Application of the BC GHGMapper™ Platform for the Alberta Methane Field Challenge

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Whiticar, M.J., Hollenbeck, D., Billwiller, B., Salas, C.J. and Christensen, L.E. (2020): Application of the BC GHGMapper™ platform for the Alberta Methane Field Challenge; *in* Geoscience BC Summary of Activities 2019: Energy and Water, Geoscience BC, Report 2020-02, p. 87–102.

Introduction

Global atmospheric methane, an important greenhouse gas (GHG), has doubled in concentration to 1862 ppm since the pre-industrial Holocene (PIH; approx. 700 ppm, Hopcroft et al., 2015). It is currently contributing a radiative forcing of approximately 0.5 watts per square metre (W/m^2; approximately 17% of total GHG, Myhre et al., 2001), i.e., an increase in the global atmospheric heat balance since the PIH. This knowledge with respect to climate change issues means that it is critical to understand the natural and anthropogenic sources and sinks of methane. Globally, the oil and gas industry contributes an estimated 24% of global anthropogenic emissions (Saunois et al., 2016). In the United States, these fugitive emissions are approximately 2.3% of total natural gas production (Alvarez et al., 2018), so they represent a financial loss, as well as an environmental concern.

In Canada, the oil and gas sector is the largest industrial emitter of methane (44%) and comprises 26% of Canada's total GHG emissions (Environment and Climate Change Canada, 2018). Studies report that 53% of active wells in Alberta are leaking methane (GreenPath Energy Ltd., 2016) and 47% in BC (Atherton et al., 2017). Oil and gas operations in Canada, such as flaring and fugitive emission from equipment and well leaks, contribute approximately 8.5% to total greenhouse gas emissions (Bachu, 2017). After the energy and transportation sectors, fugitive releases are the third largest contributor to Canadian GHG emissions (The Conference Board of Canada, 2013).

New legislation is being introduced to reduce Canadian emissions by 40–45% (Canada Department of Justice, 2019; Environment and Climate Change Canada, 2019a). One of the challenges in meeting these new regulations is the real identification and quantification of the fugitive emissions and quantitative verification of their mitigation. This is in contrast to the simple estimation (nonmeasurement) of emissions, using emission factors, that is currently being widely used to calculate and report emission inventories, e.g., National Pollutant Release Inventory (Environment and Climate Change Canada, 2019b, c).

A major constraint for the reduction in emissions is that the currently practiced methodologies to detect leaks are based on the conventional, visual, optical-gas imaging (OGI) leak detection surveys. Optical-gas imaging was developed by the United States Environmental Protection Agency's (EPA) Leak Detection and Repair (LDAR) program, an offshoot of the EPA Method 21 (United States Environmental Protection Agency, 2017). Another constraint is that the methane releases associated with the upstream operations of oil and gas can be either stochastic or more continual. The former, episodic releases make it challenging for non-continuous monitoring. The GHGMapper™ platform, described below, offers one of the first high performance, quantitative systems to make GHG measurements.

The GHGMap project is a three-year research programme to build and demonstrate the cost and logistical effectivity of the team's mobile sensing platform for greenhouse gas measurements (Geoscience BC, 2019). It is being undertaken by a consortium of groups, which includes Geoscience BC, Geochemical Analytic Services Corporation, InDro Robotics Corp., Western Economic Diversification Canada and NASA/Jet Propulsion Laboratory (NASA/JPL). This project includes testing of the GHGMapper platform, which conducts detailed, aerial, un-

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manned regional and site surveys of atmospheric GHG emissions. The GHGMapper combines the technologies of a high sensitivity open path laser spectrometer (OPLS) developed by NASA/JPL (Christensen, 2014) with a small unmanned aerial vehicle (sUAV) and 3-D sonic anemometry (Figure 1; Whiticar et al., 2018). The GHGMapper platform can rapidly measure (10 Hz measurement frequency) parts per billion levels (ppb) of greenhouse gases in the atmosphere, such as methane, ethane and carbon dioxide. The small size/weight and low power consumption of the OPLS together with the precise operation and navigation of the sUAV, make this system ideal for the detection and quantification of GHG emissions and budgets.

Over the past three years of this project, the team has quantified methane emissions at well sites, gas compressor stations, pipelines, landfills, feedlots, etc. The initial program focused on major GHG emitters in western Canada, i.e., BC and Alberta (Whiticar et al., 2018, 2019), but recently expanded to measure landfills and dairy farms in California.

This paper describes the team's participation in the Alberta Methane Field Challenge (AMFC) from June 10 to 21, 2019, near Rocky Mountain House, Alberta. Following a competitive selection process by AMFC, the GHGMap team was invited to participate. The AMFC was conceived by the Alberta Upstream Petroleum Research Fund (AUPRF), which is an industry-sponsored fund supported by the Canadian Association of Petroleum Producers (CAPP) and the Explorers and Producers Association of Canada (EPAC; Petroleum Technology Alliance Canada, 2019). The AMFC is a collaboration between the Government of Alberta, the Alberta Energy Regulator (AER) and industry, with the goal to assess the real-world performance of new methane sensing technologies in comparison with LDAR using OGI. Specifically, the AMFC seeks to compare, by conducting intensive field tests, alternative cost-effective methane emission detection and quantification technologies and methodologies. A detailed discussion and comparison of the joint AMFC findings will be published elsewhere.

Figure 1. The GHGMapper™ system with open path laser spectrometer/small unmanned aerial vehicle (OPLS/sUAV) platform.

During the AMFC, the GHGMapper system provided instantaneous, real-time measurement and data streaming to the base station. The methane data collected is stored in real-time on the OPLS and is simultaneously sent to the ground receiver station for data acquisition (Whiticar et al., 2018, 2019). The high precision navigation on the drone allows repeatable positioning of the sUAV within 50 cm and extremely reduced flying altitude (1–10 m) in contrast to helicopter or fixed-wing aircraft surveys (>150 m). These high precision, close to the surface measurements by OPLS/sUAV combined with the low flight velocities (1–3 m/s) permit increased and precise detection capabilities (Figure 2), as well as increased measurement efficiency and safety. These capabilities are unparalleled by other methods, such as handheld monitors, land vehicle-mounted mobile sensors, manned aircraft or satellites.

The team's proprietary software provided immediate feedback and back-trajectories to target leaks. The GHGMapper system only needs manual intervention at the start and end of the flights and does not necessarily need line-of-sight for the detection. However, for the AMFC, visual line of sight (VLOS) operation of the sUAV was used exclusively. The mobility of this method allowed easy and safe access to facility infrastructures, which would otherwise present challenging health, safety and environment (HSE) constraints to those using OGI/LDAR methods. In addition, during the AMFC this aerial methodology demon-

Figure 2. The GHGMapper™ system (open path laser spectrometer/small unmanned aerial vehicle platform) surveying at an Alberta Methane Field Challenge facility, June 2019.

strated the system's quick, efficient and therefore cost-reducing operations. Even though the GHGMapper system can measure other smaller gas species that are relevant to the gas energy industry, i.e., ethane, carbon dioxide, hydrogen sulphide and ammonia, etc., the system was configured to only measure methane at the AMFC. The team's approach has already been successfully demonstrated to several natural gas companies in northeastern BC.

In contrast to conventional OGI/LDAR methods, the GHGMapper platform offers an important feature and advantage – the capability to make truly, **quantitative**, methane mass flux measurements, i.e., kg $CH_4/m^2/h$, not simply heat maps or estimated emission rates. Flux is the mass of a chemical constituent (methane) transported across a vertical plane over time. In concert with high frequency and high sensitivity aerial CH_4 measurements by OPLS/sUAV, the team has pioneered the use of sonic anemometry to fly and create two-dimensional vertical flux planes, i.e., Gas Flux Curtains™, to provide quantitative cross-sectional mass transport measurements of methane on well and facility scales, as shown schematically in Figure 3.

