Pilot Study for Methane Measurement and Emissions Quantification with Next-Generation Sensor Technology at Upstream Oil and Gas Facilities

Final Report

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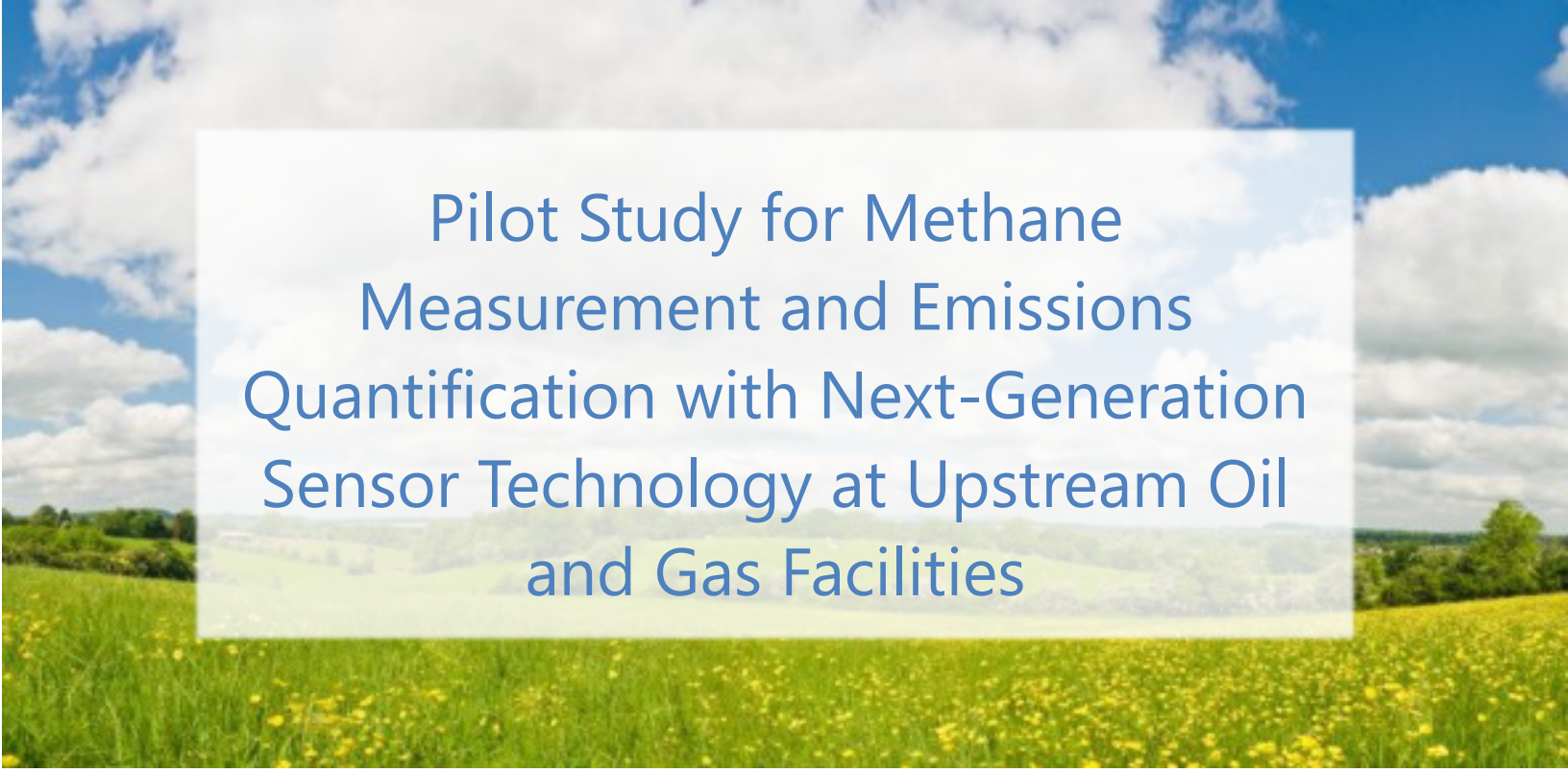

Pilot Study for Methane Measurement and Emissions Quantification with Next-Generation Sensor Technology at Upstream Oil and Gas Facilities

Prepared by

Kenneth J. Craig
Josette E. Marrero
Ryan C. Moffet
Justin S. Dumas
Sonoma Technology, Inc.
1450 N. McDowell Blvd., Suite 200
Petaluma, CA 94954-6515
Ph 707.665.9900 | F 707.665.9800
sonomatech.com

Prepared for

Alberta Upstream Petroleum Research Fund
Petroleum Technology Alliance Canada
Suite 400 Chevron Plaza, 500 - 5 Ave. SW
Calgary, Alberta T2P 3L5
Ph 403.218.7700 | F 403.920.0054
ptac.org

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Abstract

A three-week field study was undertaken during summer 2018 at a well pad near Drayton Valley, Alberta, to demonstrate the application and utility of an innovative, portable methane sensor to characterize emissions from small-scale sources at upstream oil and gas (O&G) facilities. This work helps address the Alberta Upstream Petroleum Research Fund's research priorities to develop practical solutions for identifying potential methane sources and quantifying methane emissions in the field. From this pilot project, a high-quality dataset was obtained that demonstrates the capabilities of these sensors. We found the data from these sensors to be suitable to support a wide range of applications, and to provide useful information that can be coupled with emission quantification methods to identify emission sources and quantify emission rates at upstream O&G facilities. These measurements also provide a benchmark upon which data quality objectives can be established for similar new and emerging methane sensor technologies.

Two Aeris Pico series methane sensors were tested and deployed during this pilot study. The Aeris sensor uses next-generation technology that collects data at a sufficient rate with sufficient accuracy and sensitivity, and supports a broad range of applications at upstream O&G facilities. The sensor also measures coincident ethane concentrations, and the use of ethane data to identify natural gas sources was demonstrated. Meteorological instruments were also deployed to provide context for the methane measurements and support data analysis. A series of controlled methane release experiments were conducted at the well pad to provide additional data to evaluate and demonstrate the sensors' capabilities and limitations. Finally, data from the deployment and controlled release experiments for select periods were used to demonstrate application of an inverse dispersion modeling approach that can be used to quantify methane emissions at upstream O&G facilities.

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Executive Summary

A three-week field study was undertaken during summer 2018 at a well pad near Drayton Valley, Alberta (Site 8-8), to demonstrate the application and utility of innovative, portable, next-generation methane sensors to characterize methane emissions from small-scale sources at upstream oil and gas (O&G) facilities. This work helps address the Alberta Upstream Petroleum Research Fund's research priorities to develop practical solutions for identifying potential methane sources and quantifying methane emissions in the field. From this pilot project, a high-quality dataset was obtained that demonstrates the capabilities of these sensors. We found the data from these sensors to be suitable to support a wide range of applications at O&G facilities, and to provide useful information that can be coupled with emission quantification methods to identify emission sources and quantify emission rates at O&G facilities. These measurements also provide a benchmark upon which data quality objectives can be established for similar new and emerging methane sensor technologies.

Two Aeris Technologies (Aeris) Pico series methane sensors were tested and deployed during this pilot study. Given that relatively new technology was used, two sensors were deployed to provide redundancy in the measurements. Deploying two sensors also (1) increased the likelihood of intercepting methane plumes during the deployment, (2) offered further opportunities to inter-compare methane measurements from two identical instruments, and (3) provided data to support future exploration of multi-sensor emissions location and quantification techniques. The sensors also measure coincident ethane concentrations, and the use of ethane data to identify natural gas sources was demonstrated. Meteorological measurements, which are critical to any methane measurement program, were also collected in the pilot study to provide context for the methane measurements and support data analysis. A series of controlled methane release experiments was conducted at Site 8-8 to provide additional data to evaluate and demonstrate the sensors' capabilities and limitations. Finally, data from the deployment and controlled release experiments for select periods were analyzed to test the sensors' capabilities in the field, identify methane sources at the well pad, and quantify methane emissions through application of an inverse dispersion modeling approach. An optical gas imaging and equipment survey was conducted to corroborate and validate the inferences drawn from the methane sensor measurements.

Site 8-8 is an active well pad with three pump jacks, adjoining well shacks and equipment, and a battery of six production tanks. The site was ideal for this pilot project because it had confirmed methane emissions and a layout that allowed for good instrument siting relative to the predominant winds in the region. The site also had line power, good cell signal coverage, and good road access. Data were collected at 1-second time resolution and were averaged to 1-minute resolution for data analysis.

The conclusions and recommendations from this pilot study are outlined on the following pages.

Identification of Methane Sources

Data from the methane sensors were successfully used to identify the presence of continuous (as opposed to intermittent) methane emissions from equipment at Site 8-8. The wind, methane, and ethane data were further used to successfully distinguish methane emissions from two distinct types of sources: the production tanks, and the pump jacks and adjoining equipment. Methane emissions from the tanks were confirmed prior to the deployment, but the nature of those emissions (e.g., continuous vs. intermittent) were unknown, and methane emissions from other equipment at the site were previously unknown. The use of multiple sensors to identify emissions from individual well shacks or tanks at Site 8-8 was not explored in this study. The key conclusions based on the analysis of methane and meteorological data collected at Site 8-8 are as follows.

- There were numerous instances where the methane concentrations were consistently above the local baseline concentration of 1.91 ppm, indicating continuous methane emissions from equipment at Site 8-8.
- The majority of methane data collected at Site 8-8 were between 2.00 ppm and 3.00 ppm, and nearly 10% of the data were greater than 2.50 ppm. Methane concentrations were greater than 4.00 ppm for 8 hours (1.5% of data) during the three-week deployment, and were as high as 17.3 ppm. About one-quarter of the measurements were below 2.00 ppm.
- The lowest methane concentrations were generally observed when winds were blowing from the southeast, when the sensors were upwind of the equipment at Site 8-8. Baseline methane concentrations were determined during these wind conditions, in the absence of a dedicated upwind sensor.
- Methane concentrations were correlated to a diurnal cycle in the winds that favored nighttime transport of emissions from the pump jacks and adjoining well shacks.
- Higher methane concentrations were consistently observed when winds were blowing from the west and southwest, when the sensors were downwind of the pump jacks and adjoining well shacks. Higher methane concentrations were also consistently observed when winds were blowing from the northwest, when the sensors were downwind of the production tanks. The methane sensors were downwind of either the pump jacks or the production tanks about 50% of the time during the deployment.
- Coincident ethane measurements are not critical but are helpful to confirm natural gas emission sources (as opposed to other biogenic or geologic methane sources) and differentiate between multiple emissions sources that may have unique ethane composition.
- Analysis of ethane data from the sensors showed that most of the enhanced methane concentrations could be traced to natural gas. Furthermore, two clear ethane-to-methane ratio signatures were identified: a lower-ethane signature traced to the pump jacks and/or adjoining well shacks, and a higher-ethane signature traced to the production tanks.

- The optical gas imaging and equipment survey confirmed methane emissions from all three well shacks and three of the six production tanks. Emissions were observed from engineered vents on the production tanks. Emissions were observed from specific equipment inside the well shacks, but it is unclear whether those were fugitive or venting emissions.

Quantification of Methane Emissions

An inverse dispersion modeling analysis based on the WindTrax particle model was conducted to estimate methane emissions from the well shacks and production tanks during two selected 1-hour time periods. This analysis was conducted to demonstrate the potential for using the methane sensor data with inverse dispersion modeling approaches to quantify methane emissions from upstream O&G activities. Data from the sensors were successfully used to estimate methane emission rates that were comparable to "as found" release rates measured from specific equipment by the optical gas imaging (OGI) and equipment survey conducted at the beginning of the field deployment. The "as found" release rates were determined from a Hi-Flow® Sampler (for the well shacks) or based on visual estimates from an OGI camera (for the production tanks).

The key conclusions from this analysis are as follows.

- The estimated methane emission rate from one well shack during the selected analysis period was 3.82 ± 1.91 g/min. This was comparable to the 4.53 g/min "as found" release rate measured from the OGI and equipment survey taken one month earlier.
- The estimated methane emission rate from the three production tanks with emissions during the selected analysis period was 12.24 ± 6.12 g/min. This was comparable to the 26.4 g/min "as found" release rate measured from the OGI and equipment survey taken one month earlier.
- The "as found" emission rates from the OGI survey are not meant for direct validation of the modeled emission rates, since the OGI survey used different days, methodologies, and averaging periods; however, a general (though limited) comparison, in conjunction with the uncertainty established from the controlled release experiments, suggests that the modeled emissions estimates are likely the correct order of magnitude and are probably accurate to within a factor of two.
- In conjunction with the emissions quantification tests conducted on the controlled release data, these results show that the methane sensors used in this study are capable of producing data that can support quantitative methane emission estimates.

Controlled Release Experiments

A series of 14 controlled methane release experiments were conducted at Site 8-8 to provide additional data to evaluate and demonstrate the methane sensors' capabilities and limitations. Data

from the controlled release experiments were also used to demonstrate and test the emissions quantification approach used in this study, and to establish uncertainty bounds for that approach.

Conclusions from the controlled release experiments are as follows.

- During the controlled releases, the sensors could reliably detect methane releases as small as 0.36 g/min at 25 m from the release, and 7.20 g/min at 54 m from the release. An instrument error of 1% was assumed in this determination. Larger instrument error would raise the lower limit of quantifiable detection. For example, the 0.36 g/min release at 25 m would not be detectable with a 2% instrument error.
- Emissions from five of the 14 controlled releases could not be detected. These were generally at the smaller release rates.
- Concentrations as high as 55.0 ppm were observed during the "super-emitter" test release of 82.86 g/min at 25 m from the sensor.
- Modeled emission rates were between -68% and +78% of the actual release rates, with a fractional gross error of 46%. Therefore, a 50% confidence interval was established for the inverse dispersion modeling approach demonstrated in this project. This range of uncertainty is comparable to other studies involving the stationary ground-based measurements and inverse dispersion modeling, and illustrates that data from the methane sensors used in this study can be used to establish methane emission rates that are accurate to within a factor of two. The emissions quantification approach provided better results (modeled emission rates between -7% and +37% of the actual release rate) during the earlier morning experiments when atmospheric conditions were more conducive to ideal plume behavior; these results are more indicative of the capabilities of the emissions quantification approach used in this project.

Sensor Characterization

- Data capture from the methane sensors was very high (>99%) during the Site 8-8 deployment. Data quality was also very high, and all data collected were considered valid for analysis.
- The published accuracy of the methane sensor is 1% of the measurement, and the instrument drift is 0.020 ppm peak-to-peak, or 1% of the measurement. Bench testing showed an instrument accuracy of between 1% and 2%, and a peak-to-peak drift within the published values. The precision (uncertainty) of the sensor was not published. A precision of 1% determined from bench test results and the Site 8-8 field data is a conservative and reliable uncertainty estimate for the methane measurements. This range of measurement uncertainty is sufficient to support a broad range of applications at O&G facilities, such as the detection and identification of methane releases, and the quantification of methane emission rates.

- Sensor agreement is also a measure of instrument precision. The agreement between the two methane sensors during bench testing and in the field was very good and within 1%. The time-averaged baseline concentrations calculated from the two sensors at Site 8-8 agreed to within 0.010 ppm (within 1% of the measurement).

