PTAC ALT-FEMP Project Report

Methane emissions detection, attribution, and quantification at upstream oil and gas facilities – a comparison of two truck systems and optical gas imaging

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Executive Summary

We present results from a case study examining the performance of two truck-based screening systems for detecting, attributing, and quantifying methane emissions at upstream oil and gas facilities, compared to baseline optical gas imaging (OGI)-based surveys.

The baseline OGI survey was completed with a handheld FLIR GF-320 camera coupled with a Providence Photonics QL-320 tablet for emissions quantification. The OGI survey collected component-level emissions detections and quantifications. The truck-based screening systems include the University of Calgary's PoMELO and Altus Geomatics' ExACT that each provide different information. The ExACT system detects, attributes, and quantifies facility-level emissions and the PoMELO system detects, attributes, and quantifies equipment and facility-level emissions. The ExACT system reported measurements on pad, and the PoMELO system reported measurements both on and off pad. Component-level detections and quantifications from the OGI survey were summed to the equipment and facility levels in order to compare with measurements from the truck systems. In total, 80 oil and gas facilities were surveyed in November 2018 and May 2019 using these three methods. At each facility, the methods were deployed at the same time to minimize potential differences due to temporal variations of emissions.

Results indicate strong agreement among the methods for facility-level detections. The relative accuracy of the truck systems in detecting facility-level emissions was between 86-100%. PoMELO detected emissions at 100% of facilities that were emitting according to OGI. ExACT detected emissions at 86-93% of facilities that were emitting according to OGI. In November 2018, PoMELO detected emissions at three facilities and ExACT detected emissions at one facility that OGI determined to be not emitting. ExACT and PoMELO detected similar emissions overall (86-89% agreement), but PoMELO detected emissions at three facilities in November 2018 and four facilities in May 2019 that ExACT determined were not emitting.

Equipment-level detections were compared only between OGI and PoMELO, as ExACT reported facility-level emissions. Results indicate that PoMELO identified 73-80% of the emitting and non-emitting equipment identified by OGI. PoMELO did not identify 20% of emitting equipment determined with OGI, but it identified emissions from 11-33% of the equipment OGI determined was not emitting. Part of the discrepancy may be the result of restricted downwind vehicle access and methane sources that are inherently harder to detect with OGI because of strong heat signatures interfering with methane emissions (e.g., catadyne heaters, engine exhausts).

There was overlap in estimates of facility-level emissions rates from all three methods, but there was limited statistical association between estimates from PoMELO and ExACT compared to estimates from quantitative OGI (QOGI) using the Providence Photonics QL-320. This may be problematic for work practices that rely on estimates of emissions rates to prioritize follow-up inspection.

There are several challenges comparing estimates of emissions rates among the three methods: wind conditions, atmospheric stability, on pad access downwind of equipment, and missing (out of scope) quantifications from QOGI. Approximately 50% of the facilities had full on pad access in which the trucks could drive downwind of all major equipment at close range. Similarly, off pad measurements were possible at approximately 50% of the facilities based on road access and wind direction in both campaigns. Furthermore, between 4% and 17% of emission sources could not be quantified by QOGI.

Key recommendations emerging from this research are:

1. The accuracy and reproducibility (precision) of emissions quantification with QOGI and truck-based methods requires further study.
2. Controlled release testing is recommended for evaluating detection and quantification performance.
3. Indices that qualify the completeness of screening measurements for each facility should be developed.

1. Introduction

Many new technologies and methods have emerged in the last decade to detect and measure methane emissions from oil and gas production, processing, and distribution systems (Fox et al., 2019a). Some of these technologies are commercially available, while some are still maturing through R&D and testing. Despite growing awareness and pathways for implementation via new methane regulations, general knowledge of technology performance, methodologies, work practices, and applications is relatively under-reported in the scientific literature (Ravikumar et al., 2019; Schwietzke et al., 2019). With limited evidence of performance in real-world conditions, end-users and regulators may struggle to make informed decisions about the application and approval of new technologies and methods that are designed, in principle, to find methane emissions sources at oil and gas operations that can be mitigated through repairs or other means to reduce methane emissions. To address this issue, we developed a field study to evaluate the performance of two truck-based systems for detecting, attributing, and quantifying methane emissions in comparison to an existing regulatory standard – optical gas imaging (OGI) – at upstream oil and gas facilities.

The field study (hereafter Alt-FEMP) summarized here was conducted in conjunction with the Petroleum Technology Alliance of Canada's (PTAC) Fugitive Emissions Management Program – Effectiveness Assessment (FEMP-EA) study. The FEMP-EA study sought to survey selected oil and gas facilities periodically using OGI technology to assess the effectiveness of leak detection and repair (LDAR) surveys. The performance evaluation of the two truck-based screening systems in this study was conducted alongside the FEMP-EA survey in November 2018 and in May 2019. The surveys were conducted at approximately 40 oil and gas facilities. The 'baseline' OGI survey (conducted by Davis Safety Consulting Ltd.) consisted of a FLIR GF-320 infrared camera-based component-level detection and a Providence Photonics GL-320 based quantification.

The truck-based systems tested in this study are part of a suite of new mobile technologies and methods that can be used to screen facilities for methane emissions (Fox et al., 2019a). The Emissions Attribution via Computational Techniques (ExACT) truck-based system was developed at St. Francis Xavier University and is operated commercially by Altus Geomatics. The PoMELO truck-based system was developed at the University of Calgary. As of Q4 2019, the university has commenced the process of commercializing PoMELO. Neither of these systems can resolve individual components emitting methane, but can detect, attribute, and estimate emissions at the equipment- and/or facility-level. To be effective for LDAR programs, these technologies and methods must connect data to actionable information that results in the identification of emissions sources that can be repaired; thereby reducing emissions. To be attractive to end-users and regulators, they must also be cost-effective *and* achieve equivalent emissions reduction outcomes compared to LDAR programs that use conventional technologies and methods approved by regulators (Fox et al., 2019b).

