GHGMap: Novel Approach for Aerial Measurements of Greenhouse Gas Emissions, British Columbia

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Introduction

Based on Intergovernmental Panel on Climate Change (IPCC) estimates, the annual global emissions of non–carbon dioxide greenhouse gases (GHG) are roughly 10 000 million metric tons (megatonnes, Mt) of carbon dioxide equivalents (CO_2e) or more than 23% of global GHG annual emissions (Stocker et al., 2013). This compares with global carbon dioxide (CO_2) emissions of approximately 32 000 Mt (de la Chesnaye et al., 2006). Over the last 250 years, the concentration of methane (CH_4) in the atmosphere has increased by 162%, as cited in the Global Carbon Budget 2016 (Le Quéré et al., 2016) and by the Intergovernmental Panel on Climate Change (Stocker et al., 2013). Present-day CH_4 emissions to the troposphere are ~550 Tg/yr. (550 Mt CH_4/yr.) of which 50–65% are from anthropogenic sources (Ciais et al., 2013). This equates to anthropogenic CH_4 emissions of ~6800 Mt CO_2e in 2006, which is expected to rise to ~8000 Mt CO_2e by 2020 (United States Environmental Protection Agency, 2006).

In 2014, British Columbia's (BC) total industrial GHG emissions were estimated by the BC Climate Action Secretariat to be 20.3 Mt CO_2e (BC Ministry of Environment, 2016b). This figure excludes electricity import operations and any BC operations annually emitting less than 10 kt of CO_2e/yr. This 20.3 Mt CO_2e represents about 32% of the BC total emissions of 64.5 Mt CO_2e in 2014. The BC Ministry of Environment (BCMoE) reports the total BC GHG emissions in 2014 to be 62.7 Mt CO_2e, rather than 64.5 Mt CO_2e, if 1.8 Mt CO_2e in offsets from forest management projects are subtracted (BC Ministry of Environment, 2016b). The BC 2014 GHG emission level of 64.5 Mt CO_2e is a drop from the high of >70 Mt CO_2e around 2004 (Figure 1). Energy-related activities are, by a wide margin, the highest sector of GHG emissions (~50.1 Mt CO_2e), more than waste (~5.6 Mt CO_2e), industrial processes (~3.5 Mt CO_2e), deforestation (~3.0 Mt CO_2e) and agriculture activities (~2.3 Mt CO_2e; Figure 2; BC Ministry of Environment, 2016b). A detailed

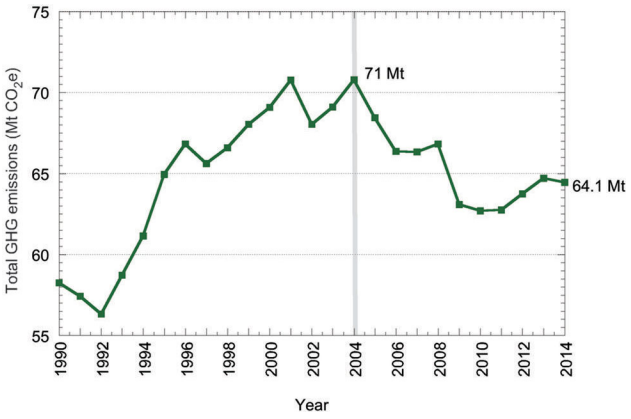

Figure 1. Estimated total greenhouse gas (GHG) emissions from 1990 to 2014 in British Columbia (from BC Ministry of Environment, 2016c). Abbreviations: CO_2e, carbon dioxide equivalents; Mt, megatonnes.

