TECHNICAL REPORT

Advanced Methane Detection and Monitoring Technologies

PTAC Project Number: 17-ARPC-01

Prepared for: Petroleum Technology Alliance Canada

Test Site Host: Encana Corporation

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Table of Contents

Executive Summary

This report presents the work performed by the BHGE-EIC (formerly known as OGTC) and GRC teams for the deployment, demonstration, and validation of BHGE methane detection and quantification technologies (currently at the latest stages of development) in the Canadian oil and gas segment.

This work was funded by Natural Resources Canada (NRCan) and administered by Petroleum Technology Alliance Canada (PTAC) with complete support and coordination with Encana Corporation including the identification of field pilot sites as well as purview of daily activities during field measurements campaigns. Project team completed nine online and in person safety training classes in BC, Canada to meet Encana's site access requirement prior to engagement in field work. Additionally, the team obtained a special flight operation certification (SFOC) for the operation of UAV System in Canadian Airspace. All test equipment were exported to Canada as part of this project and were imported back to the USA upon completion of the field testing campaigns.

The two BHGE methane detection technologies field piloted were a) Ground-based (GB or ARGUS) and b) Aerial-based (UAV or RAVEN). The field pilot took place at four Encana wellsites plus one gas compressor station near Dawson Creek, BC, Canada on two rounds of testing during August and October of 2017. The main objective was to determine whether these technologies when used to strategically scan a facility, are effective in detecting, locating and measuring methane leaks in real time.

BHGE technologies deployed were able to detect, quantify, and localize methane leaks during a series of controlled produced natural gas release experiments at the test sites. Field testing campaigns included third party verification using today's available methane detection technologies (Optical Gas Imaging and Hi Flow Sampler). All field measurement and data analysis results were reported to Encana and PTAC as Interim Report (1) and Interim Report (2). Both reports are included in the appendix.

From the successful results of this field testing, BHGE is now positioned to build on the learnings from this project to further finetune and develop these two technologies for the oil and gas industry at large and allow for enabling industry-wide reductions of methane emissions.

List of Acronyms

arpa-e	Advanced Research Projects Agency-Energy
BHGE	Baker Hughes, a GE Company
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
CSX	Cybersecurity Nexus
ECCC	Environment and Climate Change Canada
EDF	Environmental Defense Fund
EIC	Energy Innovation Center
EPA	Environmental Protection Agency
FME	Fugitive Methane Emissions
GB	Ground-Based
GHG	Greenhouse Gas
GPS	Global Positioning System
GRC-GE	Global Research Center, NY
LIDAR	Light Detection and Ranging
NRCan	Natural Resources Canada
OGI	Optical Gas Imaging
OGTC	Oil and Gas Technology Center, OK
ppm	Parts Per Million
PTAC	Petroleum Technology Alliance Canada
RAVEN	Code Name of BHGE UAV sensor technology
RGB	Red-Green-Blue (Camera)
scfm	Standard Cubic Feet Per Minute
ARGUS	Code Name of BHGE GB sensor technology
Si	Leak Source # (i = 1,2,3)
SN#	Sensor Node #
TDLAS	Tunable Diode Laser Absorption Spectrometer
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

Acknowledgment

Special thanks are given to the following individuals and companies who participated on the project and/or provided review, comments, excellent support and logistics at different times throughout the duration of the project:

Dean Jenkins	Encana Corporation
Vicrum Vaidya	Encana Corporation
Byron Sawers	Encana Corporation
Brooke Coburn	Encana Corporation
Myalee Muller	BHGE Canada
Jeanette Patel	GE Canada
Marc Godin	PTAC
Lori Mayes	PTAC
Glen Parkes	BHGE-M&S
Katy Howe	BHGE-OGTC
Sam Tanner	BHGE-OGTC
Richard St. Pierre	GE-GRC

Background

In 2011, Canadian GHG emissions for upstream oil and gas flaring, methane venting and fugitives were 34.4 million tonnes CO_2 equivalent, 65% of which were from Alberta sources. Direct methane emissions account for 89% of this amount and are primarily composed of fugitives (33%), venting (30%), and others (26%) including a number of small releases from pneumatic equipment and other process sources. Source (Overview of the GHG Emissions Inventory, Clearstone Engineering Ltd., Volume 1, March 31, 2014).

Massive resources will be required unless faster and scalable technologies are developed, demonstrated, and deployed. A bottom-up approach whereby each facility and each instrument or device is manually measured and monitored using currently available methods is extremely onerous and impractical in terms of financial and human resources. To address these challenges, BHGE collaborated with Encana with the support of NRCan and PTAC to deploy and test two innovative technologies: ground-based (GB) and unmanned aerial vehicle-based (UAV).

Objectives

This project, Advanced Methane Measurements Using Ground-based and UAV-based Sensors, is a field demonstration and validation of a methane detection and quantification system under development by BHGE for the selective, continuous, and unattended monitoring and localization of methane leaks. This project involves the use and application of BHGE's monitoring technology, related analytics tools, and applications to address knowledge gaps and evaluate technologies. BHGE partnered with Encana to gain access to a range of upstream oil and gas facility types for implementation and testing.

BHGE team tested two methane detection technologies; *Technology #1 ("ARGUS")* is a ground-based (GB) area methane monitoring system that is currently at the final development stages and is expected to be in the market by the end of 2018. It is a CSX-certified, small size wireless sensor node deployed on facilities such as well-pads and in gathering and boosting compressor stations to allow for remote, continuous detection and analytics of emissions.

Technology# 2 ("RAVEN") is an area methane measurement system using an unmanned aerial vehicle (UAV) technology that was developed by BHGE for selective detection of methane leaks. The collected data features geotagged methane concentrations output as a heat map indicating high and low concentration points at the facility, allowing for leak localization in a timely manner.

Methane Detection Technologies

Top-down and bottom-up approaches have been heavily explored over the last several years to perform methane emission detection at oil & gas facilities as a response to regulatory mandates by several regulatory agencies. A key requirement was for oil & gas operators to increase the frequency of inspections and overall Leak Detection and Repair (LDAR) programs. However, operators were faced with a dilemma in that increasing inspection frequencies would significantly increase costs and resources, as the currently utilized approaches for leak detection were time, labor, and cost-intensive. As such, several research and development programs were initiated to support industry by calling for advanced technology developers to create cost-effective solutions that could be easily deployed on-site, meet several technical requirements (such as the ability to quantify leaks, have remote connectivity, etc.), and could be deployed at-scale once commercially ready. Top-down approaches provide the ability to cover geographically dispersed assets in a short period of time (when compared with status quo approaches, such as optical gas imaging and sampling techniques). Covering large areas in shorter times ultimately results in reduced inspection costs for operators on a per site basis. On the other hand, bottom-up approaches provide accurate data at the source with a more focused coverage area and enable rigorous modeling and data analytics.

State-of-the-Art Top-Down/Bottom up Methane Emission Detection Technologies

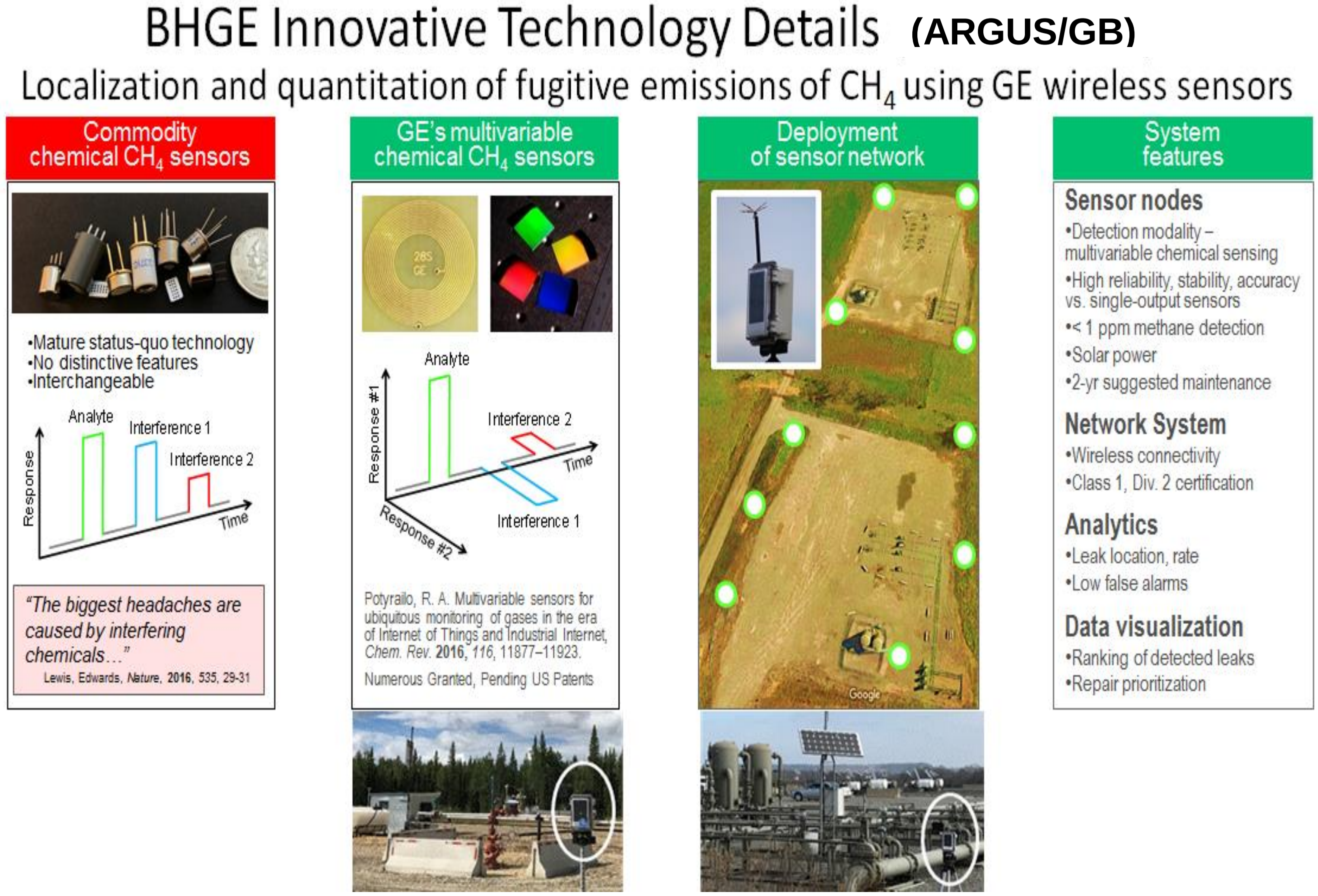
Over the past years, technology developers have been testing and developing aerial-based (top-down, or UAV) and Ground Based (bottom-up or GB) methods for methane detection. Various new projects were initiated in attempts to meet the specific technical and economic objectives laid out by the R&D programs by arpa-e and EDF. There are about 10 arpa-e MONITOR technologies under-development and more information about these technologies may be found in this link: https://www.arb.ca.gov/cc/oil-gas/Gorence_CA_Methane%20Symposium_June2016_ARPA-E.pdf

