PoMELO: An Intelligent, Multi-Sensor, Vehicle-Based System for Methane Detection, Localization & Quantification

Final Report: PTAC AUPRF 17-ARPC-05

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January 2019

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EXECUTIVE SUMMARY

Leak detection and repair (LDAR) programs are a regulatory tool for finding and mitigating fugitive methane emissions from upstream O&G infrastructure. LDAR programs typically rely on close-range techniques outlined in the US EPA's Method 21 or Alternative Work Practice; however, these techniques are slow, labor-intensive, and costly. Future LDAR programs are likely to incorporate mobile screening technologies (e.g., drones, vehicles, aircraft, and satellites) to achieve mitigation targets more cost-effectively. In this Project we developed new hardware and analytics to support vehicle-based LDAR at upstream O&G facilities. The vehicle system measures the advection of methane plumes that cross the vehicle path.

The hardware system we developed consists of an integrated multi-sensor, roof-mounted payload. Data streams from the sensors are fused to provide high-frequency, real-time measurements of the wind vector, vehicle position, and methane concentration. These data are displayed using custom software to support real-time detection and localization of methane plumes at close-range (i.e., on site) and from several kilometers downwind. Post-processing with our software packages (ATLAS and SOLAG) can be used for a more rigorous assessment of detection, localization, and quantification.

Over a 1-year period the hardware/software system completed over 8,000 km of testing in varied terrain, land cover, and weather conditions. To demonstrate the system's capabilities and data products, we present a case study using a controlled release of methane. The results indicate the system can localize discrete emissions sources to within a few meters in the cross-wind direction and estimate the flux to within 40% of the actual emissions rate. Further testing is required to understand the system's limitations and operational niches.

Future improvements to the system include the integration of artificial intelligence to improve flux estimates, route planning software tools to optimize plume intersection, automated pad-level source discrimination and localization, and hardware/software upgrades to enable passive sensing – where measurements are collected, stored, and analyzed without any operator input.

1. INTRODUCTION

Fugitive methane emissions from the O&G industry are targeted by governments seeking to cut GHG emissions but are notoriously difficult to detect and measure as methane is both odorless and colorless in upstream settings. To mitigate fugitive emissions, regulators prescribe, and operators implement leak detection and repair (LDAR) programs. Conventional, regulated LDAR technologies require close-range access, and are time-consuming, with 1–8 sites inspected per day. The inspections are critical for identifying leak sources and prescribing repairs, but they are slow and expensive. An alternative approach, known as screening, may be capable of achieving the same emissions reductions at a lower cost. Screening is a new concept for LDAR that involves the use of mobile sensing systems to measure pad-level methane emissions over large areas quickly in order to identify leaks. There are several strategies behind screening. First, screening methods facilitate *selective application of close-range techniques* like EPA's Method 21 or Alternative Work Practice. Sites can be skipped if a screening survey finds no emissions or no anomalous emissions. Second, among detected emissions sources, screening methods provide *triage and prioritization* of follow-up and repair. This reduces emissions faster as the largest leaks are repaired first. Third, screening methods focus on *super-emitter targeting*. Given the extreme positive skew of most leak-size distributions, in which ~20% of sources are responsible for ~80% of emissions, considerable mitigation could be achieved by promptly detecting and repairing super-emitters. Together, these strategies underpin the use cases of the vehicle-based sensing system we developed in our 2017/18 PTAC AUPRF Project.

There are several mobile platforms in development for methane emissions screening: drones, vehicles, aircraft, and satellites. Vehicle systems have the lowest technological and operational risk, highest operational flexibility, and greatest potential for scalability. They also offer the potential to directly integrate with existing regulatory LDAR programs because vehicles are the primary mode of transport for accessing sites. Several commercial vehicle-based systems are available as products or services. The most advanced systems are developed by ABB and Picarro but are primarily designed for locating urban gas leaks. These systems use very basic analytics and don't leverage wind measurements to enable detection, localization and flux estimation of emissions at a distance. Other systems like the Altus Geomatics/StFx and Boreal Laser GasFinderAB vehicle systems lack sensor integration and analytics for real-time data display and information. Thus, the primary motivation of this project was the lack of intelligence in current vehicle-based systems to support pad-level and fenceline screening surveys of methane emissions from upstream O&G facilities.