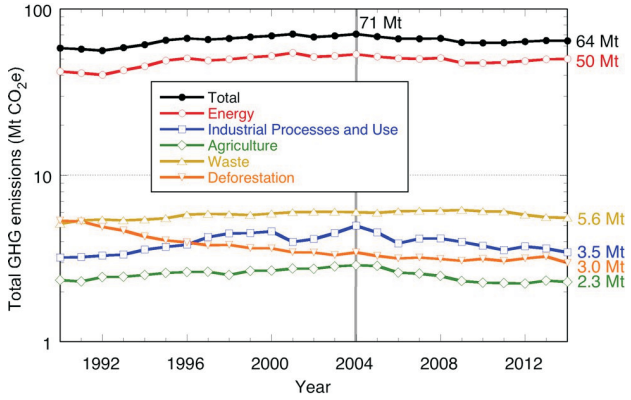

Figure 2. Estimated greenhouse gas (GHG) emissions in British Columbia from 1990 to 2014, reported by major emission sectors (from BC Ministry of Environment, 2016b). Numbers on the right side are 2014 values in megatonnes (Mt) of carbon dioxide equivalents (CO_2e).

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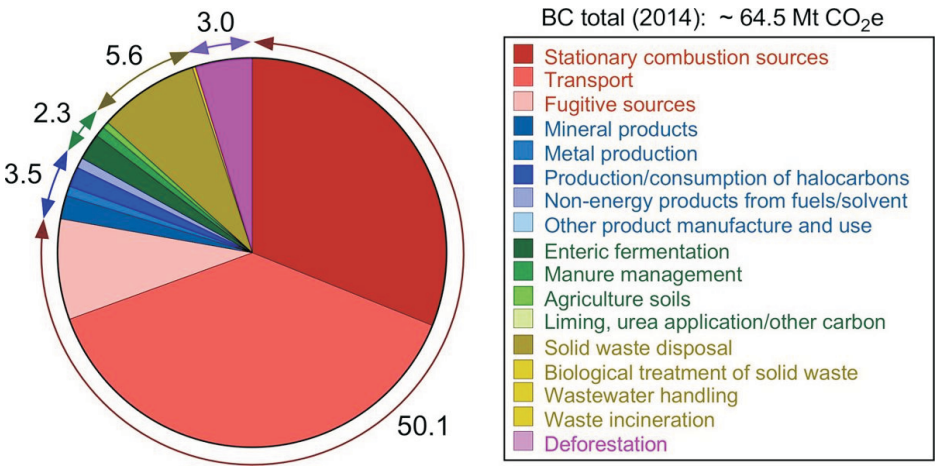

Figure 3. Detailed breakdown by subsector of estimated greenhouse gas (GHG) emissions in British Columbia for 2014. Numbers outside the wedges are 2014 emission sector values in megatonnes (Mt) of carbon dioxide equivalents (CO_2e; from BC Ministry of Environment, 2016c).

breakdown and relative proportions of the major BC GHG emissions sources within the different sectors is illustrated in Figure 3.

Within the industrial reporting sector, the major CH_4 emitters are oil and gas (50%), mining and smelting (14%) and cement/lime production (9%). In 2014, CH_4 accounted for a total of 10 Mt CO_2e, province-wide, with 3.6 Mt CO_2e attributed to the energy sector. Of this, it is estimated that over 2.8 Mt CO_2e (78%) were fugitive CH_4 emissions, whereas stationary combustion sources made up most of the remaining energy sector CH_4 emissions (0.64 Mt CO_2e; BC Ministry of Environment, 2016b).

It must be recognized that these reported CO_2e values are only best estimates and are not based on actual, routine, direct GHG measurements in BC. Rather the emission estimates rely on modelled values using the Canada's National Inventory Report (NIR), as prepared by the Environment and Climate Change Canada (ECCC) audit (Environment and Climate Change Canada, 2017). These modelled values are based on emission factors as outlined in schedules, such as the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006) or listed in the ECCC NIR on Greenhouse Gases and Sinks in Canada (Environment and Climate Change Canada, 2017). Fugitive emission estimates are based on

1) Canadian Association of Petroleum Producers (CAPP) average emission factors generated by Clearstone Engineering Ltd. (2005, 2014); and
2) augmented by data from oil and gas companies conducting formal leak management programs.

The limitations of modelling emissions are well stated in BCMoE reports as "Uncertainty in inventory estimates is inherent and the inventory should only be viewed as an approximation of total emissions." (BC Ministry of Environment, 2012, 2016a).

