Assessing the progress of the performance of continuous monitoring solutions under single-blind controlled testing protocol

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Abstract

Recent regulatory spotlight on continuous monitoring (CM) solutions and the rapid development of CM solutions has demanded the characterization of solutions performance through regular, rigorous testing using consensus test protocols. This study is the second known implementation of such protocol involving single-blind controlled testing of 9 CM solutions. Controlled releases of rates (6 to 7100) g CH_4/h over durations (0.4 to 10.2) hours under wind speed range of (0.7 to 9.9) m/s were conducted for 11 weeks. Results showed that 4 solutions achieved method detection limits (DL90s) within tested emission rate range with all 4 solutions having both the lowest DL90s (3.9 [3.0, 5.5] kg CH_4/h to 6.2 [3.7, 16.7] kg CH_4/h) and false positive rates (6.9% to 13.2%) indicating efforts at balancing low sensitivity with low false positive rate. Quantification results showed wide individual estimate uncertainties with emissions underestimation and overestimation by factors up to $>$ 14 and 42 respectively. Three solutions had $>$ 80% of their estimates within a quantification factor of 3 for controlled releases in the ranges of (0.1 – 1] kg CH_4/h and >1 kg CH_4/h. Relative to the study by Bell et al., current solutions performance, as a group, generally improved primarily due to solutions from the study by Bell et al. that retested. This result highlights the importance of regular, quality testing to the advancement of CM solutions for effective emissions mitigation.

Synopsis

The proposed adoption of CM for regulatory-compliant emissions mitigation programs demands improved measurement accuracy and well-defined uncertainties. This study evaluates and compares current performance of CMS with prior study results.

Keywords

Methane, emissions mitigation, detection limit, emissions quantification, source attribution, natural gas

Introduction

Methane, a powerful greenhouse gas (GHG) with a short atmospheric lifespan ($\approx$ 12 years), is responsible for about 30% of the rise in global temperatures, with current atmospheric concentration more than twice pre-industrial levels.[1–3] As the major component of natural gas commonly emitted across production, processing, and distribution sectors, mitigating natural gas emissions from methane emissions has economic, safety, and environmental benefits.[4,5] The oil and gas (O&G) sector is the largest industrial source ($\approx$30%) of anthropogenic methane emissions in the United States. Several studies have shown that fugitive (unplanned) methane emissions are stochastic, temporally and spatially variable with large emitters typically responsible for a substantial portion of unplanned emissions.[6–14] Continuous monitoring (CM) can improve emissions detection since these solutions near-continuously monitor entire facilities (e.g. an entire wellpad), and can identify fugitive emissions faster than existing survey methods (e.g. optical gas imaging camera surveys).[15,16]

A CM leak detection and quantification (LDAQ) solution is a technology that measures ambient emissions concentration continuously using one, or a combination of, sensing methodologies (e.g. tunable diode laser absorption spectroscopy, light detection and ranging, etc.) and interprets readings using proprietary algorithms to generate actionable results (e.g. using a gas plume image to estimate location and size of an emitter).[17] Recently, the United States Environment Protection Agency (USEPA) proposed new pathways for CM solutions to be utilized for regulatory-compliant leak detection and repair (LDAR) programs.[18] Studies have shown that large emission events, including super emitters (large, episodic emissions $\geq$100kg CH_4/h),[19–21] contribute to the observed gap between direct emission measurements, and the USEPA Greenhouse Gas Reporting Program (GHGRP) estimates[22–25] and other reporting programs.[13,14] USEPA has proposed amendment of the Subpart W of the GHGRP,[26] and the Super Emitter Response Program[27] to close the data gap using selected top down approaches (satellite, aerial, etc),[28–32] among other methods for measurements. Surveys using top down approaches are typically brief (seconds to minutes), and performance depends on the time of the day and the prevailing meteorological conditions: clear skies for satellites or specified range of atmospheric stability conditions for aerial surveys). CM solutions can provide time-resolved monitoring across a wider, but not unlimited, range of meteorological conditions to promptly alert operators when facility emissions begins to rise to abnormal levels.

To characterize detection efficacy, CM solutions must be tested to understand probability of detection, quantification accuracy and associated uncertainties, emission source localization, time to detection, operational downtime, and false positive and negative rates. CM solutions consist of three components - sensing, deployment on a facility, and proprietary algorithms that process sensed data. These three components cannot be tested independently. Therefore, testing must assess the performance of a CM solution as an integrated system that includes sensors, data acquisition/communication, proprietary algorithms, hardware, and mode of installation on the facility. The goal of testing is to ascertain the performance level of CM solutions as deployed, with specific interests on the functionalities highlighted earlier (detection, etc.), each of which can affect the detection or quantification efficacy of CM solutions. Therefore clear testing using consensus, technology-neutral, protocols are necessary to compare performance of CM solutions.

Past studies employed study-specific protocols for testing,[33] which are generally difficult to repeat, making it difficult to compare solution performance from multiple test programs. Additionally, previous evaluations of CM solutions encountered limitations related to testing complexity and prevailing meteorological/environmental conditions.[34–37] Partly in response to these results, a consensus protocol was developed by the Advancing Development of Emissions Detection (ADED) project,[38] and was used by Bell et al. for the first peer-consensus CM testing with a standardized protocol. The study result showed high variability between solutions, high uncertainty, and some bias in most assessed metrics across all the CM solutions tested.

The study presented here represents the second implementation of the ADED protocol[38] by testing 9 CM solutions, including 4 that also participated in the prior study.[39] CM solutions were tested for 11 weeks between February and April, 2023 at the Methane Emissions Technology Evaluation Center (METEC), Colorado State University (CSU), Colorado, USA. This study also divides CM solutions into the same two classes utilized in the prior study. (a) *Point sensor network* - solutions that deployed multiple point sensors that sense hydrocarbons and use proprietary algorithms to combine meteorological and concentration readings to infer detections, etc. (b) *Scanning/imaging* - solutions which uses scanning lasers or short/midwave infrared cameras to visualize gas plumes which are then combined with meteorological data to infer detections, etc. The protocols specifies both testing methods and how performance metrics are calculated. By using the same primary metrics for evaluation, results from the current study can be compared with those from the prior study,[39] to determine if solutions have progressed between test programs.

Methodology

Test Facility

Testing was conducted between February 8th and April 28th, 2023 at METEC; an 8-acre (3.2 ha) outdoor controlled testing facility primarily designed to simulate methane emissions from North American onshore O&G equipment in a controlled manner. METEC is furnished with inactive surface equipment units (e.g. wellheads, separators, etc.) intentionally fitted with leak points concealed at commonly observed sources, such as valve packing, flanges, and fittings. Units are arranged into 5 wellpads (pads 1 to 5) of varying size, complexity, and equipment unit layouts. Testing was conducted exclusively on pads 4 and 5 covering $\approx 8450\,\mathrm{m}^2$, and made up of 7 separators, 3 condensate tanks, 8 wellheads, and 2 flares (See Zimmerle et al. and SI Sections S-1 and S-2). Table S-1 includes a brief summary of the *equipment units* and *equipment groups* in pads 4/5, and how their tags are interpreted. This study utilized 53 unique emission points on pads 4/5, each of them used more than once during testing. Over the duration of the study, $\approx 80\%$ of emission points were $\leq$2m in height with the rest between 2m and 6m (See SI Figures S-7 and S-7 for the distribution of the heights of emission points used in this study).

Testing Process

The ADED protocol was developed with contributions from multiple stakeholders, including O&G industry players, academic institutions, LDAQ solution developers, environmental non-governmental organizations, and regulatory agencies (state and federal).[38] The protocol is designed to test an integrated CM solution, and does not test individual subsystems, e.g. sensing performance, optimal deployment, and/or algorithm/analytics capability. In all solutions tested here, point or imaging sensors collect raw sensor readings, which are processed by proprietary algorithms to infer actionable data, including presence/absence of emitters (detections), emission rate estimates, and emitter locations.