Best Practices and Tangible Project Outcomes

This pilot project involved a three-week methane field measurement study at the Site 8-8 well pad, along with controlled methane release experiments also conducted at Site 8-8. The project successfully demonstrated the application and utility of innovative, portable methane sensors to characterize methane emissions at an upstream oil and gas (O&G) facility. A high-quality dataset was obtained that demonstrates the capabilities of these next-generation sensors. Based on these data, we found that the Aeris Technologies (Aeris) Pico series methane sensors used in this study had sufficient data rate, accuracy, and sensitivity to support a broad range of applications at upstream O&G facilities, such as the detection and identification of methane releases, and the quantification of methane emission rates. Data from the sensors were successfully used to identify the presence of continuous (as opposed to intermittent) methane emissions from equipment at Site 8-8, and the combination of wind, methane, and ethane data were further used to successfully distinguish methane emissions from two distinct types of sources at Site 8-8 (production tanks, and pump jacks and adjoining equipment). The data were also successfully used to support quantitative methane emissions estimates based on an inverse dispersion modeling method. The measurements collected at Site 8-8 therefore provide a benchmark upon which data quality objectives can be established for similar new and emerging methane sensor technologies.

The sensors and approaches demonstrated in this project can be used to characterize real-world methane emissions at upstream O&G facilities. Collecting data to support these objectives requires methane sensors with appropriate data quality requirements (e.g., data capture rate, sensitivity, and accuracy), co-located high-quality meteorological measurements, the ability to accurately assess local baseline (upwind) methane concentrations, careful instrument siting and placement, and a robust data management system and process. These practical considerations are discussed below.

Establishing Background (Baseline) Concentrations

Establishing a baseline methane concentration is critical for establishing context for methane measurements and quantifying methane emissions at an O&G facility. The baseline can be considered a local background concentration that can vary over time and may be different from a regional, continental, or global marine background concentration. There are two ways to establish baseline concentrations:

- Collect simultaneous methane measurements upwind and downwind of the facility.
- Determine baseline concentrations from a single sensor during periods when the sensor is upwind of the facility.

Both approaches take careful field planning and sensor placement that will be unique to the layout and characteristics of the facility, topographic features in the area, and potential nearby off-site methane sources. In this pilot project, a single baseline methane value for the entire study period was determined by using the lowest 10% of methane measurements. Methane enhancements were determined by subtracting the baseline concentration from the methane observations. Longer deployments would require time-varying assessments of the baseline. Using an upwind/downwind sensor combination, the baseline can be determined directly from the upwind sensor.

Sensor Characterization and Data Quality Objectives

Sensor accuracy and sensitivity directly affect the degree to which methane enhancements can be statistically (and therefore reliably) distinguished from the background (upwind) concentration, and the sensitivity and uncertainty of any emissions quantification method. A high data capture rate can enable the detection and characterization of intermittent releases, and produces data for emission quantification approaches that characterize the emission plume by relating changes in concentration to coincident changes in wind speed and direction. Understanding the capabilities and limitations of both the sensor and the emissions quantification method is key to ensuring that project objectives can be achieved.

In this pilot project, data collected from pre- and post-deployment calibration tests, controlled methane release experiments, and the three-week field deployment were used to evaluate and demonstrate the sensors' capabilities and limitations. These activities are important and appropriate to establish credibility and confidence in any sensor and data analysis approach that may be used in the field.

The recommended data quality objectives for applying methane sensors at upstream O&G facilities depend on the intended application of the measurements. For example, the requirements for detecting methane anomalies from a facility would be less rigorous (i.e., larger precision and error could be tolerated) than the requirements needed to support emissions quantification. The data quality objectives were not formally defined prior to the pilot study, but some general objectives were used to guide the instrument selection. Data from the bench testing, controlled releases, the Site 8-8 field deployment, and the emissions quantification analyses were used to support recommendations that can be used to guide future applications of methane sensor technology at upstream O&G facilities.

Important practical conclusions and recommendations related to the sensor characterization and data quality objectives for applying sensors at upstream O&G facilities include:

- A measurement uncertainty (precision) within about ±4% is needed to reliably detect and quantify methane signals greater than about 0.100 ppm above baseline, and therefore is necessary to support emissions characterization. Larger measurement uncertainties could be tolerated to support field objectives that involve only the identification of anomalous emissions at a facility and do not require accurate quantification.

- A baseline methane concentration of 1.91 ppm was determined for the 3-week deployment. At this baseline concentration, the sensors used in this study can reliably detect a methane enhancement above baseline (measurement minus baseline) as small as 0.027 ppm at 1% measurement uncertainty. A measurement uncertainty of up to 4% would be sufficient to reliably detect and quantify signals greater than about 0.100 ppm above baseline.
- Meteorological instruments are critical and should always be co-located with the methane measurements. The meteorological data should at a minimum include wind speed, wind direction, temperature, relative humidity, and pressure, as all are needed to characterize and quantify methane emissions. The data capture rate should be at least equal to the methane measurements (i.e., at least 1 second). For wind measurements, a 3-D sonic anemometer is ideal, but a 2-D sonic anemometer is still preferred over cup-and-vane measurements.
- Data resolution must match the deployment objectives and analytical approaches being used. Data at 1-minute resolution was sufficient to meet the objectives of this study, but certain emission quantification techniques can use 1-second (1 Hz) resolution data to relate changes in concentration to coincident changes in wind speed and direction to characterize emission plumes.
- To use near-field emissions quantification methods, instruments should be located within about 15 m to 100 m of potential emission sources. At closer distances, gas plumes from elevated releases may travel over the sensors. At further distances, gas plumes may become too diluted to be characterized by the sensor. For larger O&G facilities, multiple sensors may be needed.
- Coincident ethane measurements are not critical but are helpful to confirm natural gas emission sources (as opposed to other biogenic or geologic methane sources) and to differentiate between multiple emissions sources that may have unique ethane composition. To support this type of analysis, ethane measurements should have 1% accuracy, and up to 20 ppb peak-to-peak drift.

Practical Considerations

In addition to characterizing the sensors and establishing data quality objectives, there are several practical considerations for using the Aeris sensors or sensors with similar characteristics in the field. The considerations include:

- **Cost.** Although the methane sensors deployed in this pilot project are not considered a low-cost sensor technology, we expect that the price of these and other next-generation methane sensors will drop over time as the technology matures. These sensors are significantly less expensive than a cavity ring-down spectroscope (considered a gold standard in methane measurement) and meets data quality objectives for supporting methane emissions quantification and other measurement objectives at upstream O&G facilities. When evaluating the potential benefits of the sensor technology, additional costs associated with

deployment design and execution, sensor operations and maintenance, data management, data analysis, and data delivery must also be considered.

We evaluated several potential methane sensors for this pilot project. The cost point for the sensor selected for this project provides the necessary sensitivity and accuracy that are needed for methane emission identification and quantification efforts. At this point in time, lower-cost options sacrifice sensitivity and accuracy, and these tradeoffs must be considered in the context of the field deployment objectives.

- **Temperature control**. The biggest concern for the methane sensor was overheating. Customized enclosures were developed to shield the instrumentation from heat and maintain proper laser temperature. In cold-climate deployments, a heater would be needed. In hot-climate deployment, appropriate ventilation and possibly air conditioning would be needed. A climate-controlled shelter or carefully controlled enclosure is needed to deploy this methane sensor long-term.
- **Power**. The original deployment plan included the use of deep-cycle lead-acid batteries charged by solar panels. After bench testing the instruments and planning the field logistics, we determined that using line power would reduce project risk and increase the likelihood of a successful pilot project. Therefore, the deployment requirements for this project were adjusted, and a site was selected that had line power.
- **Data communications and management**. The methane sensors had adequate on-board storage, but real-time measurement systems need robust communications (cellular was used in this deployment) and specialized offsite data management capability to receive and process high-time-resolution (1-second) data in real-time. Appropriate data quality control measures, such as range checks, stuck value checks, etc., are also necessary.[1]
- **Calibration.** Instrument calibration is important to establish and maintain accuracy in the methane measurements. The sensor does not have a published calibration procedure. Pre- and post-deployment checks against standard gases with known concentrations were conducted in this pilot project, and are recommended for any sensor and field deployment. Longer-term deployments need periodic calibration checks to guard against long-term instrument drift. A quarterly calibration check is recommended
- **Instrument issues**. The methane sensors deployed in this pilot project were relatively new to the market. We worked closely with Aeris during the testing phase of this pilot project to address various issues that were initially encountered. Working out these issues during the testing phase helped ensure that no operational issues were encountered during the Site 8-8 deployment.

[1] A range check is used to confirm that a measurement is within a realistic range of concentrations. A stuck value check is used to detect when a sensor has stopped responding appropriately to changes in concentrations.

1. Background

Methane is a potent greenhouse gas, and there is significant scientific, regulatory, and practical interest in understanding, quantifying, and reducing methane emissions from Alberta's upstream oil and gas (O&G) industry. Of particular interest are emissions from leaking or malfunctioning equipment and routine methane venting from pneumatic devices, glycol dehydrators, compressors, vessels, and tanks. The Government of Alberta's Climate Leadership Plan[2] calls for a reduction of methane gas emissions from upstream O&G operations by 45% (relative to 2014 levels) by 2025, and active regulations and legislation are directed toward addressing the issue of methane emissions from O&G operations.[3] This regulatory context provides an important impetus for the development, testing, and application of sensor-based systems that can help meet Alberta's upstream O&G industry goals.

The application of portable, next-generation methane sensors coupled with analysis techniques that may be utilized as an alternative method to identify, localize, and quantify emissions from small-scale sources at upstream or midstream O&G facilities is therefore an important topic for the Alberta Upstream Petroleum Research Fund (AUPRF). Sonoma Technology, Inc. (STI) has undertaken this study in the context of the AUPRF's research priorities related to methane—i.e., to develop more broadly applicable solutions for reducing methane emissions in ways that are both technically achievable and economically sustainable. The term "next-generation" refers to emergent sensor technology that has the potential to meet various O&G industry needs at substantially lower acquisition and operational costs compared to current "gold-standard" methane measurement systems. Recent advances in methane monitoring and analytical techniques have rendered these technologies more suitable to the AUPRF's research priorities than ever before. Methane sensors are becoming, and will continue to become, less costly, more sensitive, more portable, and easier to use.

Hence, a field study was undertaken to (1) address AUPRF's research priorities related to methane; (2) advance the understanding of the strengths and limitations of next-generation, portable methane sensors; and (3) advance the general understanding of how best to leverage sensor technologies for facility process improvements, how and when to suitably apply the technologies, and how to defend against misuse or misinterpretation of results. The specific project objectives are to (1) demonstrate application of innovative, portable methane sensors that can eventually be coupled with inverse dispersion modeling analyses; and (2) develop recommendations and quantifiable data to illustrate how this data can support emissions quantification (or inverse modeling) analysis to address transient, low-level emissions sources. This will contribute to the body of knowledge concerning best and standard practices in upstream O&G facilities.

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[2] See https://www.alberta.ca/climate-methane-emissions.aspx.

[3] AER Directive 60: Upstream Petroleum Industry Flaring, Incinerating, and Venting; AER Directive 17: Measurement Requirements for Oil and Gas Operations; and Government of Canada *Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector) (SOR/2018-66).*

This report describes the three-week deployment during summer 2018 of two portable methane concentration sensors with co-located meteorological sensors at the Site 8-8 well pad, located near Drayton Valley in Alberta, Canada. This deployment was conducted to demonstrate the utility of the methane sensors and meteorological package to characterize potential methane emissions at an O&G site, and give information about the relative strength and location of methane emissions at the site. Although methane is the primary focus of this work, the sensors deployed in this project also measure ethane (C_2H_6), which can facilitate a more refined characterization and source identification of potential methane sources.

As part of this project, the sensor package was evaluated at STI before and after the deployment and challenged with gases of known concentration and composition. The sensor package was further challenged in the field through a series of controlled release experiments that were conducted prior to the deployment. The controlled release experiments provide important data to evaluate the methane sensors in the field, and to evaluate emission quantification methods.

The end goal of these activities is to obtain a data set that can demonstrate the ability of these portable, next-generation sensors to provide information that can eventually be coupled with inverse dispersion modeling methods to estimate emission source strengths and locations at upstream O&G sites. These measurements will also provide a benchmark upon which data quality objectives can be established for similar new and emerging methane sensor technologies.

2. Methodology

2.1 Sensor Deployment

The Site 8-8 well pad was selected for this measurement campaign in consultation with PTAC and the Alberta Energy Regulator (AER). Site 8-8 is located in Alberta, Canada, near Drayton Valley (Figure 1). This site was considered ideal from a logistics standpoint because it had good road access, available line power, and adequate cellular signal coverage. This site was also considered ideal to support potential emissions quantification work because of the flat terrain with few obstructions that could complicate any plume modeling. The site has three oil wells being worked by pump jacks, separator vessels, outbuildings, various pipes, and a battery of oil storage tanks.

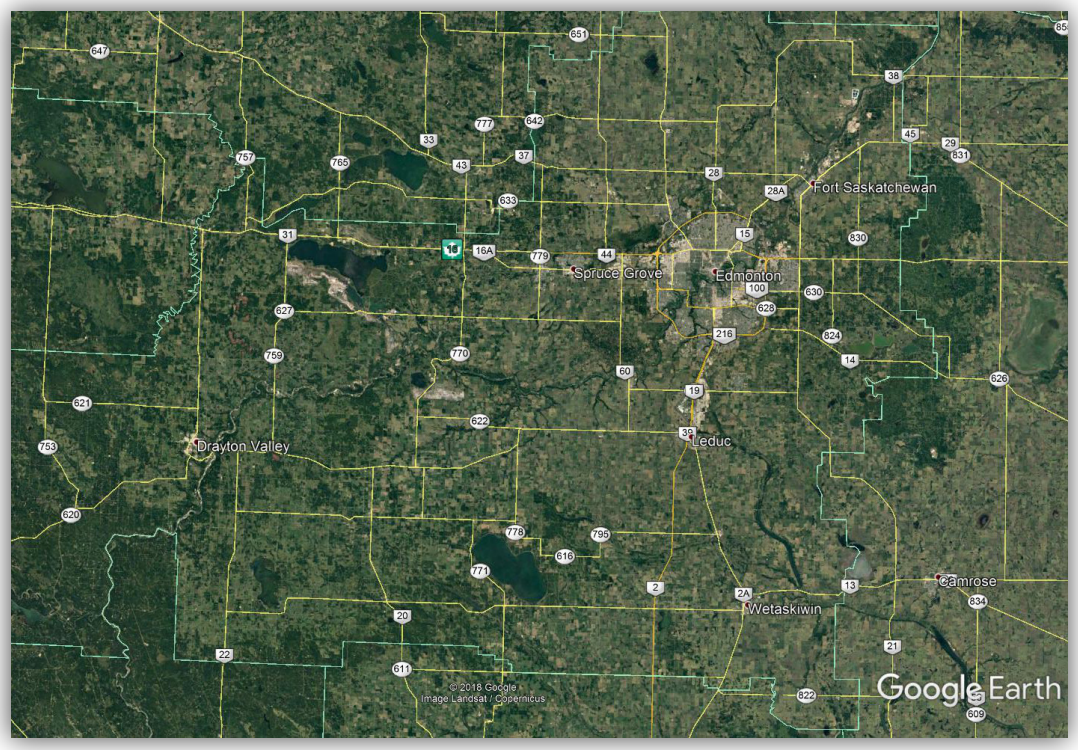

Figure 1. Geographical area in the vicinity of Site 8-8 in Alberta, Canada.

Depending on the site layout, the prevailing winds, and which site equipment has the highest possibility for methane emissions, there were several options for locating the methane and meteorological sensor packages. Figure 2 shows wind roses for June and July at Edmonton International Airport, which is the closest available long-term meteorological data site in the region. During the summer months, the region experiences winds primarily from the northwest and

southeast directions, in alignment with the orientation of the Canadian Rockies to the west. In early 2018, AER conducted a preliminary optical gas imaging (OGI) survey to confirm the presence of emissions at Site 8-8. During that survey, emissions from the tops of the storage tanks were observed. No emissions were detected at pump jacks. The adjoining well shacks and separator vessels were not examined.