For clarification, the BC reporting of GHG emissions uses the CO_2e strategies that incorporate recent science based on the IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006). Thus, the amounts of the different GHG species, such as CH_4 and nitrous oxide (N_2O), are not reported using their specific masses (e.g., Mt CH_4). Rather the amounts are converted to the amount of CO_2 that would result in the equivalent change in atmospheric radiative forcing by CO_2, that is, CO_2e. The rationale for using CO_2e is to permit a more simplified relation between different GHGs to a uniform Global Warming Potential (GWP) CO_2 basis. The emission values used by BC are given in Table 1.

Unfortunately, this IPCC CO_2e convention is somewhat arbitrary because the GWP is calculated on the basis of a presumed 100-year lifetime of CO_2. Referring to the IPCC Second Assessment Report (Houghton et al., 1996), the stated GWP of CH_4 is 21 times that of CO_2. This value was revised in the IPCC Fourth and Fifth Assessment Reports (Solomon et al., 2007; Myhre et al., 2013) to 25 times, that is, over 100 years, 1 molecule of CH_4 contributes to the GWP the equivalent of 25 molecules of CO_2. An important consideration of this CO_2e relation is that the actual lifetime of tropospheric CH_4 is approximately 10 years (not the ~100 years of CO_2). Using a 10-year average lifetime of CH_4 in the troposphere, the actual radiative forcing of CH_4 is about 104 times that of CO_2 (CO_2e^{10}), that is, 1 molecule of CH_4 is equivalent to 104 molecules of CO_2 on a decadal time scale. It should also be noted that the GWP of CH_4 is actually greater if the indirect GWP contributions from CH_4 photochemical oxidation products are considered. A further complication in calculating the GWP arises if the CH_4 were combusted to CO_2, for example, as an energy source or mitigation strategy. Due to the mass difference of 2.74 between CO_2 and CH_4 (molar mass CO_2 = 44.01 g/mol versus CH_4 = 16.04 g/mol), the actual GWP reduction by the combustion conversion would only be 38 times, not 104.

The importance of reducing fugitive CH_4 emissions can be emphasized by the following calculation using a CH_4 GWP factor of 104 CO_2e^{10} (10-year average lifetime of CH_4). The BC and Alberta provincial governments have both declared their objectives to reduce energy-related CH_4 emissions by

Table 1. Global Warming Potentials (GWPs) of important greenhouse gases (GHGs) relative to CO_2 (CO_2e) from the 1996 Intergovernmental Panel on Climate Change's Second Assessment Report (Houghton et al., 1996) and the 2007 Intergovernmental Panel on Climate Change's Fourth Assessment Report (Solomon et al., 2007). The BC Ministry of Environment's GHG inventory in 2012 (BC Ministry of Environment, 2012) used the 1996 GWP CO_2e values, whereas later reports used the 2007 GWP CO_2e values (e.g., BC Ministry of Environment, 2016b).

Greenhouse gas	100-year GWP values in 1996[1]	100-year GWP values in 2007[2]
Carbon dioxide (CO_2)	1	1
Methane (CH_4)	21	25
Nitrous oxide (N_2O)	310	298
Nitrogen trifluoride (NF_3)		17 200
Sulphur hexafluoride (SF_6)	23 900	22 800
Hydrofluorocarbon - 23 (CHF_3)	11 700	14 800
Hydrofluorocarbon - 32 (CH_2F_2)	650	675
Perfluorocarbons - 116 (C_2F_6)	9200	12 200

[1]Houghton et al. (1996)
[2]Solomon et al. (2007)

45% by 2025. The annual reduction in these CH_4 emissions for BC would be 64 kt CH_4 or 6.7 Mt CO_2e[10]. This is the equivalent of a ~33% reduction in BC's total industrial GHG emissions or a ~13% reduction of the total 50.3 Mt CO_2 emissions in the province. As mentioned above, the calculated reduction in radiative forcing would be 2.74 times less if the CH_4 emissions were combusted to CO_2 and not just eliminated.