BHGE approach vs State-of-the-art of GB FME Detection (ARGUS)

ARGUS is a methane gas leak detection technology developed by GE Global Research in collaboration with BHGE and marketed now by BHGE. It is a wireless based sensor node network that provides 24/7, 360º monitoring of costly and potent GHGs. ARGUS utilizes multivariable algorithm to eliminate numerous limitations of existing sensors with the ability to quantify multiple individual gases, accurately detect gases in the presence of numerous chemical interferences, to have self-correction for temperature, and the broad range of measurements of gas concentrations. ARGUS creates a digital mesh network and continuously and remotely 'sniffs' for leaks, without the need for human intervention. If ARGUS detects the presence of a methane leak, it will alert a central control station and/or the local site team or BHGE Services. ARGUS represents a major differentiator compared to previous batch or discrete leak measurements and will lead to a more comprehensive understanding of leak source characteristics and their mitigation. From the hardware perspective, ARGUS has a sensitivity of better than 0.5 ppm which enables detection of methane at the background level with a low operation power and small unobtrusive form factor. This sensitivity is at about 1000 times better than repair threshold level of 500 ppm required by the EPA. ARGUS supports and enables compliance to U.S. EPA OOOOa Fugitive Methane Gas Leak regulations (effective June 2017). ARGUS is also expected to support and enable compliance with the 2020 ECCC regulations on methane gas leak control. Based on team observations from years of field work there could be around 40 pieces of equipment on a given well site that have the potential to leak methane gas. ARGUS safeguards production equipment and the surrounding environment with a state of the art continuous monitoring solution. With the elimination of unnecessary leakage, ARGUS ensures that production fluids are always utilized in a cost-effective manner. Utilizing the power of cloud based predictive data analytics ARGUS assesses risks and enables prevention of failures before they occur.

Key advantages of the multivariable sensing technology vs. traditional mature technologies of gas detection are described in our comprehensive 2016 report (47 pages, 513 literature references): Multivariable Sensors for Ubiquitous Monitoring of Gases in the Era of Internet of Things and Industrial Internet, Chemical Reviews 2016, 116, 11877–11923 as referenced in this link https://pubs.acs.org/doi/abs/10.1021/acs.chemrev.6b00187

Such innovations successfully compete with traditional mature technologies of gas detection, where the high sensitivity and high-resolution features of these traditional instruments are challenged by the customer demands for low-power, unobtrusive form factors, low-cost, and no-maintenance featured in this new generation of field-deployed sensors. An overview of the Argus GB technology is shown in Figure 1 below.



BHGE Innovative Technology Details **(ARGUS/GB)**

Localization and quantitation of fugitive emissions of CH_4 using GE wireless sensors

Commodity chemical CH_4 sensors

- Mature status-quo technology
- No distinctive features
- Interchangeable

"The biggest headaches are caused by interfering chemicals…"

Lewis, Edwards, *Nature*, **2016**, *535*, 29-31

GE's multivariable chemical CH_4 sensors

Potyrailo, R. A. Multivariable sensors for ubiquitous monitoring of gases in the era of Internet of Things and Industrial Internet, *Chem. Rev.* **2016**, *116*, 11877–11923.

Numerous Granted, Pending US Patents

Deployment of sensor network

System features

Sensor nodes

- Detection modality – multivariable chemical sensing
- High reliability, stability, accuracy vs. single-output sensors
- < 1 ppm methane detection
- Solar power
- 2-yr suggested maintenance

Network System

- Wireless connectivity
- Class 1, Div. 2 certification

Analytics

- Leak location, rate
- Low false alarms

Data visualization

- Ranking of detected leaks
- Repair prioritization

Figure 1. ARGUS GB Technology Used in this Project

BHGE Technology versus State-of-the-Art UAV Technologies (RAVEN)

The BHGE UAV technology utilizes available hardware components including the UAV itself coupled to BHGE-developed data analytics. One of the main development themes since the conceptual stages of this technology was to develop a system that was "hardware agnostic" and could continuously adapt to fit the best available components on the market. The laser-based methane sensor onboard the UAV (LaserMethane Mini) was originally intended to be a handheld device, but because it is an optical, open-path sensor, its measurement accuracy of ± 10% holds up to 30 meters from the source. The laser-based technology operates on the basis of infrared absorption spectroscopy, and therefore, the measurement is determined by the quantity of the laser emitted light that gets reflected back to the receiver.

Additional sensors onboard the UAV platform include: a high sensitivity infrared camera for hotspot identification, a high resolution RGB sensor (camera) for facility modeling/mapping in post-processing, and a LIDAR scanner for distance measurements from the UAV to the ground source to augment the facility modeling.

One of the key advantages of the BHGE UAV system over other state-of-the-art technologies is in the multi-mode sensing capabilities utilized for the oil & gas inspections. Fusing the data streams from various sensors onboard enables advanced analytics. For example, the geotagged HD images from the camera are utilized in a post-processing fashion to create a stitched aerial view of the facility, as the imagery from Google Earth is low-resolution and outdated in many cases. These updated facility images are used for leak localization as the geotagged concentration heatmaps are overlaid onto the facility map to pinpoint the location of the leaks. Additionally, the distance measurements from the LIDAR scanner may be used to determine the laser scanner path length from the laser sensor to the ground object. This ultimately enables higher accuracy measurements as the laser scanner alone provides no distance information, and simply takes an integrated measurement across the length of the laser.

The high sensitivity thermal camera – while not tuned to the absorption wavelength of methane – allows for the ability to potentially identify shapes and locations of gas plumes in the atmosphere, as they may have unique thermal signatures. Thermal imagery coupled with the laser sensor’s concentration data would allow for both a qualitative and quantitative understanding of the leakage under the right conditions.

While the hardware that makes up the UAV system are all off-the-shelf, the core capability of the system lies in the analytics related to the multi-sensor fusion as well as the methane inverse dispersion modeling. A proprietary process is employed to utilize the methane concentration and weather datasets in a computational fluid dynamic (CFD) simulation to estimate leak rate and leak location.

Finally, the ability to do automated reporting is another key advantage of the BHGE system, as it ultimately eliminates the need for manual backend data processing which is currently a time-intensive process. Momentarily after the conclusion of a flight, an automated report is generated with the survey results summary and 2D concentration heatmap. Within a few hours, a more thorough report with the dispersion model estimates of leak rate and location are provided to the operator. Figure 2 below highlights the workflow of the UAV technology process, from the planning stage to the reporting.

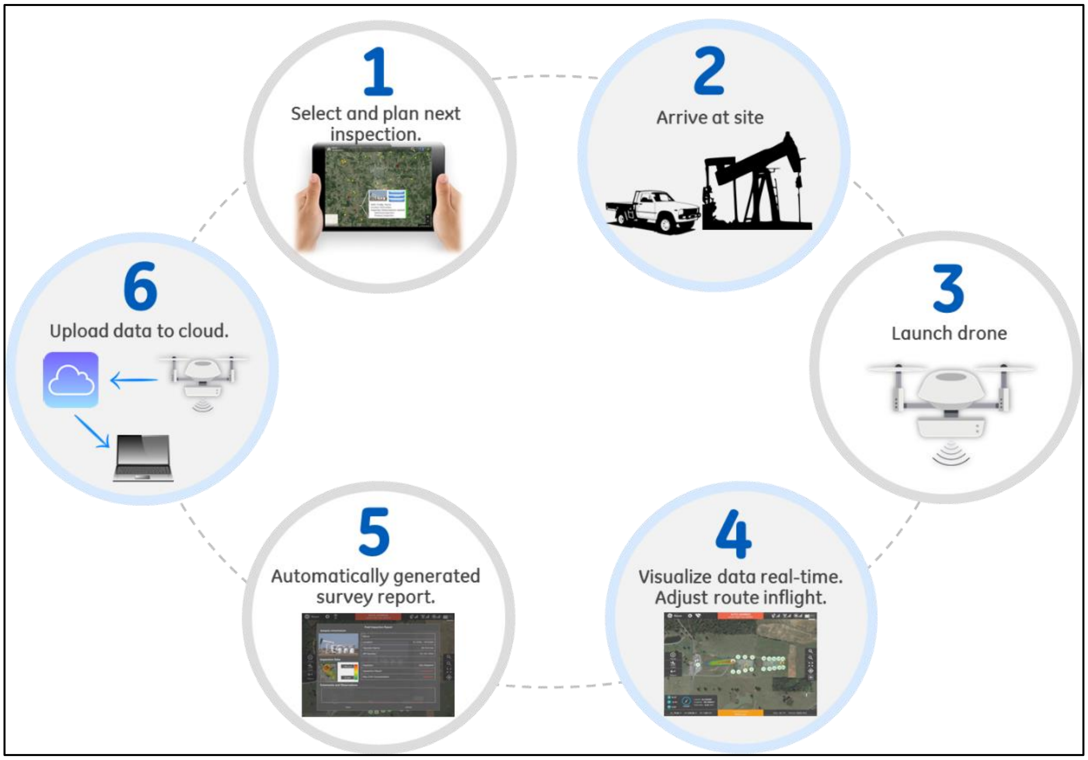


Figure 2. UAV Technology Workflow

UAV and GB methane testing platforms are shown in more detail in Appendix 1 and 2.