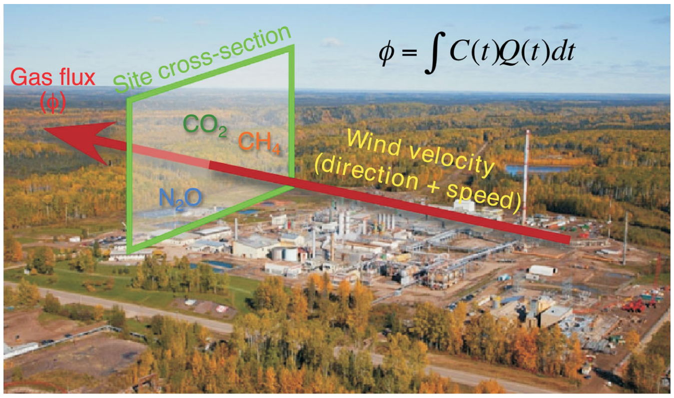

Figure 3. Schematic of quantitative, methane mass flux measurements with GHGMapper™ Gas Flux Curtain™ concept. Mass flux (ϕ) is the rate of mass flow of methane per unit area (kg $CH_4/m^2/s$), where concentration (C) and flow (Q) are integrated over time (t).

A typical methane Gas Flux Curtain determination is conducted by making continuous methane measurements while flying a series of horizontal transects that are orthogonal to the wind direction and vertically offset (approx. 1–2 m). An example of this flux plane of measurements is shown in Figure 4.

The methane mass flux (ϕ) is calculated by integrating over time (t) the air flow (Q) determined from the wind velocity (speed and direction) with the methane concentration (C), according to equation 1:

$$\phi \equiv \int C(t)Q(t)dt \tag{1}$$

Figure 5 is a visual representation (heat map) of the flux intensities at any position in the flux plane. In this example, elevated methane is generally crossing the flux plane below 10 m. To calculate the emissions from a particular site, it is critical to position the Gas Flux Curtain downwind of the facility. If necessary, a flux plane also needs to be conducted on the upwind side of the facility to determine and subtract the quantity of methane carried onto the site, i.e., remove the contribution of methane from offsite sources and normal atmospheric background. At the AMFC, this latter value ranged over the different sites from 1.9 to 2.1 ppm. Methane fluxes are frequently reported in North America as standard cubic feet per hour (SCFH; at 15°C, 101.325 kPa), but also in cubic metres or tonnes CH_4 per year (m^3 CH_4/yr. or tonnes CH_4/yr.). For conversion, 1 SCFH of methane is 0.02832 m^3 CH_4/h or 0.1775 tonnes CH_4/yr., which is approximately 9.3 gigajoules (GJ)/yr. of natural gas (depending on the natural gas composition).

Background methane abundance currently has a global value of 1.86 ppm (Dlugokencky, 2019), but there can

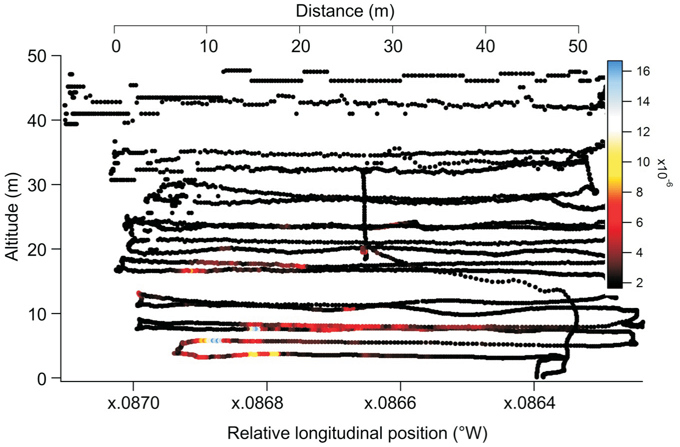

Figure 4. Example of flight tracks for creating a GHGMapper™ Gas Flux Curtain™. The colours on the tracks show relative light absorption of methane (measured by the open path laser spectrometer [OPLS]), which is directly proportional to concentration.

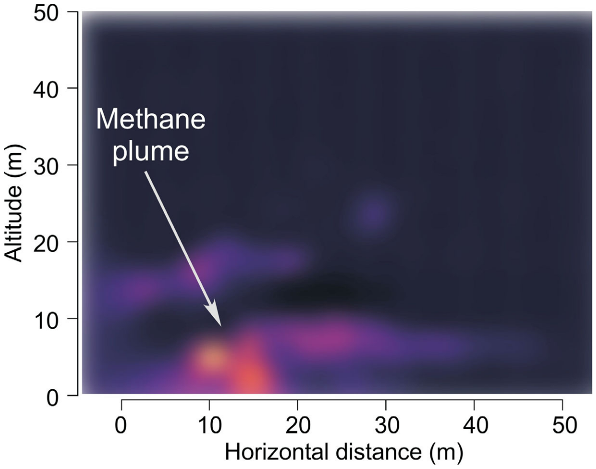

Figure 5. Example of a heat map representation of a GHG-Mapper™ Gas Flux Curtain™. The hotter colours indicate regions of higher methane concentrations.

be significant local deviations. For example, O'Connell et al. (2019) reported average values of 2.41, 1.97 and 2.03 ppm CH_4 around Lloydminster, Peace River and Medicine Hat, Alberta, respectively. In the BC Peace River region, Atherton et al. (2017) gave a mean methane value of 1.90 ppm, similar to that found by Whiticar et al. (2018). Petron et al. (2012) similarly reported methane background levels in Colorado of 1.8 to 1.9 ppm. In contrast, background methane values up to 11.9 ppm were found to be associated with Barnett Shale gas extraction in the Dallas/ Fort Worth Metroplex (Rich et al., 2014). Thus, it is important to determine the true methane background levels at each site.

AMFC Operations

The GHGMap operations from June 8 to 22 for the AMFC included mobilization/demobilization, training, briefings, field surveys and daily reporting. Forty-two of a possible 50 sites were surveyed over 10 days (June 12 to 21) during the AMFC, i.e., travelling to approximately five different sites each day. Two sites were resurveyed on a different day for comparison. Table 1 gives the types of equipment and components that were tested at the 42 sites during the AMFC program.

Figure 6 shows a map with the distribution of the 50 AMFC sites. One of the conditions for participation in the AMFC was maintaining strict confidentiality about the locations and operators of the AMFC field sites. Therefore, the sites in Figure 6 are only given as distances (in km) from a fixed longitude/latitude reference point. The distance was calculated using great-circle distance with the haversine formula, i.e., the shortest distance over the Earth's surface (Movable Type Ltd., 2019).

Each day of the AMFC, the test teams surveyed approximately five sites, which were also surveyed using conventional LDAR/OGI techniques for comparison. The results of the different approaches used in the AMFC will be reported elsewhere. This paper here will focus only on three representative examples of site surveys conducted by the GHGMapper during the AMFC. For each site selected here, the methane emission mass flux calculation is given as well as some of the following visual representations:

- flight track of GHGMapper survey at the site,
- time series plot of GHGMapper measured methane concentration with measurement altitude,
- survey heat map showing anomalies if present and the vectors to the emission source, and/or
- Gas Flux Curtain.

Example 1: Site 15 – No Detectable Emission

At some of the AMFC sites, methane emissions were nonexistent or were at only very low detection levels. Site 15 was a typical example of a site without emissions. This site is a well pad with a single pump jack located in an open field. Table 2 lists the meteorological conditions that existed during the GHGMapper survey.