The primary sources of these energy-related fugitive CH_4 emissions are

- *conventional crude oil extraction and processing: releases from wells, flow lines and batteries; venting of casing and solution gas; and evaporative losses from storage facilities;*
- *natural gas extraction and processing: releases from wells, gathering systems, field facilities and gas batteries; seal leaks; line cleaning operations; formation CO_2 removal and pneumatic devices; and*
- *natural gas transmission: equipment leaks, compressor start-up venting and purging of lines during maintenance* (e.g., plant turnaround; BC Ministry of Environment, 2012).

As these stationary and fugitive emissions represent major sources of GHGs, especially CH_4 in the western provinces, this GHGMap research and development project focuses on developing and testing new instrumentation and approaches to monitoring and verifying energy sector emissions. Any real reductions in GHG emissions, including the stationary and fugitive energy emissions of CH_4 in BC, require robust and consistent verification. This is particularly important for the consistent and correct application of carbon tax credits. Conventional methods to monitor energy sector emissions require onsite and/or ground-based measurements, that is, by people travelling to the locations and making point-source measurements by hand or collecting samples for analysis in an offsite laboratory. Fixed-wing aircraft and satellite-based surveys have attempted to make these measurements using remote methodologies but they are best suited for only very large emission sources (e.g., Johnson et al., 2017; Kshtriya, 2017). These measurement approaches are costly, time consuming, uncertain and sometimes difficult to conduct (e.g., outside parties require training and supervision, extensive logistics, etc.). The goal of GHGMap is to develop and replace these point-source and fixed-wing methodologies with fast and cost-effective, remote observational approaches.

GHGMap Project Objectives

The three-year GHGMap project is jointly funded by Geoscience BC and Western Economic Diversification Canada. The project's aim is to measure and map, in real-time and at high spatial resolution, the concentration distributions of primary GHG emissions (e.g., CH_4, CO_2, C_2H_6 [ethane]) using an optical microsensor mounted on a small unmanned aerial vehicle (sUAV). The primary component of GHGMap is the deployment of a unique 400 g optical spectrometer (open-path laser spectrometer [OPLS] developed by NASA Jet Propulsion Laboratory) on a specialized drone (InDro Robotics Inc.'s quadcopter) for the detection, location, quantification and flux calculation of GHGs over natural and fugitive GHG emitters. The GHGMap project will provide data from detailed, unmanned site-specific surveys (e.g., well and pipeline integrity, landfills, feedlots, etc.) in the western provinces of Canada (BC, Alberta, Saskatchewan). Initial testing was undertaken over a landfill site, sewage screening plant and natural gas processing, compression and distribution plants and well pad sites in BC.

The OPLS/sUAV system can detect parts per billion (ppb) levels of atmospheric GHGs at a measurement rate of 10 hertz (Hz) and fly for periods of up to 45 min. The data collected is stored on the OPLS, and simultaneously sent in real-time to the receiver station in the drone control system. The high precision navigation on the drone allows repeatable positioning of the sUAV within 50 cm; the real-time geographic position of the sUAV can be determined continuously and with high accuracy using the on-board Global Positioning System (GPS) and inertial flight navigation (IFN) instrumentation. It also has extremely reduced flying altitude (1–10 m) compared with helicopter or fixed-wing aircraft surveys (>150 m; e.g., Karion et al., 2013). These high precision, proximal measurements by OPLS/sUAV combined with the low flight velocities (1–3 m/s) permit in-

creased and precise detection capabilities. These are unparalleled by other methods, such as handheld monitors, land-vehicle–mounted mobile sensors, manned aircraft or satellites.

The NASA JPL OPLS mid-infrared methane/ethane/carbon dioxide sensor was developed and first flown on a quadcopter in early 2016 (NASA, 2016). Since then, the NASA JPL team has been working with California and U.S. federal agencies, upstream and downstream natural gas producers/distributors, and energy industry consortiums to understand how best this tool can be used.