Test Approach

Test Locations

The goal of this study was to assess the performance of both the GB and UAV sensing approaches at multiple locations that represent different facility layouts and processes. For this reason, it was decided to perform tests at multiple production facilities and the compressor station that serves those production facilities.

During Trip 1, testing was conducted at five different sites in the Dawson Creek, BC area, including four wellsites and one compressor station. While there was little variation in the layouts from wellsite to wellsite, the production wells were under different pressures (thus providing different leak rates), and the weather conditions were noticeably different at each location, which allowed for the analysis of the effect of different present conditions on the results. For Trip 2 tests, because of the similarity of each wellsite, it was decided to perform all tests at a single wellsite for each technology, and the compressor station.

The test locations from both Trip 1 and Trip 2 are shown in the Google Earth rendering in Figure 3 below, with the Trip 1 test locations highlighted by the yellow boxes and the Trip 2 by the blue. As shown in the figure, two of the wellsites and the compressor station were tested in both rounds, while two of the yellow-box wellsites were only tested in Trip 1. Tables 1 and 2 show the link between the serial numbers in the figure with the geographical information of each site and order in which the testing occurred with both technologies.

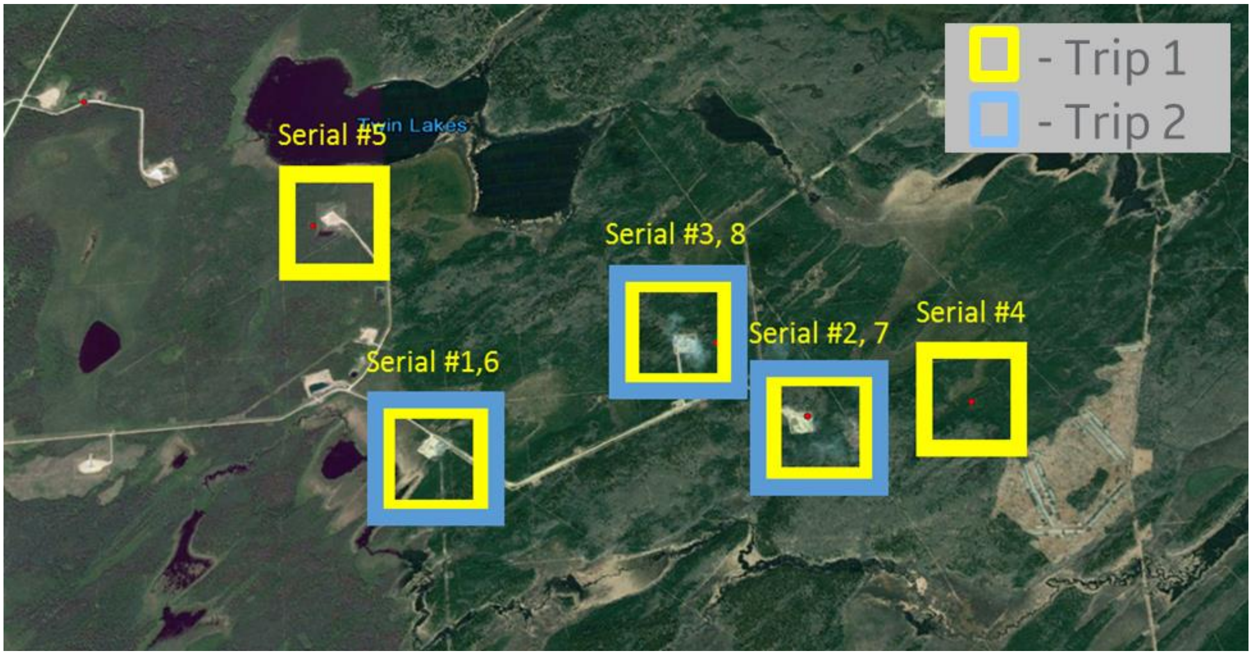


Figure 3. Trip 1 & Trip 2 Test Locations

The layouts of the four wellsites were fairly similar, with each site having similar equipment and two production wells (one of the sites had a single well on it). Figures 4 and 5 below show stitched, geo-referenced aerial images of a typical wellsite and compressor station, respectively.

Figure 4. Typical Wellsite Aerial View

Figure 5. Compressor Station Aerial View

Test Schedule

The Trip 1 tests occurred over a three-day period, from August 16 to August 18, 2017. All five UAV inspections were performed in a single day, as each flight was approximately seven minutes long. Originally, the intent was to space out the flights over a three-day period, but since the weather conditions on the first day were favorable for UAV operations, it was decided to complete all flights on the first day. In Table 1 below, the “Site Type” column shows the order in which the UAV flights were completed in Trip 1. The abbreviation “U#” indicates the order of the tests. As indicated in the table, the flights began at the compressor station and then covered the four wellsites.

The ground sensors were tested over the full three-day span, as shown in Table 1 below. The tests started at the wellsites and ended at the compressor station on the final day. Due to the time constraints, only three of the four wellsites were surveyed in Trip 1.

The Trip 2 tests occurred over a four-day period, from October 24 to October 27, 2017. As shown in Table 2 below, three of the four days were utilized for the UAV tests, and only one wellsite was surveyed in addition to the compressor station. The ground sensor tests were also conducted over a three-day span. The first test day was not utilized for the ground sensor tests because of a late start due to inclement weather.

Running all tests at a single wellsite over the period of a couple of days allowed for a significant reduction in downtime by bypassing the need to setup and tear-down the systems at each site. This ultimately allowed for thorough sensitivity analyses to be completed in the second round of testing that were not possible in the first.

Table 1: Trip 1 Test Schedule and Locations for Each Technology

Serial #	Site Name	Site Type	Site Location	Date Tested by UAV	Date Tested by GB Sensors
1	Confidential	Comp. Station (U1/G4)	Confidential	(DAY 1) 8/16/2017	(DAY 3) 8/18/2017
2		Wellsite (U4/G3)		(DAY 1) 8/16/2017	(DAY 3) 8/18/2017
3		Wellsite (U2/G2)		(DAY 1) 8/16/2017	(DAY 2) 8/17/2017
4		Wellsite (U3)		(DAY 1) 8/16/2017	(not tested)
5		Wellsite (U5/G1)		(DAY 1) 8/16/2017	(DAY 2) 8/17/2017

Table 2: Trip 2 Test Schedule and Locations for Each Technology

Serial #	Site Name	Site Type	Site Location	Date Tested by UAV	Date Tested by GB Sensors
6	Confidential	Comp. Station	Confidential	(DAY 1) 10/24/2017	(DAY 4) 10/27/2017
7		Wellsite		(DAY 2/3) 10/25/2017 10/26/2017	(not tested)
8		Wellsite		(not tested)	(DAY 2/3) 10/25/2017 10/26/2017

Reference Instruments

While both BHGE technologies tested in this study are at an advanced technology readiness level (TRL) and can currently operate in the field, they are still under-development, and thus, still under rigorous evaluation and validation. Thus, it is necessary to utilize the current best practice technologies that are proven and certified as baselines to compare BHGE's technologies/methods against. In both rounds of testing, an independent, third-party inspection company was contracted to perform inspections of all tested facilities.

Because BHGE's technologies under development are not identical to any one currently certified inspection technology, two different, approved reference instruments that would provide both leak locations and leak rates were utilized. Thus, the selection of the baseline technologies included an optical gas imaging device (OGI) to provide leak visualization and location and a Hi-Flow Sampler to provide leak rate measurements. Both inspection technologies are approved for oil & gas industrial inspections by the United States and Canadian regulatory standards.

Prior to any tests with BHGE's technologies, a baseline survey was conducted with the reference instruments. Each facility was inspected for leaks using the OGI device to scan the infrastructure to identify the presence of any existing unintended/fugitive leaks. Once identified, unintended leaks were simulated with controlled releases for testing. Prior to deployment/measurement of the leaks with BHGE's technologies, a secondary survey was conducted with the reference instruments to ensure the presence of the generated leaks. OGI was utilized a second time to confirm the presence of the generated leaks, and the Hi-Flow Sampler was used to measure leak rates.

Methodology and Test Setup

The aim of the testing in the first round was to assess the accuracy of the sensing technologies in the field under different leak scenarios and weather conditions. Surveys were conducted on a wide variety of sites that would feature a range of operational and environmental conditions. The test setup at each location was fairly similar with minimal changes in each scenario, such as altering the configuration of the ground sensors and changing UAV flight strategies to assess the changes in measurement accuracies.

In the second round, the intent was to perform all tests at a single wellsite in addition to the compressor station over several days. From the first round of tests, it was determined that operational changes from wellsite to wellsite were minor and did not warrant the constant setup and tear-down of the technologies at each location which would have resulted in reduced measurement times and less data. Additionally, staying at a single wellsite would provide for environmental changes throughout the duration of the test period (over four days). The primary goals of Trip 2 were to increase the number of data points per test with each measurement technology, and to increase the number of replicates for each test scenario to allow for a more rigorous and thorough analysis of the technologies' performance.

UAV-Based Sensing Technology

In Trip 1 tests, the UAV technology was flown once per site for a total of five flights. At each of the wellsites, a single leak was manually generated to simulate a fugitive leak at each site. An intermittent instrumentation vent was also present for all four wellsite flights. The intent of Trip 1 tests was simply to assess the UAV technology's ability to identify leak locations and leak rates at each wellsite. At the compressor station, regular operational vents were present and scattered throughout the facility. A flight was conducted to assess the baseline facility vent footprint, and no fugitive leaks were manually generated.