According to the protocol, testing involves a series of *experiments* conducted over 24 hours per day, everyday, for an extended period (weeks or months). Each *experiment* consists of 1 or up to 5 simultaneous controlled releases of gas, each emitting at a steady emission rate for a specified duration (hours). Experiments with multiple controlled release points (>1) evaluated solutions' ability to characterize each emitter. Successive experiments were separated from one another by a break period (hours), during which there was no controlled release, signaling solutions of a return to background atmospheric concentration levels. Experiments were designed with the intention to sweep the range of test (e.g. emission rate, release duration, etc.) and meteorological (e.g. wind speed, temperature, etc.) conditions needed to characterize the *probability of detection* curves of solutions tested. The entire test program was single blind – the participating solutions were unaware of the timing, location(s), durations, and emission rates of controlled releases by the test center.

CSU recruited participating CM solutions through an open invitation advertised on METEC's website, and also leveraged on contacts gathered during the development of the protocol to directly contact CM LDAQ solution developers. The study team required vendors of solutions participating in the testing to install their systems at least 3 days before the start of testing to participate in the mock testing by METEC, and to allow both METEC and CM solution vendors troubleshoot their respective setups. A portable compressed natural gas (CNG) trailer was connected to METEC's gas supply system to support large and long duration controlled releases. In between refills of the CNG trailer, the study team conducted controlled releases from the onsite storage gas cylinders. All controlled gas releases during testing were CNG with a mean gas composition by volume of 84.8% of methane, 13.1% of ethane, 1.6% of propane, and trace amount of heavier hydrocarbons and other gases. For each controlled release, METEC logged the timing, location, metered emission rate and the associated uncertainties, gas composition, and prevailing meteorological conditions, which were time averaged over the release duration.

Testing was conducted day and night, across all meteorological conditions that supported the operation of METEC, for the entire duration of the study. Exceptions included winter conditions with temperatures below the operating specifications of METEC's thermal flow meters (OMEGA FMA-17xx series). For experiments with 2 or more controlled releases flowing through a flow meter, a pre-calibration was done before releases officially began to correctly meter and log the rate of each controlled release. Emission rate of controlled releases, and experiment duration were selected considering METEC's operational constraints e.g. available gas supply, emission point orifice size, etc. The study team periodically analyzed the performance of solutions during testing to choose the emission rates and release durations for subsequent experiments. This was intended to populate test conditions with small sample size (e.g. larger rate and longer duration controlled releases, etc.) to map the *probability of detection* curve of solutions. The resulting range of emission rates and release durations in this testing were 6 to 7100 g CH_4/h and 0.4 to 10.2 hours, respectively. This implied that the study likely excluded a huge portion of real-world upstream emissions which are intermittent or of much shorter duration. These include routine emissions from actuation of pneumatic devices, blowdown events, routine flash tank emissions which collectively make up substantial fraction of methane emissions at typical United States onshore production facilities. Similarly, the study excluded larger releases (≥ 10 kg CH_4/h up to the super emitter rate) which is an important emission source category according to several studies.[19–21] The study team ensured that no two controlled releases within an experiment flowed through the same *equipment unit*, and drastically limited scenarios where 2 consecutive experiments had controlled releases flowing to the same *equipment unit*. This gave CM solutions the best opportunity to isolate and estimate the characteristics of each emitter. This represents a substantial simplification of observed emissions behavior in real O&G facilities where emitters may follow random patterns or emit at variable rates. METEC kept a maintenance record, documenting facility downtime and the timing of faulty experiments and controlled release events non-compliant with the study design (e.g. venting gas supply lines, controlled releases on wellpads not used for the study, etc.).

Performance Metrics

The vendor of each solution sent *detection reports* containing data inferred from sensed emission (e.g. emission rate, emitting source, etc.) to a unique email address provided by METEC. While this process was automated for some solutions, others required human support to interpret and prepare reports according to the template in the protocol. In some cases, such human interference delayed detection reporting to the test center by days or weeks, likewise, for solutions with automated reporting that required varying level of human support when their data transmission system failed. The email setup at METEC parsed through reports as they arrived and automatically rejected those non-compliant with the protocol's reporting template.[38] This contrasts field deployments where operators bear the burden of inferring web-based dashboards (e.g. interpreting time series methane concentrations/emission rates) of data communicated by the solutions installed in O&G facilities. This detection reporting approach eliminated inference errors and biases associated with the study team interpreting raw measurement readings of solutions. According to the protocol, each *detection report*, which either identifies a fresh emission or updates previous reports, contained at minimum the following:

- *DetectionReportID* - an incremental unique identifier of each detection report.
- *EmissionSourceID* - a unique identifier referencing the emitter the detection report identifies.
- *EmissionStartDateTime* - the estimated time and date a detected emission started emitting.
- *EquipmentUnit* - the identifier of the equipment unit on which an emission was detected.
- *Gas* - the gas specie measured to infer a detection.

Solution vendors were also allowed to report system *downtime*: periods during testing that solutions were offline (e.g. not taking measurements) which should be ignored by the study team during result analysis. Prior to the performance analysis for each solution, the study team excluded detections (1) reported during METEC maintenance and solutions downtime periods, (2) reports with *EmissionStartDateTime* before and after the analysis window of each solution, and (3) reports identifying *EquipmentUnit* outside the fence-line of METEC (OFF FACILITY) in the latest detection report. These exclusions were done to avoid bogus *false positive* detections. Similarly, the study team excluded controlled releases (1) conducted during METEC maintenance and solution downtime periods, (2) conducted outside the analysis window of the solution, and (3) with durations shorter than required to get a stable flow meter reading. These exclusions were done to avoid spurious *false negative* detections.

All detection reports referencing the same *EmissionSourceID* were grouped together as one report: for the same *EmissionSourceID*, the time at which the first detection report (smallest *DetectionReportID*) was received by METEC was paired with the data contained in the last detection report (largest *DetectionReportID*). The study team applied a buffer time of 20 minutes before and after the timing of each controlled release while matching controlled releases to detection reports. The buffer time accounted for emissions during experiment pre-calibration periods, and the residual emissions detected by solutions after the end of a controlled release. The matching scheme involved the following steps below:

- The study team sorted all controlled releases by equipment unit identifier, then by emission rate (if reported) in descending order. For each controlled release, all detections identifying emission source on the same **equipment unit** as the controlled release were selected. All selected detections with *EmissionStartDateTime* within the controlled release start and end times (including buffer time) were filtered, and sorted by emission rate (if reported) in descending order. The topmost filtered detection report was paired with the controlled release as a correct *equipment unit* level true positive (TP) detection, and the pair was removed from further matching.

- The study team resorted the remaining list of controlled releases from the step above by equipment group identifier, then by emission rate (if reported) in descending order. For each controlled release, all detections identifying emission source on the same **equipment group** as the controlled release were selected. All selected detections with *EmissionStartDateTime* within the controlled release start and end times (including buffer time) were filtered, and sorted by emission rate (if reported) in descending order. The topmost filtered detection report was paired with the controlled release as a correct *equipment group* level TP detection, and the pair was removed from further matching.

- The study team resorted the remaining list of controlled releases from the step above by emission rate (if reported) in descending order. For each controlled release, all detection reports with reported *EmissionStartDateTime* within the controlled release start and end times (including buffer time) were filtered, and sorted by emission rate (if reported) in descending order. The topmost filtered detection report was paired with the controlled release as a correct *facility* level TP detection, and the pair was removed from further matching.

- Controlled releases and detection reports remaining after the pairings were identified as false negatives (FN) and false positives (FP) detections respectively.