GHGMap Methodology

The OPLS used in the GHGMap project detects trace gases utilizing an open-path analysis region (e.g., open-path optical cell; Figure 4; Christensen, 2014). Its mid-infrared (MIR) laser produces light radiation that passes through a small volume of atmospheric gas to detect trace amounts of GHG. As the MIR radiation passes through the gas in the OPLS path, some of its energy is absorbed by the gas (light attenuation) at certain wavelengths. The range of wavelengths at which a trace gas exhibits characteristic absorption depends on the molecular properties of the trace gas (Figure 5). For example, CH_4 has strong absorbance bands at wavelengths of between 3.2 and ~3.5 µm. The MIR lasers operate in the spectral region where molecular transitions of the GHGs are up to 100 times stronger than those for near-infrared telecom lasers. The degree of absorption at the specific wavelengths is used to determine the concentration of the trace GHG according to the Beer-Lambert Law (equation 1):

$$A = a(\lambda) \cdot b \cdot c \qquad 1$$

where A is the measured light absorbance, a(λ) is the wavelength-dependent absorptivity coefficient, b is the optical path length in the OPLS, and c is the specific GHG concentration.

The highly novel innovations in the OPLS, enable this small, light, yet very sensitive instrument to be deployed on a small drone to measure GHG concentrations (CH_4, C_2H_6, CO_2). The result is extremely rapid, real-time measurements at 10 Hz (10 measurements per second), at atmospheric ppm to ppb concentration levels (i.e., at tropospheric mixing ratios). A critical feature of the OPLS, and one that demonstrably differentiates it from any other measurement instruments, including other optical spectrometers, is that the OPLS is so compact and requires such low power that it can be mounted and operated remotely on a sUAV.

Initial Activities

In BC, the OPLS (Figure 6) was mounted and flown on a sUAV (Figure 7) for several test missions over

1) municipal landfill site (Hartland Landfill, Saanich; Figure 8),
2) municipal sewage screening site (Macaulay Point Sewage Outfall, Esquimalt Land District),
3) natural gas distribution facility (Victoria region; Figure 9),
4) natural gas processing, compression, and water treatment sites (Fort St. John region; Figures 10–12), and
5) completed producing and abandoned natural gas well pad sites (Fort St. John region).

Figure 13 shows an example of the time series of CH_4 concentrations measured by OPLS and the corresponding GPS

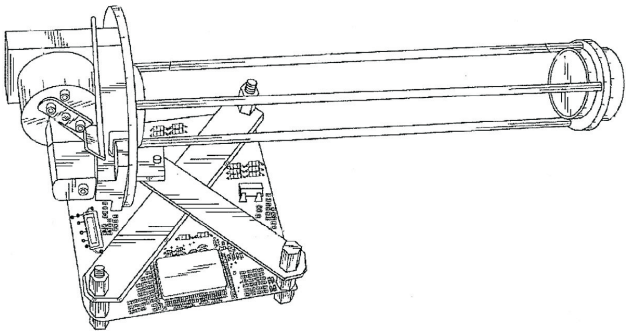

Figure 4. Patented open-path laser spectrometer (OPLS) for the measurement of greenhouse gases (modified from Christensen, 2014). The OPLS includes an electronic system, laser with thermoelectric cooler, analysis region with first and second mirrors, and detector.

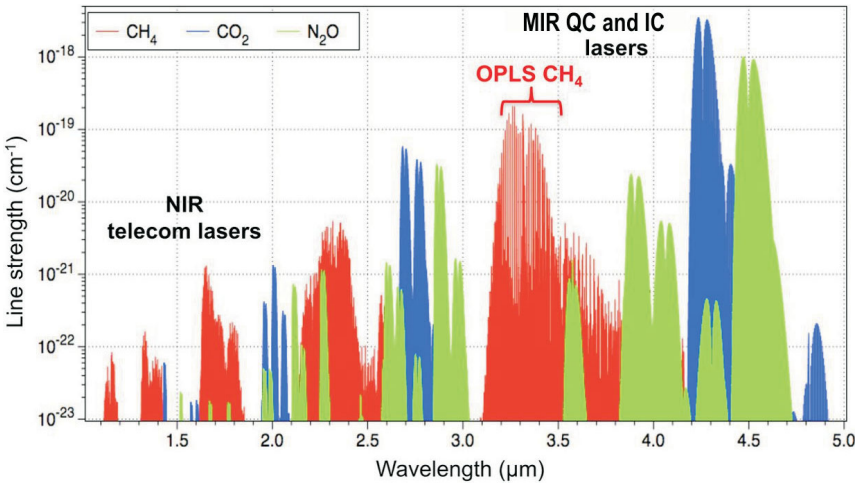

Figure 5. Infrared spectra for major greenhouse gases. The methane open-path laser spectrometer (OPLS) uses new mid-infrared (MIR) quantum cascade (QC) and interband cascade (IC) lasers. These QC and IC lasers can access molecular transitions for methane that are 100x stronger than conventional near-infrared (NIR) telecom laser spectral regions.