While the laser-based methane sensor has the ability to provide accurate measurements at distances up to 100 feet from the source, it is preferred to fly as close to the leak sources as possible while remaining at a safe distance, as the sensor takes an average concentration across the laser beam path. Therefore, the closer the laser is to the leak, the more accurate the concentration measurement. Operators generally require that the UAV flies at least 25 feet above the tallest structure for safety reasons, so at each wellsite it was determined to maintain a flight altitude of approximately 45 feet. At the compressor station, however, the tallest structure was about 45 feet high, and thus, the UAV was flown at an altitude of approximately 70 feet. Additionally, in order to ensure a sufficient density of measurement points across the flight path, the UAV was flown at an average flight speed of 10 mph. At a laser measurement frequency of 2 Hz (or two measurements per second), a flight speed of 10 mph would allow for a measurement to occur about once every 7 feet. The UAV was flown slower than 10 mph in areas closer to the leak sources to increase the measurement density even further.

One of the main advantages of the UAV-based approach is the ability to survey a large area in a shorter period of time when compared with currently used methods. This allows for an increase in the number of sites inspected per day, ultimately enabling a reduction in cost per inspection for the operator. In the Trip 1 tests, the time-savings were evident in the short flight times per site. On average, each wellsite inspection was approximately six minutes in length, whereas the compressor station inspection was slightly longer due to the increased facility footprint. As shown in Figure 6 below, the UAV was flown in a lawn mower pattern to complete at least one full pass over the asset. At flight times of 6 minutes, this allowed for over 700 measurement points to be recorded for each test. Figure 7 below represents a typical distribution of measurement points over a wellsite. As shown in Figures 6 and 7, it is necessary to plan the flight strategy such that a large portion of the measurements are taken in each direction around each of the leak sources. This is to account for present weather conditions, as wind speed and direction have a significant impact on the shape and dispersion of the gas plume in different directions. Taking measurements both on top of and around each leak source ensures that the plume is accurately measured.

While the UAV is inflight, methane concentration measurements from the laser are paired with GPS points and stored onboard the UAV, as well as the local ground station. An external weather station is placed onsite during the test to collect data on present weather conditions during the flight. In post-processing, the concentration data is time-matched with the weather data to allow for plume dispersion modeling for high-accuracy leak localization and rate estimation.

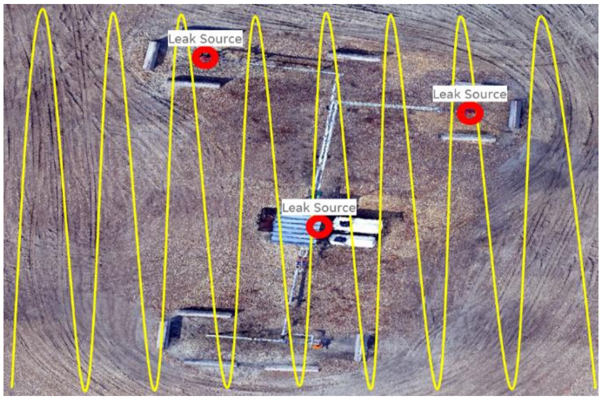


Figure 6. Typical Flight Path over Wellsite

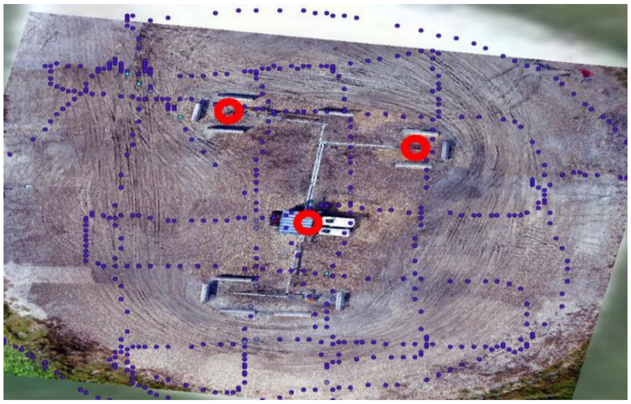


Figure 7. Actual Measurements over Wellsite

After analysis of the Trip 1 test results, it was determined that a higher density of measurement points was necessary to more accurately determine leak location and rate. As such, the flight strategy for Trip 2 was altered to increase the flight time and conduct multiple passes for each test. As shown in Figure 8 below, the number of measurement points increased significantly (when compared to Figure 7). Compared to Trip 1 tests, the flight times and number of measurements per site for Trip 2 were almost doubled, ultimately resulting in increased confidence in the output results.

In addition to increasing the flight times per site, another change in Trip 2 was the addition of replicate experiments to ensure that each test scenario had at least two to three associated datasets. This was to ensure the data quality for each experiment and to ultimately allow for a more rigorous assessment of the technology’s performance.

In Trip 2, there were three total leak sources at the wellsite, two of which were manually generated at the wellheads to simulate fugitive leaks, and one of which was an intermittent instrumentation vent (as shown in Figure 8 below). The following three leak test scenarios were considered for the full experiment, with the instrumentation vent being active for each test:

1. Only Leak Source 1 venting continuously for 10 minutes
2. Only Leak Source 2 venting continuously for 10 minutes
3. Leak Source 1 and Leak Source 2 venting continuously for 15 minutes

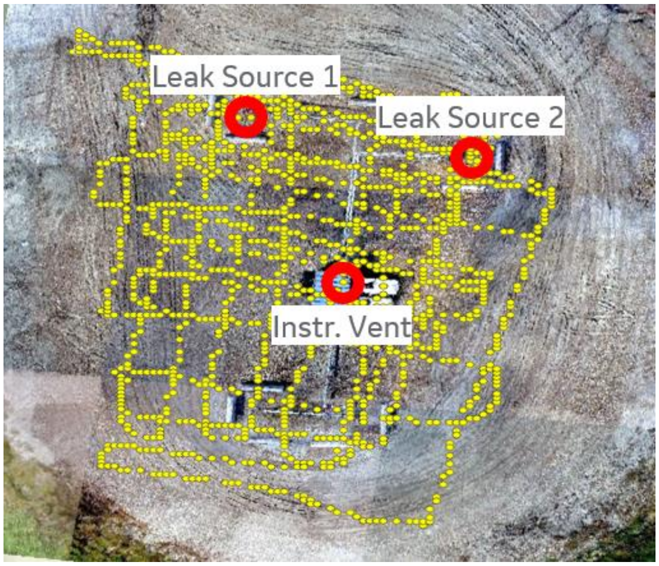


Figure 8. Trip 2 Leak Source Locations and UAV Measurement Points over Wellsite

These three test scenarios were selected as they would enable the assessment of each technology's ability to:

- determine the leak location and rate of a single fugitive leak;
- determine the leak locations and rates of two fugitive leaks;
- distinguish the leak location and rate of an operational vent;
- and distinguish between fugitive leaks and operational vents.

Ground-Based (GB) Sensing Technology

In Trip 1 tests, the GB technology was tested at three wellsites in addition to the compressor station. Similar to the UAV technology test case, leaks were manually generated at the wellheads to simulate continuous, fugitive leaks. There was also a presence of the intermittent instrumentation vent representing the normal, operational vent. Because the layout of the wellsites were similar, the variable in the tests was the configuration of the sensor network. At each wellsite, the sensors were deployed in different configurations in order to assess the effect of sensor placement on the accuracy of the model predictions. Figures 9 and 10 below show two different configurations of the sensor ("SN#") at two different wellsites relative to the leak sources ("S1/S2") and vent source. In the setup of the sensors around leak sources, the present prevailing wind direction is taken into consideration when determining the optimum configuration. The sensors were typically placed in a configuration along the direction of the wind, downstream of the leak sources to ensure that the released gas was always traveling towards the sensors.

Prior to the leak test, the ground sensors collect data for a short period of time to establish the baseline concentration levels in the area. Every facility/location has a slightly different baseline gas signature, and understanding it is key in the data processing phase, as the data collected during the gas releases must be adjusted accordingly to establish the true atmospheric concentration changes. Similar to the UAV sensing system, the ground sensor system features a weather station that continuously collects weather data throughout the period of the test. This data is fused with the concentration data to enable plume dispersion modeling in post-processing for leak localization and leak rate determination.

In the Trip 1 tests, two leak sources (S1/S2 in Figures 9 & 10 below) were simultaneously releasing gas for five to ten minutes at a time, and the instrumentation vent was intermittently leaking throughout all tests. The nine sensors collected concentration data prior to the gas releases to establish the baseline, during the release, and after closing the leak sources for a period of time to observe the dispersion of the gas from the site. This process was repeated at least three times per wellsite.

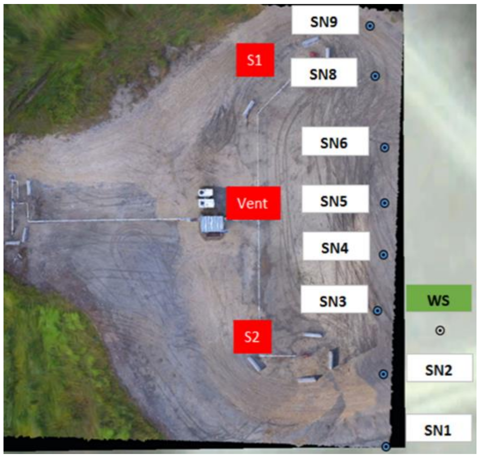


Figure 9. Straight Line Sensor Configuration Wellsite (Trip 1)

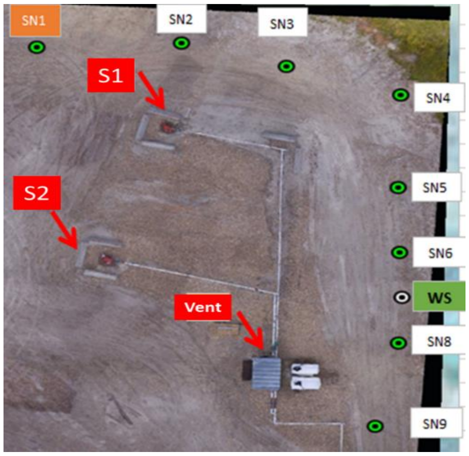


Figure 10. L-Shaped Sensor Configuration Wellsite (Trip 1)

The team also conducted a series of testing at the compressor site where sensor nodes were deployed to localize fugitive emission source(s) on the background of numerous vent sources as shown in Figure 11.