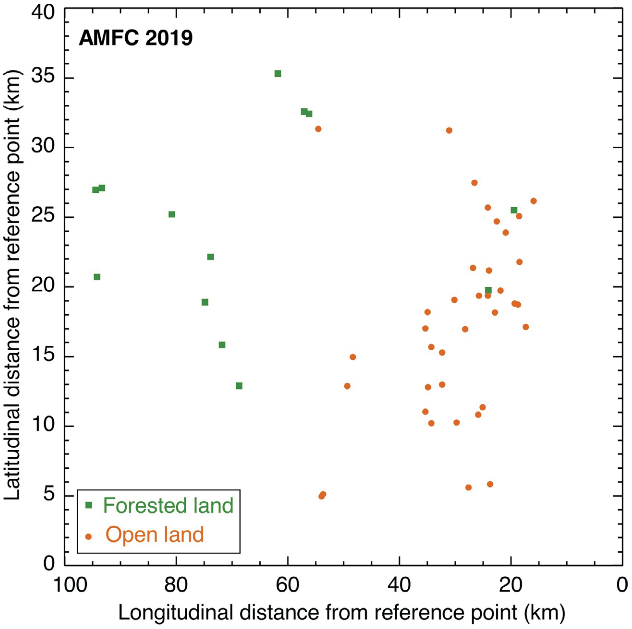

Figure 6. Location map of Alberta Methane Field Challenge (AMFC) survey sites using distance to fixed latitudinal and longitudinal reference points.

Table 1. Types of equipment and components tested during the Alberta Methane Field Challenge.

Types of equipment	Sample components
Separator	Thief hatch, threaded connection
Tank	Tank level indicator, flange connection
Wellhead	Tank pressure/vacuum relief valve, open ended line/vent
Compressor	Other tank component, engine (including fuel/start gas)
Engine	Controller, valve
Catadyne heater	Regulator, actuator
Pneumatics	Pressure safety valve (psv), chemical injection pump, instrument air tubing, door seal, pneumatic pump, compressor, cylinder head, pump packing, valve stem

Table 2. Meteorological conditions during time of measurement at Alberta Methane Field Challenge (AMFC) sites 15, 30 and 22.

AMFC site (flux)	Wind speed (m/s)	Wind direction (°)	Temperature (°C)	Pressure (kPa)	Relative humidity (%)
15 (no)	2.7 ±0.9	-34 ±12	15.9	89.85	74
30 (low)	1.2 ±0.7	6 ±80	21.3	89.80	44
22 (high)	4.0 ±0.9	-50 ±20	16.7	89.86	62

The 15 min survey at site 15 started with a full sweep of the property circumference. This was followed by the creation of a series of Gas Flux Curtains downwind of the single pump jack on site (Figure 7). At the outset, there was concern of contamination from an upwind site, but no elevated methane levels were observed at any point. Figure 8 shows the 15 min time series plot with both the GHGMapper flight altitude and real time methane concentration. The site survey in Figure 9 indicates that no anomalous or fugitive emissions were detected at AMFC site 15 (Table 3).

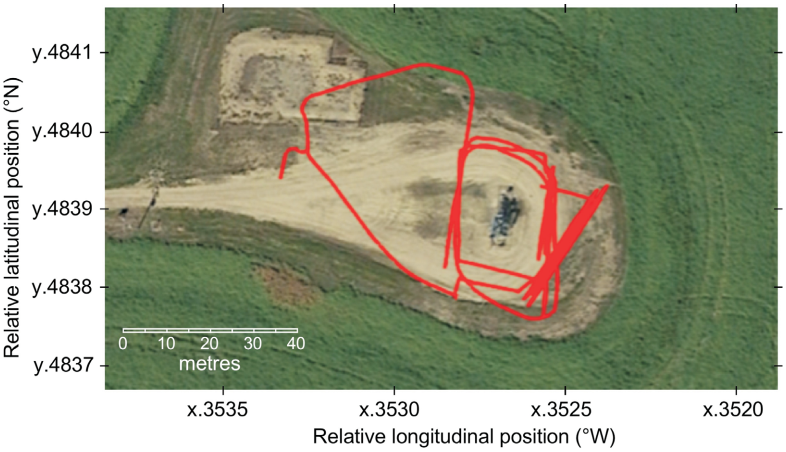

Figure 7. Flight track (red line) for GHGMapper™ survey at Alberta Methane Field Challenge site 15.

Example 2: Site 30 – Low Methane Emissions

Site 30 of the AMFC consisted of a well pad with an operating pump jack and holding tank and building located in an open field. Table 2 lists the meteorological conditions that existed during the site 30 survey.

The GHGMapper survey consisted of methane measurements on an initial inspection flight of the property circumference (Figure 10). This initial assessment was followed by creating Gas Flux Curtains downwind on the west side of the site. The altitudes and corresponding methane concentrations are indicated in the time series plot (Figure 11). Several measurements recorded moderately elevated methane concentrations of 4–6 ppm, i.e., 2–3 times the background atmospheric level. The localization heat map (Figure 12) shows, using the warmer colours, where the methane concentrations were elevated. In addition, the coloured vectors on Figure 12 indicate the trajectory to the gas source using the

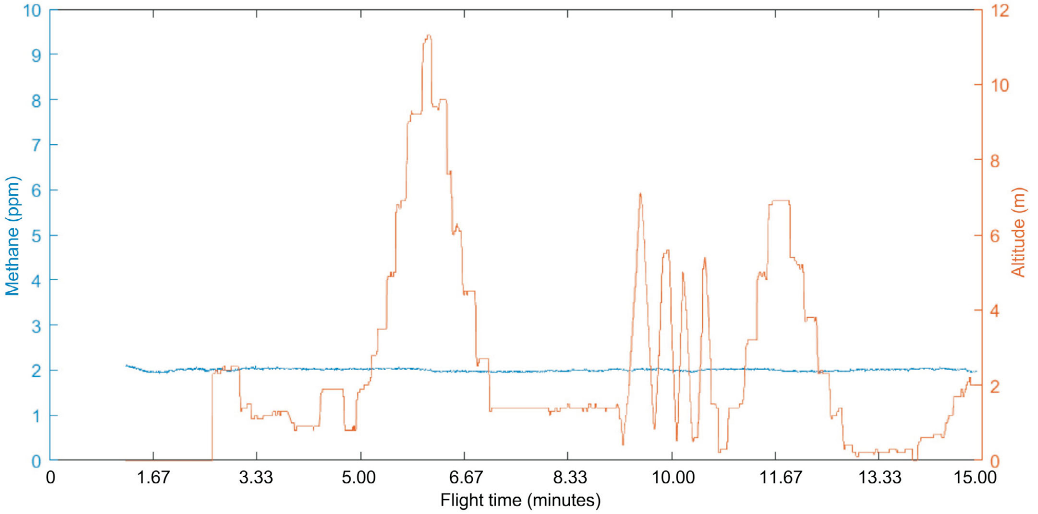

Figure 8. The GHGMapper™ flight time series plot (approx. 15 min) of methane concentration (blue trace) and altitude of the small unmanned aerial vehicle (orange trace) for Alberta Methane Field Challenge site 15. No methane anomalies or fugitive emissions were detected.

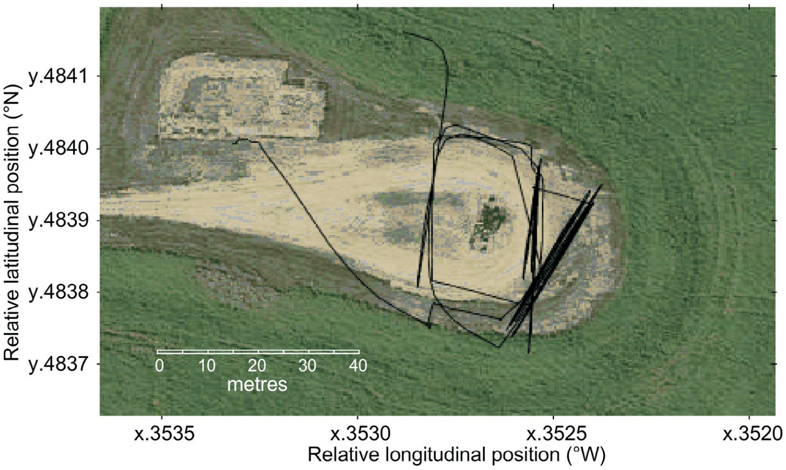

Figure 9. Heat map of the Alberta Methane Field Challenge site 15 GHGMapper™ survey. The absence of colours on the transect line (black line) indicates that no elevated methane levels were detected.