One screening strategy proposed by commercial operators is to rank (triage) facilities based on their estimated emissions rates and then apply follow-up inspection with close-range technologies at some proportion of the highest emitting facilities to identify and repair emitting components. Not all technologies apply this screen-triage-inspect-repair strategy. Triaging depends on reasonably accurate estimates of emissions rates. For context, single-blind field testing of ten screening technologies in the Stanford / Environmental Defence Fund (EDF) Mobile Monitoring Challenge (MMC) showed that most technologies were only able to provide order of magnitude emissions estimates (Ravikumar et al., 2019).

This study is an extension of the Stanford/EDF MMC to real-world conditions at upstream oil and gas facilities. We yield control on emissions rates and sources and focus on comparing method performance under representative operating conditions that will be encountered in the field if or when these technologies are implemented in LDAR programs (e.g.., accessibility, seasonality, production type, emissions sources within buildings). Both truck systems selected for this study have been described in scientific literature (Baillie et al., 2019; O'Connell et al., 2019; Barchyn and Hugenholtz, 2020). PoMELO has undergone single-blind controlled testing during Stanford/EDF MMC (Ravikumar et al., 2019), and more recently in a test program at Colorado State University's METEC facility (Barchyn and Hugenholtz, 2020).

1.1. Alt-FEMP Program Organization

To undertake the Alt-FEMP program, an organization structure was developed. It includes a Steering Committee, Project Management Team and Scientific Advisory Team. The following section describes the roles and responsibilities of each of the three organizational entities:

1.1.1. Steering Committee:

This committee was comprised of PTAC staff, provincial energy regulators, and upstream oil and gas industry members from the Air Research Planning Committee. The key roles and responsibilities of the Steering Committee were:

- Strategically lead the program to successful completion;
- Establish program objectives, scope, budget, and schedule;
- Provide guidance and support through decision making and scoping challenges;
- Provide input on the technical quality of the Study Design and execution;
- Represent the interests of Alberta and British Columbia energy regulators as well as the upstream oil and gas industry in the project;
- Lead executive level stakeholder engagement; and,
- Ensure the commercial and technical integrity of the program.

1.1.2. Project Management Team (PMT):

The PMT was made up of senior members of Cap-Op Energy Inc. and DXD Consulting Inc.
The primary roles and responsibilities of the PMT were to:

- Steward program scope, schedule and budget;
- Manage contracts and administration of program;
- Provide communications on the progress of the Program to the Steering Committee;
- Provide program decision making support;
- Manage all field-based logistics including daily site visit schedules;
- Manage field surveys for safe and technically sound execution;
- Liaise with all stakeholders (including industry head office and field staff, project participants and members of the Steering Committee); and
- Prepare reports and presentations for the Steering Committee.

1.1.3. Scientific Advisory Team (SAT):

This team comprised the first and second authors of this report. Additional academic and technical support including data processing and management were provided under the oversight of the lead advisors. Key roles and responsibilities of this team were:

- Complete the study design and site selection;
- As required, strategically adapt the program as data collection begins;
- Conduct data analyses;
- Support the PMT with information on data collection, as required, and if challenges arise in the field;

- Provide Steering Committee guidance and support regarding data collection, analyses and technical execution;
- Communicate expectations on data collection to the Steering Committee and PMT; and,
- Prepare reports and presentations for the Steering Committee.

2. Methodology

The field program consisted of methane emissions measurements at 40 upstream oil and gas facilities in November 2018 and May 2019. Three teams were deployed: one OGI team (Davis Safety Consulting Inc.; hereafter Davis Safety) and two truck teams (University of Calgary and Altus Geomatics). The OGI team collected close-range measurements of emissions sources and quantifications at the component level, while the truck teams collected screening measurements on and off the pads to resolve emissions at the equipment and facility levels. OGI data were aggregated to the equipment and facility levels for comparison with data collected by the truck teams. In this section, we provide detailed information of the technologies and methods, the facilities, field procedures, and data analysis procedures.

Throughout this report, component refers to individual emitting sources (e.g., valve, flange, etc.), while equipment refers to major pieces of infrastructure (e.g., separator, wellhead) that have multiple components. A facility is a collection of equipment that together constitute a site. For example, a wellsite (facility) can contain equipment such as well head, tank, and separator, each of which can have several components. OGI cameras detect emissions at the component-level, PoMELO detects, attributes, and quantifies emissions at the equipment-level and ExACT detects, attributes, and quantifies emissions at the facility level.

2.1. Technologies and Methods

2.1.1. Davis Safety – OGI

The OGI team used a FLIR GF320 camera for detection and a Providence Photonics QL320 for quantification. The GF320 is a type of OGI camera that is widely used by industry for detecting methane emissions. OGI cameras like the GF320 are approved methods for LDAR in Canada and the USA (EPA, 2016; Government of Canada, 2017). The QL320 is a software system for estimating emissions rates from videos collected by the GF320. The QL320s's performance has not been published in peer-reviewed literature. Results from 24 controlled release runs (at 10 rates from 16.5 to 998.7 g/h) presented by Caico et al. (2017) suggest high accuracy and nearly 1:1 positive correlation. However, tests using three controlled release rates (1, 5, and 10 L/min) by the Saskatchewan Research Council (SRC) found that flow rates with the QL320 had up to 1570% error, and typically 95% error (SRC, 2018). Importantly, the SRC results indicate that flow rate estimates from QL320 have poor reproducibility. This suggests the QL320 provides order of magnitude emissions estimates, much like the mobile screening technologies tested by Ravikumar et al. (2019). Providence Photonics regularly issues software patches to users to update the QL320 quantification algorithms, but it is unclear whether software updates since the aforementioned studies have improved both the accuracy and precision of flow rate estimates. The Alberta Methane Field Challenge conducted in 2019 tested a wide range of emission flow rates in controlled release experiments to quantify the uncertainty in QL320 estimates (Ravikumar et al., 2020).