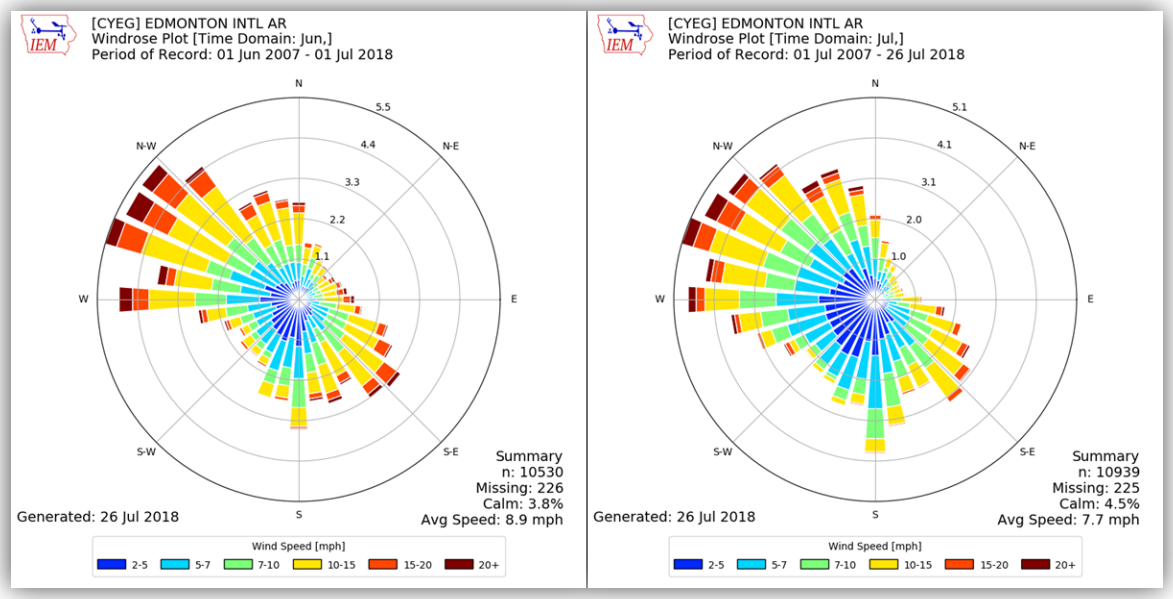

Figure 2. Wind roses at Edmonton International Airport (CYEG). The length of the stacked bars (petals) is indicative of the frequency of wind events coming from that particular direction. Wind speed is indicated by color.

Information from this preliminary OGI survey was used in conjunction with climatological wind data for the region to select the sensor locations at Site 8-8 (Figure 3). Two sensors were deployed to provide redundancy in the measurements, given that relatively new technology was involved. Deploying two sensors also increased the likelihood of intercepting methane plumes during the deployment, offered further opportunities to inter-compare methane measurements from two identical instruments, and provided data to support future exploration of multi-sensor emissions location and quantification techniques. The **East Site** package contained a methane sensor, telemetry equipment, data logger, and meteorological instrumentation. The **West Site** package, positioned 12 m from the east site, contained the second methane sensor and telemetry equipment. The relatively close proximity of the two sensors enabled their operation on a single power and communications system.

The sensors were located near the northernmost pump jack, approximately 60 m southeast of the storage tanks. The positioning of the sensors in the field relative to the pump jacks and storage tanks at Site 8-8 is shown in Figure 4. This location provided a high probability of a successful deployment, given its position downwind of storage tanks with confirmed methane emissions. Because there was

no nearby O&G equipment southeast of Site 8-8, this sensor location was also ideal for monitoring baseline methane concentrations during periods of southeast winds. Any potential methane emissions from the pump jacks and adjoining equipment could also be detected during periods of westerly or southwesterly winds.

Figure 3. Map of Site 8-8 and sensor locations. Blue diamonds show the location of the methane sensors (East Site and West Site). Red triangles show where the controlled releases occurred.

Figure 4. Sensor deployment at Site 8-8, showing the two sensor packages, the northernmost pump jack to the left, and the production tanks in the distance.

Flow obstruction is a concern for wind measurements. It is ideal to place sensors at a distance of at least 10 times the obstruction height to minimize flow distortion impacts on the wind measurements. The sensor location 60 m downwind of the production tanks is adequate to minimize flow distortion impacts on the wind measurements due to the tanks (which are 6.1 m tall). This distance is also ideal given that near-field emissions quantification analysis approaches work best when sensors are from 15 to 100 m from the emission source. Some wind flow distortion effects due to the pump jacks would be expected and are unavoidable during southeasterly and easterly winds. Note that emissions "downwash" due to flow distortions induced by the tanks deviate from "ideal dispersion" assumptions built into many emissions quantification methodologies. These downwash effects increase the uncertainty associated with emissions quantification analyses.

The sensors were deployed at Site 8-8 on June 19, 2018. Once the sensors were deployed, the power systems were brought online, and data feeds were established, the sensors were left operating in test mode for one night. The controlled methane release experiments (discussed in Section 2.3) were conducted the next day. After the controlled release experiments, the sensors were run autonomously for a three-week period. Sensor data capture was nearly 100%, and daily quality assurance checks confirmed that the meteorological and methane sensors were operating properly and collecting high-quality data throughout the deployment. Daily site logs were completed by site personnel to record activities and operational status at Site 8-8. The site logs indicated that all three pump jacks were operational during almost the entire deployment period, except for a 16-hour outage for one pump jack on July 6. Loads were hauled out of the production tanks every few days. The deployment concluded on July 10 and the sensor packages were removed from Site 8-8 on July 11. Post-deployment calibration checks were also conducted.

2.2 Sensor Package

2.2.1 Methane

For the detection of methane, the MIRA Pico Series portable middle infrared laser-based gas analyzer from Aeris Technologies, Inc. (Aeris) was selected. This sensor uses infrared absorption spectrometry to determine methane concentrations in real time at 1 Hz time-resolution with sub-ppb sensitivity and ppb-level accuracy. Table 1 summarizes the published specifications of this sensor. The instrument precision (uncertainty) is not published and is discussed in Section 4.5. When coupled with appropriate fast-response meteorological instruments, this methane sensor is capable of producing data for use in contexts ranging from methane monitoring and emission awareness to emissions quantifications (e.g., U.S. Environmental Protection Agency, 2014; Foster-Wittig et al., 2015; Brantley et al., 2014). For the deployment at Site 8-8, the sensor inlet height was 2 m above ground level (AGL).

Table 1. Aeris Pico Mobile methane sensor specifications.

Metric	Specification
Concentration range	0.01–10,000 ppm
Sensitivity	1 ppb/s
Accuracy	1%
Drift	20 ppb peak-to-peak (1-hr average) over full temperature range, or 1% of reading
Data rate	1 Hz
Size	11.5" x 8" x 3.75"
Weight	3 kg
Power consumption	15 W

The Aeris sensor cost was $32,000 USD. This price point provides the necessary sensitivity and accuracy that are needed for methane emission identification and quantification efforts, and is roughly half the list price of a cavity ring-down spectroscope (considered a gold standard in methane measurement). Power consumption (15 W) is an important consideration given the potential for deployment in remote locations without available line power. The laser, air pump, and on-board central processing unit are notable power draws on the sensor.

2.2.2 Ethane

Although ethane measurements were not the focus of this study, the Aeris sensors also simultaneously measure ethane concentrations at 1 Hz frequency. Ethane, and in particular, the ethane-to-methane ratio, can be used to help to distinguish methane emitted from biological, biogenic, and anthropogenic sources. Ethane is a component of crude oil and natural gas and would be co-emitted with methane at an upstream O&G facility, but microbial methane sources such as landfills, sewage, and wetlands produce little or no ethane. Therefore, correlated methane and ethane measurements are a good indicator of natural gas emissions. Measurements of methane isotopic signatures would provide more refined information about the origins of methane emissions (Lopez et al., 2017).

2.2.3 Meteorology

A meteorological instrument suite consisting of a sonic anemometer, temperature probe, and humidity probe was deployed alongside the methane sensors to collect synchronized high-time-resolution meteorological data. Wind measurements were provided by a two-dimensional sonic anemometer (MetOne, Model 50.5) at a rate of 1 Hz. A two-dimensional sonic anemometer was adequate for this study, but a three-dimensional sonic anemometer would allow for more detailed measurements of turbulent fluxes and turbulence intensity. Temperature and humidity, also at 1 Hz, were provided by Campbell Scientific temperature and humidity probes. The wind was measured at 2.7 m AGL, while the temperature and humidity were measured at 1.2 m AGL.

2.2.4 Enclosure

Figure 5 shows the layout of the instrument enclosure and power systems used for the instrumentation package deployed in this study. A pair of 19.5" x 17" x 12.5" Stahlin RJ1816 fiberglass reinforced thermoset polyester enclosures was developed. One methane sensor, a data logger, and a dual band modem were housed in one enclosure. The second methane sensor was housed in the second enclosure. One enclosure was mounted on a 3 m tripod along with meteorological sensors and power supply equipment. The second enclosure was mounted on a similar tripod containing only power supply equipment. The sensor enclosure and tripod assembly are shown in Figure 6.

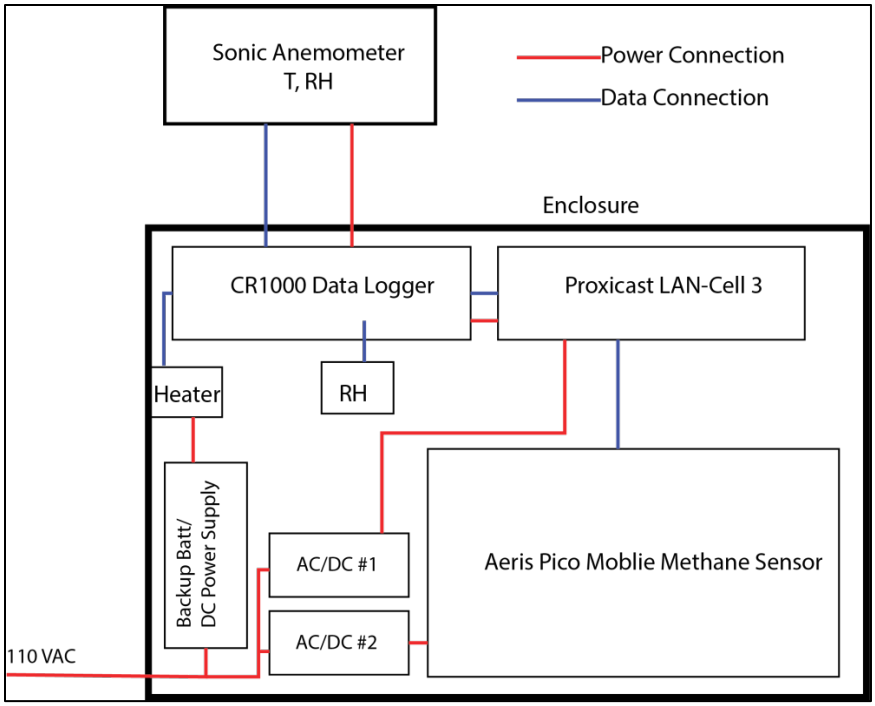

Figure 5. Physical layout and connections of the measurement and power systems. The 110 VAC refers to line power available near the pump jacks at Site 8-8.

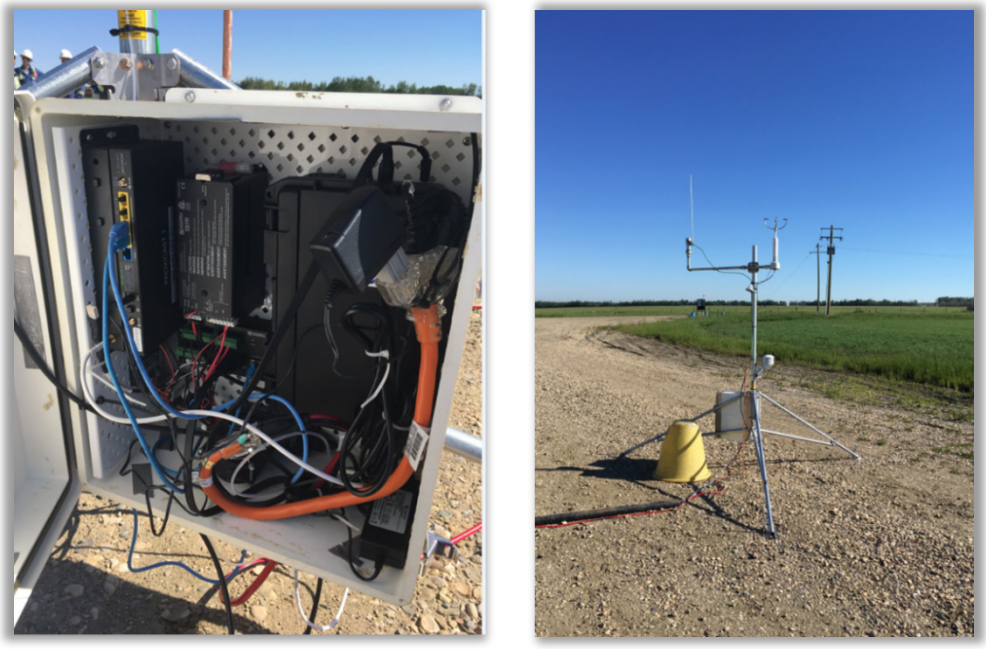

Figure 6. Sensor enclosure (left) and tripod with enclosure and meteorological instruments (right) at Site 8-8.

Since the laser and electronics in the methane sensors generate heat, maintaining an appropriate sensor temperature was an important logistical challenge; the sensor can produce unreliable results, shut down unexpectedly, or become damaged when overheated. Temperature and relative humidity were monitored both inside and outside the enclosure, and fans were installed to help dissipate heat from the enclosures as needed to keep the sensor below its specified highest operating temperature of 50ºC. Although enclosure temperatures remained below 50ºC throughout the deployment, enclosure temperatures exceeded 40ºC on several occasions when ambient temperatures approached 30ºC under full sun. After the testing and controlled release experiments on the first day, solar shields were installed to help shade the enclosures from direct sun. For a deployment during cold Canadian winters, heaters and insulation would be needed to maintain reasonable temperature within the enclosure. As an added precaution against condensation inside the enclosures, desiccant bags were used to absorb excess water vapor. The enclosures were sealed and insulated with thin reflective insulation.

2.2.5 Power

The original deployment plan included the use of deep cycle lead-acid batteries charged by solar panels. After bench testing the instruments and planning the field logistics, we determined that using line power would reduce project risk and increase the likelihood of a successful pilot project. The deployment requirements for this project were adjusted, and a site was selected that had line power. The power requirements of the instrument package would be reduced if one methane sensor was used instead of two, and there are possibly other ways to improve the efficiency of the instrument packages' power system.

The biggest concern for this methane sensor is overheating. Similar concerns may also exist for other laser-based next-generation methane sensors. If enclosure fans, insulation, and other power-efficient measures are insufficient to maintain the proper internal sensor temperature, climate control might still be needed during the hottest summer months. The sensor's internal temperature response to extreme heat and cold was not evaluated during this project.

2.2.6 Data Logging and Telemetry

Data from the east site, which included one methane sensor and the meteorological sensor package, were logged with a Campbell Scientific CR1000 data logger connected to a Proxicast LAN-Cell 3 cellular modem. A Campbell Scientific CR310 data logger was used to log data from the methane sensor at the west site. The Campbell data loggers were used to power the meteorological sensors as well as the Proxicast modem. Data was produced and logged at 1-second resolution and was polled every hour during the deployment. The data loggers were also programmed to control the enclosure fan to ensure that the enclosure remained within the operational limits of the methane sensors.