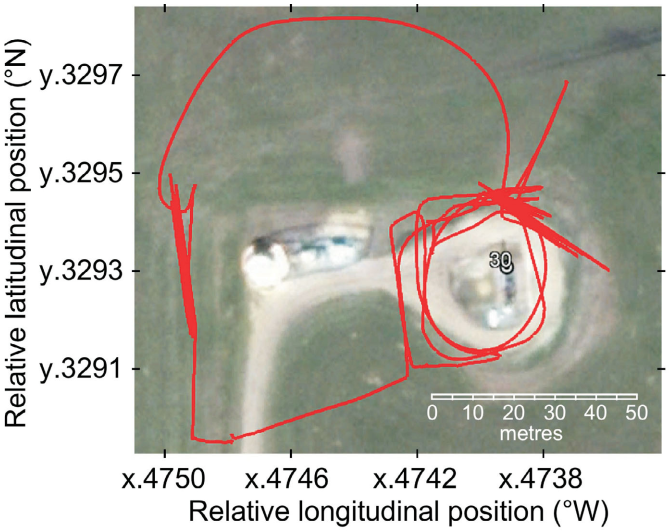

Figure 10. Flight track (red line) for GHGMapper™ survey at Alberta Methane Field Challenge site 30 (indicated).

simultaneous 3-D sonic anemometry measurements to derive wind direction and speed. The survey indicates that there is an emission source at the south end of the pump jack.

The Gas Flux Curtain (Figure 13) calculated the methane emissions from site 30 to be between 5.8 ±6.1 SCFH (1.0 tonnes CH_4/yr.; Flight 3) and 6.2 ±4.3 SCFH (1.1 tonnes CH_4/yr.; Flight 4; Table 3).

Example 3: Site 22 – High Methane Emissions

Site 22 (Figures 14, 15) is an example of an AMFC site where high methane emission rates were measured. The survey started with creating Gas Flux Curtains on the western buildings and then moving toward the east (Figure 15). The flights were interrupted twice due to rain concerns and this resulted in abbreviated curtains (Figure 16). The wind became increasingly variable as the time on site grew until the rain started. The prevailing meteorological conditions are presented in Table 2.

The surveys at site 22 found multiple indications of elevated methane from a variety of clustered pieces of equipment. The main pieces of infrastructure included the compressor, tanks just south of the compressor, the valve and fittings on the south side of site, and the buildings in the centre (Figure 14).

Two examples of surveys where elevated methane was measured are shown in Figure 16. A maximum concentration of 18 ppm was detected

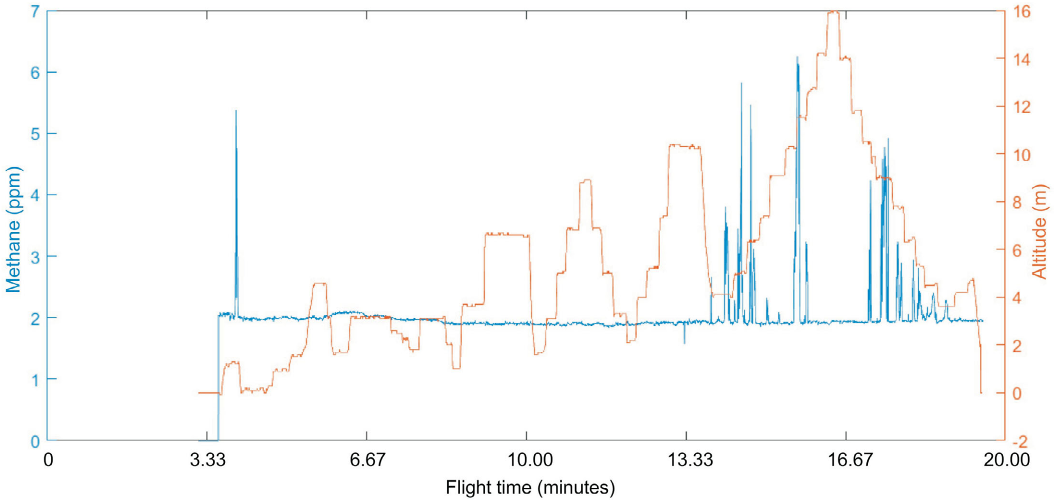

Figure 11. The GHGMapper™ flight time series plot (approx. 17 min) of methane concentration (blue trace) and altitude of the small unmanned aerial vehicle (sUAV; orange trace) for Alberta Methane Field Challenge site 30. Low methane anomalies were detected.

Table 3. Methane (CH_4) emission rates and sources measured by GHGMapper™ during surveys at the Alberta Methane Field Challenge (AMFC). Note: * at some locations, methane emissions were only measured in parts per million. Abbreviations: GJ, gigajoules; kPa, kilopascal; OGI, optical-gas imaging; SCFH, standard cubic feet per hour.

AMFC site number	Location	Emission rate of CH_4				Vent or leak	Continuous or intermittent	Distance emitter to sensor (m)	Emission location	Emission description/comments
		SCFH or ppm*	m^3/ yr.	tonnes/ yr.	tonnes/ yr./site					
1	1	10 ±5.6	2481	1.8	1.8	Both	Continuous	9.3–14.5	Building, pump jack, well head	Vent on building, and possible leak for tank and well head
2	1	6.0 ±4.7	1488		1.5	Both	Continuous	21, 7	Building, pump jack, well head	Vent on building, possible leak for well head and pump jack
	2	8.7 ±10	2158	1.5		Vent	Continuous	7	Tank	Detection at level of thief hatch
3	1	1.18 ±0.47	293	0.2	0.4	Leak	Continuous	18–20	Well head	Small near well head
	2	0.84 ±0.65	208	0.1		Leak	Continuous	15	Tanks	Curtain behind fenceline to top of tank, small emissions detected
4	1	43.4 ±24	10766	7.7	7.7	Both	Continuous	7–11	Building, pump jack	Vent on building, and emission from pump jack engine
	2	10 ppm	0	0.0		Vent	Continuous	15–20	Tank	Detection at level of thief hatch
5	1	12 ±7.8	2977	2.1	10.8	Leak	Continuous	7	Pump jack, well head	Leak indications were at ground level near pipes and fittings
	2	49 ±32	12155	8.7		Both	Continuous	10	Pump jack, well head	Leak indications were at ground level near pipes and fittings
	3	30 ppm	0	0.0		Both	Continuous	13.5	Building, pipe fittings	Wind variance difficult to calculate emission
6	1	26.5 ppm	0	0.0	0.0	Leak	Continuous	7.5	Pump jack	Leak
	2	26 ppm	0	0.0		Leak	Continuous	7.5	Engine	Leak
7	1	0.5 ±3.4	124	0.1	1.5	Both	Continuous	10	Building, tanks, well head	Leak indications were at ground level near pipes and fittings
	2	8.0 ±2.9	1984	1.4		Both	Continuous	10	Building, tanks, well head	Leak indications were at ground level near pipes and fittings
9	1	27 ±103	6698	4.8	81.6	Both	Continuous	15–20	Compressor	Doors open, compressor on, most emission detected at altitude
	2	158 ±263	39193	28.1		Both	Continuous	15–30	Compressor, building	Curtain along east and west side
	3	8.5 ±9.7	2108	1.5		Both	Continuous	15–30	Flare	Concentration detected away from ground, smaller than other leaks
	4	266 ±232	65983	47.2		Both	Continuous	15–30	Compressor, building, tanks, well	Curtain picked up lots of different sources due to variability
10	1	18 ±11	4465	3.2	3.2	Both	Continuous	11.5	Tank, piping, building	Larger spread leak by tree line low in altitude, multiple sources
11	1	4.7 ±3.9	1166	0.8	0.8	Both	Continuous	9	Emulsion tanks	Leak indications were at ground level near pipes and fittings
	2	1–2 ppm	0	0.0		Vent	Continuous	13.5	Building	Leak indication after the building doors open
12	1	29 ±36	7194	5.1	27.9	Leak	Continuous	15.6	Well head	Low lying detection
	2	128 ±85	31751	22.7		Both	Continuous	16–30	Well head, building	Low and high altitude detection, multiple leaks
13	1	0	0	0.0	1.2			7–23	Site overview	No indications
	2	7 ±2	1736	1.2				100+	Offsite property	Wide oscillations, indications of small upwind leak
15	1	0	0	0.0	0.0	None		7–15	Pump jack, engine, well head	No detection
16	1	0	0	0.0	0.0	None		15–35	Building, tank, well head, piping	No detection
17	1	2.0 ±1.1	496	0.4	0.4	Leak	Intermittent	7–10	Pump jack (south side)	Low level leak
18	1	1.2 ±3.2	298	0.2	0.2	Leak	Continuous	13–18	Pump jack	Measurement low lying likely from well head or engine
19	1	0	0	0.0	0.0			7–40	Site	High wind gust, grounded survey
20	1	1.5 ppm	0	0.0	0.0	Vent	Intermittent	40	Building	Detection after door was opened while aircraft on ground
21	1	0	0	0.0	0.0			10–30	Whole site	No emissions data