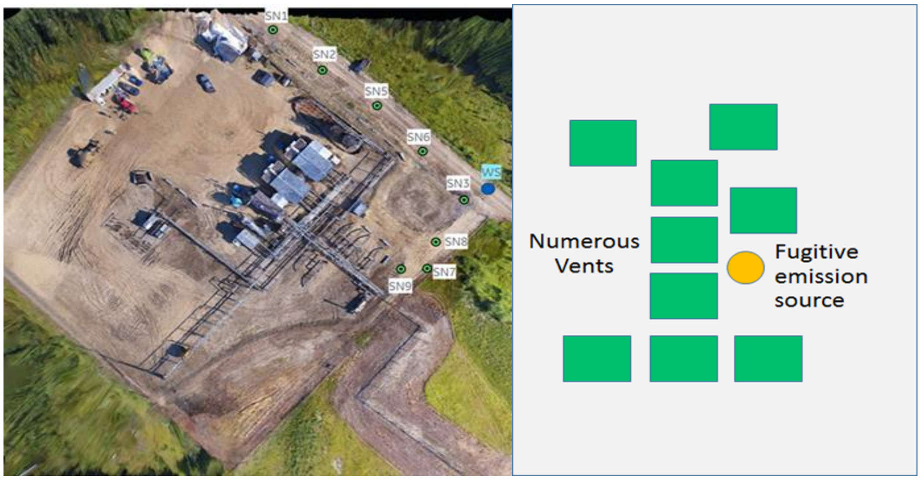


Figure 11. Sensor Configuration in Compressor Station Site (Trip 1)

Trip 2 tests were conducted in a similar fashion; the main difference was that the number of sensors were increased from 9 to 15, allowing for larger area coverage. Additionally, one of the conclusions from Trip 1 tests was that the optimum configuration of the sensors is a square/circular pattern (360°), so that the sensors are equally spaced around the perimeter of the asset. This setup ensures that the gas plume is always contained by the sensor network, and thus, the sensors will have a higher chance of capturing the concentration values regardless of the wind direction changes. The tests were run in the same manner as with the UAV technology, testing the following three leak test scenarios:

1. Only Leak Source 1 venting continuously for 10 minutes
2. Only Leak Source 2 venting continuously for 10 minutes
3. Leak Source 1 and Leak Source 2 venting continuously for 15 minutes

Figure 12 and 13 show the sensor configuration for both the wellsite and the compressor station.

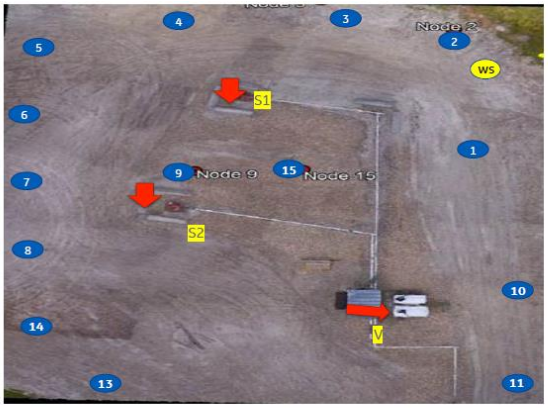


Figure 12. 360° Sensor Configuration Wellsite (Trip 2)

Figure 13. Sensor Configuration Comp. Station Site (Trip 2)

Results

UAV and GB Sensing Technologies Results

In Trip 1, for each of the 5 total flights, 2D concentration heatmaps as well as time series plots were produced, and a CFD model was run to determine the actual leak locations and leak rates on-site. The processed outputs provided several key learnings from the first round of tests, including indications that adjustments were needed in the test setup and flight operation to more accurately determine leak quantities. Prior to the Trip 1 tests, the UAV and GB technology's analytics had the ability to accurately determine the atmospheric concentrations of methane, as well as tracing the detected plumes back to the leak sources with the integration of concentration data with weather data in physics-based inverse dispersion modeling. One component of the analytics, however, that was not tested prior to the Trip 1 tests was the leak rate estimation capability on single and multiple leak sources.

Between Trips 1 and 2, development of the dispersion model continued to allow for the ability to determine leak rates in future tests. Additionally, the dispersion model was augmented to enable leak rate estimation and was tested on three different datasets. There was a noticeable improvement in the quality of the datasets in Trip 2 with simple improvements to the overall test setup and flight strategy. While the dispersion model has proven the ability to determine leak rates of a single leak source within reasonable accuracy, there are still challenges around the model's current ability to accurately determine leak rates from multiple locations.

Vented vs. Fugitive Emissions

Because the UAV technology operates by taking an instantaneous snapshot in time – as opposed to the ground sensor technology which takes continuous measurements over an extended period of time – it does not have the unique ability to distinguish between vented and fugitive emissions by assessing the time-logged concentration signatures. The UAV technology allows for the assessment of whether a leak is vented or fugitive by analyzing the location from which the gas emitted. As shown in Figure 14 below, the leak source (S1) and vent were both active throughout the test to allow for a localization assessment. As evident in the "Methane Concentration" subsection, the 2D concentration heatmaps provide strong indications of detected leaks associated back to the specific fugitive sources or the vent source.

As shown in Figure 15, there is a clear indication of the location of the detected plumes relative to the leak sources. As evident in the heatmap, there are noticeable distinctions between the fugitive leak source, "S1," and the intermittent vent, "V." Although the 2D heatmaps do not always clearly distinguish between fugitive leak sources and vents (due to prevailing wind conditions and other parameters), in this case, knowledge about the facility infrastructure will give the operator a general hypothesis. With the UAV-based technology, this is currently the only methodology at-hand to estimate whether a leak is fugitive or intentional.

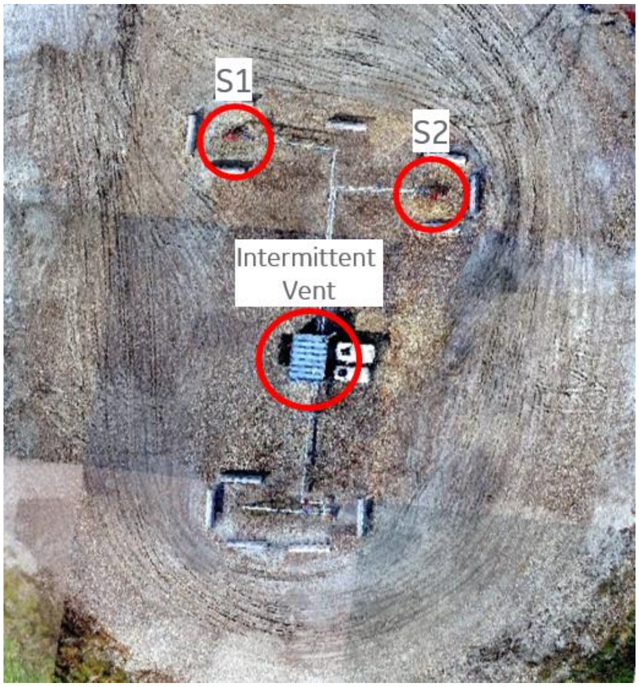


Figure 14. Leak Source Locations at Wellsite

Figure 15. Detected Plumes at Wellsite

With the GB technology the team was able to single out the anomalies in the presence of multiple vents at the compressor site. This was achieved by building numerical signatures of normal vents on site over extended periods of time, comparing the signatures of normal vents vs unknown signatures (anomalies vs. fugitive emissions) and finally determining the existence and strength of the anomalies. Figure 16 below shows the outcome of the pattern recognition method for differentiation between anomalies vs. background emissions. The data collected using Argus sensor network containing eight sensors in a weather-forecasted L-shaped formation to capture wind directions during ~140 min of duration of the test. During the first 100 min, we collected a baseline data from the site. During the next 40 min of the test, we induced three short minor “fugitive emissions” or “emission anomalies” labeled as 1, 2, and 3 in **Fig. 16d**. During the normal operation of the site, diverse independent vents produced a complicated pattern of methane emissions. Such pattern was further modulated by the wind conditions where wind direction and speed dictated the duration and levels of methane detected by each sensor. The raw responses of the deployed networked sensors over the whole 140 min of the test are depicted in **Fig. 16e** demonstrating that none of the individual sensors was able to discriminate between the vents and fugitive emissions. However, using our unsupervised pattern recognition tool we analyzed the raw sensor responses over the first 100 min of sensors data and developed a dynamic model of the normal operation of the site. We validated this model by applying it on the last 40 min of the data, correctly identifying times of all three minor fugitive methane emissions (**Fig. 16f**).

