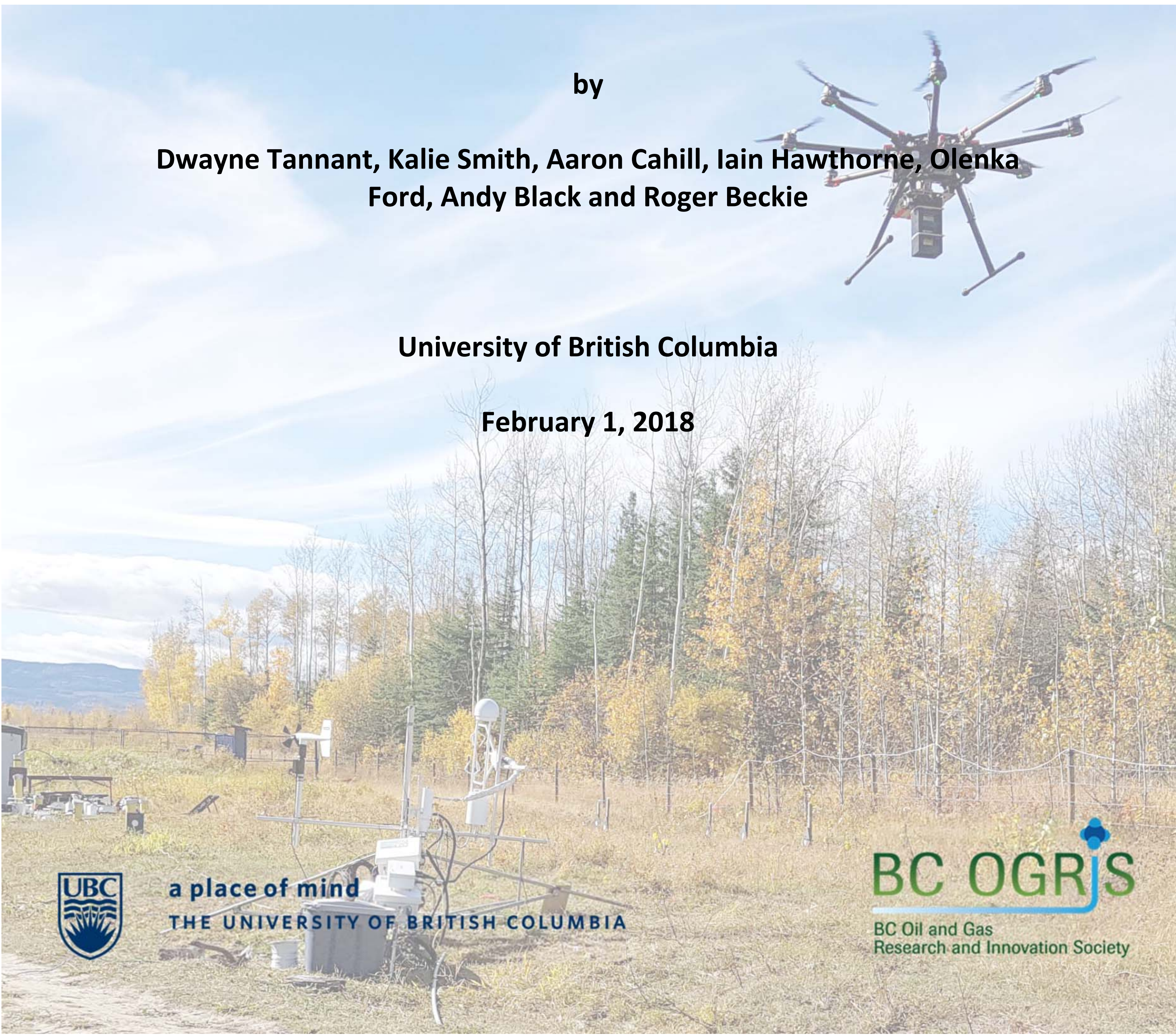
Evaluation of a Drone and Laser-Based Methane Sensor for Detection of Fugitive Methane Emissions

submitted to

BC Oil and Gas Research and Innovation Society



by

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Executive Summary

Fieldwork was conducted in the summer and fall of 2017 to test and evaluate the capabilities of a laser-based methane sensor mounted on a drone for detecting and measuring the near surface methane concentration. The fieldwork was conducted as an extension to a much larger fugitive gas investigation being conducted by the UBC Energy and Environment Research Initiative involving various controlled release experiments in NE British Columbia.

Tests of the drone-mounted laser-based methane sensor occurred for surface releases of methane in an open field, a surface release of methane in a corridor between trees, and a subsurface release of methane that later escaped through the ground surface. The methane sensor was oriented to measure the average methane concentration in a vertical column of air beneath the drone. When the sensor was working properly, measurements were obtained every 0.1 seconds. The drone was flown at heights above ground ranging from 10 to 30 m. The drone was flown under a combination of autonomous and manual control. The duration of the drone flights were typically in the range of 4 to 8 minutes.

Some of the research findings are as follows. A Laser Methane mini-G (Blue-Tooth capable model only) plus an Android phone (for logging the data) can be mounted beneath a larger commercial multirotor drone. The laser-based methane sensor can measure the background or ambient methane concentration in the air, which ranged between 0.5 and 3 ppm. A typical background methane concentration of 1.7 ppm was measured for one date. The sensor did not work well if the drone was higher than 12 to 15 m above the ground. The reason for this is that the intensity of the reflected laser beam was too low for reliable readings.

The test flights over point sources of methane (surface releases) and diffuse sources of methane (methane escaping from subsurface injection) clearly found elevated methane concentrations in the air column above the ground. The surface release rates for methane were up to 3 m^3/hr under controlled conditions and at even higher rates for uncontrolled release conditions. The tests flights were not able to map the shape of the methane plume or the methane concentrations within the plume; the methane values were quite variable. Variations in the wind velocity and direction are contribute to the methane concentration variability. Future field trials with a closely spaced grid pattern for the flight will further test the ability of the drone-mounted sensor to 'map' the methane plume.

The lessons learned from this research provide guidelines for successful use of the laser-based methane sensor on a commercial drone. The following are key to success: 1) fly less than 12 to 15 m above the ground (for grass-covered terrain), 2) fly when the wind velocity is less than ~5 m/s (for safety of the drone upon landing and for keeping the sensor pointing vertically down during the flight), 3) fly at an average velocity of 2 to 3 m/s for well pad applications (a slightly higher velocity may be appropriate for monitoring linear infrastructure such as pipelines), and 4) ensure measurements are recorded on the Blue-Tooth connected Android phone at a 10 Hz rate. For interpretation of the data over well pads it is best if 5) the drone can fly a tightly spaced

grid pattern under autonomous control and that (6) methane measurements are plotted using the more accurate GPS coordinates recorded by the drone rather than the coordinates recorded by the Android phone.

One conclusion from the research conducted so far is that a drone with a laser-based methane sensor can be used to cover a site such as a well pad of a few hectares with relative ease. The outcome of a monitoring flight would be 100s to 1000s of spatially distributed methane measurements from which the presence or absence of methane above ambient background levels can be determined with good confidence.

Further drone flights in conjunction with surface and subsurface methane gas releases are planned for the summer of 2018. This work will further confirm the conclusions arising from the 2017 fieldwork. The lessons learned will be used to improve the drone testing methodology and to further assess the capabilities of a laser-based methane sensor mounted on a drone to monitor and detect fugitive methane emissions. The goal in 2018 is to better use pre-planned autonomous flights in a grid pattern to facilitate mapping of the shape of the methane plumes. Test flights over one or more abandoned gas wells will also be conducted.

Acknowledgments

The research presented in this report was funded by the BC Oil and Gas Research and Innovation Society (BC OGRIS). The project received guidance from Brian Thomson from BCOGRIS and feedback from an advisory committee consisting of: Laurie Welch and Kevin Parsonage from BCOGC and Steven Rogak from UBC. Bara Emran from the UBC School of Engineering provided assistance during the August fieldwork and configured the equipment and software for mounting the laser-based methane sensor on the drone. The laser-based methane sensor was provided by Hetek Solutions Inc. The image processing software was provided by the principal investigator's (Dwayne Tannant) research lab.

The key members from the UBC Energy and Environment Research Initiative that were involved in the set-up and execution of the methane release experiments and involved in other forms of methane monitoring are listed as co-authors to this report.

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1 Introduction

Detection of leaks of fugitive emissions of methane from natural gas infrastructure is critical for their safe operation and for protecting the environment. Natural gas pipelines, leaky well casings, and other infrastructure can be a source of fugitive methane emissions. For example, from 1990 to 2012, 15,609 pipeline leaks were reported in Alberta (AER, 2013).

In this report, remote sensing by a drone equipped with a methane sensor is tested as a cost-effective and fast method for methane detection and monitoring. This report describes the use of a laser-based methane sensor mounted a multirotor drone and describes a series of field tests conducted in the summer and fall of 2017 to generate methane concentration maps near different methane sources. As the drone flies its flight path the average methane concentrations in a vertical air column between the drone and the ground surface are measured. The research is an extension of similar work reported by Emran et al. (2017) for monitoring methane emissions from a landfill. The work reported here is the first part of a planned series of field tests near Hudson's Hope. Further tests are planned for the summer of 2018.

The fieldwork took advantage of a much larger study being conducted by the Energy and Environment Research Initiative (EERI) being operated out of the Department of Earth, Ocean and Atmospheric Sciences at UBC Vancouver. A key aim of the EERI research group is to advance understanding on fugitive gas from energy resource development. To this end an experimental field observatory for evaluating fugitive gas leakage has been established in an area of historic and ongoing hydrocarbon resource development within the Montney Resource Play of the Western Canadian Sedimentary Basin, British Columbia, Canada. Natural gas has and will be intentionally released at surface and up to 25 m below surface at various rates and durations. Resulting migration patterns and impacts of the released natural gas are being evaluated through examination of the geology, hydrogeology, hydro-geochemistry, isotope geochemistry, hydro-geophysics, vadose zone and soil gas processes, microbiology, and atmospheric conditions. For more information on EERI and the research project that the OGRIS drone study is leveraging please visit the research program website (http://eeri.ubc.ca/).