2.3 Controlled Release Experiments

Prior to the three-week deployment, on June 20, 2018, a series of 14 controlled methane releases were performed at Site 8-8 using a high pressure cylinder with 2,300 pounds of 99.9% pure methane. These experiments are summarized in Table 2. The flow of the releases were set using a calibrated mass flow controller corresponding to release rates in the range of 0.36 to 82.86 g/min, and a dispersive release system. Winds were blowing from the southeast on June 20, and therefore the methane release system was situated to the southeast and directly upwind of the methane sensors. Figure 7 shows the experiment setup at Site 8-8. The release height was 2 m AGL, and the releases were directed parallel to the ground and toward the downwind methane sensors. Each controlled release experiment was run for approximately 10-15 minutes (Tests 13 and 14 were only 5-minute releases) to ensure enough data were collected for meaningful evaluation. The experiments were facilitated by GreenPath Energy, Ltd. (GreenPath) and by AER.

Atmospheric conditions were generally ideal for the controlled release experiments. Winds were generally 3 to 6 m/s from the south and southeast directions. As the winds shifted and became more southeasterly as the day progressed, the release system was relocated accordingly to ensure the sensors remained directly downwind of the release and within the plume centerline. Using the median of methane values measured between the controlled release tests, the baseline methane value was 1.94 ppm. This is slightly higher than the globally-averaged monthly mean methane concentration[4] of 1.85 ppm determined from marine surface sites during June 2018.

[4] See https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4.

Table 2. Summary of controlled release experiments at Site 8-8. The release height was 2 m for all experiments. Flow rates in g/min were calculated from standard cubic feet per minute (SCFM) based on methane molecular weight of 16.04 g/mol and standard atmospheric conditions at 68°F and 1 atmosphere of pressure.

Test	Distance from Sensor (m)	Regulator Pressure (PSI)	Flow Rate (SCFM)	Flow Rate (g/min)	Start Time (MST)	Duration (min)
1	25	2.0	0.02	0.36	9:08 AM	15
2	25	3.0	0.47	8.88	9:39 AM	15
3	25	4.0	1.00	18.90	10:03 AM	15
4	25	5.0	1.55	29.28	10:28 AM	15
5	25	6.0	2.17	40.98	10:51 AM	15
6	25	7.0	4.39	82.86	11:14 AM	10
7	25	1.0-1.5	0.007	0.12	11:55 AM	10
8	50	1.0-1.5	0.007	0.12	12:23 PM	10
9	54	2.0	0.03	0.54	12:44 PM	10
10	54	4.0	1.25	23.58	1:02 PM	15
11	54	3.0	0.64	12.06	1:27 PM	15
12	54	2.5	0.38	7.20	1:50 PM	15
13	59	2.5	0.38	7.20	2:17 PM	5
14	59	3.5	>0.38	>7.20	2:23 PM	5

Figure 7. Controlled release experiment setup at Site 8-8.

2.4 Emissions Quantification

An emissions quantification exercise was conducted based on data collected at Site 8-8 to demonstrate how the methane sensor selected for this project could be used to support emissions quantification, and to help support recommendations on data requirements for conducting such work. The results of this analysis are presented in Section 4.2.2.

Emissions quantification encompasses the broad array of measurement, modeling, and analytical techniques that can be used to estimate emission rates based on concentration data collected downwind of emission sources. In the context of estimating methane emissions from upstream O&G facilities, the concentration data are collected within or at the perimeter of the facility, similar to the Site 8-8 deployment. Emissions quantification techniques are often coupled to dispersion models that incorporate approximated or simplified representations of atmospheric transport and diffusion. Inverse modeling refers to the use of these models to infer emission rates based on known downwind concentrations.[5] Dispersion models fall within two broad classes. Gaussian models[6] solve analytical equations to deduce time-averaged emission plume behavior, while Lagrangian (or particle-following) models use stochastic particle simulations to deduce plume behavior. Both classes

[5] Forward modeling refers to the use of dispersion models to estimate downwind concentrations from sources with known emission rates.
[6] For example, AERMOD, or other modeling models that are based on the Gaussian plume equation.

of dispersion modeling have been used to support emissions estimation from stationary ground-based monitoring platforms (Brantley et al., 2014; Flesch et al., 2005; O'Shaughnessy and Altmaier, 2011; Foster-Wittig et al., 2015; U.S. Environmental Protection Agency, 2014).

Emissions quantification techniques that couple ground-based measurements with inverse dispersion modeling rely on accurate and precise concentration measurements. Assuming that sufficiently accurate and sensitive instruments are deployed, uncertainty in characterizing plume dispersion is typically much larger than the underlying measurement uncertainty, given the inherent uncertainty in estimating the strength of turbulent mixing[7] in the dispersion models. Under ideal plume dispersion conditions and with careful data handling, the uncertainty in these techniques can range from 25% to 60% (Foster-Wittig et al., 2015; Brantley et al., 2014). Non-ideal plume dispersion conditions (e.g., stagnation conditions), and influences from complex terrain and building downwash effects present additional challenges and can increase uncertainty.

In this project, the WindTrax Lagrangian stochastic particle model (Flesch et al., 1995; 2005), version 2.0.8.8, was used to estimate emission rates from selected controlled release experiments and data collection periods at Site 8-8. The WindTrax model releases thousands of particles[8] from an emissions source and tracks the trajectories of those particles as they travel downwind. The effects of atmospheric turbulence are simulated by applying random perturbations to the three-dimensional particle motion, based on turbulence statistics derived from ambient meteorological data and a parameterization of atmospheric turbulence. The WindTrax model has been used to quantify trace gas emissions from feed lots (Flesch et al., 2005; 2007), dairies (Flesch et al., 2009), landfills (Riddick et al., 2017), and point sources (Feitz et al., 2018)

WindTrax uses a forward Lagrangian stochastic approach to estimate emission rates from point sources. Modeled particles released from the emission source contribute to the concentration at a fixed collection volume as the particles pass through the collection volume. A relationship between the emission source strength and downwind concentrations is established, and then the emission source strength is estimated based on the measured concentration. The approach used here is based on time-averaged wind and methane concentration measurements collected over the course of 15-60 minutes. Other inverse modeling approaches, such as EPA's Other Test Method 33a (U.S. Environmental Protection Agency, 2014) are designed to make additional use of 1-second resolution data to relate changes in concentration to coincident changes in wind speed and direction to characterize the emission plume.

[7] In dispersion models, turbulent mixing is often represented by dispersion coefficients that are calculated according to any of several analytical parameterizations based on atmospheric boundary layer turbulence theory.
[8] In this study, WindTrax simulations were conducted with 500,000 particles.

3. Data

3.1 Data Collection

Data from the instrument suite at Site 8-8 were stored locally on the data logger and transmitted to STI several times a day. Dual-band cellular modems were used to connect the data loggers to the internet. STI automatically pulled data every hour to its FTP servers. Once the data were uploaded, an automatic process took the data in their raw form, parsed them, applied any necessary time offset corrections, validated them, and stored them in a Microsoft SQL Server database, effectively combining all data into a single data set. The sampling line residence time was only 1 second and therefore the sample times of the methane sensor were not adjusted. Raw data were stored and backed up each day. Cellular communications were very reliable at Site 8-8, and data capture was near 100%. There were no problems with the instruments during the deployment. The parameters that were collected from Site 8-8 and that will be provided to PTAC at project conclusion are shown in Table 3.

Table 3. Summary of data collected at Site 8-8.

Sensor	Parameter	Sensitivity	Accuracy
Aeris Pico	Methane	0.001 ppmv	0.020 ppm or 1%
Aeris Pico	Ethane	1 ppbv	20 ppb or 1%
Met One 50.5 Sonic Anemometer	Wind speed	1.0 m/s	2%
Met One 50.5 Sonic Anemometer	Wind direction	1 degree	3%
Campbell Scientific HMP 60 Temp Probe	Temperature	N/A	0.1°C
Campbell Scientific HMP RH Probe	Relative humidity	N/A	5%

3.2 Data Analysis

Data at 1 Hz resolution were extracted from the data management system for subsequent analysis, and averaged to a 1-minute time resolution. Analyses and results shown in Section 4 are based on these 1-minute averaged data. Data at both 1-minute and 1-second resolution will be made available to PTAC at the conclusion of the project.

4. Results

4.1 Analysis of Methane Concentrations

4.1.1 Baseline Methane Concentration

Establishing a baseline methane concentration is critical for establishing context for methane measurements and quantifying methane emissions at an O&G facility. Methane enhancements are determined by subtracting the baseline concentration from the methane observations. The baseline can be considered a local background concentration that can vary over time and may be different from a regional, continental, or global marine background concentration.

A statistical summary of the methane data during the three-week deployment is provided in Table 4, including the average methane values from each sensor and the interquartile range. There is generally good agreement between the two sensors, although some slight differences exist. At the east site, 28% of measurements are below 2.00 ppm, while 31% of measured methane falls below this threshold at the west site. The majority of 1-minute methane data collected in this study falls between 2.00 and 3.00 ppm (64% of data at the east site, and 58% of data at the west site).

Table 4. Statistical summary for all methane (ppm) data collected during the field study period (June 20–July 11).

Parameter	East Site (ppm)	West Site (ppm)
Average methane (with standard deviation)	2.32 (0.60)	2.35 (0.66)
Minimum	1.83	1.85
Lowest 10% (baseline)	1.91	1.90
1st quartile	1.99	1.97
Median	2.12	2.13
3rd quartile	2.44	2.49
Maximum	17.3	16.6

The baseline methane concentration is the lowest concentration that is consistently observed over a reasonable period of time, when the measurement is not affected by methane sources in the immediate vicinity. A single baseline methane value for the entire study period was determined by using the lowest 10% of methane measurements. Most of the observations in this lowest 10th percentile occurred when the sensors were upwind of equipment at Site 8-8. Using the lowest 10%

cutoff, the baseline concentration was found to be 1.91 ppm at the east site, and 1.90 ppm for the west site. Baseline concentrations for the controlled release experiments were determined separately. This approach for developing the baseline concentration is reasonable, given that 27% of the 1-minute averaged observations were below 2.00 ppm, and 15% of the observations were below 1.95 ppm. The 0.01 ppm difference (about 1%) in the baseline concentration between the two sensors agrees well with the bench testing results (see Section 4.5), and further demonstrates good sensor agreement.

4.1.2 Methane Concentration Summary

A histogram of methane concentrations at the east site are shown in Figure 8, based on 1-minute averaged data. Nearly 75% of the observations were greater than 2.00 ppm, and nearly 10% were greater than 2.50 ppm. Methane concentrations were greater than 4.00 ppm for a total of 8 hours throughout the three-week deployment, and were as high as 17.3 ppm. Note that the bin sizes vary in Figure 8; the bins are smaller at lower concentrations to illustrate the significant number of lower-concentration measurements. Larger bins were used for concentrations above 2.00 ppm to give a general indication of the spread of the distribution at the higher concentrations.

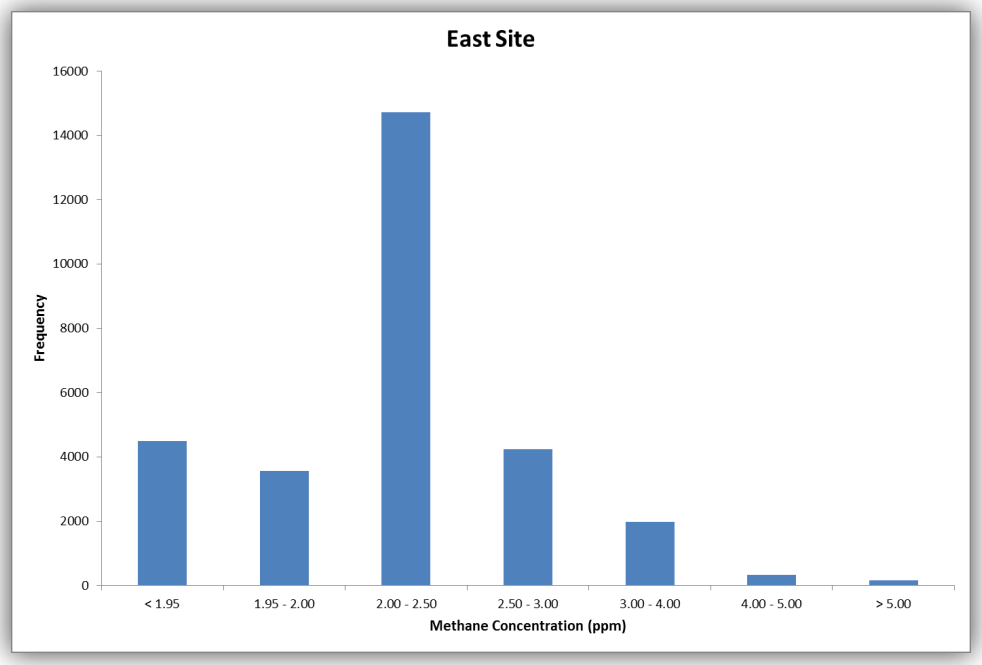

Figure 8. Histogram of methane concentrations at the east site during the Site 8-8 deployment.

Figure 9 shows time series illustrating methane values for the two sensors throughout the study period. Enhancements above baseline were observed almost every day, which suggests that there were some level of methane emissions occurring on a daily basis. A diurnal trend can be seen in the

data, with maximum daily concentrations often centered around midnight local time. This time period tends to be characterized by light winds and a shallow atmospheric boundary layer that limits the dispersion of pollutants.

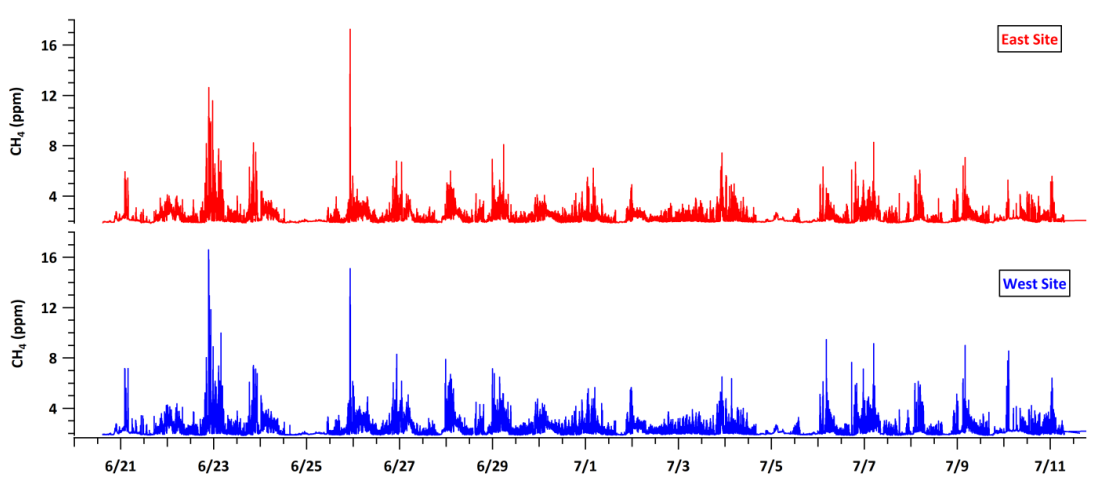

Figure 9. Time series of methane data measured from both sensors (denoted east and west) during the field study.

An analysis of the wind data at Site 8-8 shows that this cycle in methane concentrations is also related to a diurnal cycle in the winds that favors nighttime transport of emissions from the pump jack area during periods of weak southwesterly flow. The wind rose in **Figure 10** shows the most frequent wind speeds and directions observed at Site 8-8 during the study period. The frequent northwest (290 to 330 degrees) and southeast (120 to 150 degrees) winds observed at Site 8-8 are similar to the summer climatological wind patterns observed at Edmonton (see Figure 2). However, unlike at Edmonton, winds at Site 8-8 are also frequently from the southwest (240 degrees). These southwest winds tend to occur during the nighttime hours under light wind conditions, usually less than 3 m/s and often less than 1 m/s (see red colors in Figure 10). This southwesterly wind at Site 8-8 may be a nighttime drainage flow from the Canadian Rockies that impacts Site 8-8 but not Edmonton. Note that the pump jacks may influence the wind measurements somewhat during these southwesterly wind conditions. The strongest winds, at times exceeding 5 m/s, were observed from the northwest.