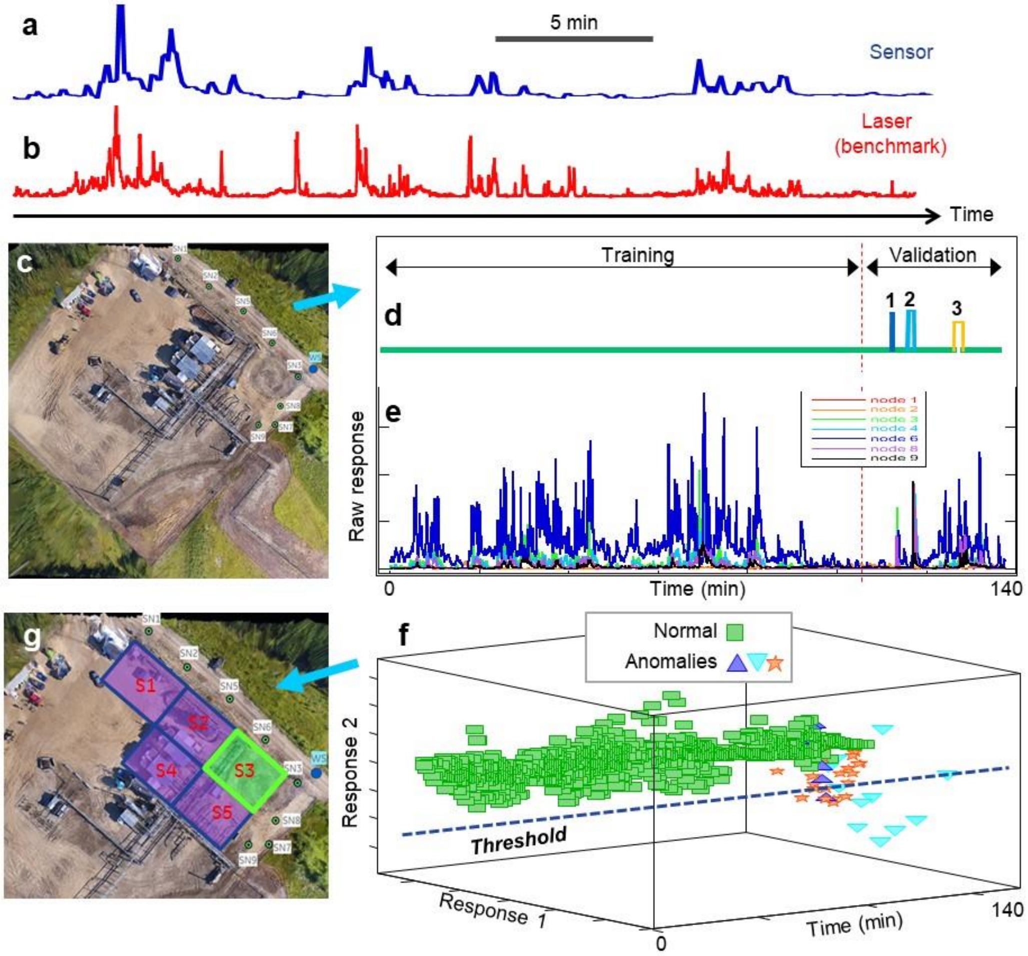


Figure 16. Data-Based Pattern Recognition Method for Signature of Normal Vents vs Anomalies

Methane Concentration

In the UAV-based technology, all measurements are in parts per million multiplied by meter (ppm*m). Because the system features an open-path laser-based methane sensor, it provides the concentration of the detected gas over the path of the laser beam. The laser accurately detects the concentration of gas present along a certain line and provides an average concentration along the laser beam path that the gas was detected.

In tests prior, the UAV technology had proven the ability to accurately measure atmospheric concentrations both in laboratory and outdoor settings. When doing leak surveys of facilities, because the laser is pointing straight to the ground, the measurement domain is limited to the flightpath of the UAV. The maximum concentration detected is heavily dependent on the location of the UAV relative to the leak source. For example, if the UAV does not fly directly over the point of leakage (due to human error in manual mode or GPS error in autonomous mode), and flies a couple of feet away, there may be a significant misrepresentation of the maximum present concentration. Therefore, the flightpath of the survey is critical in ensuring proper coverage of the leak sources and adjacent areas.

In Trip 1, this was evident in the results. Figures 17 and 18 below show the flight path of the UAV and the associated output concentration heatmaps indicating the location of the detected plumes relative to the leak sources. Figures 17 and 18 clearly highlight the difference in leak detection accuracy from a poor flightpath to a satisfactory flightpath, respectively. As shown in the Trip 2 heatmap in Figure 18, a concentration of almost   ppm-m was detected, while a concentration of only   ppm-m was detected in the Trip 1 test. Although the wind speeds for both tests were almost identical, as well as the flight altitudes (so the laser was taking a concentration average over the same distance), the concentrations detected were different by an order of magnitude. This can be attributed to the lack of sufficient coverage in Trip 1, as evident by the sparse measurement points taken across the asset. Flight paths similar to the one shown in Figure 18 were flown for the 15 wellsite flights in Trip 2, and dense measurement points consistently resulted in high concentrations detected around leak sources, as expected.

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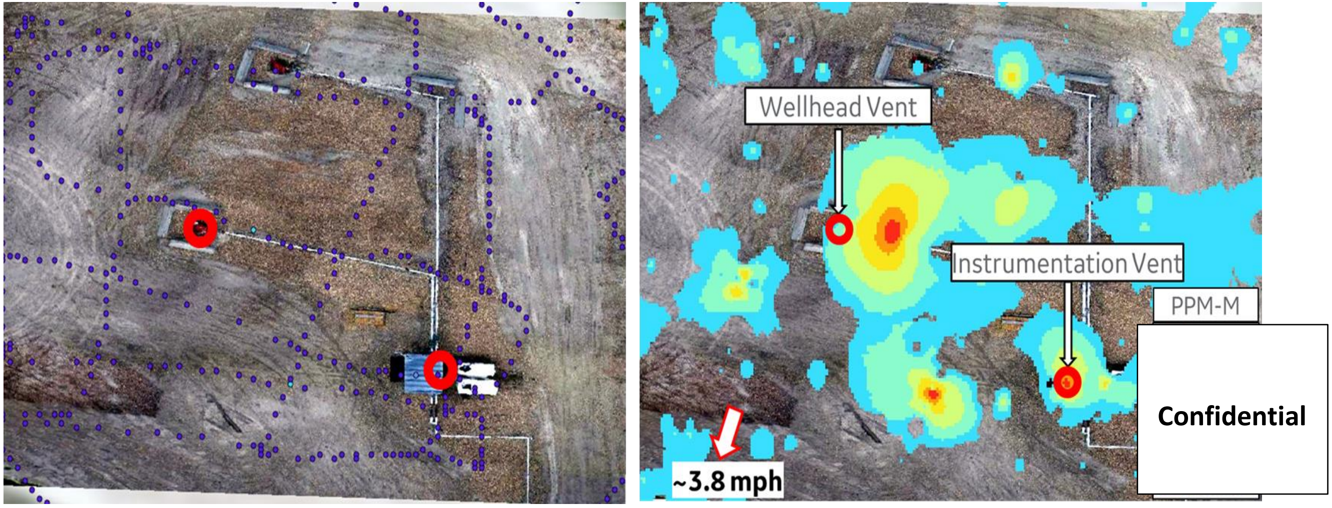

Figure 17. Trip 1 Wellsite Flight Path and Associated Concentration Heatmap

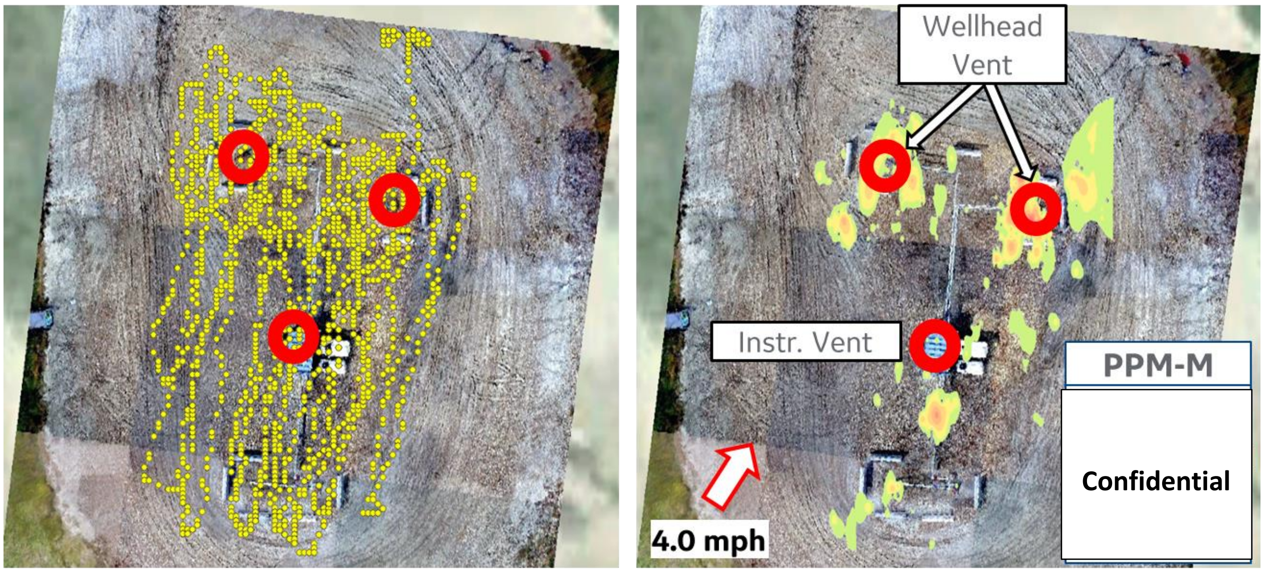

Figure 18. Trip 2 Wellsite Flight Path and Associated Concentration Heatmap

On the other hand, the GB sensors were able to continuously measure the methane concentration in ppm units over the duration of sensor deployment period as shown in Figures 19 and 20.