The initial results reported here on the evaluation of a drone and laser-based methane sensor for detection of methane was able to access EERI data for interpretation and assessment purposes.

2 Methane Sensor

A Laser Methane mini-G (LMm-G) laser methane sensor was used for the research. It was provided by Hetek Solutions Inc. It is a remote sensing device that measures the methane concentration (measured in ppm·m) in the column of air between the sensor and a reflective surface, in our case the ground. It is typically used as a handheld sensor in the natural gas industry. The sensor relies on transmitting an eye-safe laser beam with a frequency tuned to the absorption characteristics of methane gas molecules. The laser beam is directed vertically downward from the drone to the ground surface, and a portion of the beam is back scattered to the sensor. The laser beam intensity drops when the transmitted and backscattered rays pass through methane molecules. A reference laser beam not sensitive to methane absorption is also used.

The concentration of methane in the air column that the laser beam travels through is calculated by comparing the return intensity of the methane-sensitive laser beam with the reference laser beam using proprietary software. The algorithm quantifies the methane concentration in parts per million of methane multiplied by the distance between the drone and the ground (ppm·m). The sensor model that was used in its protective casing is shown in Figure 1.

The device along with mounting attachments and Android phone weighs about 1 kg. This simple configuration allows the methane sensor to be integrated into a wide range of drones that can safely carry a 1 kg payload. Specifications for the LMm-G are summarized in Table 1.

Figure 1. Laser Methane mini-G sensor.

Table 1. Specifications of Laser Methane mini-G.

Item	Specifications
Weight	530 g (without protective housing)
Approx. operating time	5 h
Detection limits	1 ~ 50,000 ppm·m
Detection distance	0.5 m ~ 30 m
Laser output level	10 mW (Class 1)
Accuracy of detection	± 10%
Operating temperature	−17 ~ 50 ◦C
Measurement frequency	10 Hz
Laser output wavelength	1653 nm
Communication method	Bluetooth Ver.2.1

2.1 GasViewer

The methane measurements were controlled and recorded using GasViewer, a software application for Android devices, developed by Tokyo Gas Engineering Co., Ltd (TGE, 2013). The software was loaded onto an Android phone. The sensor was set to measure methane concentrations at a rate of approximately 10 Hz. The sensor readings were transferred using a standard Bluetooth link to an Android phone that was also carried by the drone.

In a handheld operation mode, GasViewer can record the measurements taken by the Laser Methane mini-G sensor in real time, and display various graphical representations of the obtained data. However, when used on the drone it simply functioned to record the measurements for storage on the linked Android phone. The Android phone and methane sensor are paired via a Bluetooth connection. For each reading that is taken, the concentration measurement, intensity measurement, and error code are recorded along with the time. In addition, the approximate latitude and longitude coordinates are obtained from the phone's GPS and recorded every 0.5 seconds. The GasViewer app stores the data for each flight in a separate CSV file, which can be exported and can be used to create KML files to plot the flight paths.

The intensity reading is a measure of light the sensor is receiving with each concentration measurement reading. Each measurement is assigned an error code value based on its corresponding intensity reading. An 'error' code of 1 indicates a normal measurement. Table 2 lists the error codes that can appear next to a measurement and their meanings. The common codes that were observed during the testing reported here are 0, 1, and 5.

Table 2. Laser Methane mini-G error codes.

Error Code	Cause
0	Unreliable measurement
1	Values are measured normally
5	Not enough reflection
6	High density gas
7	Too much reflection

3 Drone

In this project, we used a DJI Spread Wings S1000 multirotor drone that was flown by Vector Geomatics Land Surveying Ltd. While a smaller drone (e.g., Spread Wings S900) could have been used, the S1000 was available and was selected for the fieldwork. The drone can safely carry a 4.4 kg payload for 10 min with a single 6S 16000 mA LiPo battery module. Additional specifications of the drone are given in the Appendix, and the drone itself is shown in Figure 2 below.

Figure 2. DJI Spread Wings S1000 drone.

The drone is equipped with a DJI WooKong-M professional multirotor autopilot flight control system consisting of a GPS and telemetry system. DJI Ground Station PC software was used to configure the system and define the flight paths with GPS way-points across the area of interest. The drone recorded a range of telemetry and location data during each flight. The data that were used for further analysis were the GPS location of the drone, drone altitude above take-off point, and time. These data were provided to us by the drone operator Vector Geomatics Land Surveying Ltd. after the flights.

A custom-designed aluminum mount plate was made to hold the methane sensor in a vertically downward orientation and to hold the Android phone. This sensor package was attached to the drone with four vibration isolating mounting bolts. The sensor package was placed underneath the drone in a position such that the combination its mass and the mass of the drone’s batteries could be roughly centred under the drone to improve the drone’s flight characteristics. This arrangement is shown on its own in Figure 3.

Figure 3. Vibration isolating mounting plate for the methane sensor and Android phone.

The methane sensor did not hang below the drone's support legs, as shown in Figure 4. This allowed the support legs to provide some protection to the sensor during take-off and landing. The retraction feature for the drone's legs was disabled during the flight as another safety measure.

Figure 4. DJI Spread Wings S1000 with a Laser Methane mini-G sensor and Android phone mounted below.

The experimental set-up with the drone and sensor combination is shown in Figure 5. The blue dots indicate the two different methane release points.

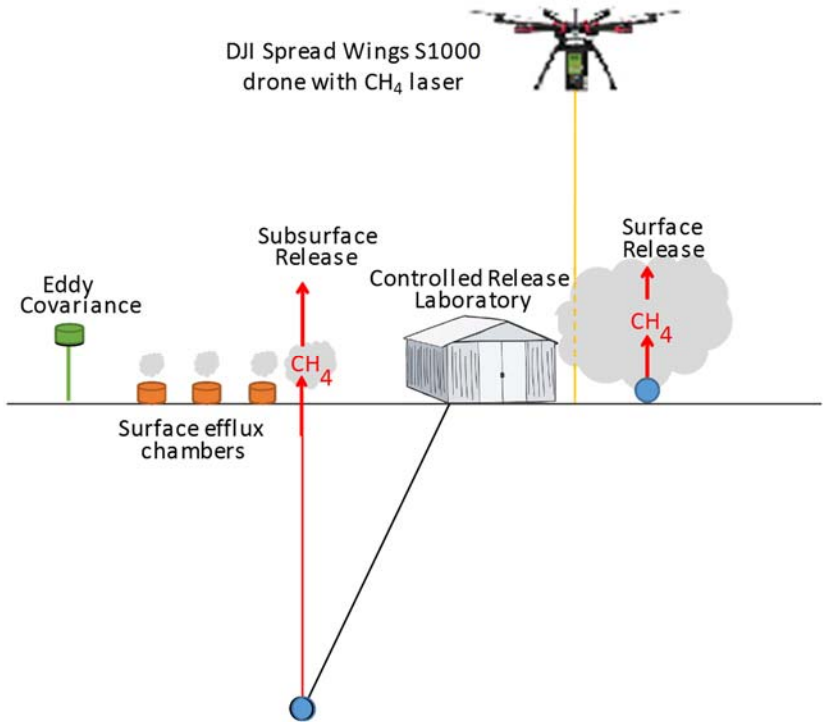

Figure 5. Methane sensor mounted to the drone to collect gas concentration data.

4 Data Processing

Post-processing of the raw recorded data was required to obtain meaningful data of methane concentrations and locations. When a flight is completed, the methane concentration data recorded by the sensor along with their GPS locations are available to the user. However, the methane concentration, intensity, and error code are recorded every 0.1 seconds while the GPS location is recorded every 0.5 seconds. The methane concentration measurement assigned to a given GPS location was taken as the average of up to 5 concentration measurements occurring within the given 0.5 second period, using only values having an error code of 1, which indicates a normal reading. There were error codes associated with some methane measurements. Measurements with error codes other than 1 were not included in the average concentration values.

The drone and the methane sensor store different data in separate CSV files, but both record the times of their respective measurements in 0.5 second increments, which can be used to link the information recorded by the two separate sources. The vlookup function in Microsoft Excel was used to match the concentration measurements in ppm·m from the methane sensor CSV files to the drone height in metres from the drone CSV files, based on the closest time stamp. While both sources of data gave a coordinate pair every 0.5 seconds, the exact times of these readings did not always perfectly match. For a given second in time, one CSV file could record data at 0.0 and

0.5 sec, while the other might have done so at 0.1 and 0.6, or 0.3 and 0.8, etc., depending on when the data recording began. Therefore, an associated concentration measurement in ppm·m and drone height in metres could be off by at most 0.25 seconds.

The LMm-G sensor records methane concentration in ppm·m observed in a column of air; therefore the higher the drone is flying, the greater these measurements will be given a uniform concentration of methane in the air. Given that different flight heights were used, we assumed that the methane concentration was uniform in an air column to calculate that average concentration by dividing the measurement (ppm·m) by the height (m) of the drone above the ground to obtain ppm values.

Before plotting the concentration data, the points were further filtered by eliminating concentration measurements observed at a drone height of less than 5 m above the takeoff point. These are associated with the takeoff and landing location of the drone.

The collected data can be transferred into Geographic Information System (GIS) software programs for display purposes. For example, Google Earth can be used to display the points as a KML file, or they can be added as a Shapefile layer overlying an orthophotograph in ArcMap. The user can easily spot areas of high methane concentration referenced by their GPS coordinates, or relative to natural landmarks on the orthophoto. The smartphone GPS coordinates were not used to display the flight paths and concentration data. Instead, the more accurate UTM coordinates recorded by the drone were used.