At each facility, the OGI team identified and reported all emissions as fugitives (leaks) or vents, although distinguishing between these emissions categories can be challenging in some cases. Several sources known to emit methane along with other gases and particulates were not reported or quantified, such as active flares, catadyne heaters, and engine exhaust. Emissions from these equipment categories are inherently harder to detect or quantify with OGI because of strong heat signatures interfering with methane emissions.

2.1.2. Overview: Truck Systems

The truck systems examined in this study measure methane plumes intersected while the vehicles are moving. Plume intersection is contingent on downwind vehicle access, source location, and several key factors affecting plume dynamics. Near source, plumes sampled in sub-minute transects are often not gaussian shaped or diffuse (Nathan et al., 2015; von Fischer et al., 2017; Yacovitch et al., 2018; Weller et al., 2018; Barchyn et al., 2019). Instead, they tend to have small, high concentration 'tongues' of methane. Gaussian approximation typically emerges after time-averaging methane concentration data over minutes to hours from measurements made at a distance from the source (e.g., Brantley et al., 2014). This contrasts with the sub-minute timescale of mobile screening methods, which are predicated on the ability to survey quickly (Fox et al., 2019a). Therefore, effective quantification from mobile surveys is challenging because of the twin issues of measuring methane concentrations and efficacy of algorithms that convert concentration to emission rate. Whether a technology under/over-estimates emissions depends on both the measured concentrations and the efficacy of the algorithms.

As outlined in Table 1, the truck systems differ in the types of sensors, algorithms, and work practices they use. Seemingly subtle differences can result in large differences in detecting, attributing, and quantifying methane emissions at upstream oil and gas facilities. Further details on ExACT and PoMELO are outlined in Baillie et al. (2019) and Barchyn and Hugenholtz (2020), respectively.

Table 1: Overview of PoMELO and ExACT truck systems.

	PoMELO	ExACT
Work Practice (in this study)	Map emitting and non-emitting equipment to guide the application of OGI	Detect and quantify facility-level emissions to prioritize follow-up OGI surveys
Sensors	Open-path methane sensor, GPS, anemometer	Cavity-ring down methane sensor, GPS, anemometer
Hardware Configuration	Portable: roof rack	Fully integrated: vehicle customizations
Data Outputs	Equipment and facility-level detection, attribution, and emissions quantification	Facility-level detection, attribution, and emissions quantification

2.1.2.1. University of Calgary – PoMELO

The University of Calgary (UofC) team used a laser-based methane-only sensor mounted on a standard field pickup truck for equipment- and site-level emissions measurements. The methane sensor uses open-path wavelength modulated spectroscopy to measure light extinction from methane absorption in the measurement path. In addition to methane, the truck is fitted with instruments such as gyros and accelerometers that measure vehicle orientation and position. The system also has an on-board anemometer to measure wind speed and wind direction, and proprietary software to fuse sensor data and output emissions information in real-time.

PoMELO detects, attributes, and quantifies emissions at the equipment level. In practice, PoMELO uses detection and attribution to guide the application of OGI in real time, but in this study OGI measurements were acquired independently. Quantification estimates are also produced for emitting equipment in near real time using proprietary methods. Further details on the PoMELO system, work practice, and performance in single blind controlled release testing are outlined by Barchyn and Hugenholtz (2020).

In this study, PoMELO acquired on pad measurements by driving around and downwind of equipment. The data generated a map of emissions locations, including the corresponding equipment, and an estimate of the emission rate for each piece of emitting equipment. Equipment-level quantifications from on pad measurements were aggregated to compare with facility-level estimates from ExACT and QOGI. Off pad data collection for facility-level emissions quantification was also accomplished at selected facilities by intersecting facility plumes on roads or access roads downwind.

2.1.2.2. Altus Group – ExACT

Altus Geomatics' ExACT system deployed a vehicle-mounted multi-gas sensing system measuring methane (CH4), δ^{13}CH4, carbon dioxide, and water vapor using cavity ring-down spectroscopy. The technology flags emitting sites and estimates emissions using a vehicle-mounted greenhouse gas analyzer, paired with GPS and meteorological measurements. The ExACT technology provides facility-level estimates of methane emissions.

ExACT has been used extensively in western Canada to measure emissions from oil and gas facilities (Atherton et al., 2017; Baillie et al., 2019; O'Connell et al., 2019). The quantification approach is based on gaussian plume modeling. A median emission rate is reported for each facility, along with minimum and maximum emissions rates for the shortest and tallest emissions sources on site, respectively. The method requires an estimate or measurement of potential emissions source heights. Quantification test results from one controlled release rate (21.9 m^3/day) are presented in O'Connell et al. (2019).

In this study, ExACT acquired on pad measurements by driving around and downwind of equipment. The median emission rate from on pad measurements was used to compare with facility-level emissions estimates from QOGI and PoMELO.

2.2. Facilities

Facilities selected for the study were located near Rocky Mountain House, Alberta. This region is underlain by the Duvernay Formation – a Devonian-aged, organic-rich shale basin with sizeable oil and gas reserves. Six representative facility types were selected: single-well oil and gas batteries, multi-well oil and gas batteries, gas gathering systems, and oil multi-well proration batteries. The frequency of each facility type is shown in Table 2. Details on facility locations are omitted to maintain anonymization of data.

Table 2: Total number of facility types surveyed in this study.