This report summarizes technical details of an advanced analytics system developed at the University of Calgary to support vehicle-based screening in LDAR programs. The integrated hardware/software system is called PoMELO – Portable Methane Emissions Localization Observatory. A demonstration study is presented to highlight the system's performance in an operational setting. At the time of writing, the system has collected data over 8,000 km of data in a range of terrain, land cover, and weather conditions.

2. PROJECT OBJECTIVE

The main objective of the 2017/18 PTAC AUPRF Project (17-ARPC-05) was to develop an analytics system to enhance the application of vehicle-based screening of methane emissions in upstream O&G settings. The analytics system we developed is sensor agnostic – it can be integrated into any existing vehicle system. The main R&D tasks we completed during the Project involved the development of a hardware system, firmware and software for real-time pad-level detection and localization, and software tools to enable detection, localization and quantification form the fenceline and greater distances (up to several kilometers downwind).

3. PoMELO OVERVIEW

During the 2017/18 PTAC AUPRF Project (17-ARPC-05) we developed the first iteration of PoMELO – an integrated hardware/software system to support vehicle-based methane emissions screening. The multi-sensor hardware system consists of (i) a fast response anemometer for measuring wind speed and direction while the vehicle is stationary or travelling at speeds up to the allowable speed limit (~110 km/h), (ii) a Global Navigation Satellite System (GNSS) for vehicle position and orientation, and (iii) an open-path methane sensor (Fig. 1). These sensors are attached to the roof of a vehicle and connected to a laptop and power supply inside the vehicle. Raw data from these sensors are fused in real-time to produce useful ancillary data and information. For example, the GNSS and anemometer data are fused to produce estimates of the true wind, which are displayed in real time. Similarly, to display the methane concentrations on a map, or otherwise link the data to infrastructure locations, the GNSS data and the methane concentrations were also fused. Some of the commercial systems outlined previously log each of these data streams separately and then combine them after a survey is complete during post-processing. Real-time data fusion increases the utility of the data for on-the-fly decision making and QA/QC.

Fig. 1: *The PoMELO hardware (left) and PoMELO Live software (right). The vertical mast is the wind sensor. The methane sensor is covered by two metal shields. The GNSS is on the far side. Power is supplied from inside the vehicle.*

In PoMELO data can be queried in real-time by an operator (passenger) while the system is in use, or they can be collected passively with minimal interaction, which reduces labor cost by eliminating the need for a passenger. We refer to the latter as “Solo Mode”, whereby the data display is turned off in order to limit driver distraction. All the hardware components and sensors are commercially available and non-exclusive, with a total cost of ~$48,000 USD. We anticipate the hardware cost will decrease in the future as new, lower-cost sensors are developed. The main innovations we developed that will survive future hardware changes are (i) the custom firmware and software that fuses and displays multi-sensor data streams and (ii) the analytics platform to detect, locate, and quantify emissions sources.

When the system is operating measurements are displayed on the laptop inside the vehicle as graphs, numeric values, and on a dynamic map that incorporates contextual geospatial layers (e.g., roads, satellite imagery, asset locations, etc.). We developed an audible alarm to indicate when the vehicle passes through a methane plume. More than 50 direct and derived variables are also recorded at 10 Hz and used for detection, localization, and emissions quantification outputs. The firmware is designed so that it can be modified for different types of sensors. This feature makes the system flexible for other types of emissions (e.g., VOCs, PMx, NOx, CO_2, H_2S, etc.).

An overview of the system architecture is shown in Fig. 2. The basic architecture separates the logging and sensor program from the display and post-processing programs. This is so the logging and post-processing programs can be programmed separately and can safely crash without endangering the logger. As well, it is easy to put the PoMELO Live program on a separate computer that is connected to the instruments in the trunk or back seat of the vehicle and connect the plotting and control pages to PoMELO Live over the internet. All the data come in and out of the PoMELO Live program through a web server in the PoMELO Live program, or by writing data files to disk.