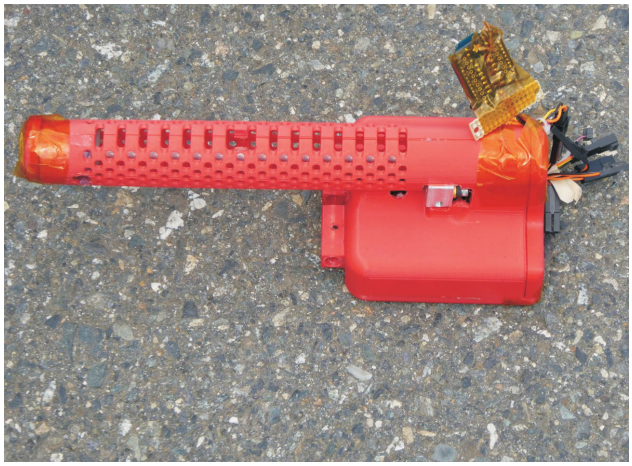

Figure 6. NASA Jet Propulsion Laboratory's open-path laser spectrometer (OPLS) detector probe head.

Figure 7. Deployment of NASA Jet Propulsion Laboratory's open-path laser spectrometer mounted on InDro Robotics Inc.'s small unmanned aerial vehicle.

Figure 8. Open-path laser spectrometer on small unmanned aerial vehicle at Hartland Landfill near Victoria, British Columbia.

Figure 9. Open-path laser spectrometer on small unmanned aerial vehicle at gas distribution plant in Victoria region, British Columbia.

Figure 10. Open-path laser spectrometer on small unmanned aerial vehicle at gas processing plant in Fort St. John region, British Columbia.

Figure 11. Open-path laser spectrometer on small unmanned aerial vehicle at gas processing plant in Fort St. John region, British Columbia.

altitude/position obtained from the sUAV (flown at a natural gas processing plant near Fort St. John, northeastern BC). The example in Figure 13 illustrates the dramatic variations in CH_4 concentrations at different locations on the survey site. Several locations have anomalous CH_4 levels over 10 ppm (~5 times the background CH_4 value of ~1.8 ppm). A single location recorded CH_4 levels over 25 ppm. The survey was also conducted with planned step changes in altitude, from ground level to over 40 m, to resolve the vertical magnitude and distribution of the anomalous CH_4 emissions. The vertical CH_4 survey pattern shows the vertical dissipation, and thus lowering, of CH_4 concentrations with elevation from the ground. This survey technique allows a 3-D definition of the geometry/pattern of the CH_4 emission anomalies at this site. This permits the generation of maps of CH_4 plumes at survey sites.

Figure 14 is a real-time Google Earth™ map view of a natural gas processing plant near Fort St. John during a flight mission. The figure shows a vector plot of the CH_4 concentration levels as colours and the wind direction and speed as the vector length. The cool colours are sites of low CH_4 concentration and the warm to hot colours show increasing levels of anomalous CH_4 concentration.

Figure 15 is an example of post-survey processing and display of the GHG data collected by OPLS/sUAV. The GHG plume is represented as a vertical flux plane of CH_4 concentrations that were measured downwind of a natural gas processing facility. Coupled with microscale meteorology data (boundary layer meteorology) obtained by 3-D–anemometer at the site or directly by instruments on the sUAV, the concentration distributions can be used for eddy covariance flux calculations (also termed eddy correlation) to measure and calculate vertical turbulent fluxes (Aubinet et al., 2012) and thus enable mass flow and quantitative emission mass estimates. The 2-D vertical plane in Figure 15 illustrates a cross-section of the CH_4 concentration downwind of the site. The CH_4 concentrations are scaled as colours with cooler to hotter colours mapped to increasing CH_4 levels.