Facility Type	Facility ID Code	November 2018	May 2019
Gas SW	351	13	13
Gas MW Batt	361	5	5
Gas GS	621	2	2
Oil SW	311	12	13
Oil MWPRO	322	5	5
Oil MW Batt	321	3	2
Total	-	40	40

During the two field campaigns, OGI, University of Calgary, and Altus surveyed 80, 80, and 58 facilities, respectively, across 43 distinct facilities. This implies that the vast majority of the 43 facilities were surveyed twice by the OGI and University of Calgary teams, once in November 2018 and again in May 2019. Not all facilities could be surveyed twice during the two field campaigns due to access restrictions, maintenance activities, or if the wells were shut in. Owing to study participant schedule constraints, Altus Geomatics surveyed 29 facilities in each field campaign. The study design required the OGI teams and the study participants to visit the same facilities on the same days; consequently, the absence of a study participant on a given day of the program reduced its facility visit counts.

2.3. Weather Conditions

Facilities were surveyed during two field periods: 13-23 November 2018 and 21-30 May 2019. The total precipitation, snow depth, and average daily air temperature during these periods are shown in Figure 1. The average air temperature in November 2018 was -1.7 °C and 10.9 °C in May 2019. Snowfall occurred several times in November during the surveys; however, teams were able to acquire methane emissions measurements. The OGI team noted instances when QOGI was not possible due to rain and snowfall. Smoke from forest fires was also observed in the May 2019 field period but did not impact the measurements.

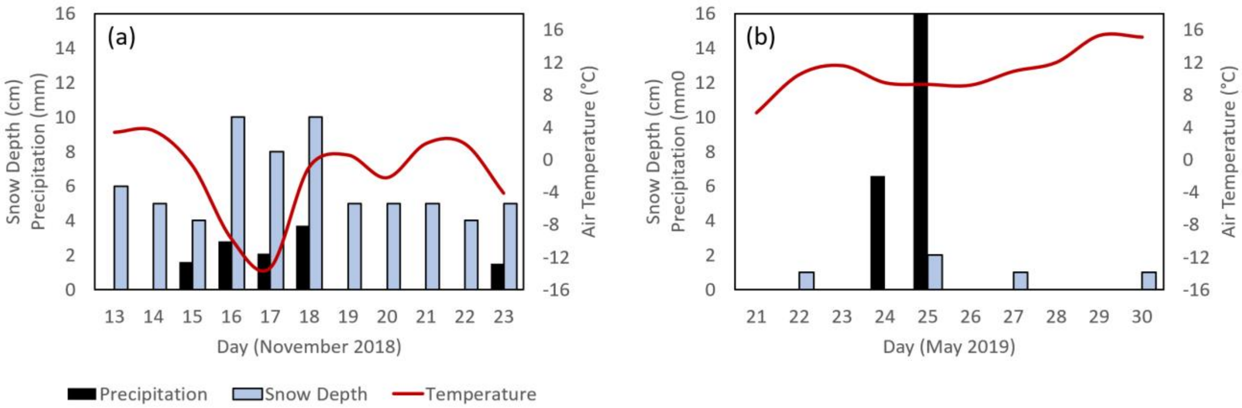

Figure 1: Weather conditions during the field periods at Rocky Mountain House, Alberta: (a) November 2018, (b) May 2019.

2.4. Field and Data Procedures

The surveys were organized so that teams arrived on site together and performed measurements at the same time. This was done to minimize temporal factors that could affect the measurements. Typically, the trucks drove on pad, around equipment at each facility before the OGI team began their survey. This survey protocol was developed to screen facilities for anomalously high emissions that posed a safety concern for the OGI team, and to minimize quantification bias associated with the sudden release of methane from buildings when doors were opened. It was noted that elevated levels of methane would emerge from some buildings when doors were opened by the OGI team, particularly in the November 2018 campaign when catadyne heaters were active inside. This resulted in very high concentrations of methane when trucks drove near the buildings immediately after doors were opened, which affected estimates of emissions rates. However, the high instantaneous concentrations of methane do not imply high emissions from these sources – difficulty in accurately quantifying diffuse (and ‘hot’) sources such as catadyne heaters using OGI systems is well known. Furthermore, this survey protocol helped to avoid bias in truck-based measurements from the physical tags that the OGI team would place on leaking equipment for future repair. Although this survey protocol was fully implemented in the May 2019, it took some time to recognize the issue in the November 2018 campaign. We estimate ~10 sites in the November 2018 campaign did not adhere to this survey protocol, although these sites were not identified when the survey was conducted. Data analysis includes all sites measured in the survey.

Off pad measurements were acquired at some facilities where downwind road access and the schedule permitted. These measurements were considered to be of secondary importance relative to the on pad measurements. Therefore, some sites were suited to off pad measurements but were not surveyed in order to maintain the daily schedule. Once on pad truck surveys and OGI measurements were complete, teams moved on to the next site.

During the surveys, teams did not share information about emissions unless a safety concern was identified. Results and reporting were completed independently. Teams submitted their data to the PMT for distribution to the SAT who then organized the data to enable analysis and comparison. Anonymized and aggregated data from each team are provided in the Supplementary file that accompany this report.

Each team reported different units for the methane emissions quantifications: (i) ExACT (m^3/day), PoMELO (g/s), and QOGI (g/h and scf/m). These represent a mix of volumetric and mass flow rates. To enable direct comparison, all units were standardized.

3. Results

3.1. Facility-Level Detections

OGI detected methane emissions at 90% of the 40 facilities surveyed in November 2018, and 98% of the 40 facilities surveyed in May 2019. More than half the emissions sources were classified as leaks (55-61%). Truck teams also detected methane emissions from most facilities, but there were some differences. Overall, the relative accuracy of the truck systems in detecting facility-level emissions was between 86-100% (Table 3). PoMELO detected emissions at 100% of facilities that were emitting according to OGI. ExACT detected emissions at 86-93% of facilities that were emitting according to OGI. In November 2018, PoMELO detected emissions at three facilities and ExACT detected emissions at one facility that OGI determined to be not emitting. ExACT and PoMELO detected similar emissions overall (86-89% agreement), but PoMELO detected emissions at three facilities in November 2018 and four facilities in May 2019 that ExACT determined were not emitting.