A schematic of the data post-processing procedure that was used is shown in Figure 6.

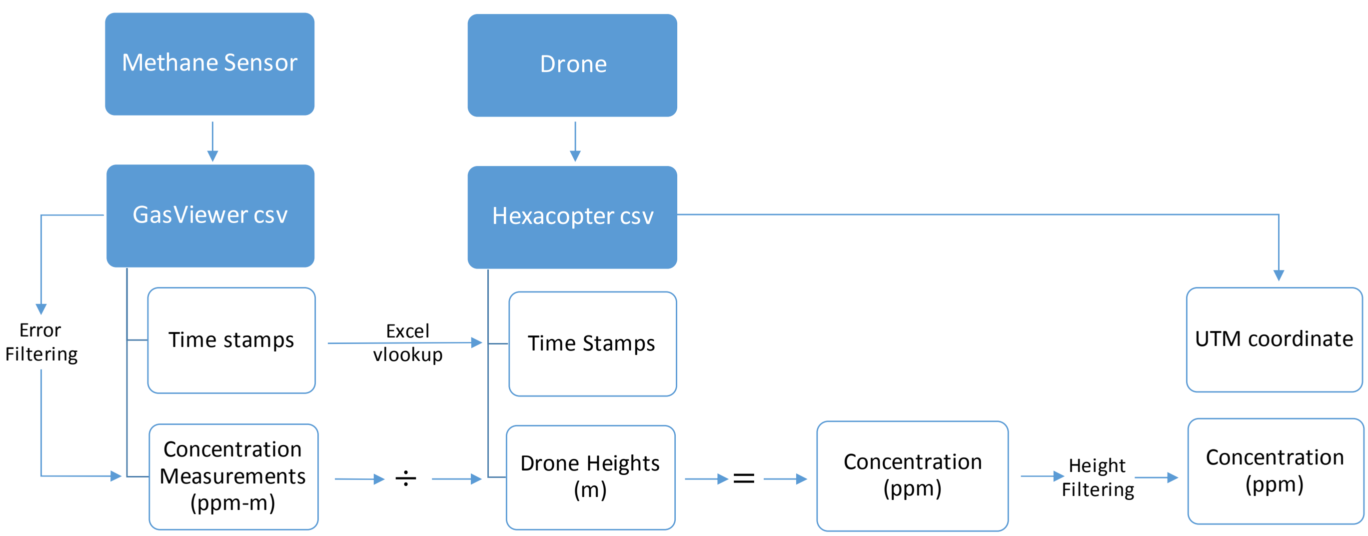

Figure 6. Data post-processing procedure.

5 Field Experiments

5.1 Locations

The drone-methane sensor combination was tested in an open, grassy field on August 9 and 10, and in a confined grassy area between trees on September 25 and 28, 2017. The testing took advantage of available sites and the presence of a larger field experiment involving controlled surface releases and subsurface injections of methane gas. The larger research project is examining the impacts of released natural gas and the migration patterns of the methane gas through different hydrogeological and atmospheric conditions. This research was being conducted by the Hudson's Hope Field Research Station team as part of the Energy and Environment Research Initiative at University of British Columbia (Cahill et al. 2018; University of British Columbia, 2017).

The open field was used for surface releases on August 9 and 10 when a tank released methane gas at a controlled rate, and on September 28, when the valve was opened on a tank of methane gas to simulate a surface release of unknown release rate. On September 25, another controlled surface release was conducted in the confined area between trees, where the controlled subsurface methane injection experiments also took place on September 28. The two test sites are shown in Figure 7.

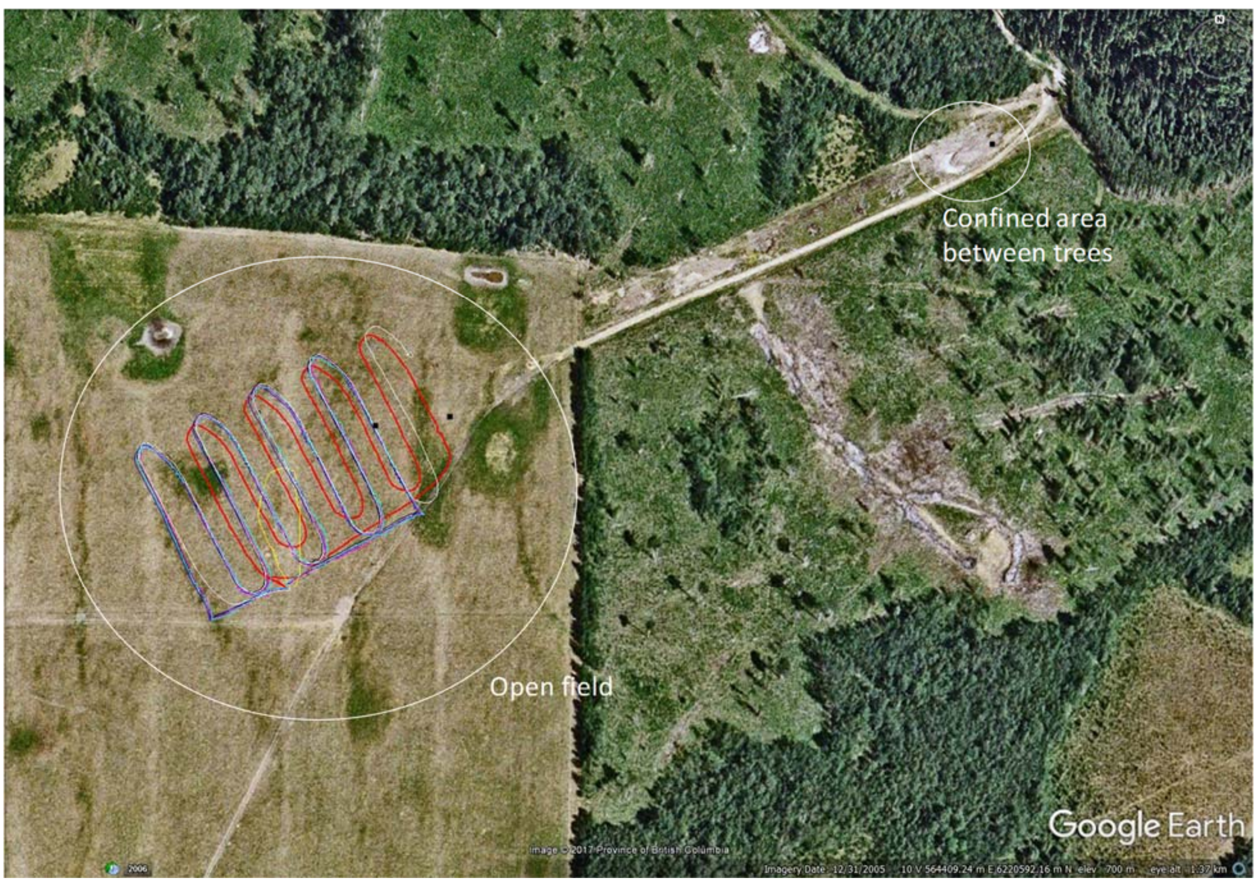

Figure 7. Location of the test sites north of Hudson's Hope (Google Earth, 2005).

5.2 Flight Planning

Measurements of methane concentrations were taken at a frequency of 10 Hz, giving a typical distance between measurements of 0.2 m when flying at 2 m/s. The drone was flown at an approximate velocity of 2 to 3 m/s for the grid pattern flight configurations, and between 1 and 2 m/s for manual flights. The drone was set to fly at different heights to test the capability of the methane sensor to obtain concentration measurements at various distances above ground. These heights ranged from 6 to 30 m above the takeoff point of the drone.

Grid flight patterns were used over the surface release site in the open field to get even coverage. Examples of pre-planned grid flight patterns are shown in subsequent sections. Flying in grid pattern was a viable option for this site because of the wide-open space and reduced risk of the drone running into trees. However, the drone was flown manually over the confined area between trees because of the confined space and concerns about hitting trees. Hence manual flights were also at a reduced speed compared to the grid flights. Flight times usually ranged between 4 and 8 minutes, mostly due to the limited battery life of the drone.

5.2.1 Challenges

While the specifications for the methane sensor indicated that it could be used at a distance up to 30 m, the laser beam reflection intensity influences the error codes assigned to each concentration measurement. The practical distance limit is dependent on the reflectivity of the surface. Because it was unknown at what height the sensor could get an acceptable amount of reflection from the grassy terrain, a variety of heights were flown.

For two flights the drone software would not allow for a flight in a pre-set grid pattern over the surface release site. The reason for this was unknown. In these cases, both on September 28, the drone operator switched the flight mode to manual and proceeded to fly the drone manually and attempt to obtain even coverage over the release area in the open field.

At times getting the GasViewer software on the phone to establish a Bluetooth connection with the methane sensor and pair the devices was difficult. Usually restarting the software or re-calibrating the sensor resolved these issues.

6 Results

6.1 August 9 and 10: Surface Release in Open Field

Over August 9 and 10, 2017, controlled surface release of methane was conducted at various rates varying from 1 to 3 m^3/hr and releasing 9 m^3 over 6 hours within the open field. A series of flights were flown over the two days, using pre-planned grid patterns with the same take-off and landing point. The four flights flown on August 9 are shown in different colours in Figure 8. A different grid pattern was flown on August 10, and the seven flight paths are shown in Figure 9. These figures illustrate that a variety of grid patterns can be flown and that the flight path can be easily adjusted in the field.

Figure 8. August 9 flight paths (Google Earth, 2005).

Figure 9. August 10 flight paths (Google Earth, 2005).