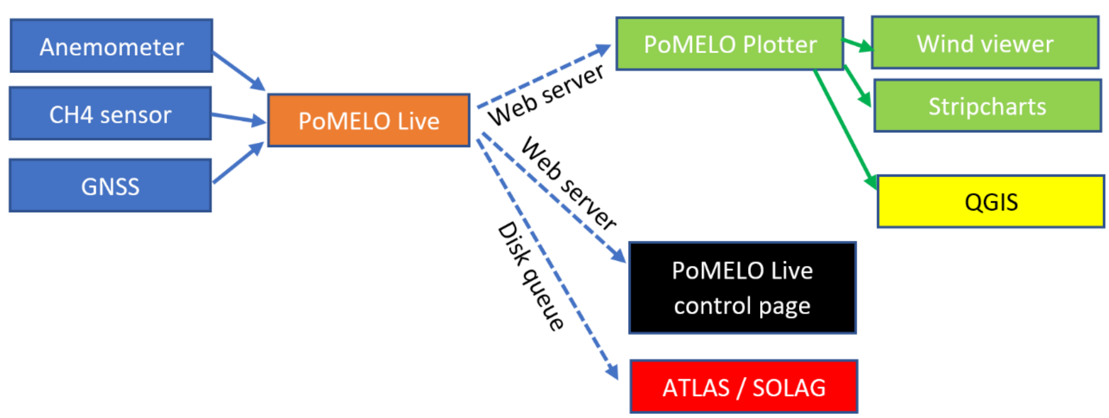

Fig. 2: *System architecture overview and linkages.*

The anemometer, methane sensor, and GNSS are logged by the PoMELO Live program. The PoMELO Live program has a web server that allows external connections. It also writes to disk when data are queued for analysis. This 'disk queue' is mined by separate software we developed for source localization and flux calculation (ATLAS and SOLAG emissions toolboxes). The ATLAS and SOLAG Toolboxes were developed in separate projects and consist of a series of tools to convert measurements from any type of mobile platform into detections, localizations, and screening-level flux estimates.

The web server allows a connection from PoMELO Plotter, which then spawns various plots, such as the Wind Viewer and custom stripcharts. The PoMELO Plotter also bridges data live to an open-source Geographic Information System called QGIS, for plotting the data spatially in real time. The PoMELO Live program also has a control web page, which displays the console output from the PoMELO Live and allows submission of commands, and quick data display.

4. PoMELO Live

The purpose of the PoMELO Live program is to (i) connect and log data from the sensors, (ii) perform real-time data fusion and ancillary calculations, (iii) open a server to connections from external plotting or analysis programs, and (iv) serve a simple control and configuration webpage. As noted, the program has a web-server architecture, so it can reside on a small embedded computer and be accessed over the network. Once the system is activated, data are collected automatically and stored locally on the laptop until the vehicle is turned off, or when the program is manually terminated by the operator. When the laptop acquires a wifi signal at the end of a survey data are transferred to a cloud storage system. The main console for PoMELO Live is shown in Fig. 3.

We developed the "Solo Mode" to support passive data acquisition and minimize driver distraction. The benefit of Solo Mode is that a passenger/operator is not required – data are collected automatically as