All performance metrics stipulated in the protocol utilized these classification results in their analysis. Key metrics are briefly described below, with full details in the protocol.[38]

Probability of Detection (POD): The fraction of binned test conditions (i.e. emission rate, release duration, etc.) classified as TP detections (i.e. $\frac{TPs}{TPs+FNs}$). *Localization Precision - (Equipment Unit):* The fraction all TP detections at each detection level (*equipment unit*, *equipment group*, and *facility*) *Localization Accuracy (Equipment Unit):* The fraction of detection reports (FPs and TPs) at each localization precision level (Equipment unit). For example, localization accuracy at equipment group or better is the fraction of all detections localized at both the equipment unit and group levels. *Quantification Accuracy:* For solutions that estimated rate (g/h) of the gas specie measured, the absolute quantification relative error for each TP detection was evaluated as the difference between reported emission estimate and controlled release rate. The relative error was evaluated by normalizing absolute error by the controlled release rate. Facility level quantification relative error was evaluated using all controlled release rates and reported emission estimates considered in the analysis of each solution, respectively aggregated over the solution's study duration. *Time to Detection:* For each TP detection, this is the time difference between when the test center received the first detection report identifying an emission source (*EmissionSourceID*) and the start time of the controlled release it paired with. *Operational factor:* The fraction of time a CM solution was operational relative to the total deployment time.

Participating Solutions

All participating CM solutions in this study installed their systems at the test site. Solution vendors decided on the number of sensors, positioning of sensors, and the *equipment groups* to monitor; the only limitations imposed by the study team were related to safety (e.g trips and falls) and obstructions (e.g. system installation near or along driveways). All but one solution (N) monitored all *equipment groups* on pads 4 and 5 of METEC. Vendors were requested to install as they would at real facilities. This implied that some vendors either installed their solutions along the fenceline of the pads or around the equipment groups monitored (SI Figure S-3). In many field applications, sensor location are likely restricted to the periphery of the facilities while the number of sensors installed per facility largely depended on cost of deployment and the size of the facility. In this study, every solution was responsible for the communication systems to connect their on-site hardware to backend servers and algorithms operating offsite; most solution utilized cellular data for this purpose. After installation and initial testing, solution personnel left the test center and operated their systems remotely, except to fix their hardware failures or other severe failure of their system(s). The test center assessed the performance of solutions capabilities supported by the data reported as shown in Table 1.

Nine CM solutions participated in this study; 4 were also part of the previous study (Bell et al.) approximately a year earlier. The participating solutions, in alphabetical order, are Honeywell, Molex, Project Canary, QLM Technology, Qube Technologies, Sensia-solutions, Sensirion, Sensit, and SLB which deployed both imaging and network of point sensor systems. Testing was performed under confidentiality agreements. Therefore, each solution is identified here by a unique identifier, with those that participated in the prior study[39] retaining their identifiers. Not all solutions tested for all metrics. Table 1 summarizes the characteristics of solutions that participated in the study, and which functionality was tested on each.

Table 1: Characteristics of participating solutions

	Sensor			**Reported Data**[†]		
ID	**Type**	**Count 2022**	**Count 2023**	**Detection**	**Quantification**	**GPS Localization**[‡]
			Participated in Bell et al.			
A[1]	Point sensor network	8	8	✓	✓	✓
B	Scanning/imaging	1	1	✓	✓	✓
D	Point sensor network	8	8	✓	✓	✓
F	Point sensor network	8	10	✓	✓	X
			Did not participate in Bell et al.			
L	Scanning/imaging	-	1	✓	✓	✓
N	Point sensor network	-	18	✓	✓	✓
O	Scanning/imaging	-	1	✓	✓	X
P	Point sensor network	-	6	✓	X	X
Q	Point sensor network	-	13	✓	X	X

[†] ✓indicates the parameter of interest was reported by the solution. 'X' indicates that it was not reported.

[‡] Indicates if the solution localized emitters by GPS coordinates.

[1] One of the sensors installed failed during the study.

Data Processing

The study by Bell et al. used binary logistic regression models (f) to map the POD curves of solutions over the range of tested conditions (i.e.emission rate, release duration, etc.), and to predict the emission rate at which a solution achieved 90% POD. However, the model in some cases produced curves with non-practical applications like unrealistic POD at zero emissions: POD at an emission rate of zero was non-zero. To correct for these issues, this study utilized power functions for POD estimation, with the intercept set to zero. The power curve was fit to detection fraction from equal-sized sets (quantile-based discretizations) of test conditions. The quantile used for each solution was constrained by the range $30 < N_p < 50$ where N_p is the number of points in each bin. N_p was set by using the quantile-based discretization that produced the highest goodness of fit (R^2) value. See SI Tables S-5 to S-13 for analysis on picking bin size for all solutions in this study, and Tables S-14 to S-24 for the recalculated POD curve for solutions from Bell et al..

As described earlier, detection reports were classified as TP or FP while unreported controlled releases as FN.[38] The protocol penalized excess detection reports identifying emission sources already identified earlier or emission sources not emitting during an experiment, as false positives. However, in some field applications of CM solutions like facility level monitoring, less priority might be placed on these excess detection notifications if at least one of the alerts correctly identified an emitter. Therefore, in a break with the previous study, this study utilized 2 classifications for FP detection reports:

1. False positive due to *no-ongoing controlled release* - a detection reported when there was no controlled release at the test center.

2. False positive due to *excess detection report* - a detection report that identified a controlled release already correctly matched to another detection report, as a new and/or different emission source. For example, reporting detections with different *EmissionSourceIDs* during an experiment with one controlled release.

Limitations of the ADED Protocol

As extensively discussed in Bell et al., the protocol assumes that while solutions provide near-continuous monitoring, they issue discrete detection alerts that are source-resolved whenever emissions were detected. This is not always the case as several solutions provide time series sensor readings through web-based dashboards for operators to read and infer detection decisions. Additionally, pads 4 and 5 (SI Figures S-1 and S-3) at METEC used for this study were designed to mimic simplified on-onshore production facilities (See Zimmerle et al. for details on how it differs from a real facility). Hence result from this study might not be applicable to more complex or midstream facilities which likely has different site configuration and emissions behavior.

Results and Discussion

In this section, we discuss study results based on the following metrics (1) Probability of detection, (2) Source localization (precision and accuracy), (3) Quantification accuracy, and (4) Time to detection. This section further shows the changes in performance of solutions individually and as a group relative to the study by Bell et al..

Primary Results and Analysis

Probability of Detection (POD): A POD curve relates the probability that a solution will detect an emission of a given rate, as composite performance over all other test conditions like release duration, emission flow rate, wind speed, e.t.c. that could affect the POD of solutions. A multi-variable logistic regression analysis of the impact of these factors on POD over tested range showed varying statistical significance across all solutions. Results indicate that emission rates significantly ($p < 0.05$) affected the POD of all solutions, with other variables affecting only a subset of solutions (See Table S-27 in SI). Figures 1 and 2 shows the POD curves for all solutions mapped over the range of emission rate tested. Figure 1 compares curves for the 4 solutions that participated in both the current study and that by Bell et al., while Figure 2 is for the other 6 solutions. Bell et al. defined the Method Detection Limit (DL90) of each solution as the emission rate at which the solution, as deployed (method), detected emitters 90% of the time, over a wide range of meteorological conditions. The study team deviated from the acronym MDL used by Bell et al. to avoid it being misinterpreted as "minimum detection limit" which might mean something different. The DL90 metric is an important consideration during the formulation of methane emissions reduction policies/programs[27] by regulations and their implementation by O&G operators. Figures 1 and 2, and Table 2 shows the DL90s of solutions.