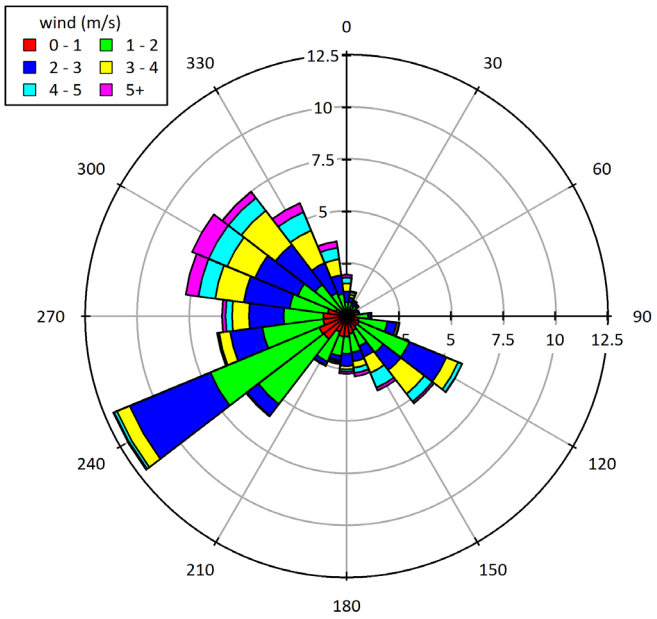

Figure 10. Wind rose showing the most frequent wind speeds and directions observed at Site 8-8 during the overall study period.

A pollution rose is a frequency distribution of wind speeds and wind directions that are color coded by pollutant concentration. Pollution roses developed from the sensor data at Site 8-8 are shown in Figure 11. When winds are from the southeast, the sensors at Site 8-8 are upwind of all potential methane sources, and methane values are therefore rarely above 2.50 ppm under those conditions. The highest methane values were observed when winds were blowing from the southwest, west, and northwest, as shown by the dark colors in Figure 11. When the winds are blowing from these directions, the methane sensors are downwind of various equipment at Site 8-8. Specifically, the sensors are downwind of the production tanks during northwest winds, and downwind of pump jacks and adjoining well shacks during southwest winds. The methane sensors were downwind of either the production tanks for the pump jacks about 50% of the time during the deployment. Based on the data, it was apparent that there were continuous (as opposed to intermittent) methane emissions from these equipment. When the sensors were downwind of the emission sources at Site 8-8, the methane concentrations were consistently above baseline levels and infrequently dropped to baseline levels for short periods of time. Based on this data, we consider this a continuous release. There were no observed increases in methane concentrations that could be uniquely correlated to specific activity that was logged at Site 8-8, such as the periodic unloading of production tanks.

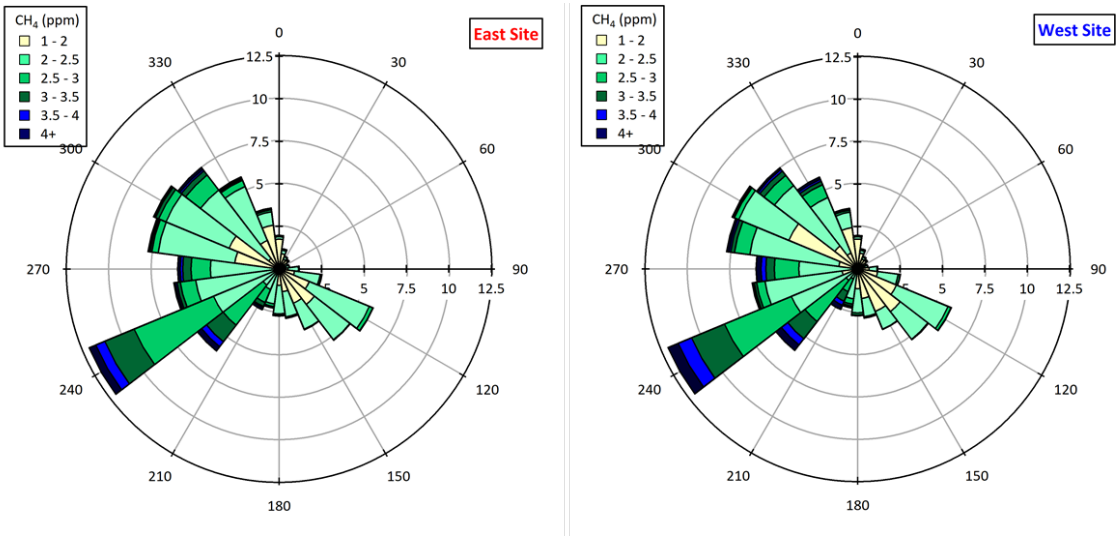

Figure 11. Pollution roses for methane at the east and west sites during the study period. The highest methane concentrations were often observed during southwesterly to northwesterly winds.

4.1.3 Weekly Analysis

Data were split into weekly bins to better highlight weekly trends in the data. For each week, wind roses and time series plots were generated. Although meteorological conditions varied somewhat from week to week, the correlations between higher methane concentrations and wind directions remained consistent. Weekly statistics are summarized in Table 5.

Table 5. Summary of weekly data collected at Site 8-8.

Parameter	Week 1 June 20 – June 27	Week 2 June 28 – July 4	Week 3 July 5 – July 11
CH_4 concentration range at east site	1.83 – 17.2 ppm	1.87 – 8.08 ppm	1.84 – 8.27 ppm
CH_4 concentration range at west site	1.85 – 16.6 ppm	1.86 – 7.88 ppm	1.85 – 9.46 ppm
Prevailing wind direction	Southwest and southeast	Northwest and southwest	Southeast
Average wind speed	2.5 m/s	2.4 m/s	1.9 m/s

Wind roses and time series plots from the first week of deployment, from June 20 (after the controlled release experiments) to June 27, are shown in Figure 12. During this first week, methane concentrations ranged from 1.83 ppm to 17.2 ppm at the east site and from 1.85 ppm to 16.6 ppm at the west site. Winds during this first week were most commonly from the southwest or southeast, with an average speed of 2.5 m/s. Some northwest winds were also observed. Methane concentrations greater than 4.00 ppm were observed only when the wind was blowing from the southwest, west, or northwest (when the sensors were downwind of equipment at Site 8-8), and these higher concentrations occurred most often during evening hours. Spikes in the time series are common between 20:00 and 04:00 local time. The lowest methane concentrations occurred when winds were from the southeast.

Data from the second week of the deployment (June 28–July 4) are shown in Figure 13. Methane concentrations ranged from 1.87 ppm to 8.08 ppm at the east site and from 1.86 ppm to 7.88 ppm at the west site. Winds were most often from the southwest or northwest, with an average wind speed of 2.4 m/s. Unlike the first week, winds from the southeast were very infrequent, and the lowest methane concentrations occurred when winds were from the north.

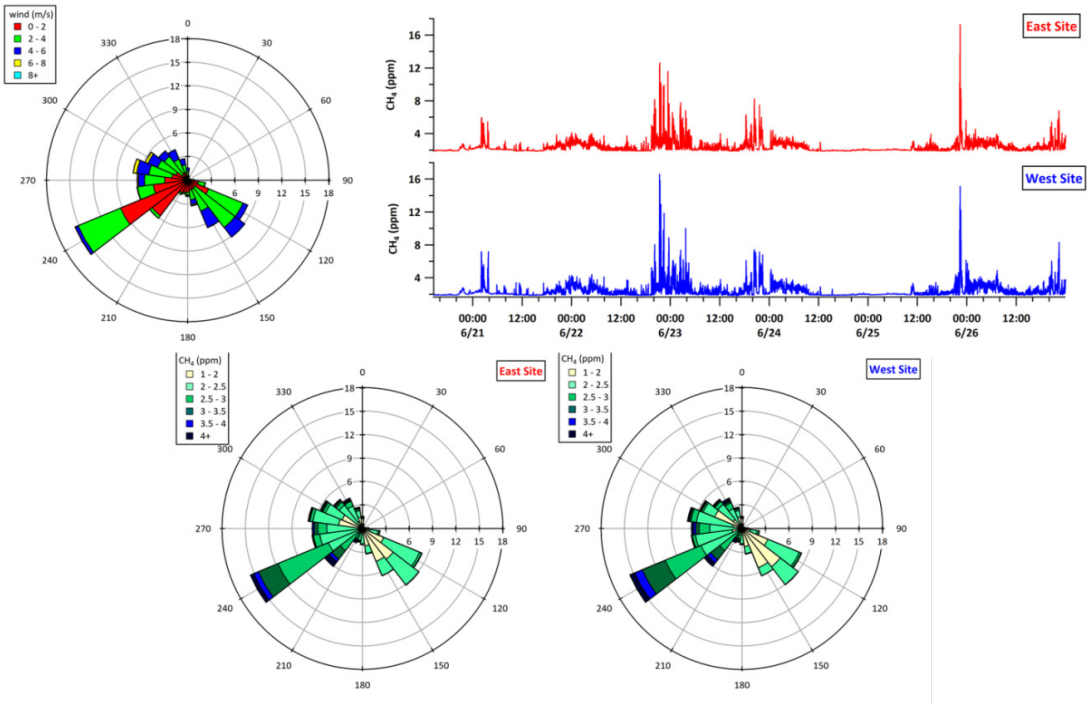

Figure 12. Wind data (top left), methane time series (top right), and methane pollution roses (bottom) from the period between the afternoon of June 20 (after controlled release experiments) and June 27.

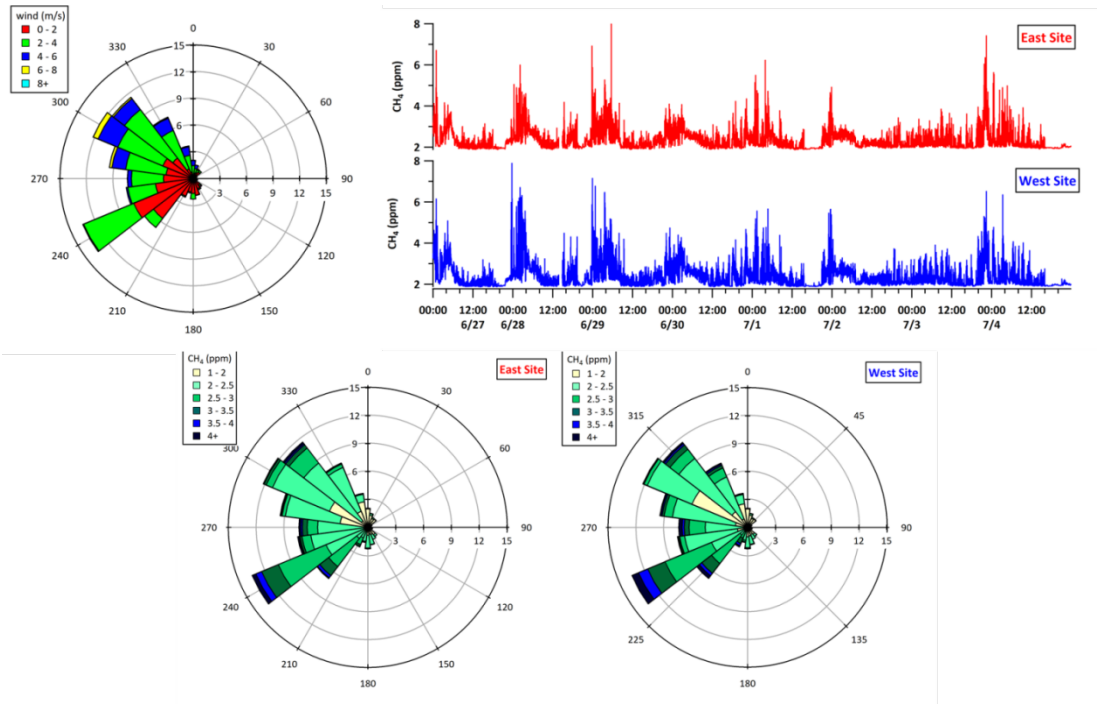

Figure 13. Wind data (top left), methane time series (top right), and methane pollution roses (bottom) for the period starting June 28 and ending on July 4.

Data from the third and final week of deployment (July 5–July 11) are shown in Figure 14. Methane concentrations ranged from 1.84 ppm to 8.27 ppm at the east site and from 1.85 ppm to 9.46 ppm at the west site. During this week, winds were most frequently from the southeast and were generally calmer than during the previous weeks, averaging 1.9 m/s. Again, the highest methane concentrations were observed when winds were from the southwest, or from the direction of the pump jacks and the adjoining equipment. The lowest methane concentrations were observed during northerly and southeasterly winds.

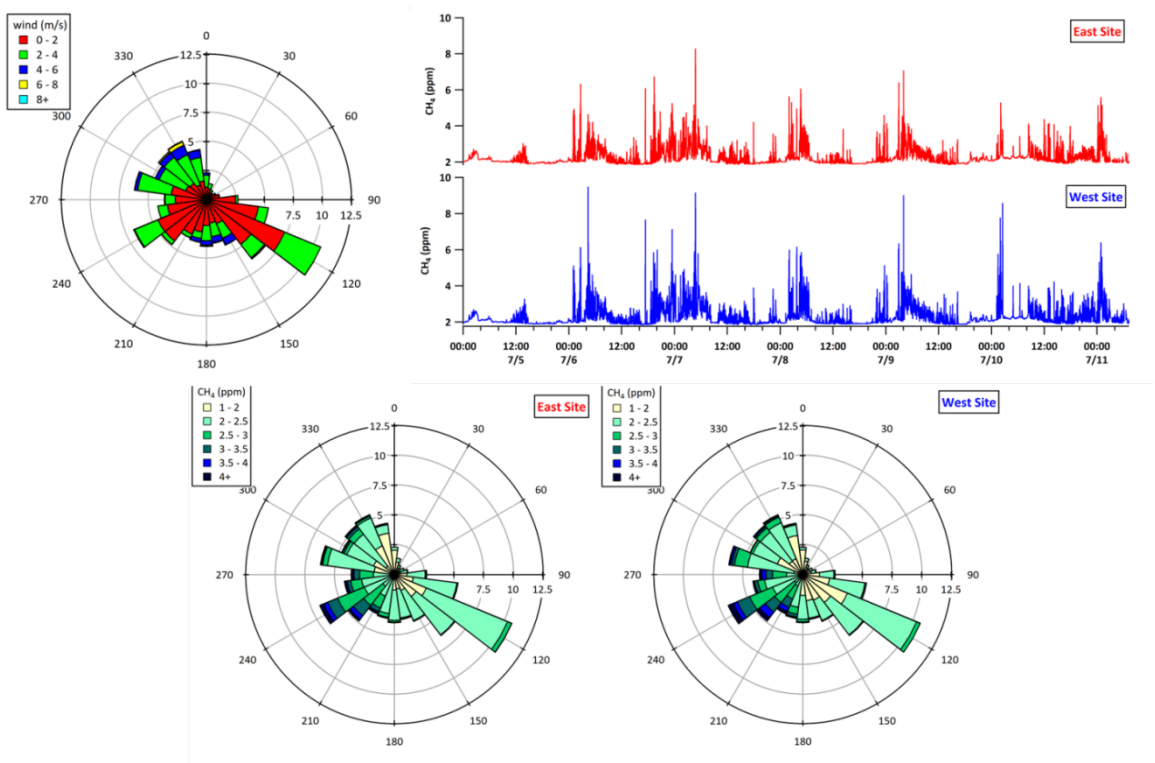

Figure 14. Wind data (top left), methane time series (top right), and methane pollution roses (bottom) during the last week of the study, between July 5 and July 11.