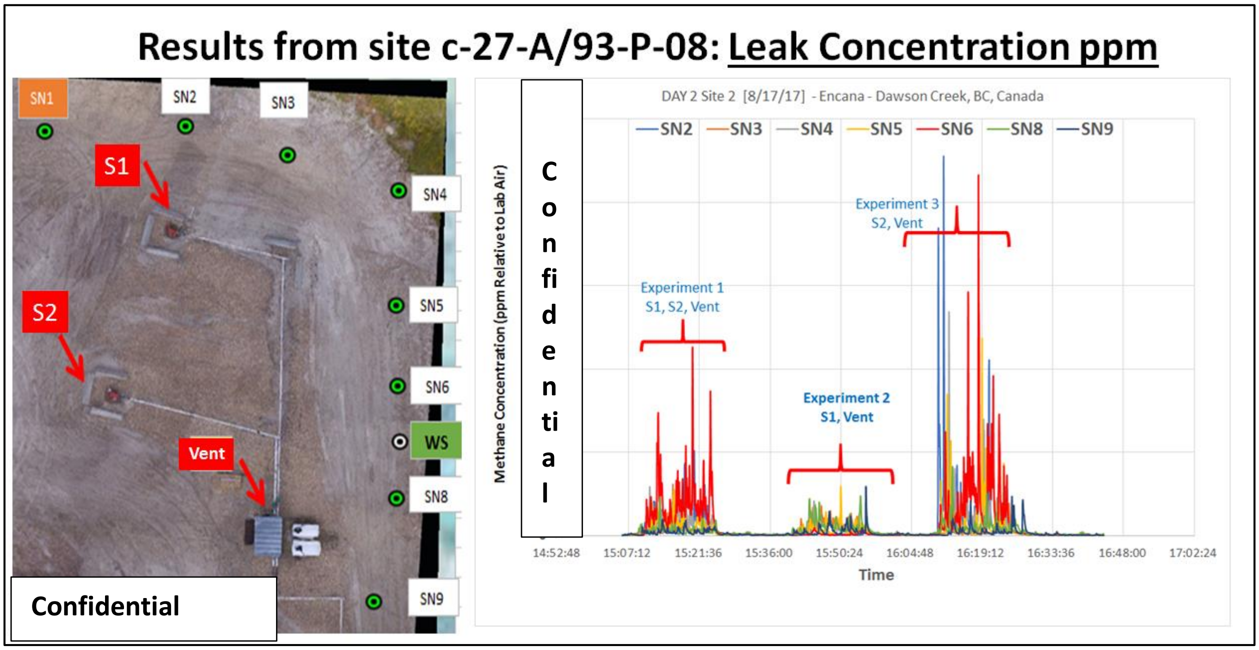

Figure 19. Trip 1 Wellsite Methane Concentration Time Series

Figure 19 shows the deployment of GB sensor network during Trip 1 containing eight sensors in a weather-forecasted L-shaped formation to capture wind directions during duration of the test. Three experiments were completed where a controlled release of methane were initiated manually for about 10 minutes followed by 10 minutes pause to allow for a sensor baseline reset. Methane concentration in ppm for each experiment were measured and charted.

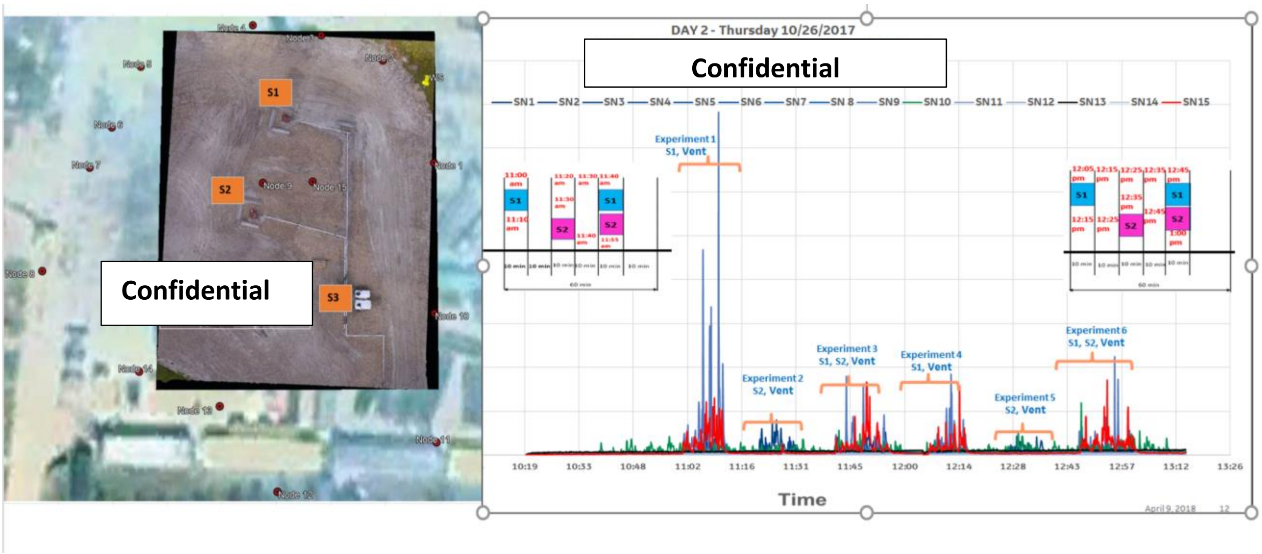

Figure 20. Trip 2 Wellsite Methane Concentration Time Series

Figure 20 shows the deployment of GB sensor network during Trip 2. This time a larger number of sensors (15 sensors) we deployed in lieu of 8 sensors in Trip 1 and in more of a circular shape to capture wind directions during duration of the test. Additionally, Six experiments were completed where a controlled release of methane were initiated manually for about 10 minutes followed by 10 minutes pause to allow for a sensor baseline reset.

Detailed concentration heat maps and time series data are shown in Appendix 1 and 2 for both technologies.

Methane Leak Rate

In Trip 2, leak rate estimation was made possible with the development of advanced inverse dispersion modeling capabilities. One of the main goals of Trip 2 was to accurately estimate the leak rates utilizing both the concentration and weather condition inputs. Within a CFD environment, a simulation of leakage was created based on the concentration and weather data inputs. For a comparison of the model results with the industry standard, all model outputs were compared against measurements taken with a Hi-Flo Sampler by an independent party. Although the dispersion model is currently in a state where it is able to estimate leak rate and location for a single leak source, an assessment was also conducted to understand the limitations around estimating these metrics for multiple leak sources.

Below, comparisons are performed between the readings of the Hi-Flow Sampler by an independent party and the calculated values from the BHGE system. Critical in these comparisons is to note that a Hi-Flow Sampler technology is manually operated and has an accepted significant variability as reported in numerous studies such as *“Touché Howard, Thomas W. Ferrara & Amy Townsend-Small (2015) Sensor transition failure in the high flow sampler: Implications for methane emission inventories of natural gas infrastructure*, Journal of the Air & Waste Management Association, 65:7, 856-862,DOI:10.1080/10962247.2015.1025925 http://dx.doi.org/10.1080/10962247.2015.1025925”

Thus, although in the discussions below we compare two methods and report the percent difference between these two methods, this comparison does not include an intrinsic variability of the Hi-Flow Sampler method that has been reported to be +/- 10% on its own.

Figure 21 below shows the 2D concentration heatmap and leaking source (S1) for the site at which the dispersion modeling leak rate estimation was conducted. For this test, S1 was leaking for approximately 10 minutes, and the leak rate was measured by the Hi-Flow Sampler prior to the UAV flights and GB sensor network deployment. On the other hand, the Hi-Flow Sampler reported a leak rate of scfm, while the dispersion model estimated a leak rate of scfm (about an difference).

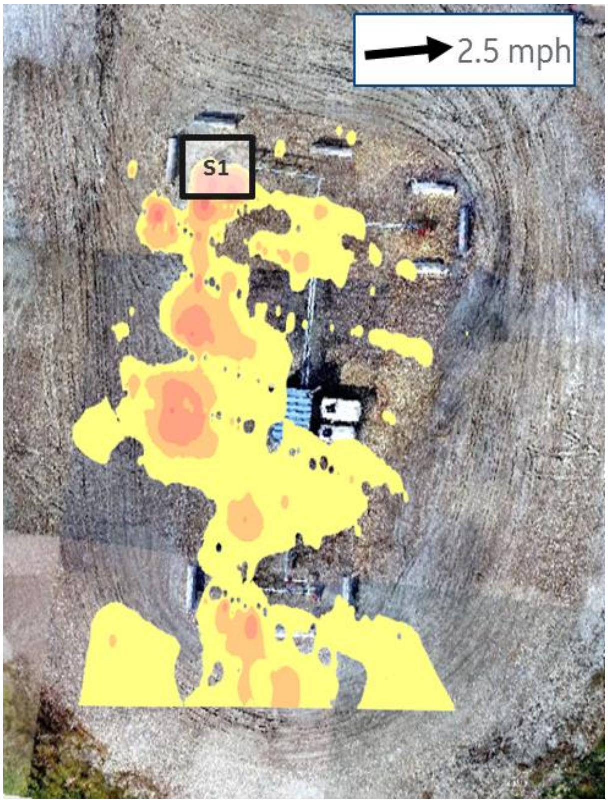

Figure 21. Single Leak Rate Location

Figure 22. Multiple Leak Source Locations

Once the ability to estimate leak rates from a single leak source was validated, the ability to estimate multiple leak rates was assessed. Figure 22 shows the location of the leak sources, with the primary fugitive leak sources indicated as S1 and S2. The intermittent vent “v” also appeared to be leaking, as shown by the heatmap, but the dispersion model was only assessed on the primary fugitive leak sources. The results from the dispersion modeling are shown below in comparison with the benchmark device. As indicated by Table 4, the percent differences for S1 and S2 are 34% and respectively. As expected, the percentage difference for the first leak source was significantly lower than that of S2. This was simply due to the fact that the model has yet to be fully calibrated to handle multiple leak sources. Refinement to the model is in-progress, and in its final state, it should be able to determine leak rates from any arbitrary number of potential leak sources.

Table 4: Multiple Leak Source Leak Rate Estimation Results

Leak Source	Hi-Flow Sampler Measurement (scfm)	Dispersion Model CFD Estimate (scfm)	Percent Difference
S1	Confidential		
S2			

While the percentage differences of leak rate estimations are relatively large, the ability to estimate leak rate from concentration and wind data is a relatively new analytic capability, and further refinement of the model and assessment of other input parameters is currently in-progress in order to more closely align with the benchmark results. Additionally, the accuracy of the Hi-Flow Sampler measurements is another factor in this comparison. While it is the agreed upon industry standard leak rate measurement device, there exists a significant discrepancy between the outputs of this device when compared with highly accurate gas flow controllers in laboratory tests. Additional assessments will be conducted to determine the accuracy of the Hi-Flow Sampler and whether or not to use it or another measurement strategy to determine the true accuracy of the dispersion model leak rate estimates.

Detailed leak rate estimation analysis and results are shown in Appendix 1 and 2 for both technologies.