3.2. Equipment-Level Detections and Attributions

Equipment-level detections were only compared between OGI and PoMELO (Table 4). ExACT does not specify equipment-level detections. We found 198 and 195 equipment-level detections that could be compared between OGI and PoMELO in November 2018 and May 2019, respectively. Using OGI as the reference, we found that PoMELO attributed the presence and absence of emissions to 73% (*n* = 145) and 80% (*n* = 152) of the equipment that could be compared with OGI in November 2018 and May 2019, respectively. We also found that PoMELO detected emissions from 11-33% of the equipment that was deemed to be non-emitting based on OGI in both campaigns. These could be false detections by PoMELO, misattributions, emitting sources not included in the OGI reporting (e.g., exhaust), or they could be detections that were not resolved with OGI.

3.3. Facility-Level Quantifications

QOGI-estimated emissions rates indicate that approximately 25% by mass in both field campaigns were attributed to leaks, with the remaining attributed to vents. QOGI rates were more than 4x greater in May 2019 compared to November 2018. In November 2018, the total number of emissions sources recorded by OGI was 255. In May 2019, the total number was 451. As indicated, more than half these emissions sources were leaks (55-61%). However, there was a proportion of emissions in both field campaigns that could not be quantified (listed as CNQ) with QOGI: 17.6% in November 2018 (33 leaks and 12 vents) and 4% in May 2019 (9 leaks and 10 vents). The result is that 9% of the emissions sources detected by OGI in both field campaigns are missing from the facility-level emissions rates estimated by QOGI. This could impact the proportion of emissions categorized as leaks versus vents and comparison to emissions estimates from the truck systems.

Table 3: Confusion matrices for facility-level detection performance evaluation. An interpretation guide is presented in sub-table (a). Samples sizes (*n*) noted for each pairing. Sub-tables (b)-(d) are for November 2018. Sub-tables (e)-(f) are for May 2019.

NOVEMBER 2018

a)	Tech B detection	Tech B non detection	
Tech A detection			***Relative Sensitivity***
Tech A non detection			
	Relative Precision		***Relative Accuracy***

b)	PoMELO detection	PoMELO non detection	*n* = 39
OGI detection	36	0	100%
OGI non detection	3	0	
	92%		92%

c)	ExACT detection	ExACT non detection	*n* = 33
OGI detection	28	2	93%
OGI non detection	1	2	
	97%		91%

d)	ExACT detection	ExACT non detection	*n* = 28
PoMELO detection	25	3	89%
PoMELO non detection	0	0	
	100%		89%

MAY 2019

e)	PoMELO detection	PoMELO non detection	*n* = 39
OGI detection	38	0	100%
OGI non detection	0	1	
	100%		100%

f)	ExACT detection	ExACT non detection	*n* = 29
OGI detection	24	4	86%
OGI non detection	0	1	
	100%		86%

g)	ExACT detection	ExACT non detection	*n* = 29
PoMELO detection	24	4	86%
PoMELO non detection	0	1	
	100%		86%

Table 4: Confusion matrices for equipment-level detection performance evaluation: (a) November 2018, (b) May 2019. ExACT is excluded because it does not report equipment-level detections. Samples sizes noted for each pairing.

a)	PoMELO detection	PoMELO non detection	*n* = 198
OGI detection	70	18	80%
OGI non detection	35	75	
	67%		73%

b)	PoMELO detection	PoMELO non detection	*n* = 195
OGI detection	106	25	81%
OGI non detection	14	50	
	88%		80%

Boxplots indicate that on and off pad emissions rates estimated by the truck systems were within the range reported by QOGI, excluding outliers (Figure 2). However, in May 2019 the range of emissions rates estimated from ExACT were consistently much lower than emissions rates estimated by QOGI and PoMELO. Figure 3 shows that emissions estimates differ by up to several orders of magnitude on a facility-by-facility basis. There is a smaller range in November 2018 than in May 2019 where some estimates differ by over three orders of magnitude. Notably, the estimated emissions rates from ExACT are consistently one-to-two orders of magnitude lower than those from QOGI in May 2019.

We used Wilcoxon Signed Ranks Test (WSRT) to evaluate the null hypothesis that the median difference in emissions estimates from each method equal zero. WSRT is the non-parametric equivalent to the *t*-test, which is appropriate in this case as the distributions are non-normally distributed (Figure 2). If the null hypothesis is rejected, the samples are likely from different distributions. This is not a measure of equivalence, but it does indicate how similar the distributions of emissions rates from each method are to each other. We reject the null hypothesis if the *p*-value computed from the test is < 0.05, which signals that the distributions of emissions rates are nonidentical.