Table 3 (continued)

AMFC site number	Location	Emission rate of CH_4				Vent or leak	Continuous or intermittent	Distance emitter to sensor (m)	Emission location	Emission description/comments
		SCFH or ppm*	m^3/ yr.	tonnes/ yr.	tonnes/ yr./site					
22	1	2.7 ±1.4	670	0.5	53.5	Both		17	Central/west buildings and tanks	Detected small concentrations metres off ground cluster buildings
	2	0.4 ±0.2	99	0.1		Leak		10	Pipeline, fittings, valves	Low level detection
	3	14 ±20	3473	2.5		Both		40–60	Buildings, tanks, pipeline	Curtain captured emission from west at low and high altitude levels
	4	144 ±36	35720	25.6		Both		40–100	Entire site	Curtain aimed to hit most of site based on wind direction at the time
	5	37 ±12	9178	6.6		Both		40–60	Buildings, tanks, pipeline	Low lying emissions, no compressor emissions detected
	6	28 ±10	6946	5.0		Leak		30	Tanks	Some mixing with compressor emissions
	7	75 ±26	18604	13.3		Both		30	Compressor	
23	1	2.9 ±0.9	719	0.5	57.2	Leak	Continuous	22	Underground tank	Weak low lying detection
	2	17 ±5.7	4217	3.0		Leak	Continuous	9	Tank	Strong sharp indications
	3	35 ±10	8682	6.2		Leak	Continuous	7	Well head	Strong sharp/wider indications
	4	205 ±71	50852	36.4		Leak	Continuous	40–60	Northern pipeline and buildings	Sharp and wider indications
	5	62 ±12	15380	11.0		Leak	Continuous	35–40	Central tanks and buildings	Low, medium and high lying leaks
24	1	56 ±21	13891	9.9	32.5		Continuous	7–10	Building	Detected relatively low lying leak
	2	127 ±45	31503	22.6			Continuous	7–10	Building	Detected relatively low lying leak
25	1	25 ±8.0	6201	4.4	4.4	Leak	Continuous	15–25	Tanks, piping	Fairly strong consistent indications
27	1	0.35 ±0.67	87	0.1	0.1			10–50	Tank	Small hits at lower altitudes
30	1	5.8 ±6.1	1439	1.0	1.0	Leak	Continuous	20	Tank	Both low and high lying leaks
	1	6.2 ±4.3	1538	1.1		Leak	Continuous	20	Tank	Both low and high lying leaks
31	1	1.2 ±0.9	298	0.2	6.3	Leak	Continuous	7	Well head	Low lying leak
	2	23 ±13	5705	4.1		Leak	Continuous	7–20	Entire site	Morning
	3	3.0 ±2.8	744	0.5		Both	Continuous	20	Building	Evening
	4	2.1 ±2.7	521	0.4		Both	Continuous	14	Pipeline, building	Evening
	5	0.7 ±1.8	174	0.1		Both	Continuous	14–26	Pipeline, buildings	Evening
	6	0.7 ±5.4	174	0.1		Both	Continuous	26	Building	Evening
	7	4.7 ±1.5	1166	0.8		Both	Continuous	14–26	Buildings, tanks, pipeline	Evening
32	1	7.0 ±1.5	1736	1.2	3.2	Both	Continuous	15–40	Building, well head	Curtain to east of building downwind of both well head and building
	2	9.8 ±3.4	2431	1.7		Leak	Continuous	15–40	Building, well head	Curtain to east of building downwind of both well head and building
	3	1.4 ±0.4	347	0.2		Leak	Continuous	10–13	Tank	Low lying measured to east of tank
33	1	45 ±11	11163	8.0	8.0	Leak	Continuous	15	Pump jack, building	Low lying leak
34	1	7.3 ±5.5	1811	1.3	2.8	Vent?	Continuous	11	Pump jack, building	Consistent measurements low lying by building
	2	3.2 ±1.3	794	0.6		Leak	Intermittent	17	Tank	Sparse measurements high and low lying
	3	2.5 ±1.2	620	0.4		Vent?	Continuous	11–17	Pump jack, building	Small measurements
	4	2.5 ±0.9	620	0.4		Leak	Intermittent	11	Tank	Small measurements
37	1	6.8 ±2.0	1687	1.2	1.2	Leak	Continuous	14	Tanks, piping	Fairly strong consistent indications

Table 3 (continued)

AMFC site number	Location	Emission rate of CH_4 SCFH or ppm*	m^3/ yr.	tonnes/ yr.	tonnes/ yr./site	Vent or leak	Continuous or intermittent	Distance emitter to sensor (m)	Emission location	Emission description/comments
38	1	14.4 ±6	3572	2.6	3.5	Leak	Continuous	20–50	Site overview	Very low ppm, indication of a leak upwind
	2	1.9 ±0.5	471	0.3		Leak	Continuous	20	Pump jack	Leaks detected at 1–4 m altitude
	3	3.5 ±1.7	868	0.6		Leak	Continuous	14–17	Building	Low lying leaks
39	1	28.7 ±11.6	7119	5.1	13.9	Both	Continuous	11–15	Well head, building, tanks	Mix of low and high altitude emissions, suspect building vent or tank
	2	16.7 ±6.2	4143	3.0		Vent	Continuous	11–15	Well head, building, tanks	High level detection, suspect vent on building
	3	26.6 ±10	6598	4.7		Both	Continuous	7–25	Compressor building, pipeline	High level leak, suspect building vent or structure and pipeline
	4	6.1 ±2.7	1513	1.1		Leak	Continuous	7–9	Compressor building	Low level leaks
40	1	1.6 ±0.45	397	0.3	0.3	Leak	Continuous	7–10	Well head, tank	Low level leaks
41	1	31 ±7	7690	5.5	5.5	Leak	Continuous	17–20	Building	Consistent measurements from building/tank area possibly
42	1	7.2 ±5.7	1786	1.3	1.9	Both	Continuous	7–15	Tank, building	Bunch of small leaks near ground
	2	2.5 ±2.8	620	0.4		Leak	Continuous	10–15	Well head	Curtain by well head
	3	1.1 ±1.5	273	0.2		Leak	Continuous	10	Building	Small indications
43	1	52 ±13	12899	9.2	9.2	Leak	Continuous	14	Building	Low lying leak
43 repeat	1	29 ±9	7194	5.1	5.1	Leak	Continuous	20	Building	Low lying indications
44	1	29 ±27	7194	5.1	5.1	Leak	Continuous	10	Compressor, building	Site level emission measurement
46	1	1.9 ±1.1	471	0.3	0.3	Vent	Intermittent	20	Building, well head	Faint measurement only after doors opened by OGI crew
47	1	255 ±83	63255	45.3	52.4	Leak	Continuous	14	Tank	Low level leak with large indications
	2	25 ±16	6201	4.4		Both	Continuous	15	Buildings, well head	Relatively low level indications on each side of the site
	3	15 ±4	3721	2.7		Leak	Continuous	15	Well head	
47 repeat	1	1.5 ±0.9	372	0.3	2.4	Leak	Continuous	10	Tank	Small hits at lower altitudes
	2	12 ±32	2977	2.1		Leak	Continuous	10–20	Well head, pump jack, building	Few indications at low and medium altitudes
48	1	4.8 ±1.4	1191	0.9	1.9	Leak	Continuous	13	Well head	Low lying sharp indications
	2	5.2 ±1.9	1290	0.9		Leak	Continuous	17–73	Pump jack, well head	Low and high lying indications
	3	0.66 ±0.17	164	0.1		Vent?	Continuous	13	Tank	Small indications
	4	0.3–0.6 ppm	0	0.0			Continuous	7	Building	Small low lying indications
49	1	15 ±15.5	3721	2.7	2.9	Leak	Continuous	10	Building, well head	Low lying detection, majority of detection pointed towards building
	2	1.4 ±0.95	347	0.2		Leak	Continuous	12	Tank	Low lying detection at low emission levels
50	1	0.3 ±0.1	74	0.1	2.4		Intermittent	20	Building	High wind variance, low wind speed
	2	0.3 ±1.0	74	0.1			Intermittent	14–20	Building, compressor	High wind variance, low wind speed
	3	2.6 ±0.7	645	0.5			Intermittent	14	Compressor	High wind variance, low wind speed
	4	2.4 ±2.0	595	0.4			Intermittent	14–20	Building, well head, compressor	High wind variance, low wind speed
	5	7.9 ±1.0	1960	1.4			Intermittent	30–65	Site overall	High wind variance, low wind speed