- Performance from current study (2023): Overall, Figures 1 and 2 showed that the POD curves predicted the DL90s of 8 of 9 solutions ranging from 3.9 [3.0, 5.5] kg CH_4/h to

18.2 [7.9, 90.5] kg CH_4/h. The DL90s of 4 of the 8 solutions fell within the range of emission rates tested in the study. Table 2 shows that the 4 solutions with the lowest FP rates (6.9% to 13.2%) also had the lowest DL90s (3.9 [3.0, 5.5] kg CH_4/h to 6.2 [3.7, 16.7] kg CH_4/h), while 3 of the 4 solutions had the lowest FN rates (27.4% to 32.9%) in the study (SI Figure S-10). This indicates efforts at balancing method sensitivity (i.e. low DL90) with low FP and FN rates. In contrast, the remaining 6 solutions had relatively higher DL90s (no solution within tested emission rate range), FP rates (all solutions $> 20\%$), and FN rates (5 solutions $\geq 50\%$) which might indicate struggles at emissions detection. At a minimum detection threshold of 0.40 kg CH_4/h (as stipulated in the final rule by the USEPA), results indicate that 5 of the 9 solutions will have $\geq$ 50% POD.[41]

For the *scanning/imaging* solutions, FP rate spanned between 7.7% to 34.6% with the DL90 of 1 of the 3 solutions within tested range. While the FP rates of *point sensor network* solutions were between 6.9% to 38.1% with the DL90 of 3 of the 5 solutions that estimated DL90s within tested range. A review of the percentage of false positives due to excess detections (4.5% to 91.5% with 7 of 9 solutions having values $\geq 50\%$) suggests that if the intended application of most solutions is to correctly alert operators of ongoing emissions with less priority on what is emitting and the number of emitters, then these solutions would have much lower FP rates than predicted by the protocol. Otherwise, follow-up OGI surveys might take longer time by investigating misleading alerts which is costly. A Spearman's rank correlation analysis showed that the count of sensors deployed by solutions did not necessarily affect method sensitivity of solutions (p value > 0.5) as solutions that deployed more sensors did not always have lower DL90 compared to solutions that installed fewer sensors. Aside from the difference in the sensor type, quality, and proprietary algorithms which can vary the performance of solutions, one potential explanation for this observation might be over-deployment of sensors by some solutions. However, given the reporting constraints of the test protocol, solutions did not attribute detections to any sensor(s) hence making the assessment of over-deployment (if any) very challenging in this study. In general, TP rate tended to increase with release rate for all solutions as shown by the figures above and SI Table S-25. See SI Figures S-12 to S-17 for POD curves for all solutions based on release duration, wind speed, and release rate normalized by windspeed. See SI Figures S-18 to S-19 for POD curves using logistic regression for reference.

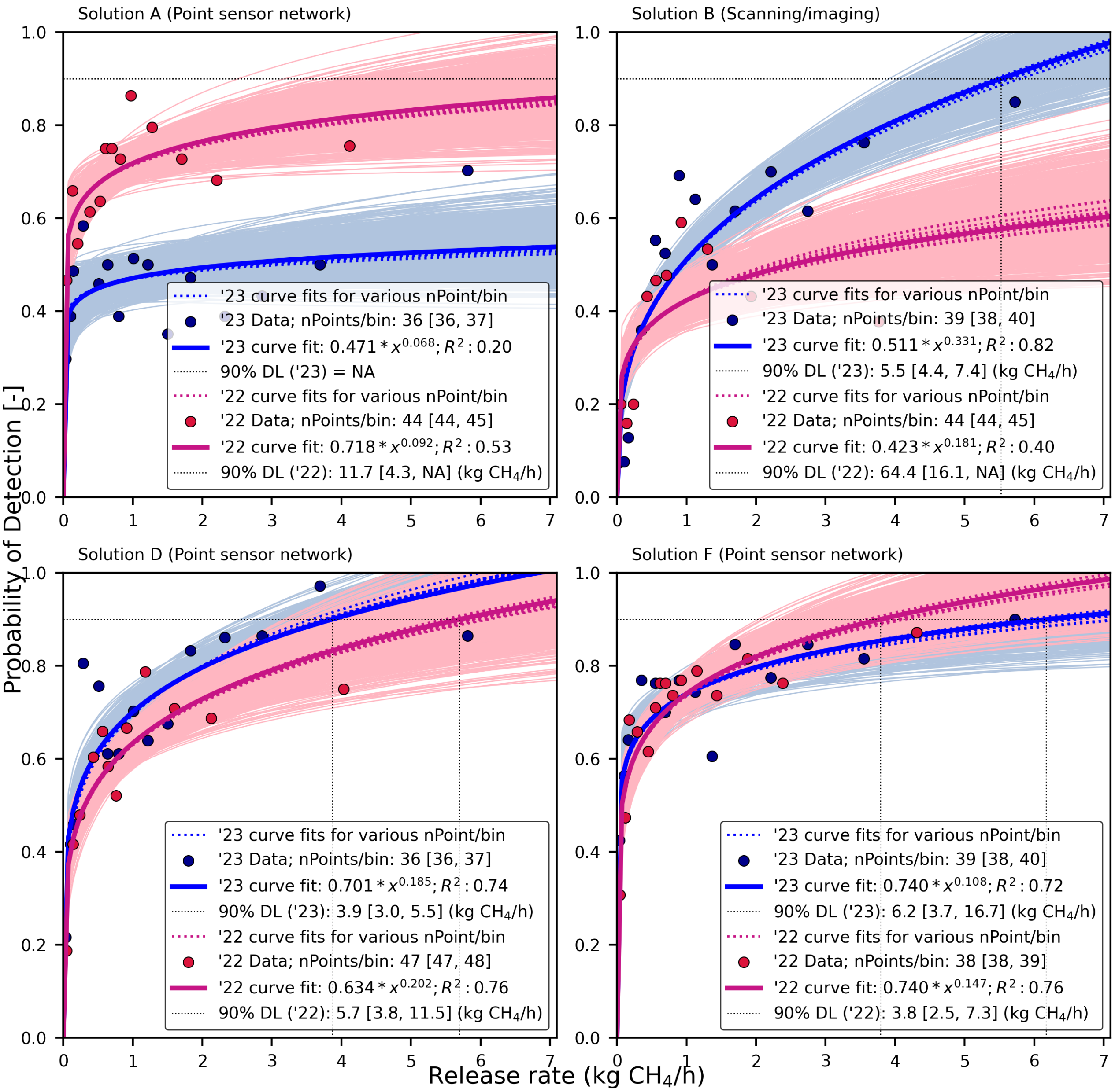
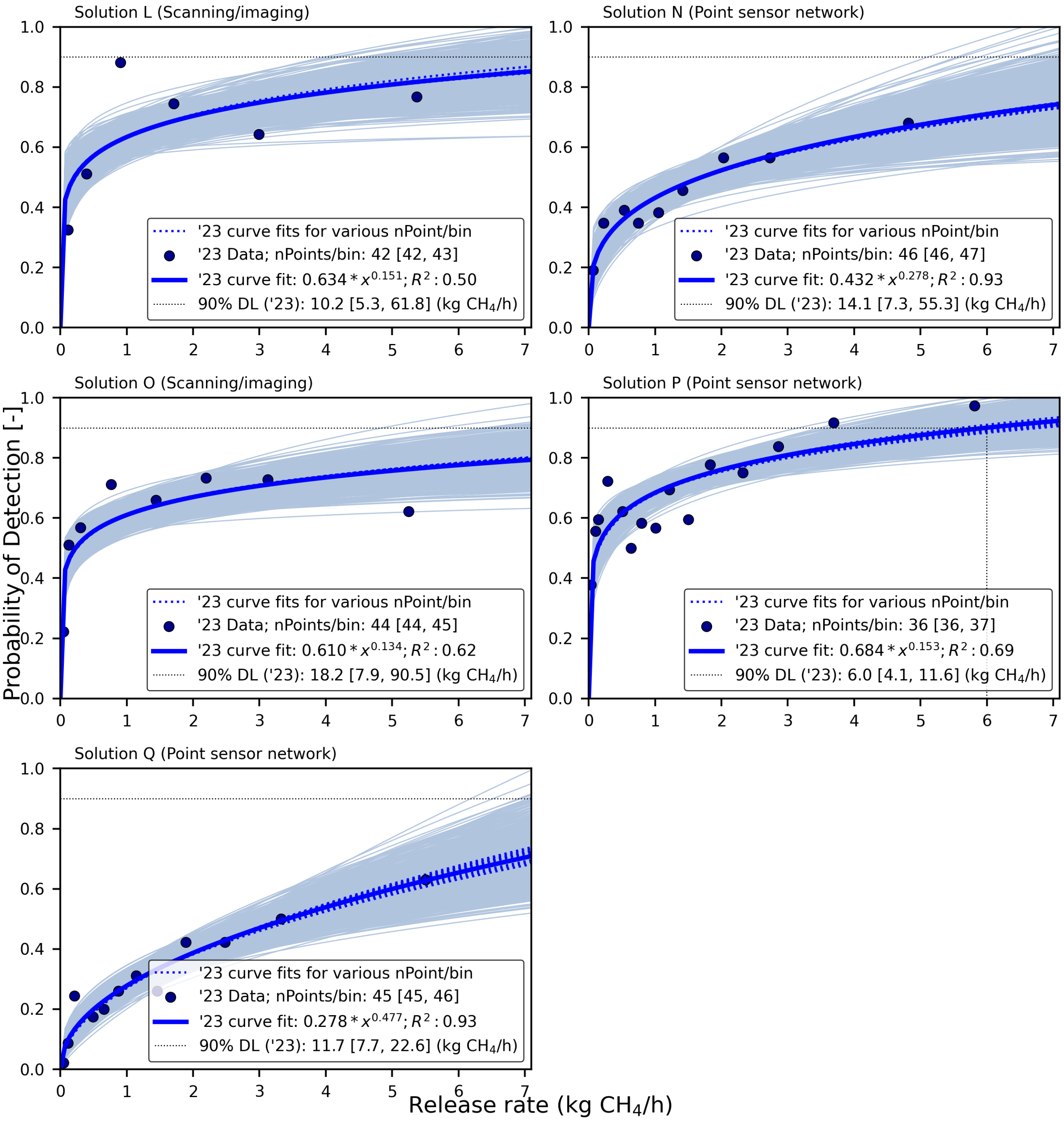


