric methane in los angeles, California, USA: influence of fugitive fossil fuel emissions *J. Geophys. Res.: Atmos.* **117** D07308
- Varon D J, Jacob D J, McKeever J, Jervis D, Durak B O A, Xia Y and Huang Y 2018 Quantifying methane point sources from fine-scale satellite observations of atmospheric methane plumes *Atmos. Meas. Tech.* **11** 5673–86
- Vaughn T L, Bell C S, Pickering C K, Schwietzke S, Heath G A, Pétron G, Zimmerle D J, Schnell R C and Nummedal D 2018 Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region *Proc. Natl Acad. Soc.* **115** 11712–7
- Verhulst K R et al 2017 Carbon dioxide and methane measurements from the los angeles megacity carbon project: I. Calibration, urban enhancements, and uncertainty estimates *Atmos. Chem. Phys. Discuss.* **17** 8313–41
- von Fischer J C, Brewer P E, Chamberlain S, Gaylord A and von Fischer J 2016 Mobile natural gas leak surveys indicate that two utilities have high false negative rates *AGU Fall Meeting Abstracts*
- Wainner R T, Nicholas F A, Laderer M C and Frish M B 2017 Scanning, standoff TDLAS leak imaging and quantification *SPIE Commercial + Scientific Sensing and Imaging* (International Society for Optics and Photonics) p 1021006
- Weller Z, Roscioli J R, Daube W C, Lamb B K, Ferrara T, Brewer P E and von Fischer J C 2018 Vehicle-based methane surveys for finding natural gas leaks and estimating their size: validation and uncertainty *Environ. Sci. Technol.* **52** 11922–30
- Yacovitch T I, Daube C, Vaughn T L, Bell C S, Roscioli J R, Knighton W B, Nelson D D, Zimmerle D, Pétron G and Herndon S C 2017 Natural gas facility methane emissions: measurements by tracer flux ratio in two US natural gas producing basins *Elem. Sci. Anth.* **5** 69
- Yacovitch T I, Herndon S C, Pétron G, Kofler J, Lyon D, Zahniser M S and Kolb C E 2015 Mobile laboratory observations of methane emissions in the barnett shale region *Environ. Sci. Technol.* **49** 7889–95
- Yang S, Talbot R, Frish M, Golston L, Aubut N, Zondlo M, Gretencord C and McSpiritt J 2018 Natural gas fugitive leak detection using an unmanned aerial vehicle: measurement system description and mass balance approach *Atmosphere* **9** 383
- Yen C-H and Horng J-J 2009 Volatile organic compounds (VOCs) emission characteristics and control strategies for a petrochemical industrial area in middle Taiwan *J. Environ. Sci. Health A* **44** 1424–9
- Zavala-Araiza D et al 2015a Reconciling divergent estimates of oil and gas methane emissions *Proc. Natl Acad. Sci.* **112** 15597–602
- Zavala-Araiza D et al 2015b Toward a functional definition of methane super-emitters: application to natural gas production sites *Environ. Sci. Technol.* **49** 8167–74
- Zavala-Araiza D et al 2017 Super-emitters in natural gas infrastructure are caused by abnormal process conditions *Nat. Commun.* **8** 14012
- Zazzeri G, Lowry D, Fisher R E, France J L, Lanoisellé M and Nisbet E G 2015 Plume mapping and isotopic characterisation of anthropogenic methane sources *Atmos. Environ.* **110** 151–62