A photo of the drone flying over the open field during this part of the investigation is shown in Figure 10.

Figure 10. Drone flying over the open field during a surface controlled release.

After the fieldwork was completed and the CSV files from the methane sensor were examined, the data were found to contain numerous error codes other than 1. It was discovered after inspecting the sensor that there was cracked glass over the laser beam transmission window, which likely affected the intensity and the orientation of the laser beam from the sensor. This damage to the sensor probably affected the validity of the measurements and triggered error codes. Furthermore, most error codes were associated with there not being enough reflection (low measured intensity). It was suspected that the height of these flights, which were between 25 and 30 m, were too high for the sensor to receive sufficient laser light reflected from the ground.

From these dates, the only real information of value obtained was that a variety of grid patterns could be flown over this site. It was decided to take advantage of the next surface release on September 25, with a methane sensor that did not have broken glass, and to fly closer to the ground to improve the intensity of the reflected light, thus reducing the error codes in the data.

6.2 September 25: Surface Release in Confined Area Between Trees

The flights that were flown on September 25, 2017, were approximately 10 m above the takeoff point instead of 25 to 30 m used earlier. The release of methane started at 1:37 pm initially at a rate of 72 m^3/day decreasing in 3 steps over 3 hours and 10 minutes to 7 m^3/day. A total of 4852 litres of compressed natural gas (at standard temperature and pressure) were released during this testing phase. The release rates and times are shown in Figure 11.

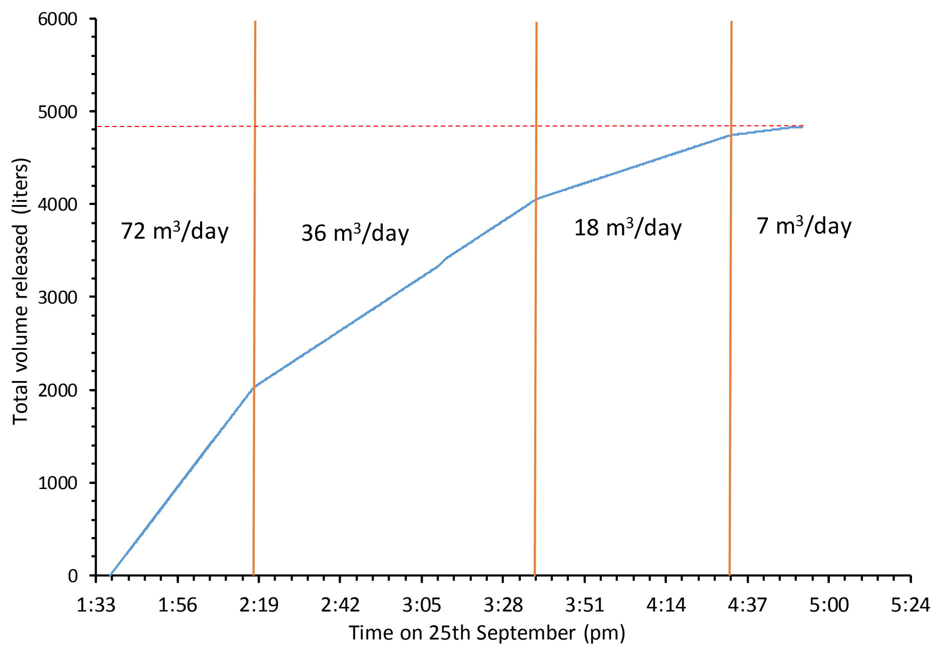

Figure 11. Cumulative total volume (in litres at STP) of natural gas released at a decreasing release rate (separated by orange lines) with time on Sept. 25 for surface release investigation.

There were five drone flights. The first one started at 1:29 pm, to obtain background methane readings, before the methane release initiated. Unfortunately that data from this flight contained error codes and was not useable. There were four flights conducted while the methane was being released. While it would have been better to have flown an autonomous grid pattern, the surface release was conducted in the confined area between trees, and the drone operator did not want to risk having the drone crash into trees and elected to fly under manual control only. Half-hourly average wind direction and speed are shown in Figure 12. Throughout the surface and subsurface release experiment the wind direction was dominantly from the SSW between 195-225° and the average wind velocity was usually below 2 m/s. The wind velocity in the early afternoon, which was the time of the flights, was generally at near the peak, reaching a level where control of the drone was becoming challenging. At the test site, gusts of wind up to 5 or 6 m/s were recorded at 2 m above the ground at the time of the flights. Nevertheless, the drone operator was able to complete four successful flights (with the drone almost flipping over on one landing in the wind).

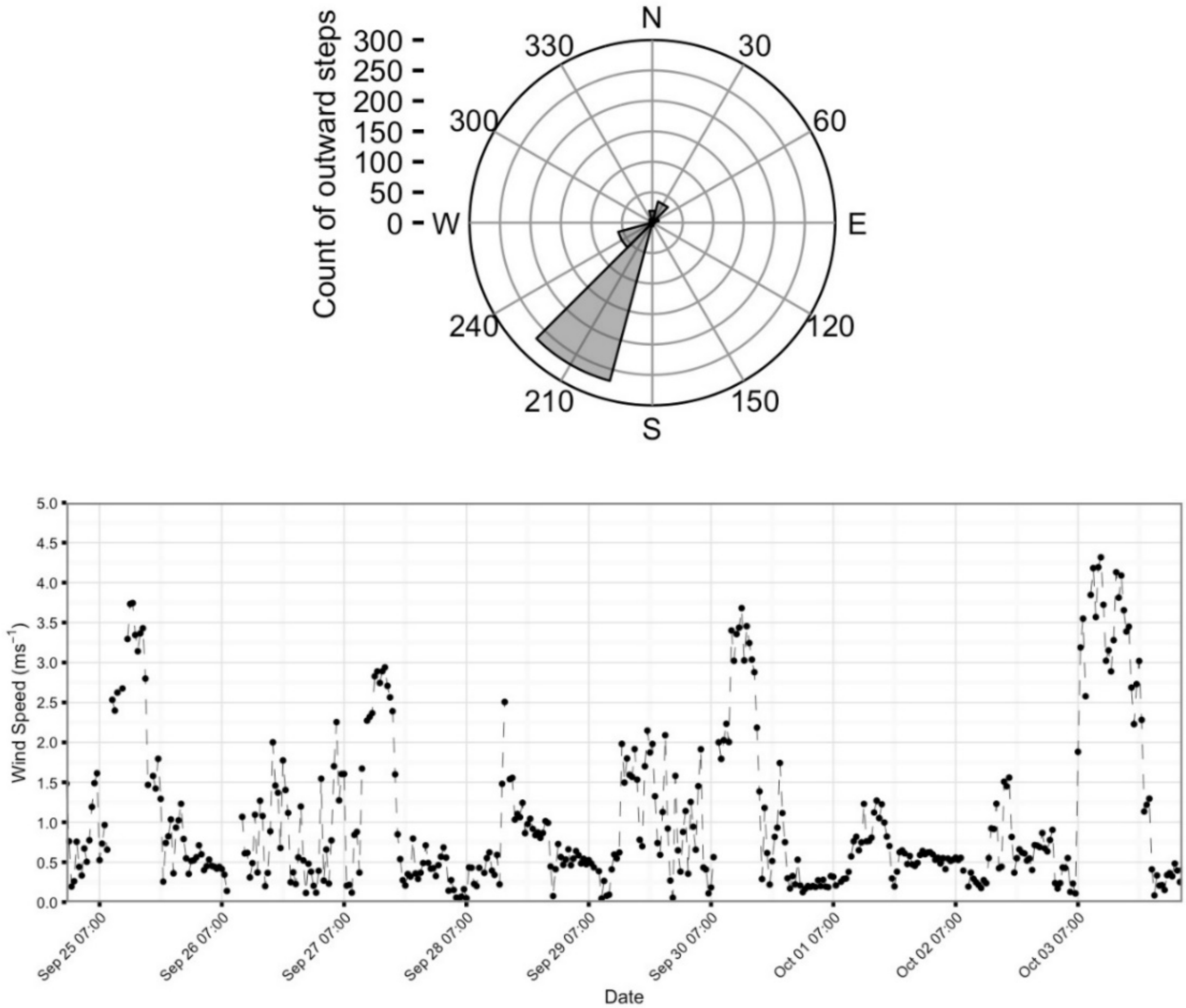

Figure 12. Half-hourly average wind direction (top) and wind speed (bottom); wind direction comes from 422 measurements at the eddy covariance tower.

Unfortunately, after these flights were completed, it was later discovered that the GasViewer software had an averaging setting turned on, where the resulting CSV file provided only one measurement, which is an average concentration measurement and intensity reading observed throughout the duration that measurements were collected for each flight. Data obtained are summarized in Table 3. The average drone height above the ground for the five flights was 3.6 m while the drone was set to typically fly approximately 10 m above the ground for the main portion of its flight. This average includes the time that the drone was on the ground at the beginning and the end of each flight while the methane detector was still taking readings. The average methane concentration in ppm for each flight was determined from the average ppm·m measurement from the GasViewer divided by the average height of the senor above the drone for the same time period. The flight durations listed in Table 3 are times that the drone was at a height above ground greater than 5 m.

Table 3. September 25 flight data.