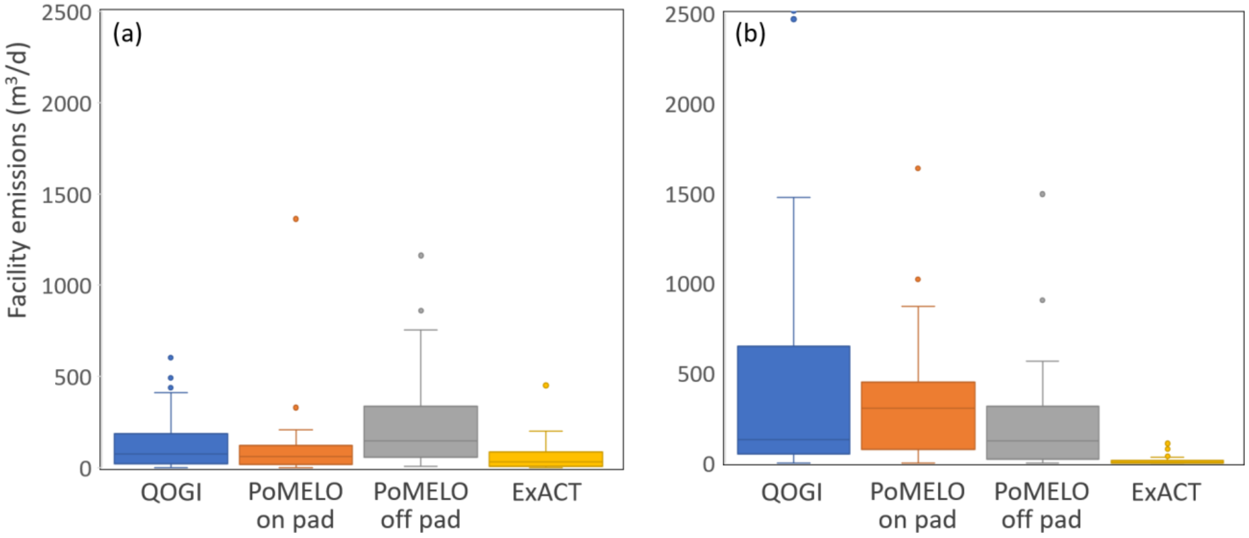

Figure 2: Boxplots from (a) November 2018 and (b) May 2019. Some outliers (dots) are not shown. Outlier totals in November 2018 were: QOGI = 3, PoMELO on pad = 3, PoMELO off pad = 3, ExACT = 1). Outlier totals in May 2019 were: QOGI = 4, PoMELO on pad = 2, PoMELO off pad = 2, ExACT = 3).

We applied the WSRT to paired emissions estimates from each method: QOGI vs PoMELO on pad, QOGI vs PoMELO off pad, QOGI vs ExACT, PoMELO on pad vs ExACT, and PoMELO off pad vs ExACT. The number of facilities with paired emissions estimates varied between these groupings in both field periods because there were discrepancies in the sites surveyed by all three teams and whether they were able to derive estimates of emissions rates from their data (Table 5). At the 0.05 significance level (two-tailed), results indicate that the distributions were not significantly different in November 2018, with the exception of the emissions estimates from PoMELO off pad vs ExACT (Table 5). In May 2019, the distributions of emissions rates from QOGI vs PoMELO on and off pad were not significantly different (i.e., $p > 0.05$). The distribution of emissions rates from ExACT were significantly different compared to estimates from QOGI (i.e., $p < 0.05$).

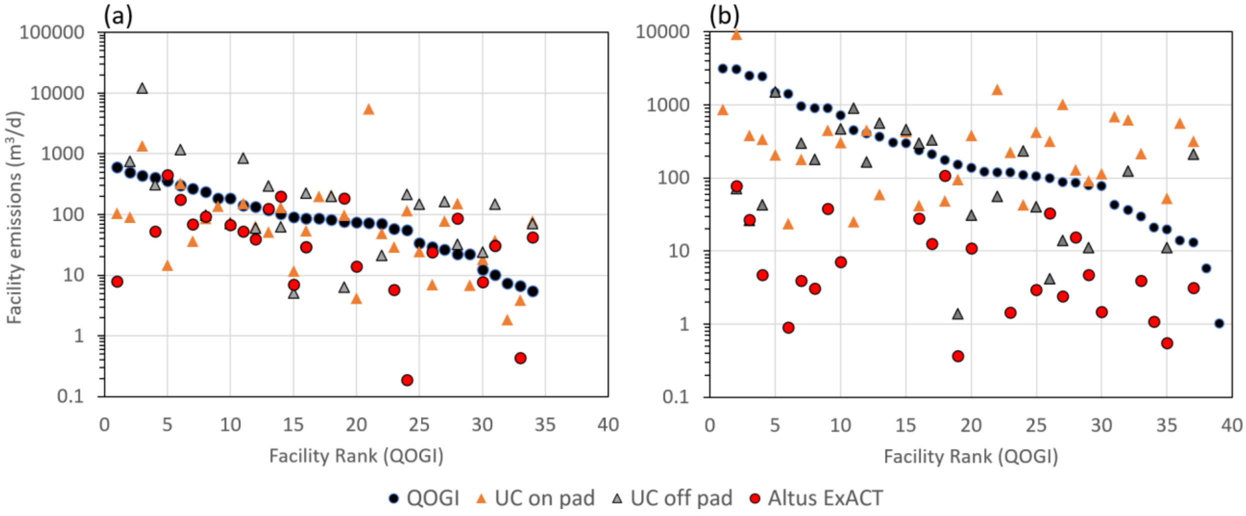

Figure 3: Rank-ordered estimates of emissions rates relative to QOGI: (a) November 2018, (b) May 2019.

Least-squares regression indicates little agreement between emissions rates estimated by each method (Table 5). In November 2018, the only statistically significant relationship (at $p < 0.05$) was between QOGI and PoMELO off pad ($R^2 = 0.366$, $p = 0.011$, $n = 23$). In May 2019, the only statistically significant relationships were between QOGI and PoMELO on pad ($R^2 = 0.24$, $p < 0.01$, $n = 33$) and between PoMELO on pad and ExACT ($R^2 = 0.24$, $p = 0.016$, $n = 24$). The slope of the regression line deviated significantly from 1 for ExACT in May 2019, which is reflected in the low emissions estimates relative to the other methods noted earlier and in Figure 2b.