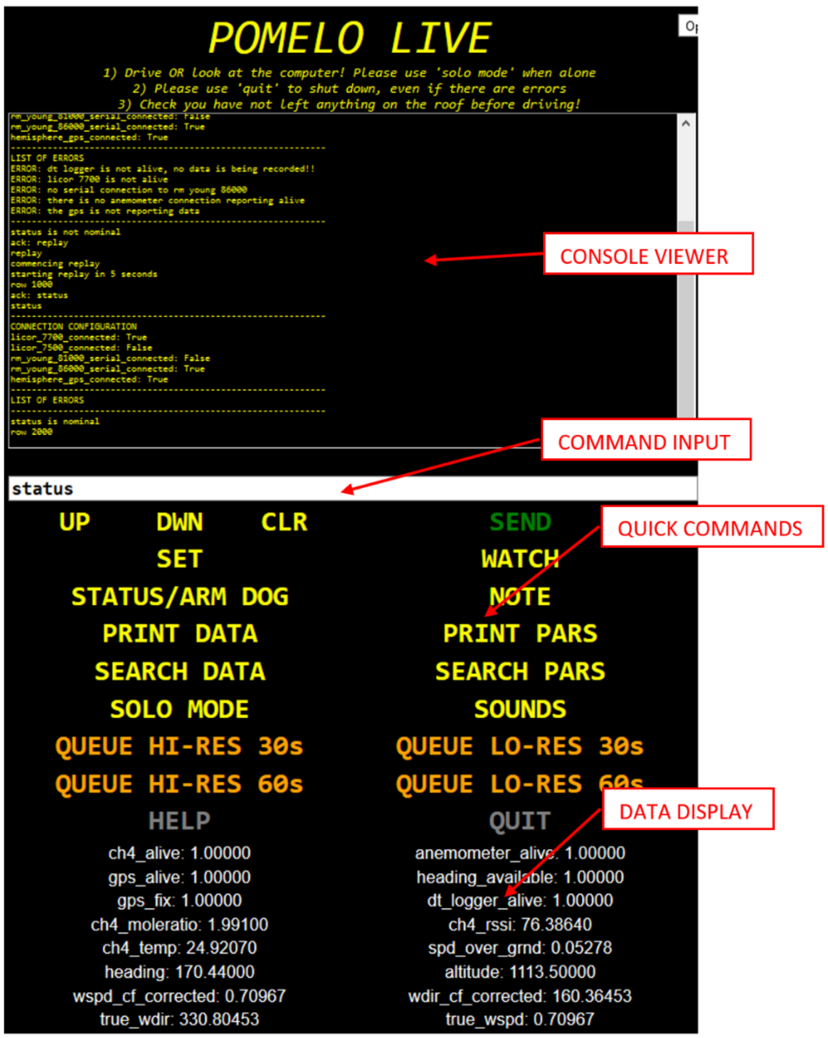

__Fig. 3:__ Key elements of the PoMELO Live software interface. The current version of the software is designed for R&D. A more user-friendly interface will be developed once the system transitions from research-grade to commercial-grade. For now, the priority is developing the algorithms and tools rather than aesthetics.

soon as the system is activated. This can help reduce the cost of surveys because the only labor cost is the driver. When Solo Mode is toggled on all the data going out of PoMELO Live to the PoMELO Plotter and the display page is set to 0.0. The driver cannot see any real-time data on the graphs or map. This reduces driver distraction as there is nothing interesting to observe on the laptop. The audible alarm will still function in order to alert the driver when they pass through a plume, but there are no visuals to examine. The data re-appear when the vehicle stops moving, as determined by the GNSS. All other features continue working when Solo Mode is activated.

5. PoMELO Plotter

The PoMELO plotter is a generic plotting utility we developed for graphing numeric data in real time. It connects to a server to request data continuously. It provides a user interface to launch a series of plots that allow the passenger to monitor relevant data streams. The main display elements are the stripcharts, Wind Viewer, and mapping utility. More than 50 variables can be displayed as stripcharts, but typically the main variable of interest is the methane concentration. Many variables can also be displayed simultaneously on the same stripchart. The main elements of PoMELO Plotter are shown in Fig. 4.