Flight	Start time (hh:mm:ss)	Duration (mm:ss)	Average measurement (ppm·m)	Average concentration (ppm)
1	13:29:12	02:53	Not usable	-
2	13:46:23	03:08	14	3.9
3	13:57:19	04:03	17	4.7
4	14:49:15	04:48	7	1.9
5	14:58:03	05:13	10	2.8

As expected, the average methane concentration measurements from these flights are slightly above the background or ambient methane level in the air, i.e., air not influenced by either the surface or subsurface releases. Figure 13 shows an example of measurements taken when the LMm-G sensor was located near but upwind of the injection site (a day later). The laser beam was directed roughly horizontally across the ground over a 10 m distance to a solid reflective surface at an elevation of approximately 1 m above the ground. The background methane concentration in the air was found to typically range from 0.5 and 3 ppm based on these hand-held measurements taken at the ground level with the LMm-G sensor. This figure shows that the typical methane concentration in the air at this time was roughly 1.7 ppm. Even with averaging turned on in the GasViewer software and the drone spending part of its flight time up-wind of the methane release point, the average methane concentration values listed in Table 3 were expected to exceed background levels. The average values for flights 2 and 3 are higher than the averages for flights 4 and 5. This is consistent with the surface release rate for the methane that was decreased by a factor of 2 for the final two flights (Figure 11).

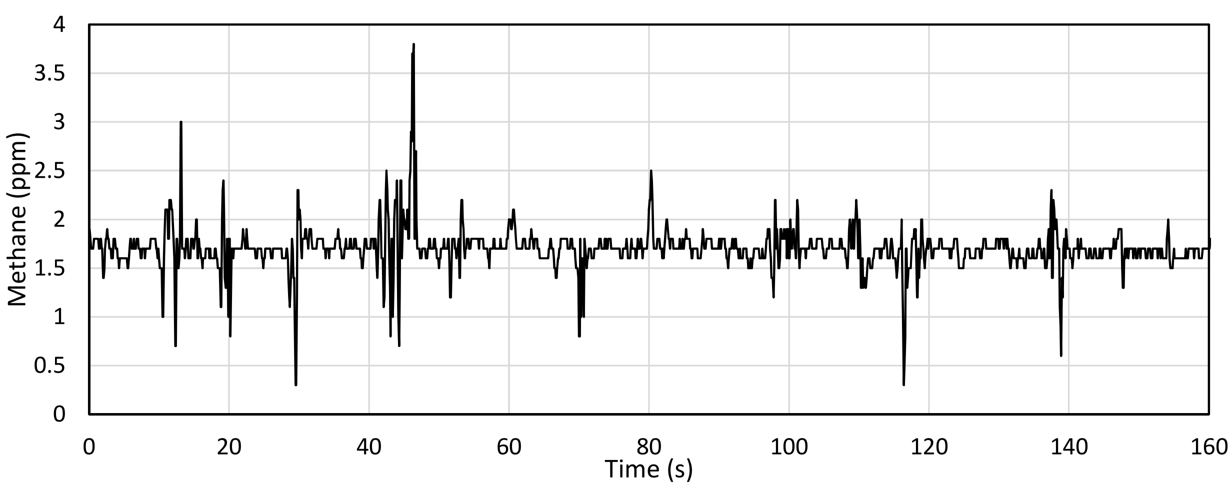

Figure 13. Background methane concentrations measured up wind of the release site at one metre above ground level over a 10 m horizontal distance (September 26 starting at 15:29).

The flux of CH_4 measured by the eddy covariance equipment during the same period is shown in Figure 14. These results show that the methane was dispersed across the experimental site at a magnitude correlated to its release rate.

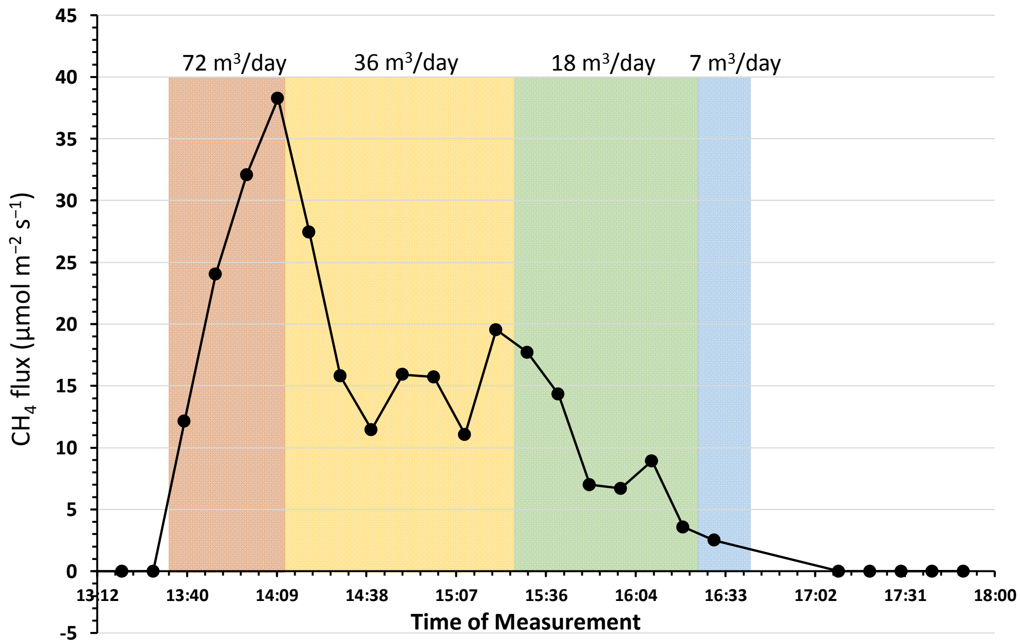

Figure 14. Eddy covariance CH_4 flux measurements by surface release rates (m^3/day) during the surface release investigation.

6.3 September 28: Subsurface Methane Efflux and Surface Release Monitoring

Five drone flights were conducted on September 28. Three of these occurred over the subsurface methane injection site and two occurred over an uncontrolled release of methane from a point source in the open field. Controlled subsurface injection of methane gas 12 m into the ground at the subsurface injection site began on September 26 and was to continue injecting at a rate of 7 m^3/day for five days. On the morning of September 27, it was found that at some point over the previous evening the injection had stopped. The injection was restarted on the morning of September 27, and methane gas was steadily injected for over 24 hours before the flights were done the following day. Hand-held measurements taken 1 m above the ground were done again away from the injection site, to verify that 0.5 to 3 ppm was a typical background methane concentration.

A summary of the five flights done on September 28 is provided in Table 4. The durations listed are the time period during which the drone was flying higher than 5 m above the ground. For flight 4, the drone was operated at two different heights.

Table 4. September 28 flight details.

Flight	Start time (hh:mm:ss)	Duration (mm:ss)	Drone height (m)	Flight location	Comments
1	12:14:43	04:21	10	Confined area between trees	Attempting a 2 m grid pattern
2	12:36:09	04:40	6	Confined area between trees	Hovering over injection well
3	13:12:29	05:16	10	Open field	Flying back and forth over release point
4	13:25:08	03:17	25, then 15	Open field	Flying back and forth over release point
5	13:54:08	06:02	15	Confined area between trees	Hovering over injection well, then flying over bank with exposed shale

6.3.1 Flights Over Subsurface Injection Site (Confined Area Between Trees)

Three drone flights were performed over the subsurface injection site a few days after the methane injection had started. Monitoring over the previous few days had indicated that the injected methane was slowly making it way to the ground surface. There was clear evidence that methane was escaping from the ground at the time the drone flights were conducted. Consequently, drone flights were initiated to assess if the laser system could detect any of the subsurface derived gas being emitted.

Methane measurements obtained from drone flights (flights 1, 2, and 5) done at the subsurface injection site are plotted over an orthophoto constructed from photographs taken during the September 2017 trip using Pix4D software. All concentration data (after post-processing as outlined in Section 4) from the three flights flown over the subsurface injection site are plotted in Figure 15.