Table 5: Summary statistics from Wilcoxon Signed Rank Tests (WSRT) and least-squares regression. Asterisks indicate pairings where emissions rates are significantly different at the 0.05 significance level (two-tailed). Bold values indicate pairings with *p*-values < 0.05.

	n		WSRT *p*-values		Least-squares regression					
					R^2		*p*-value		slope	
Pairing	Nov 2018	May 2019	Nov 2018	May 2019	Nov 2018	May 2019	Nov 2018	May 2019	Nov 2018	May 2019
QOGI vs PoMELO on pad	34	33	0.250	0.849	0.095	**0.243**	0.077	**0.004**	0.601	0.286
QOGI vs PoMELO off pad	23	25	0.069	0.153	**0.366**	0.011	**0.002**	0.616	0.281	0.267
QOGI vs ExACT	24	25	0.059	<0.001*	0.104	0.111	0.124	0.078	0.492	11.08
PoMELO on pad vs ExACT	24	24	0.317	<0.001*	0.056	**0.236**	0.267	**0.016**	0.170	33.45
PoMELO off pad vs ExACT	19	19	0.033*	0.002*	0.086	0.014	0.224	0.628	0.833	-1.080

We examined agreement among the methods in ranking facilities in each field period according to the estimated emissions rates. Ranking is proposed as a strategy by some commercial providers as information to base triaging decisions about follow-up OGI inspection. Some proportion of the highest emitting facilities are prioritized for follow-up OGI inspection as they may contain large leaks.

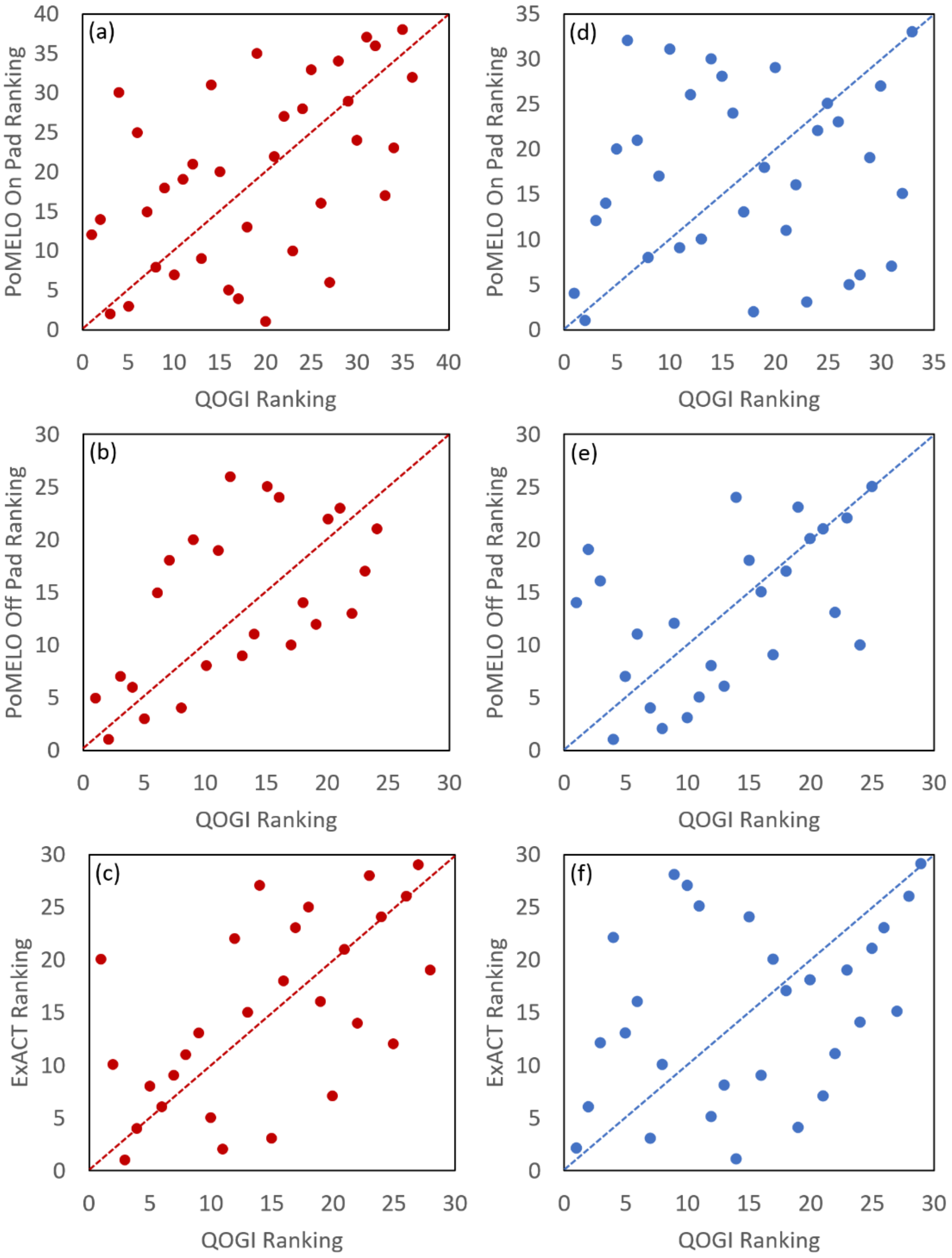

Figure 4: Comparison of facility rankings according to estimated emissions rates using QOGI as the reference. Panels (a)-(c) show results from November 2018. Panels (d)-(f) show results from May 2019.

The analysis consisted of pairing emissions estimates for each method, removing facilities with missing estimates for one or both methods, and then ranking facilities for each pairing from highest to lowest. The ranking from the highest to lowest emitting facilities follows the sequence: 1, 2, 3, …., *n*. Results are shown in Figure 4 using estimates from QOGI as the reference. A perfect match is indicated by the straight lines in each graph; however, there is considerable scatter in all pairings, indicating that there is little agreement among the methods examined. Ultimately, ranking based on controlled release testing is more appropriate for evaluating the reliability of this triaging strategy.