Methane Leak Source Location (Localization)

In addition to the leak rate estimation, leak location estimation is also a primary output from the dispersion modeling effort. Within the CFD simulation environment, different combinations of leak source candidate locations are analyzed to ultimately converge on the most likely leak source candidate(s) based on the highest correlation coefficients. The leak locations were known prior to the tests, and the predicted leak locations resultant from the dispersion modeling were compared against those known locations for an assessment of accuracy. The leak location predictions were assessed in the same manner as the leak rate estimations; as previously stated, the model is currently at a state that allows for single leak rate and location estimates, but the location accuracy was tested on single and multiple leak sources to better understand the current limitations.

Utilizing the 2D base map view of the facility and the associated flight path for the test, the dispersion model boundaries were defined. As Figure 23 shows, the output from the dispersion model is a contour heatmap that shows where the highest probability leak locations are. This contoured heatmap is then overlaid onto the facility base map (fitted to the CFD boundaries), and the estimated leak location is then assigned a GPS coordinate where it can then be compared against the actual leak locations.

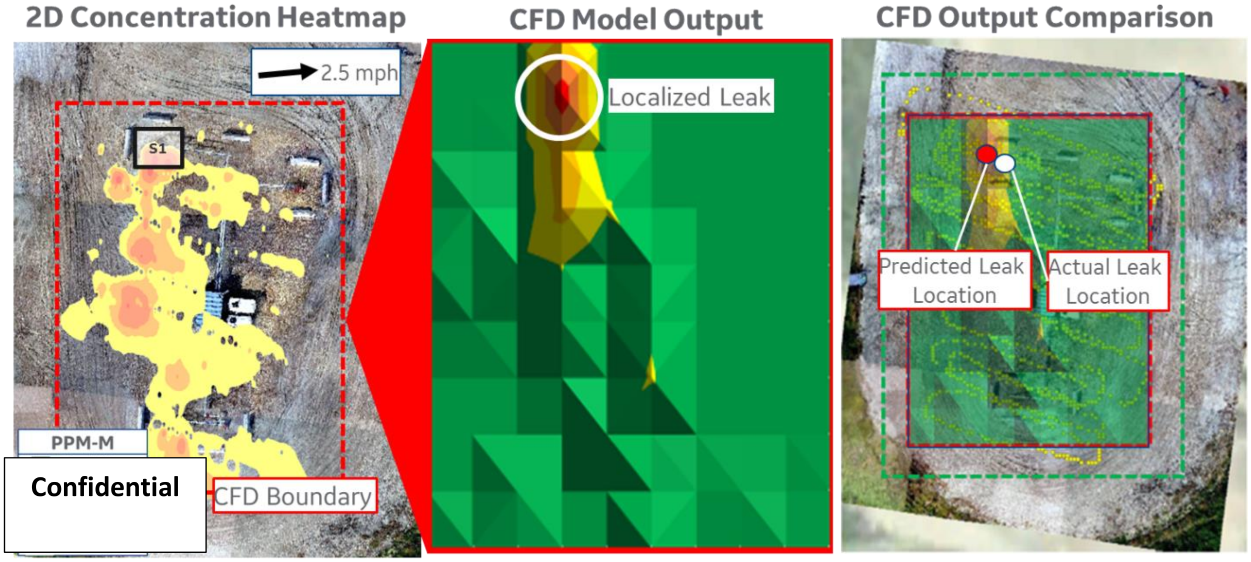

Figure 23: Single Leak Source Concentration Heatmap, CFD Model Generated Contour Heatmap, and Comparative Map Comparing Predicted to Actual Leak Location

Table 5: Single Leak Source Leak Location Estimation Results

Actual Leak Location Coordinates	Predicted Leak Location Coordinates	Distance Accuracy (feet)
Confidential		

As indicated in the Figure 23 CFD output comparison map, in the first test case where only one leak source (indicated as “S1”) was leaking, the CFD model was able to predict the leak location to within a accuracy. Given the fact that the leak was heavily dispersed over a large portion of the facility and high concentrations were detected at locations far from the main leak source, the ability of the CFD model to trace those dispersed plumes back to the original leak source within approximately 6 feet is promising in the model’s current state (Table 5).

Once the leak location prediction capability of the model was established for a single leak source, the model was tested to assess the limitations in predicting locations for multiple leak sources. Figure 24 below shows the original concentration heatmap, the contoured CFD prediction heatmap, and the final overlay of the CFD output onto the base map of the facility. In this assessment, two leak sources (“S1” and “S2”) were simultaneously leaking. As indicated in the comparative view and Table 6, the model was able to predict with reasonable accuracy the location of S2 at approximately feet difference, while the prediction of S1’s location was off by about 9 feet. This may be attributed to the fact that the S2 leak source was larger, and thus the detected, adjacent plumes enabled the model to more accurately determine the location of the source. While the location prediction of leak source S1 was off by about 9 feet, the error is within reason given that the model is currently tuned to look at a single leak source. With further optimization of the model, this error may be reduced.

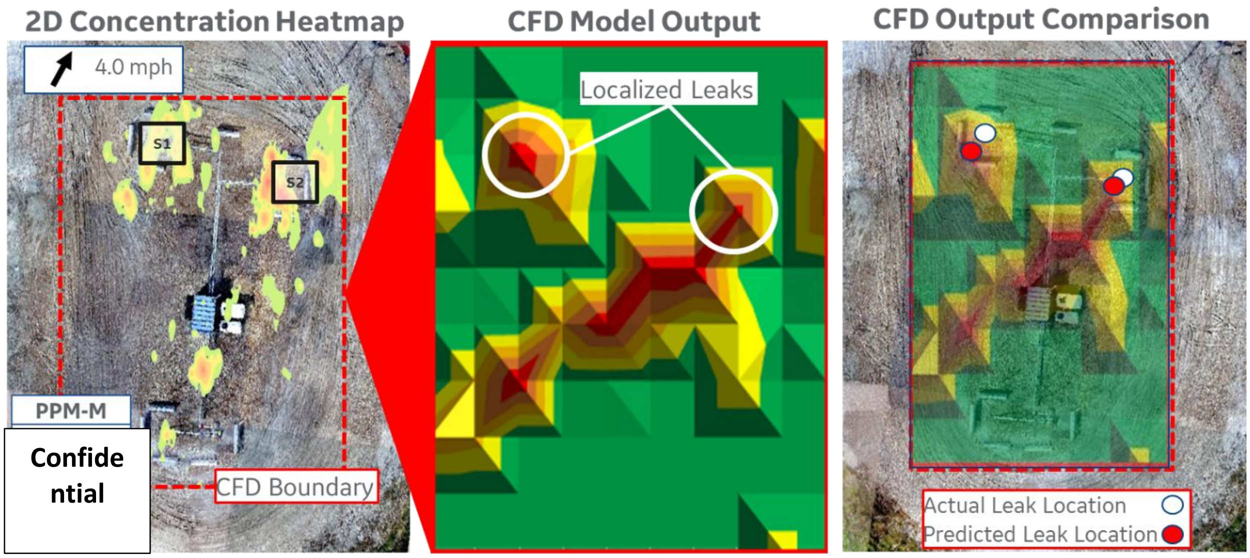

Figure 24: Multiple Leak Source Concentration Heatmap, CFD Model Generated Contour Heatmap, and Comparative Map Comparing Predicted to Actual Leak Locations

Table 6: Single Leak Source Leak Location Estimation Results

Leak Source	Actual Leak Location Coordinates	Predicted Leak Location Coordinates	Distance Accuracy (feet)
S1	**Confidential**		
S2			

Detailed leak source location analysis and results are shown in Appendix 1 and 2.

Proposed Future Work

The tests from Trips 1 and 2 allowed for the successful optimization of the UAV flight operation, GB sensor network optimization as well the advancement of the inverse dispersion modeling capabilities. From these tests, the performance of the both UAV and GB technologies were well-understood and next steps in the development were clearly identified.

The development on the UAV platform itself, as it pertains to the hardware, is close to completion, as all of the required sensors have been successfully integrated, and the data acquisition system is functional. One potential improvement, however, is in the acquisition of the weather data. Because the weather station was added at a later stage of the system development, it was not integrated into the original ground control station and is currently a stand-alone system. Fusing the weather data directly with the methane concentration data in a single data acquisition system will help to eliminate any potential discrepancies in the data collection phase, and thus, eliminate potential errors in the associated processed data output.

GB Sensor ruggedization is currently underway for full scale commercial deployment in 2018 (Product ARGUS). This includes development of an integrated dashboard and a cloud-based, user-friendly application for reporting & data management/maintenance and schedule/record keeping, as well as continuing to refine the dispersion model for enhanced leak localization and leak rate estimation for multiple leak sources. Other work also includes the optimization of the computer processing for predictive leak location and rate transition to cloud-based computing for enhanced computing performance (target processing time is < 1 hour).

The ability to continue development on the UAV and GB systems is dependent on strong industry partnerships, as subjecting the system to real-world environments at oil & gas facilities helps to advance the development at an accelerated pace. The performance of the dispersion modeling capability will only be truly understood with frequent leak tests at customer sites, under real operating conditions.

Conclusions

The BHGE team in collaboration with the Encana team successfully demonstrated two new clean energy technologies (ARGUS and RAVEN) for reliable, scalable, rapidly deployable and efficient (with respect to human and financial resources) detection and quantification of methane emissions in the Alberta oil and gas sector. The project took place at Encana well sites and compressor station in BC, Canada during August and October of 2017.

BHGE's monitoring technologies, related analytics tools, and applications were effective in detecting and locating methane leaks in real-time and BHGE envisions that these proven effective monitoring technologies will assist customers by reducing manual inspection requirements and costs by alerting personnel only to those circumstances where detected leakage is high enough to warrant a follow up visit or repair.

By the proven field results obtained from these field campaigns, BHGE is in a good position to offer these alternative, advanced, and low-cost detection technologies to the oil and gas industry at large, enabling industry-wide reductions in methane emissions.