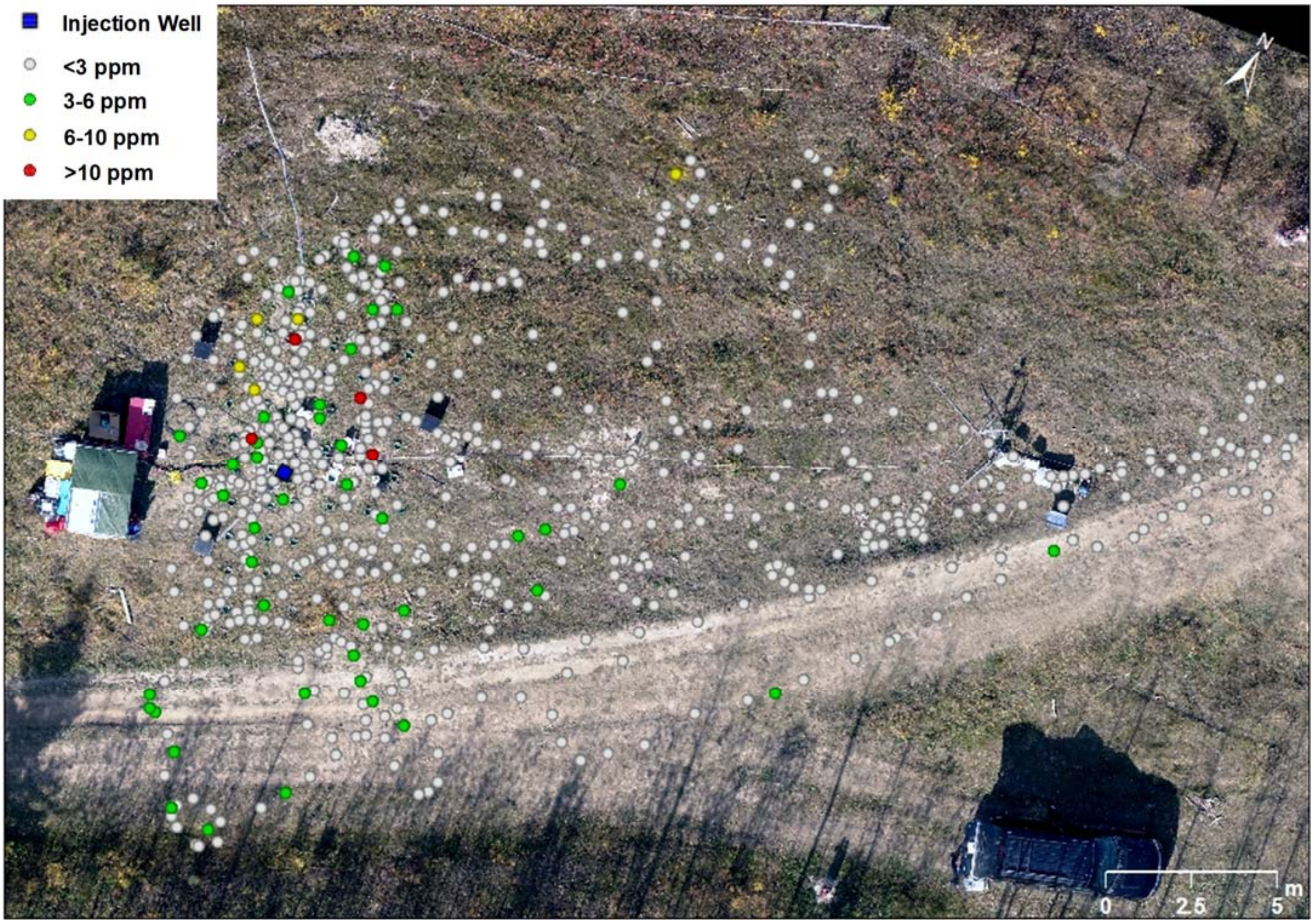

Figure 15. Average air column methane concentrations obtained from all flights over injection site.

The concentration data obtained from flights 1, 2, and 5 are individually plotted in the top, middle, and bottom figures, respectively, in Figure 16. This also provides insight as to the manual flight paths that were flown. Higher methane concentrations are seen in flight 5, which was later in the day and therefore the methane gas had been injecting into the subsurface longer and wind speed (and therefore likely gas dispersion) had picked up.

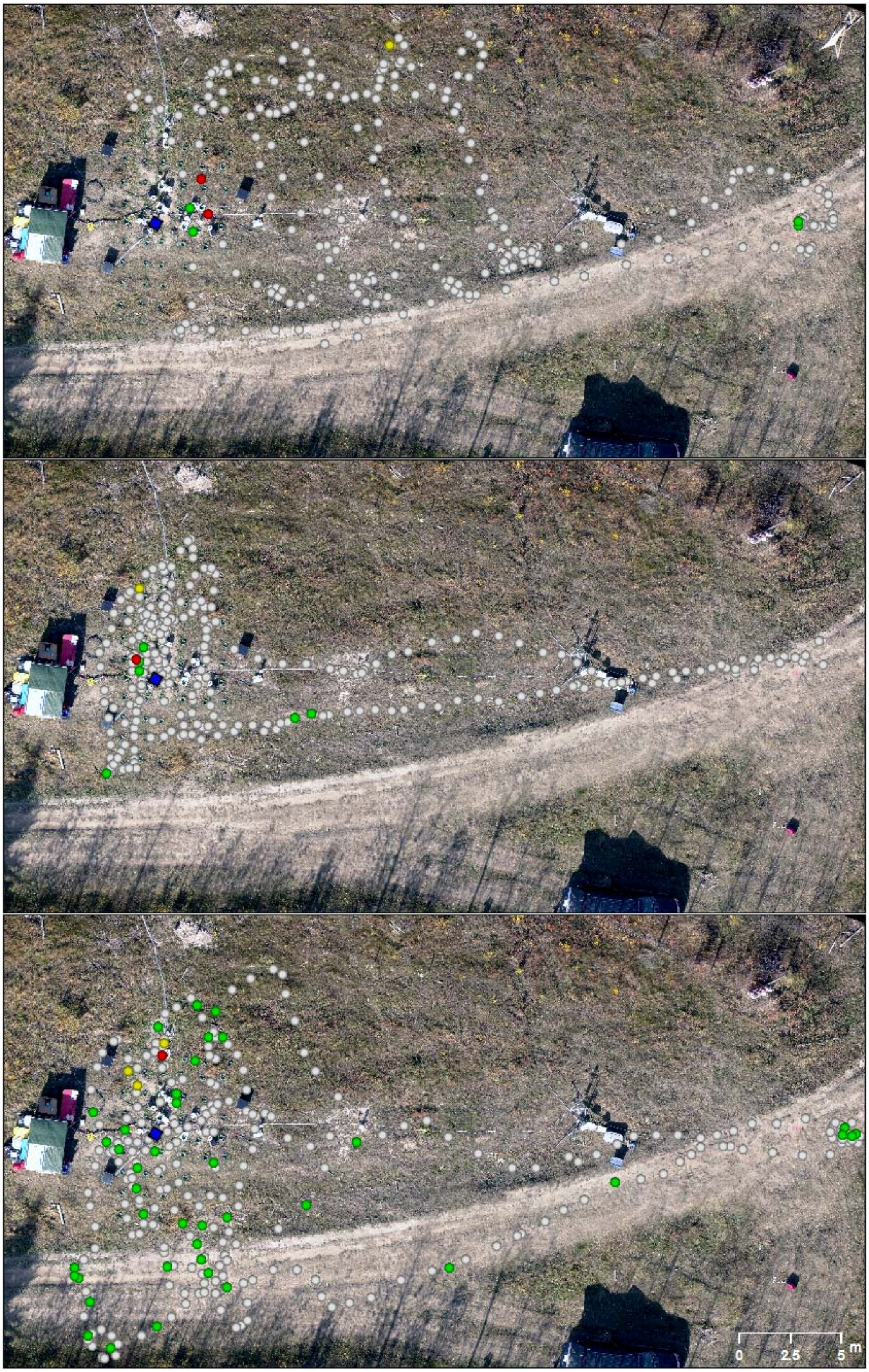

Figure 16. Average methane concentrations from flight 1 (top), 2 (middle), and 5 (bottom).

Atmospheric conditions, including the speed and direction of the wind and its variability can affect methane readings observed at the ground level. Drone flights conducted on the same day were usually within hours of one another, around late morning to mid-afternoon, and surface efflux was continually measured while eddy covariance equipment was set up to monitor the wind and other atmospheric conditions over time.

Surface efflux for methane at a hotspot 2 m offset from the injection point measured from long term chambers is shown in Figure 17. This figure shows a significant efflux event started 3 days after injection of methane began and this day (September 28) coincided with the drone-based laser measurements.

Eddy covariance fluxes for CH_4 and CO_2 measured for the first 3 days of the subsurface release are shown in Figure 18. Both the surface efflux and eddy covariance measurements confirmed that methane was emitting from the ground surface and dispersing into the air across the experimental site.

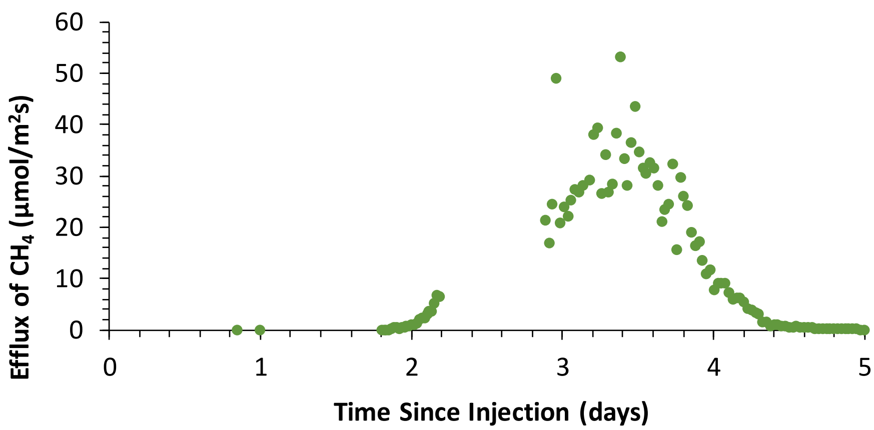

Figure 17. Surface efflux of methane adjacent to the subsurface release well.

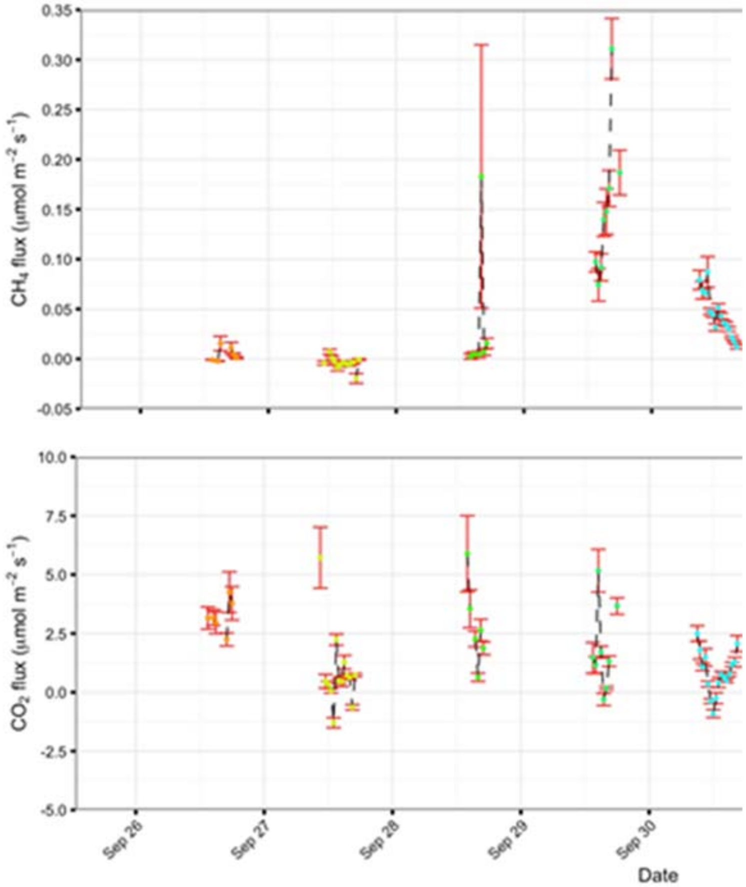

Figure 18. Flux of CH_4 and CO_2 measured by eddy covariance located downwind from injection site.