3.4. Equipment-Level Quantifications

We aggregated component-level emissions rates estimated from QOGI to equipment-level and correlated the equipment reported by the OGI team and the PoMELO team. We identified 42 and 45 equipment-level emissions estimates to reliably compare in November 2018 and May 2019, respectively. Least-squares regression did not yield significant relationships in either period; however, WSRT indicated that the distributions of equipment-level emissions rates estimated from QOGI versus PoMELO on pad were not significantly different. Equipment-level comparisons were not performed for the ExACT system as it provided facility-level emissions measurements.

4. Discussion and Conclusions

Results indicate that there is broad agreement between the three methods in detecting facility-level emissions (Table 3), with a handful of exceptions. However, the agreement decreases slightly for equipment-level detections, and then substantially for the facility- and equipment-level emissions quantifications. Detection is the most reliable information product from all three methods, while emissions quantification is less advanced and represents an open research challenge for the methods examined in the context of upstream oil and gas facilities. A similar outcome was implied by Ravikumar et al. (2019) based on results from the Stanford/EDF MMC.

Comparison of emissions rates from these methods is challenged by many confounding variables. First, there are limitations to OGI-based quantifications. Part of this limitation is the performance of the QL320 algorithms for quantifying emissions. An exhaustive performance evaluation has not been published to document the sensitivity of the algorithms to various external factors like background, wind speed, air and gas temperatures, gas composition, exit velocity, sunlight, etc. A comprehensive performance evaluation is needed to build confidence in the estimates. The other OGI-based limitation is related to practical issues encountered in the field that either precluded or interfered with quantifications: presence of nearby plumes, precipitation, intermittent emissions, software issues, sunlight reflection, and plumes that could not be accessed to obtain close-range images and videos. Because of these factors, 9% of all emissions sources detected by OGI could not be quantified. This affected estimates of emissions rates from some facilities more than others. For example, at one gas gathering system 39% (*n* = 21) of the emissions sources identified by OGI could not be quantified with the QL320, mostly due to interference from other nearby emissions sources and heaters. It is worth noting that even more established quantification methods such as Bacharach Hi-Flow Sampler are susceptible to these and other issues, which preclude or complicate quantification. Furthermore, many emission sources that may have been detected were not quantified because of the high heat signatures interfering with emissions estimates (e.g. flares, catadyne heaters, engine exhausts, etc.).

Another challenge in comparing estimates of emissions rates is that the truck systems could not completely circle all the equipment at the facilities. The result is that the trucks did not intersect all the plumes, so the equipment- and facility-level emissions estimates are based on incomplete data. According to observations from one of the teams, we estimate that approximately 50% of the facilities surveyed in both field periods could not be completely circled by the trucks because of facility layout or other access issues. Furthermore, most facilities have tanks along the edges of the pads, which precluded measurements by the truck teams unless the access road was located downwind during the surveys. Comparison of incomplete measurements is not a reliable approach to assess performance. Truck systems should develop a data quality index that provides, among other things, an assessment of the completeness of the survey – whether the vehicle was able to drive downwind of all the equipment on site.

Other factors affecting the comparability of emissions estimates included venting from doors opened during the OGI surveys, as noted in November 2018, and other activities on site that caused fluctuations of emissions, such as tanker trucks loading liquids. It is also important to consider that close-range (on pad) quantification of plumes based on mobile measurements is a relatively new and unconventional application of dispersion modeling principles that are largely underpinned by time-averaged measurements from fixed locations. The application of gaussian methods to non-gaussian plumes may be problematic (e.g., Barchyn et al., 2019). Without controlled release testing, a reliable assessment of quantification accuracy is not possible. Controlled release testing is the only appropriate method to evaluate quantification precision and accuracy.

Estimates of emissions rates from the three methods examined indicate limited agreement – some estimates varied by several orders of magnitude. This translated into limited agreement in the rankings of emitting facilities based on emissions rates. LDAR programs that apply this strategy require further consideration as errors in ranking could jeopardize equivalence. Further research is needed to assess the roles of error and uncertainty for screening-based LDAR programs that rely on emissions quantification.

5. Recommendations

a) The accuracy and reproducibility (precision) of emissions quantification with QOGI and truck-based methods requires further study. Quantification is not a requirement of regulations in Alberta or federally (Government of Canada, 2017; AER 2018), but it is required in British Columbia (BC) and by some screening methods to triage and prioritize follow-up OGI inspection.

b) Testing at upstream O&G facilities allows for operational conditions to be assessed, such as downwind accessibility for truck-based methods. There is however a trade-off with this approach in terms of the inability to control emissions sources and rates. Results from this study highlight the need for exhaustive controlled release testing of new technologies in order to derive more conclusive evidence of performance in terms of detection and attribution skill and quantification accuracy and precision. These data can then be combined with operational data on survey speed, on pad/off pad downwind accessibility, and other factors to estimate mitigation potential and cost.

c) Truck systems should develop a data quality index that provides, among other things, an assessment of the completeness of the survey i.e., whether the vehicle was able to drive downwind of all the equipment on site. In addition, new technologies undertaking LDAR surveys should develop a work practice guidance document that identifies and provides solutions to known technological limitations.

Statement of Interests

AR, MG, BB, CR, and WF have no competing interests. CH is one of the lead developers of the University of Calgary's PoMELO system. To mitigate any potential for bias, all data management, analyses, and reporting efforts were conducted with an administrative firewall between the SAT and the PoMELO field study participants. Additionally, the Steering Committee and PMT independently reviewed data analyses, interim presentations and draft reports developed by the SAT.

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