Ongoing Activities

The current 2017–2018 research and development focus of GHGMap is on

1) optimal integration of OPLS with a sUAV, including GPS navigation, light detecting and ranging (LiDAR) instrument altitude, high definition (HD) video hyperspectral imaging and real-time GHG measurement and drone operation;
2) development of quantitative GHG flux measurement capability using ground-based sonic 3-D–anemometry and a micro, sonic, 3-D–anemometer mounted directly on the sUAV, permitting quantitative determinations of the mass of GHG released (e.g., kg CH_4/yr.), rather than just a GHG distribution map for a survey region; this development will provide information on active localization versus passive back-trajectory modelling;
3) development of real-time and post-survey data processing, reporting and visualization tools; and
4) experimental deployment of OPLS/sUAV over major natural and human-made GHG emission sources (e.g., oil and gas operations, landfills, thermokarst lakes, feedlots, etc.).

Figure 12. Open-path laser spectrometer on small unmanned aerial vehicle at water clarification pond in Fort St. John region, British Columbia.

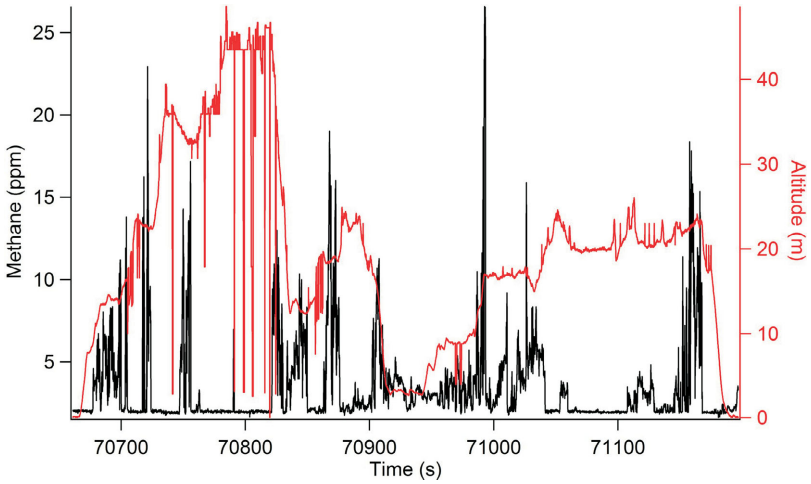

Figure 13. Example of real-time survey results at a gas plant near Fort St. John, British Columbia, using an open-path laser spectrometer (OPLS) on a small unmanned aerial vehicle (sUAV) system. The relationship between OPLS-measured methane concentration anomalies in the atmosphere (black line) and the GPS altitude of the sUAV (red line) is shown.

Figure 14. Example of a vector plot of methane emission data collected by an open-path laser spectrometer (OPLS) on a small unmanned aerial vehicle (sUAV) system at a natural gas well pad, near Fort St. John, British Columbia. Methane concentrations are scaled as cooler to hotter colours indicating increasing levels of anomalous methane concentration. The vector lengths indicate the wind direction and speed. The black line is the flight track. Map data: Google, DigitalGlobe.