Figure 1: The probability of detection (POD) versus emission rate (kg CH$_4$/h) for point sensor network solutions solutions (A, D, and F) and a scanning/imagine solution (B) fitted using power functions. The x-axis is divided into equal-sized bins with each marker (pod) as the fraction of controlled releases in a bin classified as true positives. Data points from the study by Bell et al. (2022) is overlayed on the current results for comparison. The emission rate at which the POD reaches 90% is indicated as the method detection limit (DL90) for each solution. Each pod data point is bootstrapped to produce a cloud of curves illustrating associated uncertainty. When the bootstrapping could not evaluate the lower and upper empirical Confidence Limit (CL) on a solution's DL90 best estimate, they are given as 0 and NA respectively. Curve fits (dotted colored lines) obtained using other quantile-based discretizations are shown for comparison. The DL90s of 3 of the 4 solutions (B, D, and F) in the current study were within tested emission rate range. The mean count of points per bin along with the min. and max. counts across all bins is also shown in the figure.


Solution L (Scanning/imaging)

Solution N (Point sensor network)

Solution O (Scanning/imaging)

Solution P (Point sensor network)

Solution Q (Point sensor network)

Figure 2: The probability of detection (POD) versus emission rate (kg CH$_4$/h) for solutions L, N, O, P, and Q fitted using power function. Solution N, P, and Q are point sensor networks, while solution L and O is a scanning/imaging solutions. The x-axis of each plot is divided into equal-sized bins with each marker (pod) calculated as the fraction of controlled releases in a bin classified as true positives. Each pod data point is bootstrapped to produce a cloud of curves illustrating associated uncertainty. When the bootstrapping could not evaluate the lower and upper empirical Confidence Limit (CL) on the best estimate of a solution's DL90, they are given as 0 and NA respectively. Curve fits (dotted colored lines) obtained using other Quantile-based discretizations are shown for comparison. The emission rate at which the POD reaches 90% is indicated as the method detection limit (DL90) for each solution. The best estimate of the DL90 of only solution P is within the tested emission rate range. The mean count of points per bin along with the min. and max. counts across all bins is stated in the plot legend.

- Comparing general performance from Bell et al. to current study: Results from the study by Bell et al. showed that more solutions struggled at balancing low MDL, FP rate, and FN rate when compared to current test results. Two of 11 solutions showed efforts at balancing all 3 metrics relative to other solutions, while others showed mixed performance. For example, solution E had the lowest DL90 (1.3 [0.5, 8.1] kg CH_4/h) and FN rate (12.3%) but had the highest FP rate (82.6%) in the study. While Solution J was among solutions with the lowest DL90 (4.0 [3.4, 5.1] kg CH_4/h) and FP rate (0.0%) but had one of the highest FN rate (76.0%) in the study (SI Tables S-26 and S-28). These results have noted the tendency for solutions to trade-off detection sensitivity with false positive and negative rates: Changing solution settings to reduce DL90 tends to increase FP rate. In general, setting algorithms to reduce DL90 also makes it more difficult to distinguish smaller fugitive emissions from background concentrations (i.e. sensor or algorithmic noise), leading to background fluctuations being classified as false positive emissions detections. Conversely, higher DL90s can imply solutions missing relatively smaller rate emissions which typically makes up majority of field measurement studies (by count) resulting in high FN rates. However, generally, solutions from the current study showed more efforts at balancing low DL90 with low false negative and positive rates compared to the results by Bell et al..

- Comparing the performance of the four solutions common to both studies: Two solutions, B and D, showed reduced DL90 with false negative and positive rates relative to the study by Bell et al.. The FP and FN rate of solution F - with highly overlapping DL90 uncertainty across both studies - also dropped. These data indicate a general improvement in efforts to balance method sensitivity with FP and FN rates. Given that these solutions installed same number of sensors as in Bell et al. except for solution F which increased from 8 to 10, improved performance could be attributed to improved analytics/algorithms and/or more favorable test conditions as shown in SI Table S-4 (higher emission rates, longer release durations, and lower windspeeds). At higher emission rates, solutions either exceeded or approached their respective DL90s while testing at calmer wind speeds likely reduced turbulent gas plume dispersion in support of more stable/steady measurements. Longer release durations likely gave *scanning/imaging* solutions multiple opportunities to visualize and identify emissions or longer averaging time of ambient concentration measurement to infer detections by *point sensor network* solutions.

Table 2: Summary of the number of controlled releases and detection reports considered in the analysis of each CM solution. The break down of the false positive rates for all solutions using the ADED protocol is also shown together with the false negative rate, and DL90s predicted by each solution. Solutions are sorted in order of increasing All false positive rate.

	Count		**FP (%)**[†]				
ID	**Controlled Release**	**Detection Reports**	**All**	**No Controlled Release**	**Excess Detections**	**FN (%)**	**DL90**[‡] **(kg CH_4/h)**
			Result from the current study for all participating CM solutions				
D	547	403	6.9	28.6	71.4	31.4	3.9 [3.0, 5.5]
B	547	300	7.7	39.1	60.9	49.4	5.5 [4.4, 7.4]
F	547	444	10.6	8.5	91.5	27.4	6.2 [3.7, 16.7]
P	547	423	13.2	23.2	76.8	32.9	6.0 [4.1, 11.6]
N	417	223	18.4	29.3	70.7	56.4	14.1 [7.3, 55.3]
L	256	254	35.0	95.5	4.5	35.5	10.2 [5.3, 61.8]
O	357	324	34.6	33.0	67.0	40.6	18.2 [7.9, 90.5]
Q	547	260	38.1	21.2	78.8	70.6	11.7 [7.7, 22.6]
A[1]	547	487	47.8	61.8	38.2	53.6	NA
			Results from Bell et al. for the 4 CM solutions that participated in both studies.				
D	574	376	10.4	79.5	20.5	41.3	5.7 [3.8, 11.5]
F	574	516	22.5	39.7	60.3	30.3	3.8 [2.5, 7.3]
B	445	250	31.2	61.5	38.5	61.3	64.4 [16.1, NA]
A	574	986	59.8	26.9	73.1	31.0	11.7 [4.3, NA]

[†] **All** is the percentage of all detections classified as false positive based on the ADED protocol.

[†] **No controlled release** is the fraction of all false positives that is due to detection reports sent when there was no controlled release at the test center.

[†] **Excess TP Detections** is the fraction of all false positives that is due to excess detections identifying controlled releases that have been matched already as a new and/or different emitter.

[‡] When the POD curve could not evaluate the DL90, they are given as "NA". Similarly, when the lower and upper empirical 95% Confidence interval (CI) on a solution's DL90 could not ve evaluated, they are given as 0 and NA respectively.

[1] One of the sensors installed failed during the study.