Average	26.4	6549	3.6	9.5	Code	**Flux level** (tonnes/yr.)	**Notes**
Standard deviation	51.1	12670	7.0	18.2	🟩	= no measured emissions (0)	Some slight rounding errors are present
Median	7	1736	1.0	2.4	🟦	= low measured emissions (>0 to <1.0)	1 tonne CH_4 = 1397 m^3 CH_4 (at 15°C, 101.325 kPa)
Maximum	266	65983	36.6	81.6	🟨	= moderate measured emissions (>1.0 to <10)	1 SCFH = 0.02832 m^3 CH_4/h (at 15°C, 101.325 kPa)
Minimum	0	0	0	0	🟥	= high measured emissions (>10)	1 GJ = 27.5 m^3 CH_4 or 26.8 m^3 natural gas (15°C, 101.325 kPa)

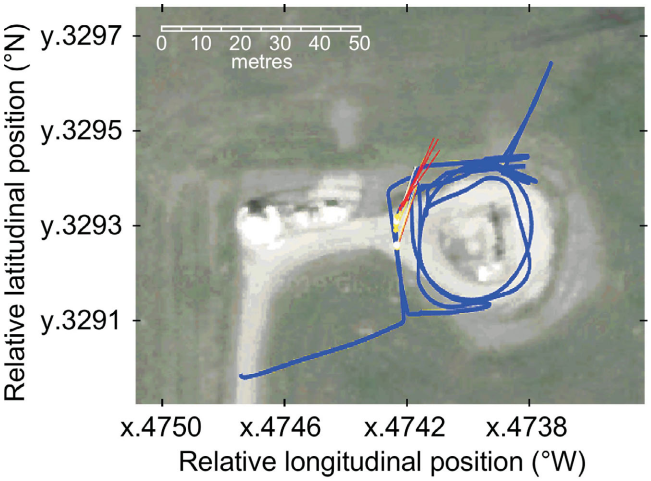

Figure 12. Heat map of the GHGMapper™ survey at Alberta Methane Field Challenge site 30. The hotter colours on the transect line indicate elevated methane levels detected.

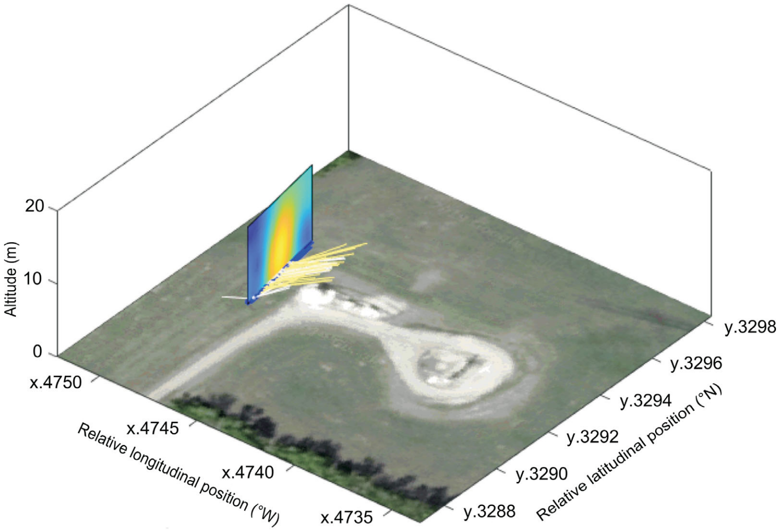

Figure 13. Example of GHGMapper™ Gas Flux Curtain™ for Alberta Methane Field Challenge site 30 with low methane emission anomalies. The warmer colours on the vertical flux plane indicate zones of higher methane flux. The coloured vector lines point toward the source of the emission.

at one location, which is approximately 10 times the natural background level. Figure 17 shows examples of vector plots at site 22. The points in any flight where higher methane emissions were detected are indicated on the heat map as an overlay of coloured circles (larger and hotter colours indicate higher methane concentration). In addition, the methane concentration colour-coded wind vectors on the figures point in direction of the wind. Figure 18 shows an example of an intense Gas Flux Curtain on the eastern margin of site 22.

The overall site 22 methane emissions are summarized in Table 3. The highest emission at one location on the site was 144 SCFH, which is approximately 36 000 CH_4 m^3/yr., 25.6 tonnes CH_4/yr. or about 1300 GJ/yr. natural gas. Based on current gas pricing this single leak translates to roughly $2300 market transacted price (approx. $1.75/GJ; Gas Alberta Inc., 2019) or $10 000 residential consumer price (approx. $7.50/GJ; FortisBC, 2019). Considering that a typical passenger vehicle emits about 4.6 tonnes CO_2/yr., and 1 tonnes CH_4 has the global warming potential (GWP) of 25 tonnes CO_2e, this loss represents the emission equivalent of about 140 vehicles (Solomon et al., 2007; Stocker et al., 2013).

Discussion and Summary

The AMFC program offered GHGMap an excellent venue to test the GHGMapper platform and Gas Flux Curtain methodology to provide quantitative measurements of greenhouse gases at a variety oil and gas facilities. The 42 plus 2 repeated (sites 43 and 47) AMFC sites surveyed over 10 days often included multiple flights at each site. Despite some poor weather days with sporadic rain, the GHGMapper was successfully deployed each day from June 12 to 21. No technical or operative issues were experienced with the equipment. As part of the AMFC requirement, daily reports that summarized the results of the sites surveyed were provided each day.

The intensity of the methane fluxes was subdivided into four emission level groups namely: no, low, moderate and high. Table 4 provides the overview of the methane flux

Table 4. Summary of methane (CH_4) fluxes measured by GHGMapper™ surveys during the Alberta Methane Field Challenge.

Emission level classification	Methane flux range (tonnes CH_4/yr.)	Number of sites	Percentage of total sites	Sites
No	0	7	16.6	6, 15, 16, 19, 20, 21, 27
Low	>0 to <1.0	8	19.0	3, 11, 17, 18, 30, 37, 40, 46
Moderate	>1.0 to <10.0	21	50.0	1, 2, 4, 5, 7, 10, 13, 25, 31, 32, 33, 34, 38, 39, 41, 42, 43, 44, 48, 49, 50
High	<10.0	6	14.3	6, 9, 12, 22, 23, 24, 47

classification thresholds (tonnes CH_4/yr.) and the grouping of the AMFC sites.