4.1.4 Ethane-to-Methane Ratio Analysis

Simultaneous methane and ethane concentrations from the east site during the Site 8-8 deployment are shown in Figure 15. The data points are color coded by wind direction. Baseline ethane concentrations were near 0 ppb ± 20 ppb—the high northern hemisphere ethane background concentration is around 1.5 ppb (Simpson et al., 2012)—and a significant ethane enhancement (above baseline) was apparent in a large number of observations. The ethane concentrations were generally well correlated with methane, which is an indicator of anthropogenic natural gas emissions.

Based on these correlations, there are two clear ethane-to-methane ratio signatures associated with unique and well-defined wind directions. The red dots in Figure 15 depict a lower-ethane signature associated with westerly and southwesterly winds. The pump jacks and adjoining equipment are the upwind source of this lower-ethane emission. The brown dots in Figure 15 depict a higher-ethane signature associated with northwesterly winds. The production tanks are the upwind source of this higher-ethane release.

The different ethane-to-methane ratios may be due to a vapor pressure effect. When petroleum is first pulled out of the ground, it may have more methane relative to ethane, because methane under pressure has limited opportunity to be off-gassed. As a result, emissions from the pump jacks and adjoining equipment would have lower ethane content. As the petroleum spends time above ground

under less pressure, methane off-gasses faster, leaving the product depleted in methane relative to ethane. As a result, emissions from the production tanks would have higher ethane content. The ethane-to-methane ratio of the petroleum product and any gaseous emissions can also vary across well pads within a petroleum play, and across different petroleum plays.

A third but less-defined ethane signature is apparent at higher methane concentrations with ethane concentrations of approximately 10 ppb ± 20 ppb. The emission sources associated with this third signature are unclear but are probably not from equipment at Site 8-8, since the ethane concentrations are low (no discernable enhancement from background) and the wind directions associated with this signature do not point toward equipment at Site 8-8. A minority of observations with methane greater than 2.50 ppm are associated with this third ethane signature.

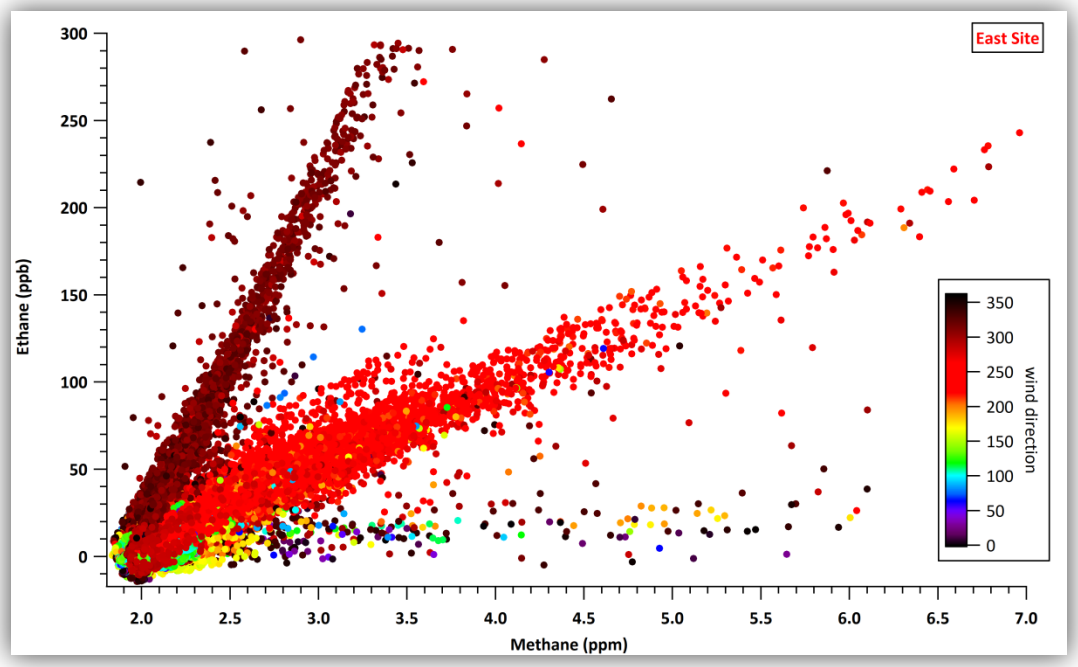

Figure 15. Methane and ethane concentrations at Site 8-8 from the east site. Data points are color coded by wind direction.

Some data points did not fall within these three ethane signatures. Possible explanations include (1) the ethane content of emissions from a particular piece of equipment was temporarily different from the typically observed ethane content; (2) the sensor measured a mix of emissions with different ethane signatures from multiple equipment; or (3) there was a short-term impact from an off-site anthropogenic methane emission source.

4.2 Controlled Release Experiments

4.2.1 Data Summary

Methane sensor data from the controlled release experiments described in Section 2.3 are summarized in Figure 16 and in Table 6. A statistical summary of data from selected releases is shown in Table 7. The time series plots in Figure 16 correspond to data from the 14 controlled releases that were conducted on June 20, 2018. Both sensors are included in the time series (Figure 16), but the east site was best aligned with the methane source during most of the controlled releases. Therefore, only data from the east site are included in Table 6 and 7.

The methane release rates ranged from 0.36 g/min to 82.86 g/min. The highest methane concentration across all experiments was 55.0 ppm during Test 6, which was considered a "super-emitter" test (82.86 g/min, 4.39 SCFM). Time-averaged concentrations during the releases were typically much smaller than the short-duration peaks. The sensors did not detect the smallest test release of 0.12 g/min at the 25 m distance (Test 7), but detected successively larger releases at that distance in Tests 1-6, including releases as small as 0.36 g/min in Test 1. At the 50-60 m distance (Tests 8-14), the sensors could only detect methane from the larger releases rates in Test 10 (23.58 g/min), Test 11 (12.06 g/min), and Test 12 (7.20 g/min). While the sensors detected the 7.20 g/min release at 54 m (Test 12), they were unable to detect similar release rates in subsequent tests at 59 m (Tests 13 and 14). Doubling the downwind distance raised the minimum detectable release rate by a factor of 200 (from 0.36 g/min to 7.20 g/min), reflecting the well-known exponential fall-off in concentrations with downwind distance from a source. The minimum emission rate that can be estimated from an inverse dispersion modeling analysis follows this same trend.

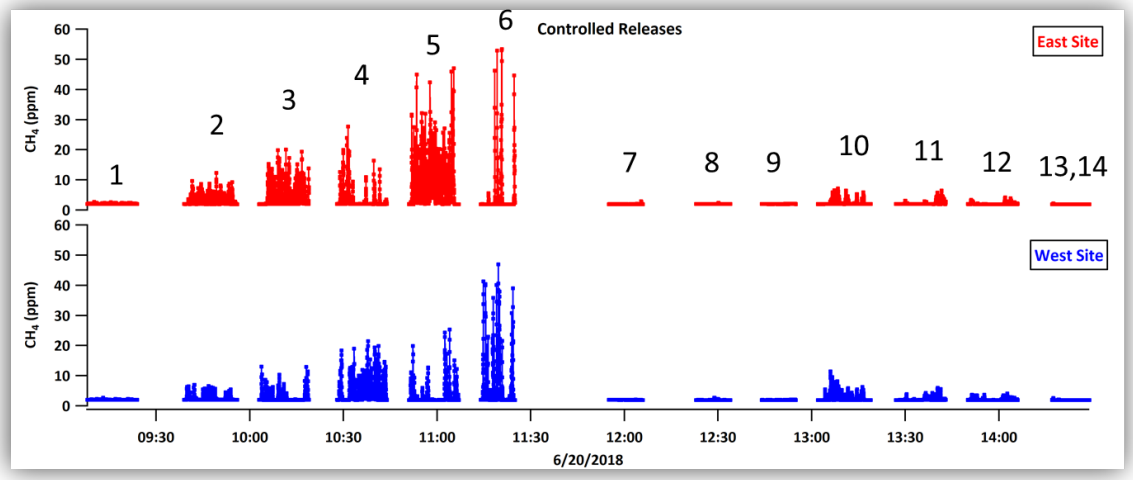

Figure 16. Methane concentrations at the east and west sites during the controlled release experiments, based on 1-second data.

Table 6. Summary of meteorology and methane data from the east site during the controlled release experiments at Site 8-8.

Test	Distance from Sensor (m)	Flow Rate (g/min)	Flow Rate (SCFM)	Wind Conditions	Temperature (°C)	Maximum methane Concentration (ppmv)
1	25	0.36	0.02	163° at 3.0 m/s	23.2	2.71
2	25	8.88	0.47	169° at 4.2 m/s	23.8	12.3
3	25	18.90	1.00	173° at 4.5 m/s	24.2	20.0
4	25	29.28	1.55	152° at 4.2 m/s	24.8	27.6
5	25	40.98	2.17	170° at 4.7 m/s	25.1	47.0
6	25	82.86	4.39	145° at 4.2 m/s	25.5	53.3
7	25	0.12	0.007	164° at 3.9 m/s	26.2	2.86
8	50	0.12	0.007	156° at 3.8 m/s	26.4	2.37
9	54	0.54	0.03	148° at 4.2 m/s	26.4	2.10
10	54	23.58	1.25	146° at 3.5 m/s	26.7	7.10
11	54	12.06	0.64	137° at 3.7 m/s	26.9	6.45
12	54	7.20	0.38	138° at 4.3 m/s	26.9	4.14
13	59	7.20	0.38	120° at 3.7 m/s	26.9	2.19
14	59	> 7.20	> 0.38	115° at 3.9 m/s	26.9	1.91

Table 7. Statistical summary of methane data (ppm) from the east site for select controlled releases on June 20, 2018, based on 1-second data.

Parameter	Test 2	Test 6	Test 10	Test 11
Time (MST)	9:39 – 9:55	11:14 – 11:24	13:02 – 13:18	13:27 – 13:42
WS (m/s), WD (°)	4.2, 169	4.2, 165	3.4, 139	3.7, 137
Average (SD)	2.94 (1.43)	3.62 (6.55)	2.31 (0.84)	2.13 (0.53)
Minimum	1.91	1.90	1.93	1.93
1st quartile	1.95	1.91	1.94	1.95
Median	2.27	1.91	1.95	1.95
3rd quartile	3.41	1.92	2.08	1.97
Maximum	12.3	53.4	7.10	6.45

4.2.2 Emissions Quantification Tests

Methane emissions quantification was conducted for the controlled release experiments based on the WindTrax particle model (see Section 2). This analysis was performed to demonstrate and test the inverse modeling approach based on methane data from the sensors, and to establish approximate error bounds for the approach. These were conducted as "blind" tests in that the actual release rates were not revealed to the data analysts until after the emissions quantification was completed.

A baseline methane concentration was determined for each release by calculating the average methane concentration measured during the time gaps between each controlled release. Winds during the controlled release experiments were generally from the south and southeast. The equipment at Site 8-8 was downwind of the sensors, and therefore these baseline concentrations were not affected by emissions from Site 8-8. Time-averaged methane (CH_4) enhancements (ΔCH_4) were determined by subtracting the baseline concentration from the time-averaged methane concentration measured during the release. Data with 1-minute averaged wind direction more than ± 30 degrees from the average wind direction were excluded. These ΔCH_4 concentrations, along with time-averaged wind and temperature data during each controlled release, were input into the WindTrax model to estimate emission rates for each release. The weather on June 20 was sunny with a light-to-moderate breeze. Therefore, the "bright sunshine" weather option was selected in WindTrax to estimate atmospheric stability conditions. The "bare soil" surface option was selected in WindTrax to characterize the ground surface (roughness length of 0.01 m). For each release, a WindTrax simulation was conducted with 500,000 particles, based on a release that was 2 m AGL, directed parallel to the ground and toward the downwind methane sensor.

Two methane sensors separated by 12 m were deployed downwind of the controlled releases. Since winds shifted during the day on June 20, this arrangement helped to increase the number of successful releases where the methane plumes were directly aligned with at least one downwind sensor. For the emission estimates, one sensor was designated as the downwind sensor for each release, based on the average wind direction measured during the release. For the morning releases (Tests 1-8), the east site was typically downwind. For the afternoon releases (Tests 9-14), winds shifted and the west site was typically downwind.

A summary of results from the controlled release emissions quantification analysis is shown in **Table 8**. The modeled emission rates were between -68% and +78% of the actual release rates, with a fractional gross error[9] of 46%. This range of uncertainty is comparable to other studies involving the stationary ground-based measurements and inverse dispersion modeling (Caulton et al., 2017), and illustrates that data from the sensors can be used to establish screening-level methane emission rates that are accurate to within a factor of two. The inverse dispersion modeling approach applied here provided the best results (modeled emission rates between -7% and +37%) during the earlier

[9] Fractional gross error is defined as $\frac{2}{N}\sum_{i=1}^{N}\left|\frac{P-O}{P+O}\right|$ where P is the predicted concentration and O is the observed concentration. Fractional gross error is reported as % and is bounded by 0% to 200%.

morning experiments, when atmospheric conditions were more conducive to ideal plume behavior. Therefore, the results from the earlier morning experiments are more indicative of the capabilities of this emissions quantification. As the day progressed, winds became more erratic as atmospheric conditions became more unstable in response to strong solar heating. As a result, the modeled emission rates compared less favorably to the actual emission rates (see Tests 5-14).

The uncertainty in the emissions quantification could likely be improved by using more stringent data filtering for wind direction and for very stable and unstable atmospheric conditions that lead to non-ideal plume behavior. The uncertainty range could also be improved with more refined analysis approaches that, for example, use turbulence statistics from the sonic anemometer to characterize the atmospheric stability parameters, or use the 1-second resolution data to relate changes in concentration to coincident changes in wind speed and direction. For example, Feitz et al. (2018) reported an uncertainty of 20% using the WindTrax forward Lagrangian stochastic approach with turbulent statistics from a 3d sonic anemometer, stringent data filtering, and data collection over multiple time periods, while Brantley et al. (2014) and Foster-Wittig et al. (2015) reported uncertainties of 25-60% using the point-source Gaussian approach (U.S. Environmental Protection Agency, 2014) with stringent data filtering.

Table 8. Summary of emissions quantification results estimated with data from the controlled release experiments at Site 8-8 on June 20, 2018. Emissions quantification was not conducted to tests where ΔCH_4 could not be distinguished from background within instrument error.

Test	Distance (m)	Sensor	Measured CH_4 (ppm)	Baseline CH_4 (ppm)	ΔCH_4 (ppm)	Measured Release (g/min)	Modeled Release (g/min)	Model Error
1	25	East	2.03 ± 0.023	1.98 ± 0.020	0.05 ± 0.030	0.38	0.33	-13%
2	25	East	3.07 ± 0.031	1.94 ± 0.019	1.13 ± 0.036	8.88	9.55	8%
3	25	East	4.83 ± 0.048	1.99 ± 0.020	2.84 ± 0.052	18.89	25.94	37%
4	25	West	4.96 ± 0.050	1.94 ± 0.019	3.02 ± 0.053	29.27	27.34	-7%
5	25	East	8.11 ± 0.081	1.92 ± 0.019	6.19 ± 0.083	40.98	72.78	78%
6	25	West	5.85 ± 0.059	1.94 ± 0.019	3.91 ± 0.062	82.91	32.83	-60%
7	25	East	1.94 ± 0.019	1.94 ± 0.019	0.00 ± 0.027	0.13	–	–
8	50	East	1.96 ± 0.020	1.94 ± 0.019	0.02 ± 0.028	0.13	–	–
9	54	West	1.93 ± 0.019	1.91 ± 0.019	0.02 ± 0.027	0.57	–	–
10	54	West	2.72 ± 0.027	1.92 ± 0.019	0.80 ± 0.033	23.61	14.43	-39%
11	54	West	2.12 ± 0.021	1.93 ± 0.019	0.19 ± 0.028	12.09	3.89	-68%
12	54	West	2.08 ± 0.028	1.91 ± 0.019	0.17 ± 0.034	7.18	3.75	-48%
13	59	West	1.93 ± 0.019	1.91 ± 0.019	0.02 ± 0.027	7.18	–	–
14	59	West	1.91 ± 0.019	1.91 ± 0.019	0.00 ± 0.027	7.18	–	–

Uncertainty in the methane concentrations shown in Table 8 was based on a measurement uncertainty of 1% determined from analysis of the field data and bench tests (see Section 4.5). The measurement uncertainty affects the minimum methane enhancement that can be reliably detected, and therefore sets the minimum emission rate that can be reliably estimated. Uncertainty of the methane measurement and baseline concentration measurement was propagated through the ΔCH_4 calculation. For the smallest releases in Tests 7 and 8, ΔCH_4 could not be distinguished within the measurement error, and therefore the emissions quantification was not reported for those releases.