Source localization: As discussed earlier, the protocol required solutions to report the equipment unit housing any identified emitter. For each solution, sensor density was defined as the ratio of the number of sensors deployed by the solution to designated test center (pads 4/5 at METEC) surface area (m^2). Tables 3 and S-29 (in the SI) summarized the sensor densities ($sensors/m^2$), and the emission source localization precision and accuracy results of solutions participating in this study and those in the study by Bell et al.. Similar localization metrics were evaluated if solutions reported GPS coordinates of identified emitters. See the performance report of each solution in the SI for those analysis.

- Performance from current study (2023): At the equipment unit level, all 3 *scanning/imaging* solutions had the highest localization precisions ($> 70\%$) and accuracies ($> 40\%$) with the smallest sensor densities (0.000118 $sensors/m^2$). For the 6 *point sensor network* solutions, only 1 solution (also with the largest sensor density) had localization precision and accuracy $> 40\%$. At the equipment group level or better (equipment group + unit level), all *scanning/imaging* solutions had $> 95\%$ localization precision, and accuracy range of 58.3% to 91.3% while for the *point sensor network* solutions, 3 solutions had precisions $> 90\%$ and accuracies $> 70\%$, with sensor density range of 0.000947 $sensors/m^2$ to 0.00213 $sensors/m^2$. These results illustrate the higher tendency of *scanning/imaging* solutions in this study to correctly narrow down emitters for follow-up OGI surveys than *point sensor network* solutions despite installing the lowest number of sensors. In general, 6 of the 9 solutions had localization precisions more than 90% at the equipment group level or more, while 5 of 9 solutions had localization accuracy $> 70\%$ also at that level. As indicated earlier, for operators deploying CM solutions at multiple (some times in 100s), bigger facilities , narrowing down the source of emitters, if fit for purpose, can have huge time- and cost saving benefits for operators. However, this functionality might not be an important consideration if the intended application or the inherent capacity of a solution does not support source level localization (i.e. facility level emissions monitoring).

- Comparing general performance from Bell et al. to current study: At the equipment unit level, 3 of 5 *scanning/imaging* solutions had the highest localization precisions ($>$ 60%) and accuracies ($>$ 40%) with the sensor density range of 0.000118 sensors/m^2 to 0.00416 sensors/m^2. All *point sensor network* solutions had precisions $<$ 50% and accuracies $<$ 20% at that level. At the equipment group level or better (equipment group + unit level), one solution (with the largest sensor density) had $>$ 90% localization precision and $>$ 70% accuracy. As a group, when compared to the current study results, performance generally improved from the study by Bell et al.. These improvements could be attributed to the rapid development of the algorithms/analytics of solutions; often the major driver of source localization in CM solutions. Favorable test conditions as shown in SI Table S-4 (higher emission rates, longer release durations, and lower windspeeds) could also be a factor as solutions had longer and multiple opportunities to see the gas plumes (*scanning/imaging* solutions) or gather ambient measurement data (*point sensor network* solutions) at relatively calmer wind conditions to arrive at better localization estimates relative to prior study.

- Comparing the performance of the four solutions common to both studies: The localization precisions and accuracies of solutions B, D, and F (with larger sensor density in the current study) improved at both equipment unit level, and equipment group level or better, relative to the study by Bell et al.. Solution A had mixed result with only localization precision at equipment group level or better improving.

Table 3: Summary of emission source localization (equipment unit) precision and accuracy for all participating solutions arranged in decreasing localization precision equipment unit level.

			Source Localization (Equipment Unit)					
			Precision (%)			**Accuracy (%)**		
ID	**Sensor Density (sensors/m^2)**	**Count of TPs**	**Unit Level**	**Group Level**	**Facility Level**	**Unit**	**Group Level or Better**	**Facility Level or Better**
Result from the current study for all participating CM solutions								
B	0.000118	277	89.5	9.4	1.1	82.7	91.3	92.3
L	0.000118	165	86.7	10.9	2.4	56.3	63.4	65.0
O	0.000118	212	76.4	12.7	10.9	50.0	58.3	65.4
N	0.00213	182	51.6	41.8	6.6	42.2	76.2	81.6
F	0.00118	397	40.8	53.9	5.3	36.5	84.7	89.4
Q	0.00154	161	28.0	54.0	18.0	17.3	50.8	61.9
D	0.000947	375	27.2	68.8	4.0	25.3	89.3	93.1
P	0.00071	367	27.0	56.9	16.1	23.4	72.8	86.8
A[1]	0.000947	254	26.0	49.6	24.4	13.6	39.4	52.2
Results from Bell et al. for the 4 CM solutions that participated in both studies.								
B	0.000118	172	70.9	15.7	13.4	48.8	59.6	68.8
A	0.000947	396	28.0	39.4	32.6	11.3	27.1	40.2
F	0.000947	400	24.8	50.2	25.0	19.2	58.1	77.5
D	0.000947	337	0.0	52.8	47.2	0.0	47.3	89.6

[1] One of the sensors installed failed during the study.

Quantification Accuracy: Seven of 9 solutions tested emissions quantification capability. Panels (a) and (b) of Figure 3 are box and whisker plots showing quantification relative error distribution for each solution for controlled release rate ranges of [0.1 - 1) kg CH_4/h and >1 kg CH_4/h respectively. Emission rates in the range [0.1 - 1) kg CH_4/h roughly represents equipment component leak rates typically identified through OGI surveys[23,42,43] while rates in the range >1 kg CH_4/h represents relatively larger leak rates due to process failures at production facilities.[42,44] Panel (c) of the figure is an error bar plot showing facility level quantification relative errors (actual and simulated mean) for solutions over the duration tested, along with associated uncertainties obtained through bootstrapping (See SI Section S-9.2 for bootstrapping procedure). Across all panels, the grey shaded area shows emission rate estimation range within a quantification factor of 3 ($-67\%|\frac{1}{3}\times$, $+200\%|3\times$) of actual release rates. Results of the 4 solutions that also tested in the study by Bell et al. are shown in the plots for comparison. Tables 4 and S-30 (in the SI) summarizes for both this study and Bell et al. the percentage of reported estimates within a factor 3 for (1) all controlled releases detected (2) detected controlled releases within the range [0.1 - 1) kg CH_4/h, and (3) detected controlled releases within the range >1 kg CH_4/h.

- Performance from current study (2023): Considering all controlled release rates classified as TP, solutions had 54% to 90% of their estimates within a factor of 3. For emission rates within the range [0.1 - 1) kg CH_4/h, Figure 3 and Table 4 shows that the individual estimate relative errors of all solutions were positively skewed (mean > median). Four of 7 solutions (including 2 of 3 *scanning/imaging* solutions) in this range had 79% to 96% of their estimates within a factor of 3 while the remaining solutions had 1% to 55% of their estimates also within the factor. At 95% empirical confidence interval, 1 of 7 solution (*scanning/imaging*), had both the lower and upper individual estimate relative error limits within a factor of 3, while 4 of 7 solutions (including 2 of 5 *point sensor network* solutions) had both of their limits within a factor of 10 ($-90\%|\frac{1}{10}\times$, $+900\%|10\times$). In general, individual estimates ranged from $\approx \frac{1}{5}\times$ to $\approx 42\times$ the actual rates in this range. Typically, field operations are characterized by higher background methane concentration than what is obtainable at METEC. Hence, the detection and quantification of some emissions with rates in this range can be challenging for solutions as emissions are intermittent and can easily blend with background methane concentration. However, assuming current solutions performances are extrapolated to the field, the majority of rates estimates in this range by most solutions might be within a factor of 3 (mostly by over-estimation as mean relative errors are skewed high) with individual estimates having wide uncertainty. For emission rates within the range >1 kg CH_4/h, the individual estimate relative errors for all solutions were positively skewed. All the solutions had 61% to 89% of their estimates of rates in this range within a factor of 3. Five of 7 solutions (including all *scanning/imaging* solutions) had ≥71% of their estimates within a factor of 3, while the remaining solutions having about 62% of their estimates also within the factor. At 95% empirical confidence interval, 5 of 7 solutions (including all *scanning/imaging* solutions) had both lower and upper individual estimate relative error limits within a factor of 10. In general, single estimates ranged from $\approx \frac{1}{13}\times$ to $\approx 18\times$ the actual rates in this range. In field deployments, the wide uncertainty limit on individual estimates for rates in this range can produce grossly misleading results for LDAR programs. For example, overestimating a relatively large emission (e.g. leak rate of 7.1 kg CH_4/h - maximum rate tested in this study) by 18× can lead to a bogus alert of emissions at a scale of a super emitter (≥100 kg CH_4/h). Generally, in this emission rate range, solutions with a majority of their estimated emissions within a factor of 3 increased, indicating that solutions were likely better at quantifying larger emissions compared to smaller ones (SI Figure S-26).