During the GHGMapper surveys, a wide range in methane fluxes were encountered and referenced against background atmospheric methane. The histograms in Figure 19 show the range in fluxes measured and their distribution. The fluxes within a particular site could be highly variable and intermittent. Seven of the 42 sites had no measureable methane fluxes, e.g., 0 tonnes CH_4/yr. (Tables 3, 4, highlighted in green). Another eight sites had only low measureable methane fluxes, e.g., <1.0 tonnes CH_4/yr. (Tables 3, 4, highlighted in blue). Together these 15 sites of no or low methane flux comprised 36% of the total. On the higher end of the spectrum (Figure 19), 21 sites had methane fluxes at moderate levels of 1.0 to 10.0 tonnes CH_4/yr. (Tables 3, 4, highlighted in yellow), whereas six sites had high levels >10 tonnes CH_4/yr. (Tables 3, 4, highlighted in red) with maximum methane flux values of 266 SCFH at site 9, 255 SCFH at site 47 and 205 SCFH at site 23. This translates to 47.2, 45.3 and 36.4 tonnes CH_4/yr. emitted at sites 9, 47 and 23, respectively (Table 3). The 27 moderate and high methane flux sites comprise 64% of the total sites surveyed.

Methane fluxes above 100 SCFH were observed in several instances (Table 3, Figure 19), but at any location on the AMFC sites the average was 26.4 SCFH (3.6 tonnes CH_4/yr.) and median value was 7 SCFH (1 tonnes CH_4/yr.). The large standard deviation of 51.1 SCFH (7 tonnes CH_4/yr.; Table 3) indicates the high variability between sites. The intra-site variability is underscored by the comparison of the repeat survey at site 47, which ranged from 1.5 to 255 SCFH (0.3 to 45.3 tonnes CH_4/yr.; Table 3). When the individual emissions on each site are integrated into a site total flux (ignoring the two repeats), then the average, median and standard deviation values are 9.8, 2.5 and 18.5 tonnes CH_4/yr., respectively.

Figure 14. Facilities at Alberta Methane Field Challenge site 22.

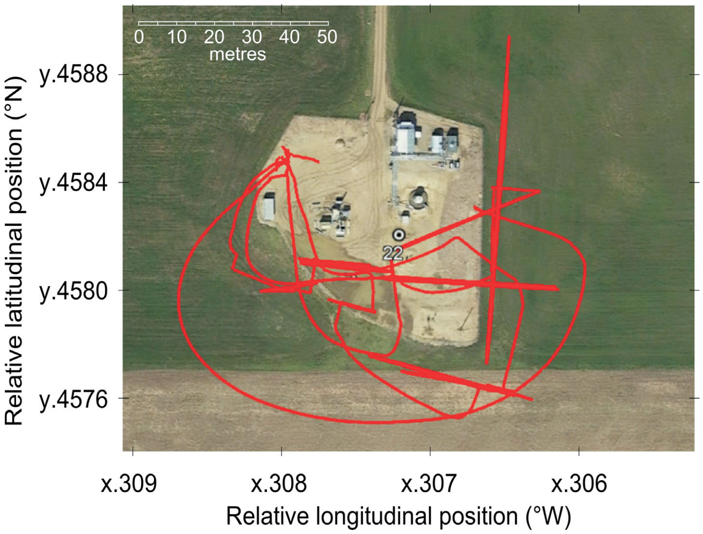

Figure 15. Flight tracks (red line) for GHGMapper™ survey at Alberta Methane Field Challenge site 22 (indicated).

To place these methane emissions in perspective, these findings were compared to those of Allen et al. (2013). They reported the following national emission rates: 1) unloading of gas well liquids leak 0.75–4.7 tonnes CH_4/well/yr., 2) pneumatic devices leak 1.1 tonnes CH_4/device/yr., 3) chemical injection pumps leak 1.6 tonnes CH_4/device/yr., and 4) equipment leak 0.5 tonnes CH_4/well/yr. Clearly, many individual locations on the AMFC sites had notably larger methane fluxes (average 3.6 ±7.0 tonnes CH_4/yr. and maximum of 36.6 tonnes CH_4/yr., Table 3) than those of Allen et al. (2013). Kang et al. (2014) also measured a wide variation in well leakage in Pennsylvania, ranging from undetectable to a high of 3000 tonnes CH_4/well/yr., and a mean of 99 tonnes CH_4/well/yr. In the UK, Boothroyd et al. (2016) examined fugitive methane emissions from 103 abandoned onshore wells and reported that 30% of these wells had fugitive methane emissions with a mean of 15 ±25 kg CH_4/well/yr. This is consistent with others who

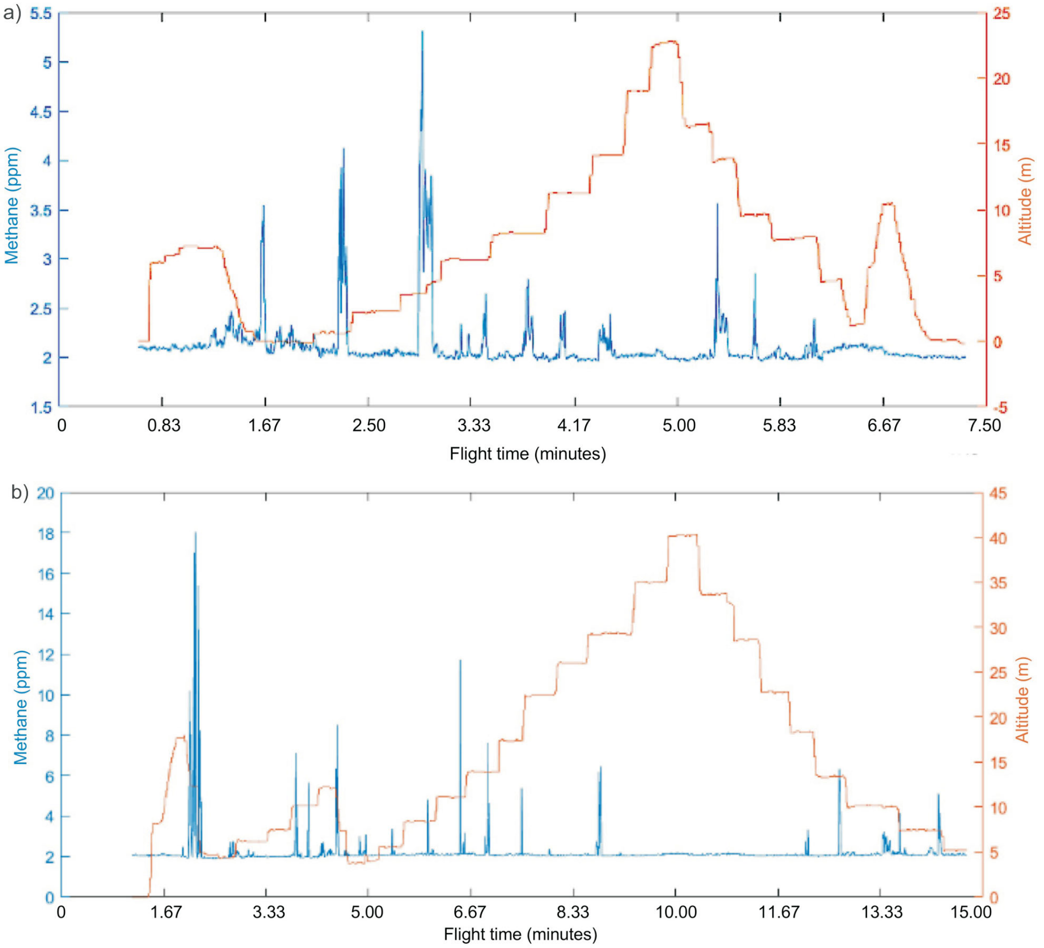

Figure 16. Two GHGMapper™ flight time series plot (**a)** approx. 7 min and **b)** approx. 15 min) of methane concentration (blue trace) and altitude of the small unmanned aerial vehicle (orange trace) for Alberta Methane Field Challenge site 22. High methane anomalies were detected.