6.3.2 Flights Over Surface Release Site (Open Field)

Because reliable methane concentration data were not obtained on either of the previous surface release dates, the team brought a tank of methane gas into the open field and cracked open the valve to simulate a surface release. While the release rate is not known (but certainly in excess of 100 m^3/day), the objective was to provide a basis for comparison with methane concentrations observed at the subsurface injection site.

All processed and filtered concentration data obtained from flights 3 and 4 that were flown over the surface release site are plotted in Figure 19. The methane concentration measurements are plotted over an orthophoto made from aerial photos taken in July 2017, hence the difference in vegetation colour between the two site orthophoto underlays (Figure 16 versus Figure 19).

The two flights were flown manually because for unknown reasons, the drone would not fly in a pre-planned grid pattern, and the operator switched the flight mode to manual.

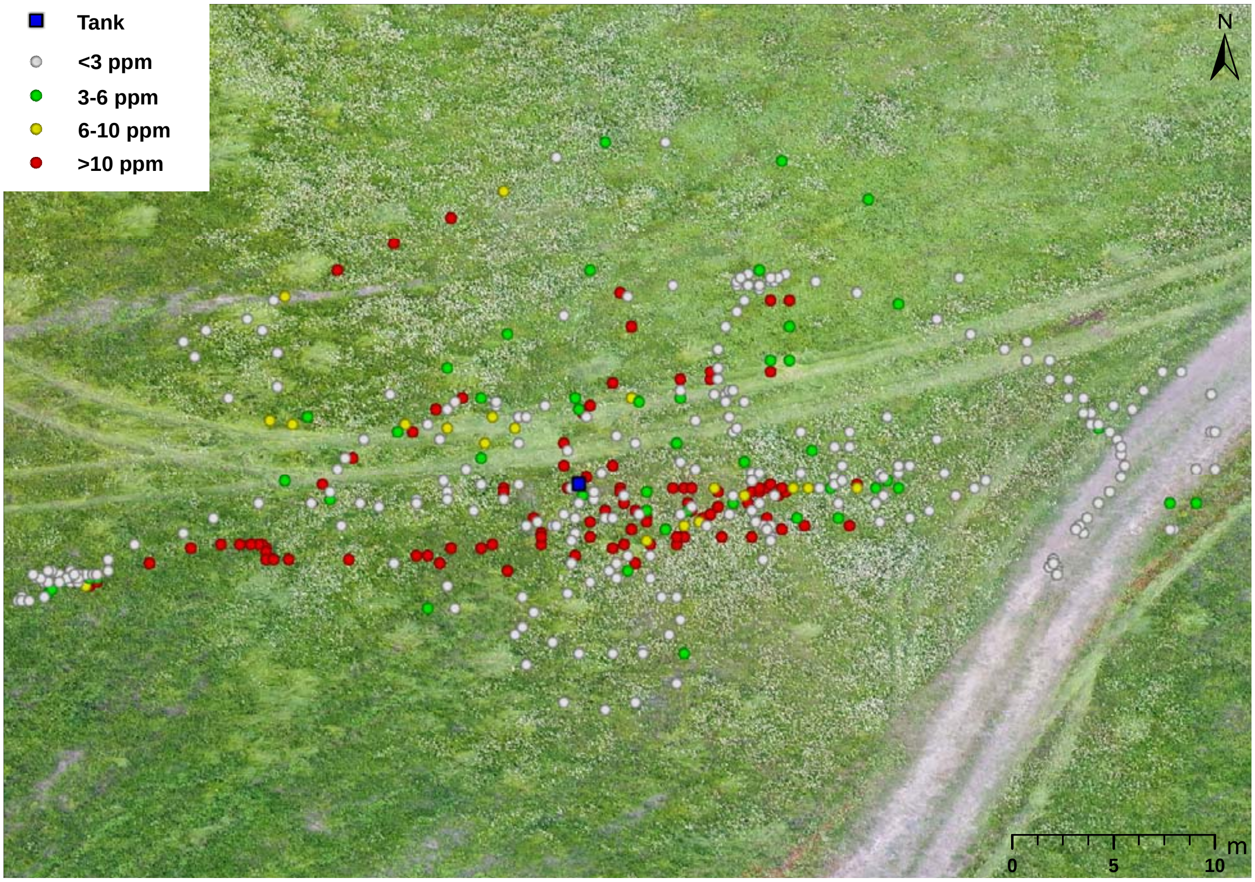

Figure 19. Average methane concentrations obtained from all flights over surface release site.

The concentration data obtained from flights 3 and 4 are individually plotted in the top and bottom figures, respectively, in Figure 20. It is worth noting that after the filtering of the flight 4 data, there were far fewer points plotted because the initial 25 m flying height above takeoff resulted in heavily error coded data due to insufficient laser beam reflection.

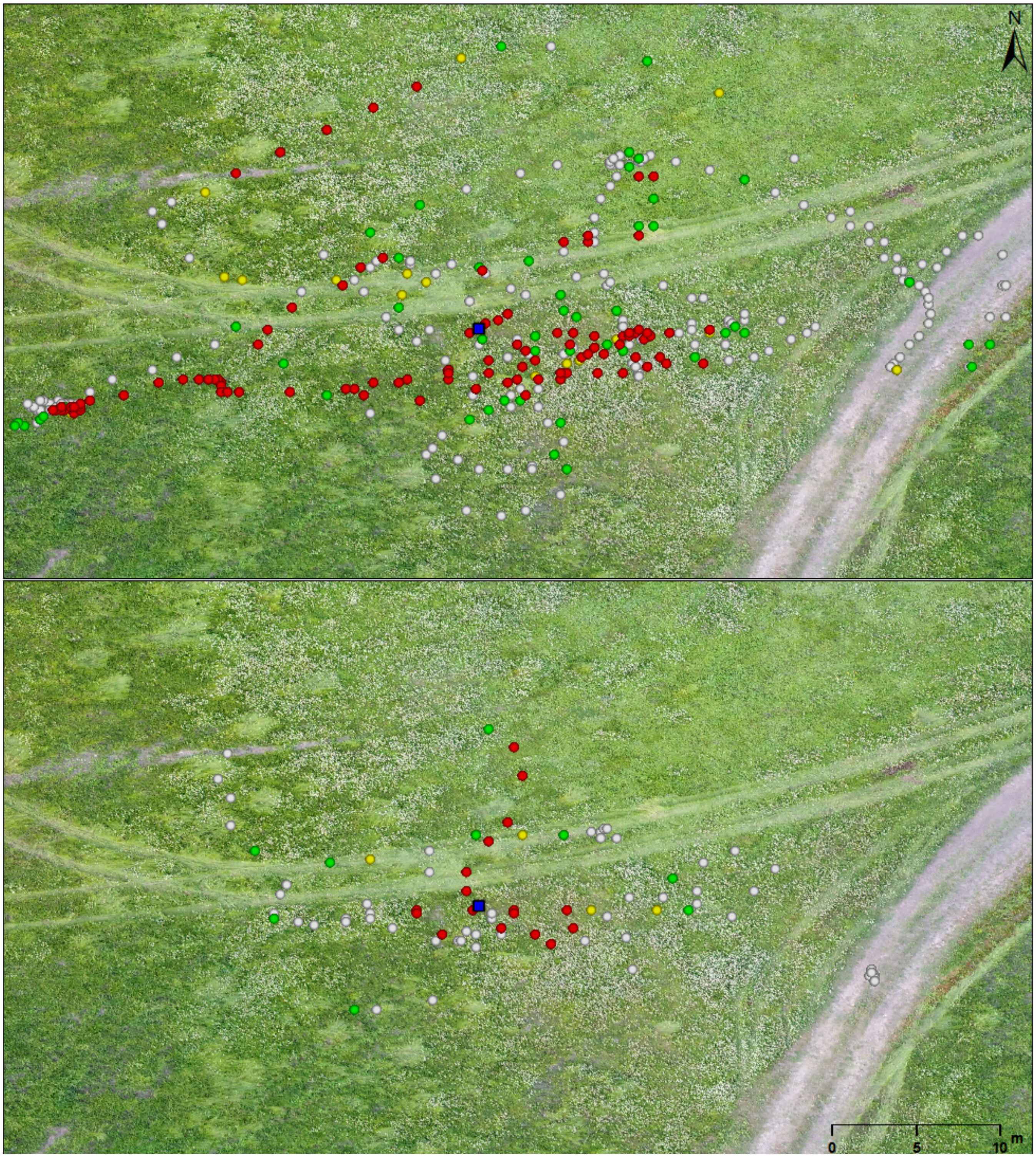

Figure 20. Average methane concentrations from flight 3 (top) and 4 (bottom) with the blue square showing the approximate methane release point.

The wind velocity was low in the open field and its direction was noted to be quite variable. This might help explain the wide dispersion of higher methane concentration measurements around the release point.

6.4 Impact of Drone Height on Measurement Intensity and Error Codes

One of the fieldwork objectives was to determine the height at which to fly the drone so that the methane sensor could provide reliable methane concentration measurements. Without doing any filtering of the data based on height, all 18,613 sensor measurements from the 5 flights conducted on September 28 were sorted based on the error code. In the histogram in Figure 21, the percentage of measurements taken for a given metre of drone height that have error codes not equal to 1 is shown.