At the facility level, over the the study duration, 6 of 7 solutions estimated emissions within a factor of 2 $(-50\%|\frac{1}{2}\times, +100\%|2\times)$ with their respective simulated lower and upper limits within a factor of ≈3. Given the increasing interest in facility-level quantification as inferred from the USEPA final rule, this result indicate that these solutions are likely to provide facility-level emissions estimation with higher accuracy and narrower uncertainty than single estimates which has important policy implications. See SI Figures S-27 and S-28 for the impact of release duration and wind speed on the individual estimates relative errors of solutions.

- Comparing general performance from Bell et al.: The quantification performance in the study by Bell et al., as summarized in Tables 4 and S-30 (in the SI) showed that as a group, solutions experienced more difficulty at accurately quantifying emissions relative to the current study. For all controlled releases rates, 3 solutions in the current study had fraction of estimates within a factor of 3, greater than the highest value obtained in the study by Bell et al. (74%). Similarly, for emission rate ranges [0.1 - 1) kg CH_4/h and >1 kg CH_4/h, 4 and 3 solutions had fraction of estimates within a factor of 3, greater than the highest values (76% and 80% respectively) obtained in the previous study. In general, as a group, quantification results from the current study improved relative to that by Bell et al. although individual estimates still have high uncertainty. There was no drastic change in facility level quantification performance as all but one solution estimated facility level emissions within a factor of 2 in both studies. As highlighted earlier, this improvement as a group could be attributed to favorable testing conditions and/or improvement in analytics of solutions especially for the 4 solutions retesting in the current study.

- Comparing the performance of the four solutions common to both studies: Relative to the study by Bell et al., for all controlled releases detected, and those within the range [0.1 - 1) kg CH_4/h, the percentage of estimates within a factor of 3 increased for solutions B, F, and D, while only that of solutions B and D increased for emission rates in the range >1 kg CH_4/h. At 95% empirical confidence interval, the individual estimate relative error limits of solution B became narrower for emission rates in the range [0.1 - 1) kg CH_4/h but had mixed result for rates in the range >1 kg CH_4/h. Solutions D and F had mixed results for both emission rate ranges while for solution A, the uncertainty got wider for both emission rate ranges. At facility level, all 4 solutions improved in quantification accuracy.

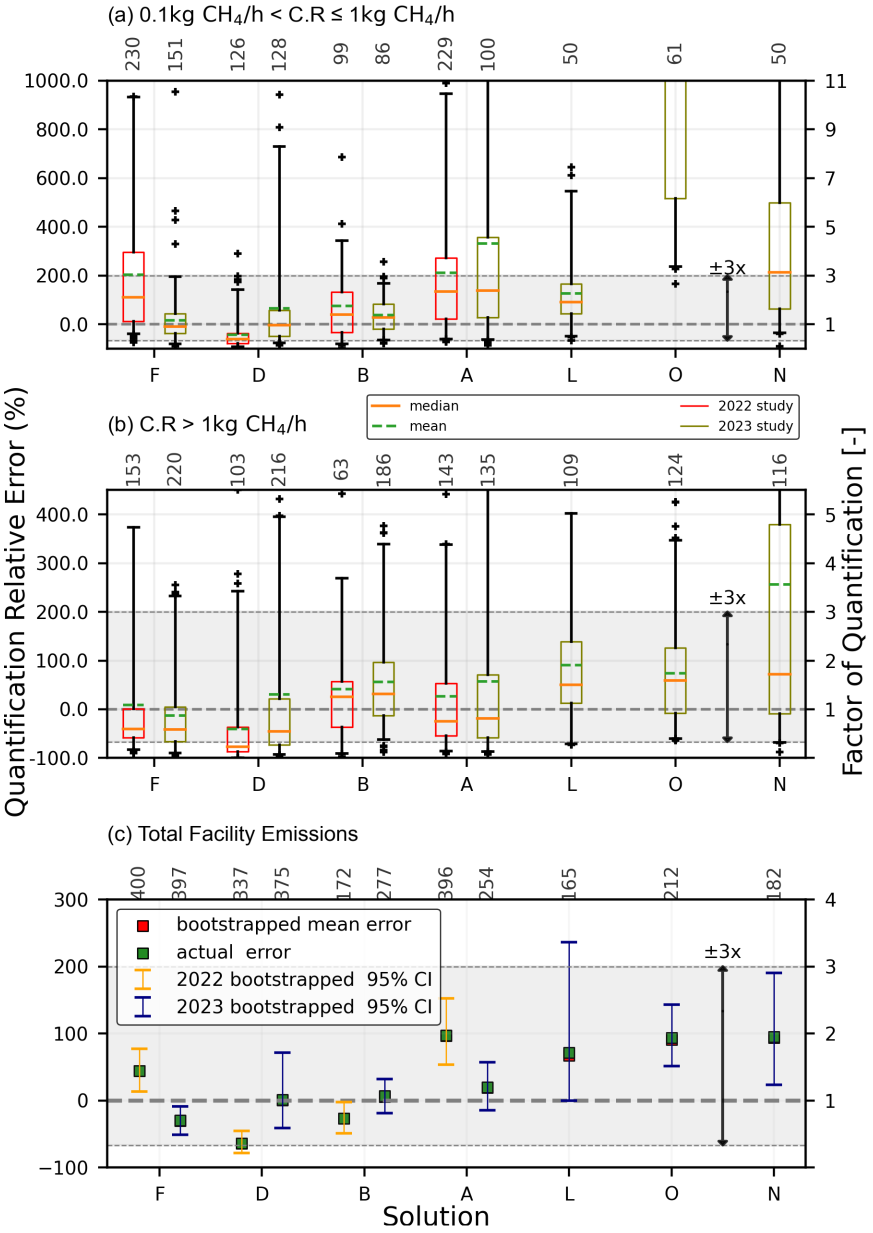


Figure 3: Quantification relative error for solutions categorized by (a) controlled release rate [0.1 - 1) kg CH_4/h, (b) controlled release rate $\geq$ 1kg CH_4/h, and (c) total facility emissions. The bottom panel (c) summarizes the site-level relative error for each solution arranged in increasing order from left (sol. F) to right (sol. M) based on current study data. The site-level relative error is bootstrapped to estimate the uncertainty on the actual error. Markers represent bootstrapped site-level mean relative error (red), and the actual site-level relative error (green) respectively. Whiskers represents the 95% CI on the bootstrapped mean relative error. The middle (b) and top panels (a) are boxplots summarizing relative error distribution for each solution over selected range of controlled release rates. Each box represent the inter-quartile range of data with whiskers including 95% of data. The upper y-axis of (a) and (b) are arbitrarily trimmed at 400% and 1000% respectively with the full 95% CI shown in Table 4. Across all panels, results from the study by Bell et al. (2022) is also shown to facilitate comparison. The x-axis of all panels are arranged based on (c) while the shaded zone indicates region within a quantification factor of 3.

Table 4: Summary of single-estimate quantification for solutions along with their 95% empirical confidence limits. The percentage of measurements within a factor of 3 is shown for both current study and the previous study for comparison.