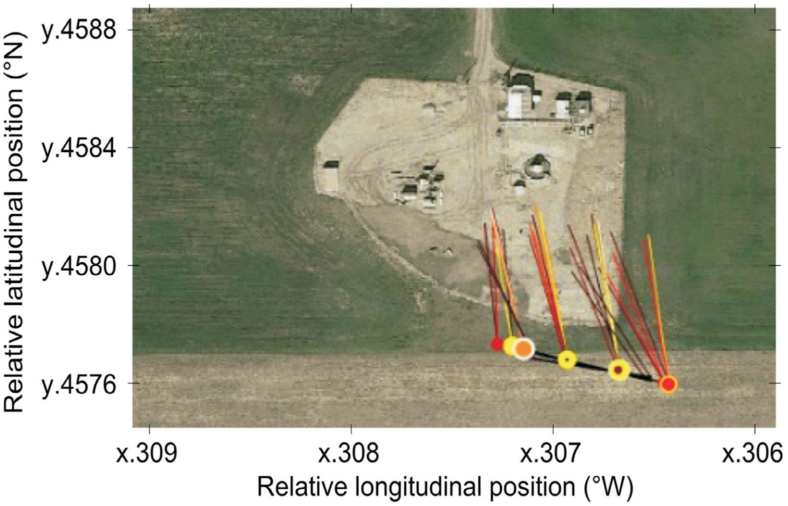

Figure 17. Heat maps of the Alberta Methane Field Challenge site 22 GHG-Mapper™ survey. The hotter colours on the transect line indicate the elevated methane levels detected.

find that inactive wells overall have lower emissions than active wells, e.g., Bachu and Watson (2006).

Hardie and Lewis (2015), who examined well leakage of methane by surface casing vent flow (SCVF) and gas migration (GM) in Alberta and BC, found that 76% of the wells had <2 tonnes CH_4/well/yr. They also reported that 41% (Alberta) and 58% (BC) of the wells have leaks of <0.2 tonnes CH_4/well/yr., but noted that some well leaks exceed 200 tonnes CH_4/well/yr. Currently in BC, the regulation for acceptable SCVF is 300 m^3/well/day or approx. 78 tonnes CH_4/well/yr. (Higgins, 2018). Recently, Werring (2018) reported on the methane fugitive emissions in BC measured by vehicle. Werring estimated that the average methane leakage from well surface casing vents is between 2.3 and 2.9 tonnes CH_4/well/yr., which is lower than the BC Oil and Gas Commission database es-

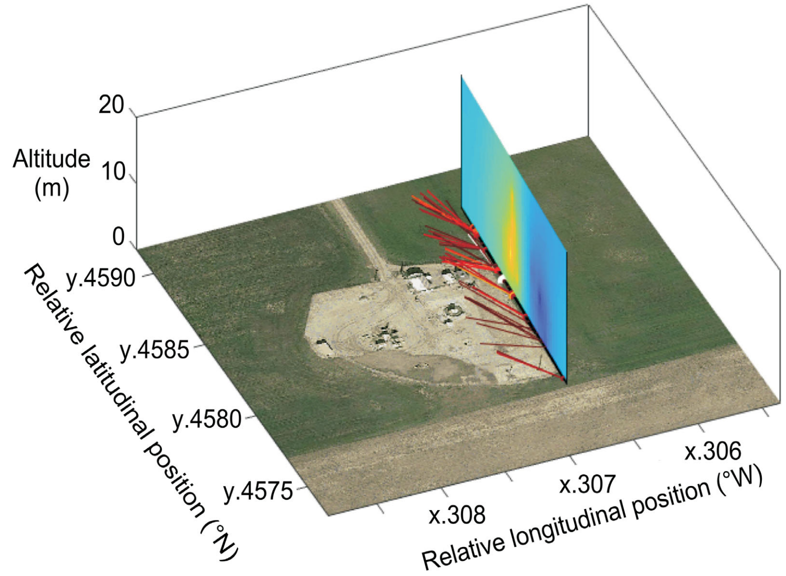

Figure 18. Example of GHGMapper™ Gas Flux Curtain™ for Alberta Methane Field Challenge site 22 with high methane emission anomalies. The warmer colours on the vertical flux plane indicate zones of higher methane flux. The coloured vector lines point toward the source of the emission.

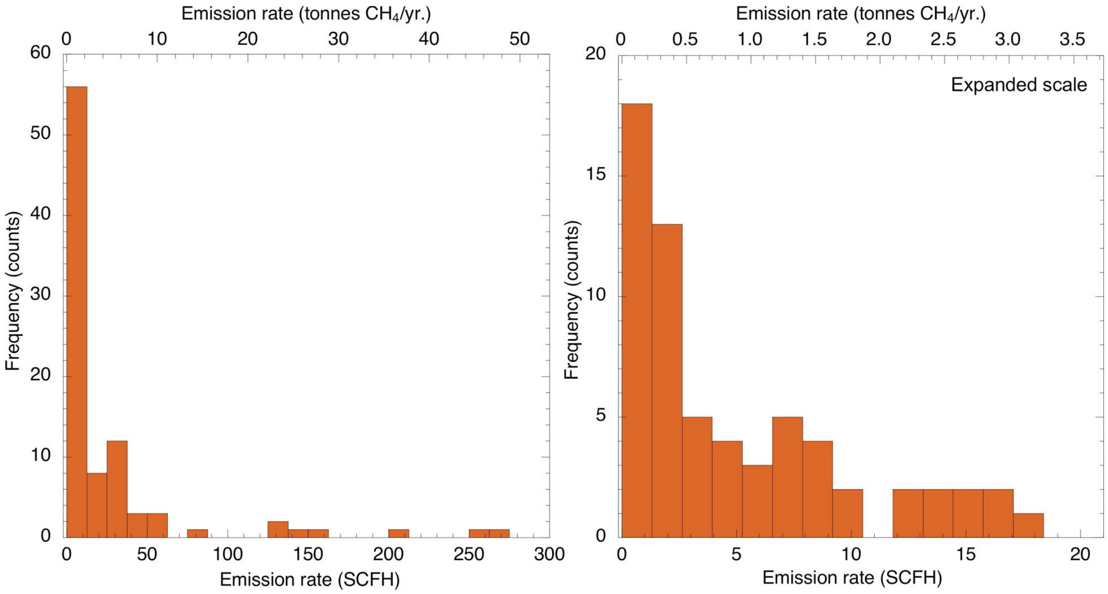

Figure 19. Histogram of methane (CH_4) emission rates from all sites surveyed during the Alberta Methane Field Challenge. The histogram on the right has an expanded scale. Abbreviation: SCFH, standard cubic feet per hour.

timates of 5.9 ±94 tonnes CH_4/well/yr. for wells with any reported SCVF emissions (BC Oil and Gas Commission, 2019). This estimate is similar to the median integrated value of 2.5 tonnes CH_4/yr. measured for the AMFC sites (albeit not SCVF sites), although the average of 9.8 and maximum of 81.6 tonnes CH_4/yr. is substantially higher (ignoring the two repeats).

By using the small and robust high sensitivity GHGMapper with gas sensors on unmanned aerial vehicles during the AMFC, the team was able to demonstrate a fast, safe and quantitative replacement of traditional, nonquantitative devices to determine gas emissions. The GHGMapper™ offers a real alternative to efficiently survey gas sources with true gas flux measurements on scales from metres to kilometres.

Acknowledgments

The GHGMap team would like to thank Petroleum Technology Alliance Canada's (PTAC) Alberta Upstream Petroleum Research Fund for initiating and supporting the Alberta Methane Field Challenge (AMFC). The time and effort of the AMFC organization team is appreciated, especially B. Barlow (DXD Consulting Inc.), T. Such (PTAC) and L. Mayes (PTAC). The team also acknowledge the various oil and gas operators in Alberta who generously provided their facilities for the AMFC.

Funding for GHGMap is generously provided by grants from Geoscience BC and Western Economic Diversification Canada.

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