As the afternoon progressed, the winds shifted toward the east-southeast. The methane release points were adjusted throughout the afternoon to accommodate for this wind shift and keep the release directed downwind of the sensors. Neither of the two sensors detected a methane enhancement (within measurement error) during the last two controlled releases (Tests 13 and 14), because the release rates were too small to be detected at the 59 m distance, or because the east-southeast winds (at 120 and 115 degrees) during those tests directed the methane plume away from the sensors. Those releases were also shorter in duration (5-7 minutes) compared to the other releases. For these reasons, inverse modeling was not conducted for Tests 13 and 14.

4.3 Emissions Quantification

The emissions quantification analysis was based on methane data collected during two targeted time periods during the Site 8-8 deployment, using the Lagrangian particle modeling approach as implemented in the WindTrax model (see Section 2). This analysis was conducted to demonstrate the potential for using the sensor data with inverse dispersion modeling approaches to quantify methane emissions from upstream O&G activities. A similar analysis conducted from the controlled release experiments (Section 4.2) established credibility and potential uncertainty associated with this approach. At the time of analysis, the emission rates were unknown. Rates for specific releases were later estimated using a Hi-Flow® Sampler, or were based on visual estimate from an OGI camera during an equipment survey conducted on June 20, 2018 (see Section 4.4).

4.3.1 Analysis Period Selection

Two time periods with persistent methane enhancements and consistent, well-behaved winds of at least 2 m/s at Site 8-8 were identified for emissions quantification. Based on the data analysis (and later confirmed from the OGI and equipment survey discussed in Section 4.4), there were methane emissions coming from the pump jacks and adjoining equipment, as well as the production tanks. Thus, one analysis time period was selected to depict emissions from each source.

Figure 17 contains a time series of methane concentrations and wind data (illustrated as wind vectors pointing toward the direction of air flow) at the east site for the two analysis periods. The top panel depicts data on June 30 from 05:00 to 06:00 local time, when the sensors were affected by

emissions from the pump jacks and adjoining equipment. Winds during this early morning period were from the southwest (235 degrees) at 3 m/s, placing the sensors directly downwind of the middle pump jack and the southernmost well shack. The average methane concentration was 2.51 ppm (or 0.60 ± 0.030 ppm above baseline).

The middle panel depicts data on July 2 from 19:15 to 20:15 local time, when the sensors were affected by emissions from the production tanks. Winds during this early evening period were from the northwest (315 degrees) at 3.0 m/s, placing the east site directly downwind of the production well shack. The average methane concentration was 2.31 ppm (or 0.40 ± 0.030 ppm above baseline), with short-term spikes as high as 3.50 ppm.

For contrast, the bottom panel of Figure 17 depicts data on June 24 from 18:00 to 19:00 local time, when the equipment at Site 8-8 was downwind of the sensor and the sensor was not affected by emissions from Site 8-8. Winds during this period were from the southeast, and the average methane concentration was near baseline levels (1.91 ppm). The methane time series is smooth with no data spikes, in contrast to the methane time series during periods when emissions were affecting the sensor. Inverse modeling was not conducted for this baseline example.

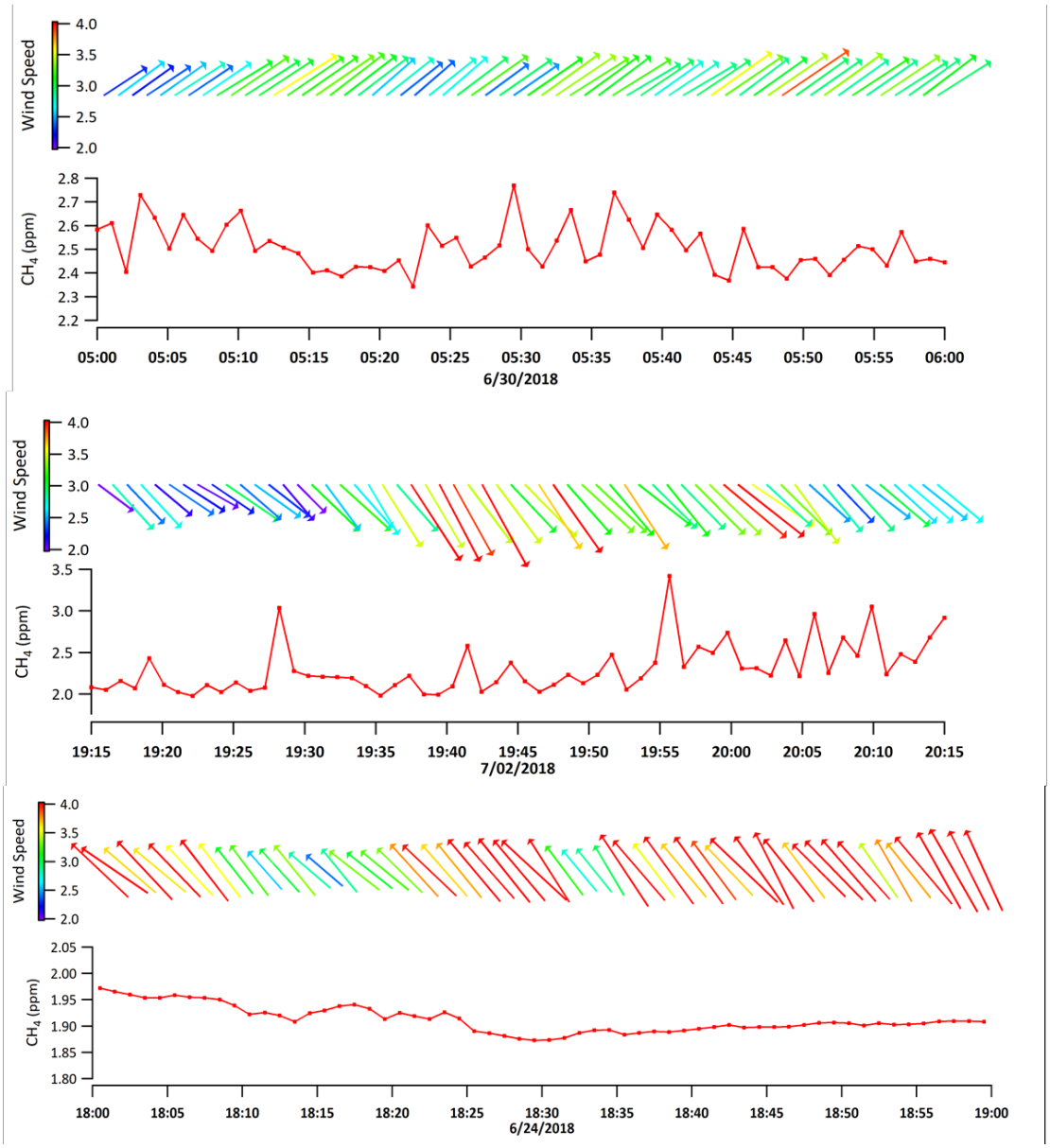

Figure 17. Methane concentrations and winds at the east site for June 30 from 05:00 to 06:00 (top panel), July 2 from 19:15 to 20:15 (middle panel), and June 24 from 18:00 to 19:00 (bottom panel).

4.3.2 Emission Rate Estimates

Data from the two analysis periods described above were used in an inverse dispersion modeling analysis to estimate emissions. The methane and meteorological data were averaged over each 1-hour analysis period, resulting in time-averaged methane emission rate estimates applicable to those specific hours. The baseline methane concentration was determined to be 1.91 ppm based on data collected throughout the three-week deployment period (see Section 4.1.1). Time-averaged

methane enhancements (ΔCH_4) were determined by subtracting the baseline concentration from the time-averaged methane concentration. These ΔCH_4 concentrations, along with time-averaged wind and temperature data during each analysis period, were input into the WindTrax model to estimate emission rates.

Because the preliminary OGI survey at Site 8-8 showed no emissions from the pump jacks, we assumed the methane emissions that were monitored from that area of the well pad were coming from the well shacks. The east site may have been impacted by emissions from multiple well shacks during this analysis period, but for modeling purposes the pump jack emissions were assumed to occur from the southernmost well shack (50 m from the east site) through a vent from the well shack at 6 ft above the ground (based on site photographs). The preliminary OGI survey showed emissions from the top of multiple production tanks. For modeling purposes, the tank emissions were assumed to occur from a single point at the middle of the tank battery (70 m from the east site) at a height of 20 feet.

Weather conditions during the June 30 analysis period (well shack emissions) were clear and cool (9.7°C and warming during the hour) with high humidity (around 85%), and therefore were classified in WindTrax as "slight sunshine" given that it was sunrise and the sun had just risen above the horizon. Weather conditions during the July 2 analysis period (tank emissions) were clear and relatively cool (11.5°C) with high humidity (around 90%), and were therefore classified in WindTrax as "slight sunshine" given that the sun was still above the horizon. As in the controlled release experiments, the "bare soil" surface option was selected in WindTrax to characterize the ground surface (roughness length of 0.01 m).

Estimated emissions rates from the well shacks and production tanks during these selected analysis periods are shown in **Table 9**. The "as found" emission rates are from the OGI and equipment survey that was conducted on June 20 (see Section 4.4), but the results from this survey were not disclosed until after the data analysis was completed. The emission rates estimated here are comparable to the release rates determined from the OGI survey. The as found emission rates are from different days, methodologies, and averaging periods and therefore are not meant to be directly comparable to the modeled estimates, but a general comparison suggests that emissions estimates are likely the correct order of magnitude. This result, in conjunction with the controlled release analysis, suggests that the methane sensors deployed here are capable of producing data that can support quantitative methane emission estimates. The emission rates calculated here are representative of the 1-hour analysis periods that were analyzed. A more robust analysis of the data from Site 8-8 would likely provide a very reasonable estimate of emission rates from field data, with reasonable uncertainty bounds. A more robust analysis would involve analyzing the 1-second resolution data (as opposed to the 1-minute averaged data that were analyzed in this study), applying a more refined data filtering approach to screen out data that were collected under less ideal dispersion conditions, and implementing a more sophisticated inverse dispersion modeling approach.

Table 9. Summary of the emissions quantification analysis conducted on two selected analysis periods at Site 8-8 on June 30 (well shack) and July 2 (production tanks). The confidence intervals for the methane data are based on 1% measurement uncertainty. A 50% confidence interval for the modeled emission rates is based on prior published literature and inverse modeling conducted for the controlled release experiments. The "as found" emission rates were reported from the June 20, 2018, OGI and equipment survey for one of the three well shacks and all of the production tanks (see Table 10).

Site 8-8 Emissions Source	Downwind Distance	Release Height	Measured CH_4 (ppm)	Baseline CH_4 (ppm)	ΔCH_4 (ppm)	Modeled Emission Rate (g/min)	"As Found" Measured Emission Rate (g/min)
Well Shack	50 m	1.8 m	2.51 ± 0.025	1.91 ± 0.019	0.60 ± 0.030	3.82 ± 1.91	4.53
Tanks	70 m	6.1 m	2.31 ± 0.031	1.91 ± 0.019	0.40 ± 0.030	12.24 ± 6.12	26.43

4.4 Optical Gas Imaging (OGI) and Equipment Survey

On June 20, GreenPath conducted a complete OGI and equipment survey at Site 8-8 to collect detailed information about fugitive methane releases at the site. The results of this survey were not disclosed until after the sensor data analysis was complete. GreenPath scanned all equipment at Site 8-8 with a FLIR camera and further characterized each detected emission source with a portable gas analyzer probe.

The survey results are shown in Table 10. This survey confirmed the releases from the storage tank battery that were identified in AER's preliminary OGI survey conducted in early 2018. On June 20, venting was observed from three of the six production tanks (see Figure 18). The three tanks with confirmed venting contained bitumen. Venting was observed through the engineered vents on the production tanks (the thief hatches were closed on all six tanks). The methane enhancements observed under northwest wind conditions were from continuous storage tank venting. The "as found" release rates from the tanks were determined based on visual estimate with the OGI camera.

Table 10. Methane emissions at Site 8-8 from the OGI and equipment survey. The g/min release was calculated assuming 100% methane, atmospheric pressure of 1013.25 mb, and ambient temperature of 293.13 K.

Equipment	Process	"As Found" Release Rate (SCFM)	"As Found" Release Rate (g/min)
Tank T2 02/01-10 (Venting)	Tankage	0.15	2.83
Tank T-2 00/01-10 (Venting)	Tankage	0.75	14.16
Tank T-2 02/08-10 (Venting)	Tankage	0.50	9.44
102/01-10 (Well shack, harnessed instrument vent)	Filter/Separation	0.21	3.97
100/01-10 (Well shack, harnessed instrument vent)	Filter/Separation	0.24	4.53
8-10 (Well shack, harnessed instrument vent)	Filter/Separation	0.19	3.59

The survey also revealed emissions from the three well shacks that stand alongside the pump jacks (see Figure 18). Since GreenPath's survey did not show emissions from the nearby pump jacks, the methane enhancements observed under southwest wind conditions were likely from the well shacks. It is unclear whether those were fugitive or venting emissions. The "as found" release rates from the well shacks were quantified with a Hi-Flow® Sampler.

Figure 18. Well shack (left) and production tanks (right) at Site 8-8 with methane emissions.

4.5 Sensor Testing

Prior to and following the sensor deployment at Site 8-8, bench testing was conducted to confirm sensor operation; verify the sensors' accuracy, precision, and drift; and support recommendations regarding data quality objectives for applying methane sensors in the field. The sensors were challenged using a series of NIST-certified standard methane gas concentrations at 5, 10, 30, and 50 ppm. These levels have been used for calibration checks in similar studies (e.g., Roscioli et al., 2015). Testing was carried out using standard gases, dilution calibrators, and zero-air generators. Sensor accuracy was determined by comparing the concentrations reported by the sensor to the standard gas concentration in each test. Conducting the same tests before and after the deployment characterizes any instrument drift that may have occurred during deployment. Ethane was not tested.

The results of this bench testing are shown in Table 11. Both methane sensors demonstrated accuracy generally within 2% of the standard gas concentrations that were tested.[10] The published instrument accuracy is 1%. Agreement between the two methane sensors was generally within 1% at the gas concentrations that were tested. Similar agreement was observed when the sensors were running site-by-side for several days at STI in ambient air, and in the field at Site 8-8. Sensor agreement is one measure of the precision or uncertainty in the measurement.

Table 11. Methane sensor pre- and post-deployment calibration test results.