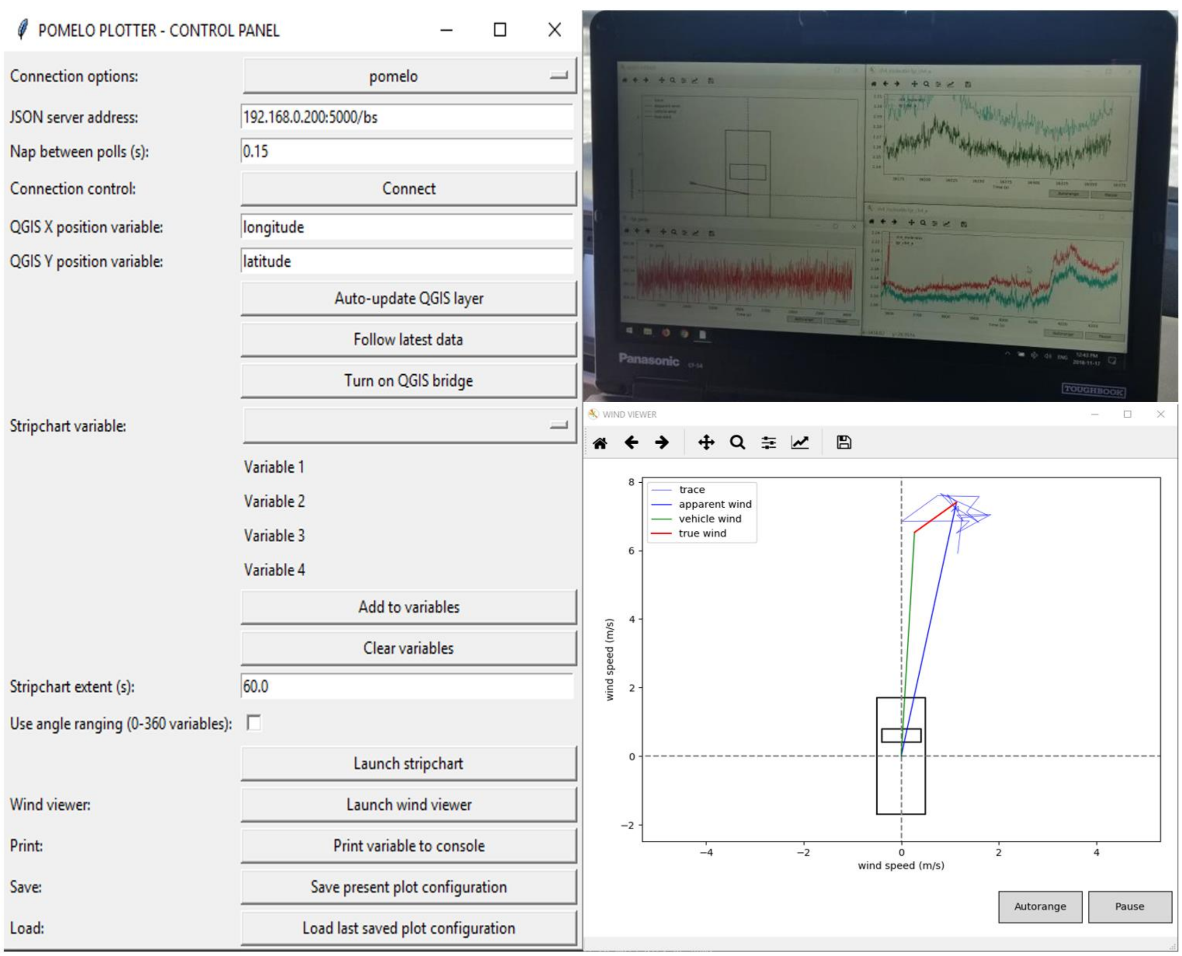

Fig. 4: *PoMELO Plotter elements: user interface (left), stripcharts (top right), and Wind Viewer (lower right).*

The Wind Viewer displays the true wind vector in real time after correction. Seeing the wind direction relative to the vehicle orientation allows for immediate localization of emissions when paired with the audible alarm. The Wind Viewer appears as if it is looking from vertical, with top of the plot facing the direction of travel. There are 3 wind vectors displayed. The green line is the vehicle wind, that is the induced wind from motion. The blue line is the wind measured from the anemometer, relative to the vehicle heading. The red line is the true wind vector (i.e., apparent wind – vehicle wind).

6. DEMONSTRATION

PoMELO has been extensively tested, with more than 8,000 km of surveys conducted to date in a range of terrain, land cover, and weather conditions. The hardware is robust and has acquired measurements in adverse weather: light rain, snow, and dust. There has been no downtime. We've made continuous improvements to both the hardware and software and are actively developing new tools for expanded functionality.

PoMELO was one of 10 technologies evaluated during the EDF / Stanford Mobile Monitoring Challenge (MMC) in May 2018. The MMC was an international, invite-only competition sponsored by EDF and several major US energy companies. The structure of the competition involved controlled (blind) releases of methane from multiple sources, with no information provided as to the location, rate, or number of sources. We completed 73 blind tests with PoMELO over 5 days. We provided real time detection, localization, and quantification, and acquired measurements during rain. The MMC denotes achievement of TRL6.

Results from the MMC will be published by researchers from Stanford and Harrisburg Universities sometime in the first half of 2019. We are unable to share our results prior to the publication. However, we performed several experiment campaigns using controlled releases during the PTAC AUPRF Project to demonstrate the system's performance for detection, localization, and quantification. We report here one of those experiments.

6.1. Description of Experiment

The field experiment was performed on 17 October 2018 at a site near Brooks, AB (Fig. 5). We used a controlled release of methane to generate a plume. The vehicle system was driven along a road downwind of the release point. The experiment simulates a screening survey, in which the vehicle completes a single pass through a plume on a public road. The goal of this type of surveying is to produce screening-grade estimations to triage follow up work. Closer passes are possible, but the plume is typically very narrow and poorly developed near source, which makes quantification more challenging. In this experiment the vehicle was roughly 400 m downwind of the release point. The controlled release rate was 2.556 g s^{-1}. The experiment was conducted with strong southwesterly winds and an air temperature of approximately 23° C.

6.2. Concentration Map and Detection

The methane concentrations from the single pass are shown in Fig. 6. We had high confidence the vehicle would intersect the plume in this pass given the strong unidirectional winds and stable conditions during the experiment. At strong wind speeds, plumes tend to be narrow, well constrained, and predictable.

Fig. 5: Controlled release experiment. The yellow release stack is shown with the compressed natural gas trailer shown on the right. Visible on the left is the vehicle system approaching the plume, which is invisible.