	Estimates within ±3× (%) Error relative to CR[2] ($-67\%\|\frac{1}{3}\times$, $+200\%\|3\times$) **CR (kg CH_4/h)**			**Relative Quantification Error (%)** **CR (0.1 – 1] kg CH_4/h**			**CR >1 kg CH_4/h**		
ID	**All**	**(0.1 – 1]**	**> 1**	**Mean**	**Median**	**95% CI**	**Mean**	**Median**	**95% CL**
Results from the current study for all participating CM solutions									
B	90	96	89	37.4	28.1	[-65.0, 168.5]	55.7	31.5	[-62.3, 339.4]
L	81	84	81	126.2	91.2	[-49.5, 546.6]	90.4	50.0	[-70.7, 402.2]
F	78	90	71	15.7	-9.6	[-80.4, 195.5]	-12.8	-41.8	[-89.6, 232.3]
D	67	79	61	64.5	-3.0	[-75.8, 729.0]	30.8	-45.8	[-92.5, 395.7]
A[1]	60	55	72	330.4	138.4	[-62.2, 1803.4]	57.6	-18.3	[-86.3, 612.5]
N	56	48	62	1036.6	212.8	[-36.2, 2900.9]	256.0	72.0	[-68.0, 1671.6]
O	54	1	86	1751.2	1074.9	[235.9, 4071.5]	73.4	58.8	[-60.4, 347.0]
Results from Bell et al. for the 4 CM solutions that participated in both studies.									
B	74	76	80	74.6	39.5	[-81.1, 343.2]	41.9	25.3	[-90.2, 268.8]
F	65	62	75	202.2	110.9	[-39.7, 933.2]	9.2	-40.5	[-82.5, 373.6]
A	64	65	73	211.3	134.2	[-60.9, 946.8]	27.1	-24.2	[-85.6, 338.5]
D	48	60	34	-43.0	-60.1	[-92.6, 141.4]	-40.0	-77.0	[-99.9, 242.4]

[1] One of the sensors installed failed during the study.

[2] Columns identify fraction of estimates in the study by Bell et al. and that of the current study which were within a factor of three relative to the controlled release rate.

Time to Detection: As briefly discussed earlier, the emissions mitigation potential of CM solutions also depends on the fraction of deployment duration during which solutions are operational to collect and transmit data (operational time),[27] and how quickly emitters are identified and communicated to operators. Tables S-4 and S-3 (in the SI) shows the operational factors of solutions in this study and in Bell et al.. Figure 4 and Table S-31 (in the SI) shows the calculated time to detection for true positive detections by solutions. In this study, 2 solutions (P and Q) did not automate their detection reporting process. Since the study team could not assess the extent of human support (if any) for solutions with automated reporting especially when there was failure in data transmission, assessed time to detection also captured the inefficiencies likely introduced by human interference e.g. time taken to manually prepare detection reports as prescribed by the test protocol.[38]

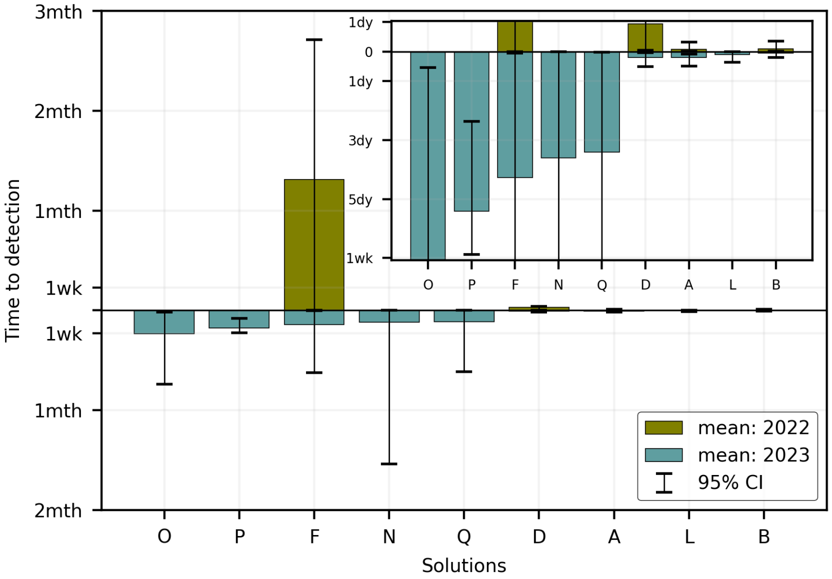


Figure 4: Time to detection for all participating solutions from both the previous (2022) and current studies. The bars representing the mean time to detection are sorted in decreasing order from left (solution O) to right (solution B) using data from the current study. The time to detection of the 4 solutions (A, B, D, and F) from Bell et al. is shown in the upper half of the figure while that of the current study is shown on the bottom half. Whiskers represent the 2.5 (lower) and 97.5 (upper) percentiles of the data for each solution. The insert is a miniature version of the original plot with the upper y-axis trimmed at a time to detection of 1 day, and the lower y-axis trimmed at a time to detection of 1 week.

- Performance from current study (2023): Figure 4 shows that at 95% empirical confidence interval, 4 of 9 solutions had mean times to detection < 5 hours with upper limits < 15 hours; 2 solutions had upper limits less than the maximum release duration in this study (10.2 hours). Unlike the profile of emissions in this study (steady rates released for hours), several leaks typically found in the field are intermittent, hence solutions typically have shorter windows than available in this study to collect and communicate measurement data to operators. Additionally, results show that 6 of 9 solutions were operational at least 90% of their deployment time with 5 solutions operational throughout the study (operational factor of 1 - SI Table S-2). The USEPA stipulates a rolling 12-month average operational downtime $< 10\%$ (operational factor $> 90\%$) in their final for CM solutions.[41]

- Comparing general performance from Bell et al. For the study by Bell et al., at 95% empirical confidence interval, 3 of 11 solutions had mean times to detection < 5 hours with upper limits < 15 hours and 1 solution had upper limit less than the maximum release duration considered for the solution. Results shows that, as a group, relative to Bell et al., current study results generally improved in this area.

- Comparing the performance of the four solutions common to both studies: At 95% empirical confidence interval, the mean times to detection, their respective lower and upper limits, and operational factors for solutions B, D, and F improved relative to previous results in Bell et al..

Implications

The growing interest by stakeholders including O&G operators and regulators, in CM as a faster, temporally resolved approach for methane emissions detection, measurement, and mitigation, is driving rapid development of CM solutions. Therefore, regular and robust testing of solutions are required to characterize and compare performance levels (intra and inter solutions) using a standardized/consensus testing protocol. This study is the second implementation (first by Bell et al.) of a consensus protocol (ADED CM protocol) to assess progress of solutions. Results from the study highlights a few key points. Firstly, solutions that tested before generally exhibited better performance on many performance metrics relative to (1) their previous performance in Bell et al., (2) other solutions testing for the first time under the protocol. Majority of solutions that retested in this study had the lowest FP rates and DL90s, and the highest localization accuracy at equipment group or better performance in the study. They were also among solutions with the lowest FN rates and highest quantification performance (estimates within a factor of 3) across different emission rate ranges ([0.1 - 1) kg CH_4/h and >1 kg CH_4/h). Similarly, across all metrics assessed, most of the solutions that retested improved in performance when compared to their previous results highlighting the benefits of regular quality testing. Users however should be cautious given that these results are likely more representative of non-intermittent emissions from fugitive events which make up relatively smaller fraction of reported upstream emissions. Secondly, single source emission estimates by solutions still has wide uncertainty which is unsuitable for accurate measurement-based inventory development and reporting programs. On the other hand, solutions had better quantification accuracy with narrower uncertainty at the facility-level. This result, if replicable in the field and applied to sites similar to METEC, shows promises of reliable facility-level quantification performance by these solutions especially when adopted for regulatory programs in the near-future provided that the observed rapid development of CM solutions was sustained. Overall, solutions need not have excellent performance across all metrics assessed in this study to be useful i.e., rapid detection of large emissions sources for repairs might not require accurate quantification. As well, higher DL90 at low FP rate could mitigate larger emissions with minimal cost of followup investigations.

Supporting Information

Zip folder of solutions' performance reports (PDF), data tables (XLSX), and data tables guide (XLSX). Detailed description of the test facility, solutions deployment, additional results, guide to the performance reports, and bootstrapping methodology (PDF).

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