Test	Standard Gas Concentration [ppm]	Sensor 100015 [ppm]	Sensor 100016 [ppm]	Accuracy 100015	Accuracy 100016	Sensor Agreement
Pre-Deployment (4/15/2018)	5.00	4.72	4.79	-5.9%	-4.2%	1.5%
	10.0	9.93	10.0	-0.7%	0.3%	1.0%
	30.0	30.4	30.7	1.3%	2.3%	1.0%
	50.0	49.6	50.1	-0.8%	0.2%	1.0%
Post-Deployment (8/6/2018)	4.98	4.90	4.88	-1.6%	-2.0%	-0.4%
	10.0	9.82	9.87	-1.8%	-1.3%	0.5%
	30.7	30.7	30.9	0.0%	0.8%	0.8%
	49.7	50.2	50.5	1.1%	1.7%	0.6%

[10] The error may have been greater for the first pre-deployment test at 5.00 ppm because the gas lines may not have been fully "conditioned" to the new gas composition. Based on the other tests, the sensor accuracy is generally within ±2%.

The methane sensor is expected to have a small drift of up to ±0.020 ppm (or 1% of reading) over the standard range of atmospheric conditions, due to thermal motion of the instrument optics.[11] No noticeable instrument drift was noted from the bench testing or field deployment data, but instrument noise of around 1% of the measurement was noted.

The instrument precision (uncertainty) establishes the minimum methane enhancement that can be reliably measured[12] and therefore places a lower bound on methane releases that can be quantified for a given distance, release height, and meteorological condition. The precision of the methane sensors was not published. One measure of precision is the standard deviation of consecutive measurements over a defined period of time with relatively constant concentrations and no influences from nearby methane emission sources. During the June 24 analysis period between 18:30 and 19:00 local time (see Figure 17), the methane concentration was at baseline levels (average of 1.90 ppm), and the standard deviation of the data was 0.01 ppm, or 0.5% of the measurement. Sensor agreement, also a measure of precision, ranged from 0.5% to 1.0% during this period. An instrument precision of 1% was therefore determined to be a conservative and reliable uncertainty estimate for the methane measurements. This level of uncertainty is very good and is sufficient for most practical field applications and emissions quantification efforts. Some studies involving inverse dispersion modeling methods exclude measurement resulting in time-averaged in-plume methane enhancements smaller than 0.10 ppm (e.g., Brantley et al., 2014) to improve the quality of the emissions rate estimate.

The recommended data quality objectives for applying methane sensors at O&G facilities depend on the intended application of the measurements. For example, the requirements for detecting anomalies in methane concentration would be less rigorous than requirements to support emissions source location and quantification or to support the identification of specific source types at an O&G facility.

[11] The near-infrared absorption lines upon which the methane measurement is made are not expected to contribute to any instrument drift.

[12] At a baseline concentration of 1.910 ppm, the minimum reliable methane enhancement would be 0.027 ppm at 1% measurement uncertainty after propagating uncertainty between two measurements (the baseline value and the measured value).

5. Conclusions and Recommendations

A three-week field study was undertaken during summer 2018 at a well pad near Drayton Valley, Alberta (Site 8-8), to demonstrate the application and utility of innovative, portable, next-generation methane sensors to characterize methane emissions from small-scale sources at upstream O&G facilities. This work helps address the AUPRF's research priorities to develop practical solutions for identifying potential methane sources and quantifying methane emissions in the field. From this pilot project, a high-quality dataset was obtained that demonstrates the capabilities of these sensors. We found the data from these sensors to be suitable to support a wide range of applications at O&G facilities; they provide useful information that can be coupled with emission quantification methods to identify emission sources and quantify emission rates at O&G facilities. These measurements also provide a benchmark upon which data quality objectives can be established for similar new and emerging methane sensor technologies.

Two Aeris Pico series methane sensors were tested and deployed during this pilot study. The sensor has sufficient data rate, accuracy, and sensitivity to support a broad range of applications at upstream O&G facilities, such as the detection and identification of methane releases, and the quantification of methane emission rates. The sensor also measures coincident ethane concentrations, and the use of ethane data to identify natural gas sources was demonstrated. Co-located meteorological measurements are critical to any methane measurement program, and these were deployed in the pilot study to provide context for the methane measurements and support data analysis. A series of controlled methane release experiments was conducted at Site 8-8 to provide additional data to evaluate and demonstrate the sensors' capabilities and limitations. Finally, data from the deployment and controlled release experiments for select periods were used to demonstrate application of an inverse dispersion modeling approach that can be used to quantify methane emissions at upstream O&G facilities. The use of multiple sensors to identify emissions from individual well shacks or production tanks at Site 8-8 was not explored in this study.

Site 8-8 is an active well pad with three pump jacks with adjoining well shacks and equipment, and a battery of six production tanks. The site was ideal for this pilot project because it had confirmed methane emissions and a layout that allowed for good instrument siting relative to the predominant winds in the regions. The site also had line power, good cell signal coverage, and good road access. Data were collected at 1-second time resolution and were averaged to 1-minute resolution for data analysis.

The conclusions and recommendations from this pilot study are outlined below.

Identification of Methane Sources

The key conclusions based on the analysis of methane and meteorological data collected at Site 8-8 are as follows.

- There were numerous instances where the methane concentrations were consistently above the local baseline concentration of 1.91 ppm, indicating continuous methane emissions from equipment at Site 8-8.
- The majority of methane data collected at Site 8-8 were between 2.00 ppm and 3.00 ppm, and nearly 10% of the data were greater than 2.50 ppm. Methane concentrations were greater than 4.00 ppm for 8 hours (1.5% of data) during the three-week deployment, and were as high as 17.3 ppm. About one-quarter of the measurements were below 2.00 ppm.
- The lowest methane concentrations were generally observed when winds were blowing from the southeast, when the sensors were upwind of the equipment at Site 8-8. Baseline methane concentrations were determined during these wind conditions, in the absence of a dedicated upwind sensor.
- Methane concentrations were correlated to a diurnal cycle in the winds that favored nighttime transport of emissions from the pump jacks and adjoining well shacks.
- Higher methane concentrations were consistently observed when winds were blowing from the west and southwest, when the sensors were downwind of the pump jacks and adjoining well shacks. Higher methane concentrations were also consistently observed when winds were blowing from the northwest, when the sensors were downwind of the production tanks. The methane sensors were downwind of either the pump jacks or the production tanks about 50% of the time during the deployment.
- Analysis of ethane data from the sensors showed that most of the enhanced methane concentrations could be traced to natural gas. Furthermore, two clear ethane-to-methane ratio signatures were identified: a lower-ethane signature traced to the pump jacks and/or adjoining well shacks, and a higher-ethane signature traced to the production tanks.
- The OGI and equipment survey confirmed methane emissions from all three well shacks and from three of the six production tanks. Emissions were observed from engineered vents on the production tanks. Emissions were observed from specific equipment inside the well shacks, but it is unclear whether those were fugitive or venting emissions.

Quantification of Methane Emissions

An inverse dispersion analysis based on the WindTrax particle model was conducted to estimate methane emissions from the well shacks and production tanks during two selected 1-hour time periods from the deployment. These emission estimates were compared to “as found” release rates that were determined by either (1) the use of a Hi-Flow® Sampler, or (2) a visual estimate from a OGI

camera during the OGI and equipment survey conducted at the beginning of the field deployment. This analysis was conducted to demonstrate the potential for using the sensor data with inverse dispersion modeling approaches to quantify methane emissions from upstream O&G activities.

The key conclusions from this analysis are as follows.

- The estimated methane emission rate from one well shack during the selected analysis period was 3.82 ± 1.91 g/min. This was comparable to the 4.53 g/min "as found" release rate measured from the OGI and equipment survey taken one month earlier.
- The estimated methane emission rate from the three production tanks with emissions during the selected analysis period was 12.24 ± 6.12 g/min. This was comparable to the 26.4 g/min "as found" release rate measured from the OGI and equipment survey taken one month earlier.
- The "as found" emission rates from the OGI survey are not meant for direct validation of the modeled emission rates, since the OGI survey used different days, methodologies, and averaging periods; however, a general (though limited) comparison, in conjunction with the uncertainty established from the controlled release experiments, suggests that the modeled emissions estimates are likely the correct order-of-magnitude and are probably accurate to within a factor of two.
- In conjunction with the emissions quantification tests conducted on the controlled release data, these results show that the sensors used in this project are capable of producing data that can support quantitative methane emission estimates.

Controlled Release Experiments

A series of 14 controlled methane release experiments were conducted at Site 8-8 to provide additional data to evaluate and demonstrate the sensors' capabilities and limitations. Data from the controlled release were also used to demonstrate and test the use of an emissions quantification method based on inverse dispersion modeling, and to develop uncertainty bounds for that approach.

Conclusions from the controlled release experiments are as follows.

- During the controlled releases, the sensors could reliably detect methane releases as small as 0.36 g/min at 25 m from the release, and 7.20 g/min at 54 m from the release. An instrument error of 1% was assumed in this determination. Larger instrument error would raise the lower limit of quantifiable detection. For example, the 0.36 g/min release at 25 m would not be detectable with a 2% instrument error.
- Emissions from five of the 14 controlled releases could not be detected. These were generally at the smaller release rates.

- Concentrations as high as 55.0 ppm were observed during the "super-emitter" test release of 82.86 g/min test at 25 m from the sensor.
- Modeled emission rates were between -68% and +78% of the actual release rates, with a fractional gross error of 46%. Therefore, a 50% confidence interval was established for the inverse dispersion modeling approach demonstrated in this project. This range of uncertainty is comparable to other studies involving the stationary ground-based measurements and inverse dispersion modeling, and illustrates that data from the methane sensors used in this study can be used to establish methane emission rates that are accurate to within a factor of two. The emissions quantification approach provided better results (modeled emission rates between -7% and +37% of the actual release rate) during the earlier morning experiments when atmospheric conditions were more conducive to ideal plume behavior; these results are more indicative of the capabilities of the emissions quantification approach used in this project.

Sensor Characterization

- Data capture from the methane sensors was very high (>99%) during the Site 8-8 deployment. Data quality was also very high, and all data collected were considered valid for analysis.
- The published accuracy of the methane sensor is 1% of the measurement, and the instrument drift is 0.020 ppm peak-to-peak, or 1% of the measurement. Bench testing showed an instrument accuracy of between 1% and 2%, and a peak-to-peak drift within the published values. The precision (uncertainty) of the sensor was not published. A precision of 1% determined from bench test results and the Site 8-8 field data is a conservative and reliable uncertainty estimate for the methane measurements. This range of measurement uncertainty is sufficient to support a broad range of applications at O&G facilities, such as the detection and identification of methane releases, and the quantification of methane emission rates.
- Sensor agreement is also a measure of instrument precision. The agreement between the two methane sensors during bench testing and in the field was very good and was within 1%. The time-averaged baseline concentrations calculated from the two sensors at Site 8-8 agreed to within 0.010 ppm (within 1 % of the measurement).

Data Quality Objectives

The recommended data quality objectives for applying methane sensors at O&G facilities depends on the intended application of the measurements. For example, the requirements for detecting methane anomalies from a facility would be less rigorous (i.e., larger precision and error could be tolerated) than the requirements needed to support emissions quantification. The data quality objectives were not formally defined prior to the pilot study, but some general objectives were used to guide the instrument selection.

Based on evaluations of data from bench testing, controlled releases, the Site 8-8 field deployment, and the emissions quantification analyses, the following recommendations can be used to guide future applications of methane sensor technology at upstream O&G facilities.

- A baseline concentration of 1.91 ppm was determined for the 3-week deployment. At this baseline concentration, the sensors can reliably detect a methane enhancement above baseline (measurement minus baseline) as small as 0.027 ppm at 1% measurement uncertainty. A measurement uncertainty of up to 4% would be sufficient to reliably detect and quantify signals greater than about 0.10 ppm above baseline. Therefore, a measurement uncertainty (precision) within about ±4% is needed to support emissions quantifications at upstream O&G facilities. Larger measurement uncertainties could be tolerated to support field objectives that involve only the identification of anomalous emissions at a facility and do not require accurate quantification.
- Meteorological instruments are critical and should always be co-located with the methane measurements. The meteorological data should at a minimum include wind speed, wind direction, temperature, relative humidity, and pressure, as all are needed to characterize and quantify methane emissions. The data capture rate should be at least equal to the methane measurements (i.e., at least 1 second). For wind measurements, a 3-D sonic anemometer is ideal, but a 2-D sonic anemometer is still preferred over cup-and-vane measurements.
- Data resolution must match the deployment objectives and analytical approaches being used. Data at 1-minute resolution was sufficient to meet the objectives of this study, but certain emission quantification techniques can use 1-second resolution data to relate changes in concentration to coincident changes in wind speed and direction to characterize emission plumes.
- To use near-field emissions quantification methods, instruments should be located within about 15 m to 100 m of potential emission sources. At closer distances, gas plumes from elevated releases may travel over the sensors. At farther distances, gas plumes may become too diluted to be characterized by the sensor. For larger O&G facilities, multiple sensors may be needed.
- Coincident ethane measurements are not critical but are helpful to confirm natural gas emission sources (as opposed to other biogenic or geologic methane sources), and differentiate between multiple emissions sources that may have unique ethane composition. To support this type of analysis, ethane measurements should have 1% accuracy, and up to 20 ppb peak-to-peak drift.

Practical Considerations

There are several other practical considerations for using Aeris sensors or sensors with similar characteristics in the field. These considerations include:

- **Cost.** Although the methane sensors deployed in this pilot project are not considered a low-cost sensor technology, we expect that the price of these and other modest-cost methane sensors will drop over time as the technology matures. These sensors are significantly less expensive than a cavity ring-down spectroscope (considered a gold standard in methane measurement) and meets data quality objectives for supporting methane emissions quantification and other measurement objectives at upstream O&G facilities. When evaluating the potential benefits of the sensor technology, additional costs associated with deployment design and execution, sensor operations and maintenance, data management, data analysis, and data delivery must also be considered.

  We evaluated several potential methane sensors for this pilot project. The cost point for the sensor selected for this project provides the necessary sensitivity and accuracy that are needed for methane emission identification and quantification efforts. At this point in time, lower-cost options sacrifice sensitivity and accuracy, and these tradeoffs must be considered in the context of the field deployment objectives.

- **Temperature control**. The biggest concern for the methane sensor was overheating. Customized enclosures were developed to shield the instrumentation from heat and maintain proper laser temperature. In cold-climate deployments, a heater would be needed. In hot-climate deployments, appropriate ventilation and possibly air conditioning would be needed. A climate-controlled shelter or carefully controlled enclosure is needed to deploy this sensor long-term.

- **Power**. The original deployment plan included the use of deep-cycle lead-acid batteries charged by solar panels. After bench testing the instruments and planning the field logistics, we determined that using line power would reduce project risk and increase the likelihood of a successful pilot project. Therefore the deployment requirements for this project were adjusted, and a site was selected that had line power.

- **Data communications and management**. The methane sensors had adequate on-board storage, but real-time measurement systems need robust communications (cellular was used in this deployment) and specialized offsite data management capability to receive and process high time-resolution (1-second) data in real-time. Appropriate data quality control measures, such as range checks, stuck value checks, etc., are also necessary.[13]

- **Calibration.** Instrument calibration is important to establish and maintain accuracy in the methane measurements. The sensor does not have a published calibration procedure. Pre- and post-deployment checks against standard gases with known concentrations were conducted in this pilot project, and are recommended for any sensor and field deployment. Longer-term deployments need periodic calibration checks to guard against long-term instrument drift. A quarterly calibration check is recommended.

[13] A range check is used to confirm that a measurement is within a realistic range of concentrations. A stuck value check is used to detect when a sensor has stopped responding appropriately to changes in concentrations.

- **Instrument issues**. The methane sensors deployed in this pilot project were relatively new to the market. We worked closely with Aeris during the testing phase of this pilot project to address various issues that were initially encountered. Working out these issues during the testing phase helped ensure that no operational issues were encountered during the Site 8-8 deployment.

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