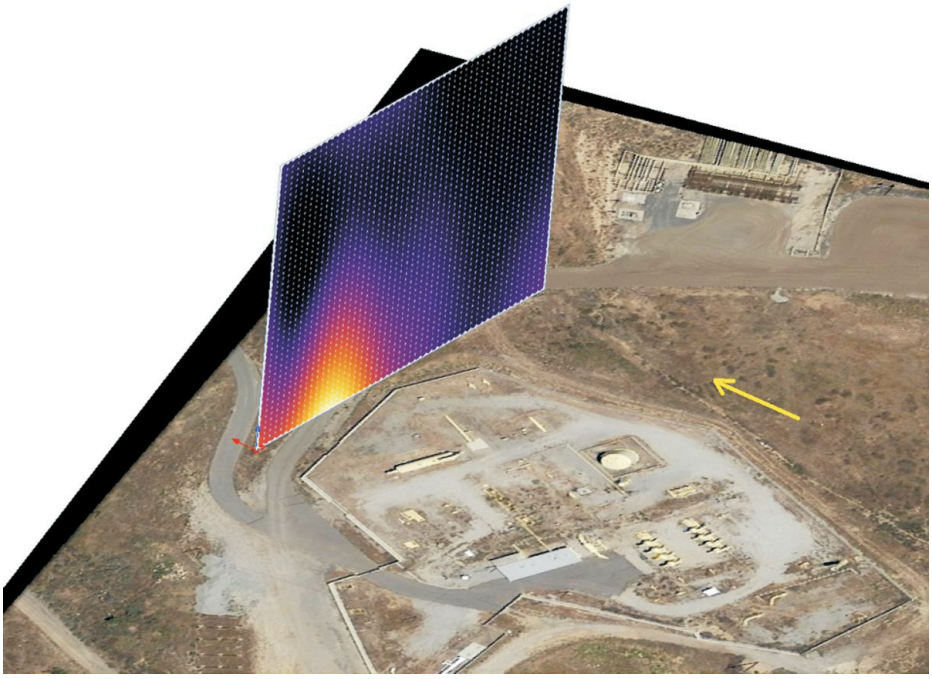

Figure 15. Example of post-survey processing and display of methane emission data collected using an open-path laser spectrometer on a small unmanned aerial vehicle system at a natural gas processing facility. The 2-D vertical plane shows the cross-section of methane concentrations scaled as colours, with cooler (blue) to hotter (red to yellow to white) colours mapped to increasing methane levels. The yellow arrow indicates the predominant wind direction.

Conclusions

The effects and consequences of climate change, brought on significantly through increased anthropogenic emissions of GHGs, pose serious global social, environmental and economic challenges. Today, established emission models with minimal actual measurements are generally relied upon to characterize the GHGs emission inventories. Although these models may represent a consensus approach for estimating and reporting of GHGs, and provide a convenient methodology to establish GHG assessments, they are seriously flawed. Part of the problem with implementing wide-scale GHG measurements is, in fact, the scale. Traditionally, GHG measurements are made using stationary, point-source instrumentation. However, the coverage (measurement density) is limited in space and time, and suffers from data underrepresentation. Any reduction in GHG emissions requires robust and verifiable GHG information and budgets based on quantitative measurements.

Recently, mobile measurements by land vehicles have offered some improvement, but these are costly and limited to accessible locations. Satellites have the potential to provide global coverage but, unfortunately, the satellites (e.g., SCIAMACHY, GOSAT, TES, GHGSat, AIRS on Aqua, IASI on Metop, SathyabamaSat and even the recently launched TROPOMI) have either insufficient spatial resolution and/or sensitivity to detect small- and medium-sized GHG emissions, such as from a compressor plant, and thus are of limited use for facilities with footprints of less than a kilometre. Studies that include aircraft-based measurements, using fixed-wing aircraft, provide good coverage and detail (e.g., CalNex, INTEX-A, HIAPER, HIPPO). Their limitations lie in a) the minimal flight elevations, which limit the size of emission that can be identified; and b) the operational costs of surveys.

The GHGMap OPLS/sUAV system offers a novel, mobile, technological approach that can efficiently bridge the spatial gap between point-source/ground and fixed-wing aircraft/satellite measurement scales. The OPLS/sUAV system is a fast, precise and cost-effective method to conduct site-specific and regional surveys, including conventional (landfills, gas plants, feedlots, etc.) and challenging locations and facilities (pipelines, dams, thermokarst lakes, etc.). Extensive deployments of the OPLS/sUAV system represent an emerging opportunity for various GHG stakeholders, including governments, First Nations, industry and the public.

This new monitoring method permits verifiable control and quantification of emission provenances, budgets and mitigation operations. The initial GHGMap program is focusing primarily on waste, agriculture and energy GHG emissions in western Canada, but the work will expand in scope to other major GHG emitters nationally and potentially internationally.

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