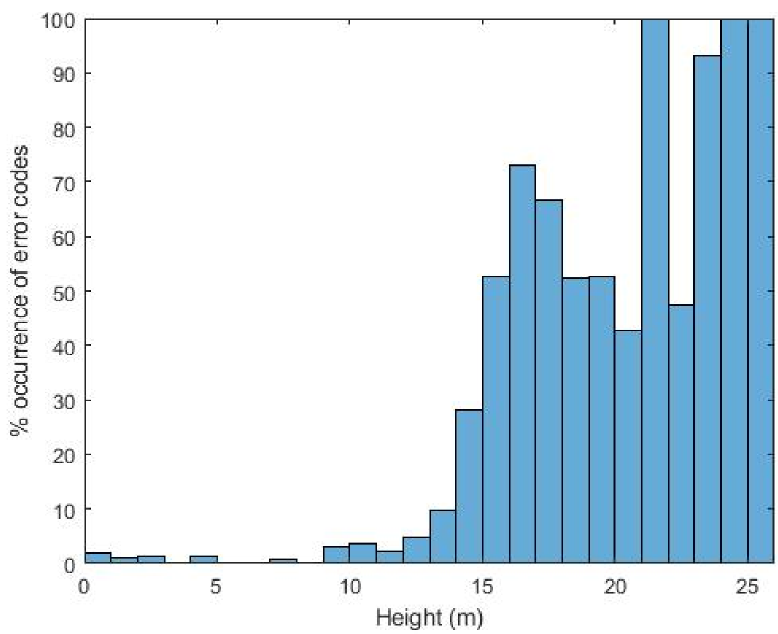

Figure 21. Sensor error code occurrence with drone height over grassy terrain.

Between 10 m and 15 m height, the percentage of measurements with abnormal error codes increases significantly. More than 50% of the readings are unreliable when the drone is more than 15 or 16 m above the ground. The data included in this plot are all from flights conducted on the same day (September 28) but at two different locations. However, each location consisted of flat ground covered with brown grass and other low vegetation.

All of the methane sensor measurements were also sorted by intensity to see if there is a direct correlation between intensity and error codes. The observed trend between intensity and error code from sorting the data from these flights is shown in Table 5. Error codes of 7 were not observed in the data, so the intensity range for this value is unknown.

Table 5. Error codes based on intensity range.

Intensity Range	Error Code
<20	5
20-49	0
>49	1

7 Future Fieldwork Plans

A new campaign of drone flights in conjunction with surface and subsurface methane gas release is planned for the summer of 2018. Lessons learned from this first phase of the investigation will be used to improve the drone testing methodology and to assess further the capabilities of a laser-based methane sensor mounted on a drone to monitor and detect fugitive emissions.

The test site for 2018 will be located a few kilometres to the east of the site used in 2017. The 2018 test site consists of flat grassy terrain in a large open field with occasional shrubs and small trees. The drone will be able to fly safely over the whole area at an elevation higher than 5 m.

The goal in 2018 is to better use pre-planned autonomous flights in a grid pattern to facilitate mapping of the shape of the methane plumes. Controlled (metered) surface releases of methane from a point source near the ground will be used again. In addition, a subsurface injection test will also occur. This time the methane will be injected at a greater depth and below the water table, and the quantity and duration of the injection will be longer. The flight heights will be between 6 and 12 m.

The test site is located within 500 m of an abandoned gas well. A test flight over this well will also be conducted. At this site, the flight height may go up to 15 m because better reflectivity is expected from the relatively bare ground. One objective of the testing is to evaluate the impact that vegetation type and density on the ground have on the reflected intensity of the laser beam. This will help to establish practical distance limits when using the laser-based methane sensor.

In addition to the drone-based work, the laser-based methane sensor will also be used in the normal hand-held mode at ground level to measure ambient methane levels and to investigate whether any methane is seeping from around the abandoned gas well.

8 Discussion and Conclusions

The fieldwork conducted in 2017 encountered a few challenges and learning opportunities. The laser-based methane sensor was damaged for one set of flights and did not yield reliable data. The logging software for the methane readings was inadvertently set up in an averaging mode for another set of flights which reduced the level of detail that was measured. Some flights were flown at an elevation above the ground that was too high for the laser-based methane sensor to yield reliable readings. The drone could not be flown in the desired autonomous grid-like flight pattern at some locations because either the flight control software was not performing normally or the drone operator was not comfortable at allowing the drone to fly autonomous at an elevation lower than the tree tops in a fairly constrict space. The knowledge gained from these trials and tribulations will be used to design the fieldwork planned for the summer of 2018.

Work is ongoing to interpret and compare methane measurements taken with the three different methods described in this report (i.e., drone-mounted laser, eddy covariance and surface efflux). Such a comparison is not fully developed and is more complex than it may seem because the measurements are derived in very different ways and in different units which are not directly comparable.

One key conclusion from this research is that a drone with a laser-based methane sensor can be used to cover a site such as a well pad of a few hectares with relative ease. In this application, the drone operator would likely be within good line of sight with the drone thus facilitating various flight options from manual control to autonomous pre-determined flight paths. A single flight or a few successive flights (with battery changes) could cover the area of interest in under an hour. This application of a drone with a laser-based methane sensor is mission ready with existing commercial hardware and software.

For a field application where a linear feature like a pipeline needs to be monitored there are some limitations. The flight time is limited (<15 minutes) for typical commercial drones that can carry the weight of the sensor/phone combination. For a pipeline, a single return flight along the feature can be conducted at a moderate flight speed of 4 to 5 m/s. In this case, the drone can cover only about 1.5 km of distance after allowing for take-off and landing with a reserve power supply. With a 10 Hz measurement rate, the methane concentration would be measured every 0.4 to 0.5 m or every 0.2 to 0.25 m for a return trip over the same ground. A 1.5 km flight distance will require permission under a Special Flight Operations Certificate and it will be nearly impossible to observe the drone at this distance. An operations strategy could be to place the drone operator in the middle of a 1.5 km section of pipeline so that the drone is never farther than 750 m away. Nevertheless, there are important practical constraints when using a multi-rotor drone for long sections of linear infrastructure.

The maximum practical height for using the Laser Methane mini-G sensor when flying over grassy terrain or low vegetation is approximately 10 to 12 m above the ground. At heights exceeding 15 m, more than half of the methane concentration measurements are unreliable as they are tagged with error codes that indicate a low return intensity of the laser beam and at heights above 20 m, very little useful data can be obtained. The error code is a function the reception of light reflected from the ground surface. Therefore, the maximum practical flying height likely varies based on the type of terrain and vegetation cover.

The ground where the tests were performed was fairly flat had less than 1 m of elevation difference. If the drone/sensor combination were used over ground with considerable elevation change, then a more complex flight path would be required to ensure that the drone remains at a constant height above the ground. This could be accomplished by use of a digital terrain model to pre-program a flight path that accommodates the changes in ground elevation. Another option is to add a small laser distance sensor to the drone to provide real-time height-above-ground measurements to the autonomous flight controller to move the drone vertically as it flies its programmed flight path. Both solutions exist today, but neither was used and tested in the fieldwork that was performed.

The methane detector was able to measure background or ambient methane concentrations in the air. At the test site, this value was roughly 1.7 ppm, although it ranged between 0.5 and 3 ppm. Thus when measured values exceeded roughly 3 ppm, this was fairly clear evidence that some of the released methane was being detected. Methane concentrations above 10 ppm were observed during the testing with methane releases at the surface and for the tests over the subsurface methane injection site.

For spatially concentrated methane plumes, the laser-based methane sensor can measure the presence of the methane without being located within the plume. This could be an advantage over other methane sensors that require sampling of the air containing the methane. The rapid sampling rate (10 Hz) is also helpful when the sensor is being carried by drone, which can travel much faster than a person can walk. The laser-based methane sensor cannot distinguish between a diffuse methane plume and a very concentrated methane plume as the measurement is always an 'average' over the length of the air column that laser beam is shot through. However, by repeating flights at different heights above the ground, it may be possible to get a rough assessment of the vertical concentration profile. However, this would be limited to a narrow range of heights above the ground that the sensor can effectively operate.

From the limited testing completed so far, it appears that the methane plume originating from a point source (surface release tests) and a diffuse source (subsurface release tests) varies in space and time, probably largely in response to changes in the wind velocity and direction, including wind turbulence near the ground surface.

The GPS location tags for each measurement contain errors. If the GPS on the Android phone is used to georeferenced the measurements, the errors can be many metres. The GPS on the drone is more accurate, and it was used to georeference the measurements reported here. Using the drone GPS coordinates takes more data post-processing effort to link these coordinates with the measured methane concentrations recorded by the GasViewer software on the Android phone. Whether this is an issue or not in practice will depend on the desired accuracy for the measurement locations.

A pipeline monitoring application where the pipeline route is in a narrow strip between trees, and the trees are taller than 10 to 20 m would require the drone to fly a long distance below the tree tops if a Laser Methane mini-G was used. This would require fairly accurate georeferencing for the drone position. The use of collision avoidance sensors on the drone could be used to help avoid collisions with trees.

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Appendix - Drone Specifications

The S1000+ weighs 4.4 kg and has a maximum takeoff weight of 11 kg. The drone has a diagonal frame width of 1045 mm. It uses a 6S 15000mAh battery, allowing it to fly for up to 15 minutes (@15000 mAh and 9.5 kg takeoff weight). The maximum power consumption is 4000 W whereas the hover power consumption is 1500 W (@9.5 kg takeoff weight).

The S1000+'s gimbal bracket is separated from the main frame by specifically designed dampers. This significantly reduces high-frequency vibrations. A 40 A electronic speed controller is built in to each arm. The 4114 pro motors, high performance 1552 folding propellers, and V-type mixer design combine to give each arm of the S1000+ a maximum thrust of 2.5 kg. Working environment temperature for the drone is -10°C to 40°C.