Detection of the plume in this example (Fig. 7) was not difficult because: (i) the methane sensor in the vehicle system has very low noise and is highly sensitive, (ii) the plume was well defined and narrow due to windy conditions, (iii) the stable atmospheric conditions led to little vertical mixing of the plume, (iv) there were no other plumes in the area, and (v) the release rate was relatively large at 2.556 g s^{-1}. The plume detection algorithm in our software is adjustable based on the desired sensitivity. The desired sensitivity depends on the complexity of the detection task and tolerance for false positives.

6.3. Source Localization

In this example, we used the localization feature in the ATLAS Emissions Toolbox to estimate the position of the source after the survey was complete. The probability of a location being the source location is shown with relative colors (Fig. 8). The top localization estimate, which would be used in this case, had a total positional error of 75 m relative to the real source, but the cross wind error was < 5 m. If the infrastructure was not oriented parallel to the wind direction, we could localize much better than 75 m as the actual source locations would be constrained to areas associated with infrastructure. We are developing a 'snapping' method to constrain source locations more definitively using known positions of assets.

Similar to other experiments, the most difficult aspect of localization is the upwind-downwind position. Shifts in wind direction are required to better constrain this position, or if there is good understanding of the relative position of infrastructure, we could better understand the location estimate by disqualifying many of the source estimates to those that are coincident with the actual infrastructure that could be emitting. Although this disqualification can be done in the ATLAS Emissions Toolbox by specifying pre-disqualified candidate source locations, for purposes of demonstration and understanding errors, we typically consider an unrealistically large number of candidate source locations.

Fig 6: *Measured methane concentrations from a single pass with the truck system. The truck was driven across an access road oblique to the wind direction. The approximate downwind direction is shown. The plume traversed the flat grass field towards the NE.*

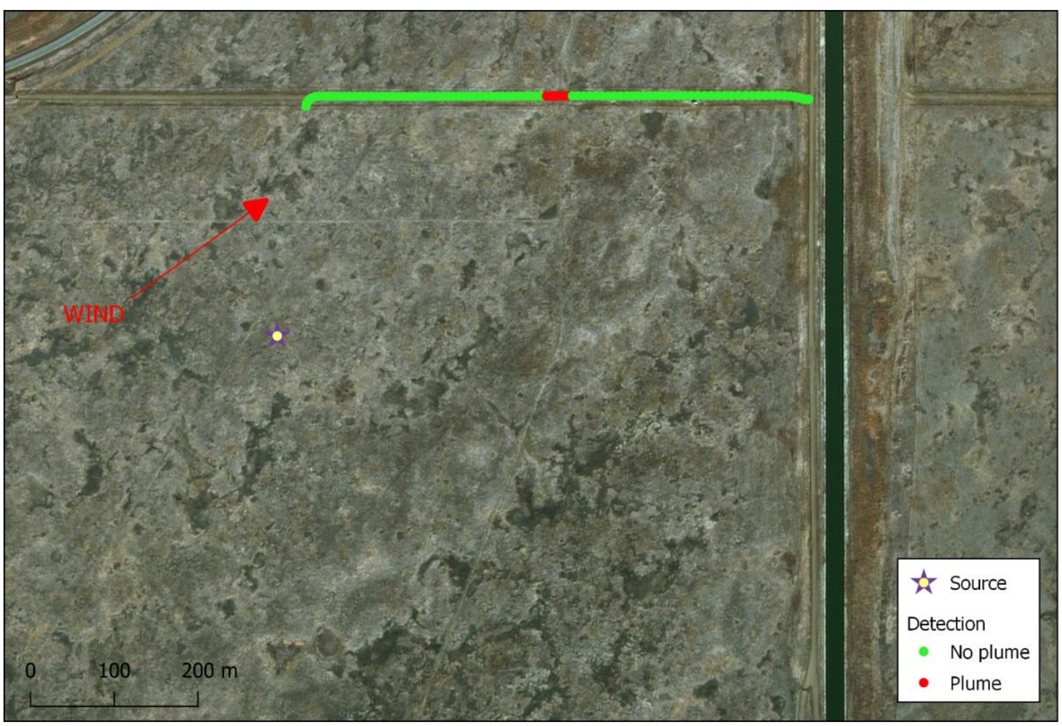

Fig. 7: *Plume detection: the red dots show areas that were tagged by our algorithm for plume detection.*

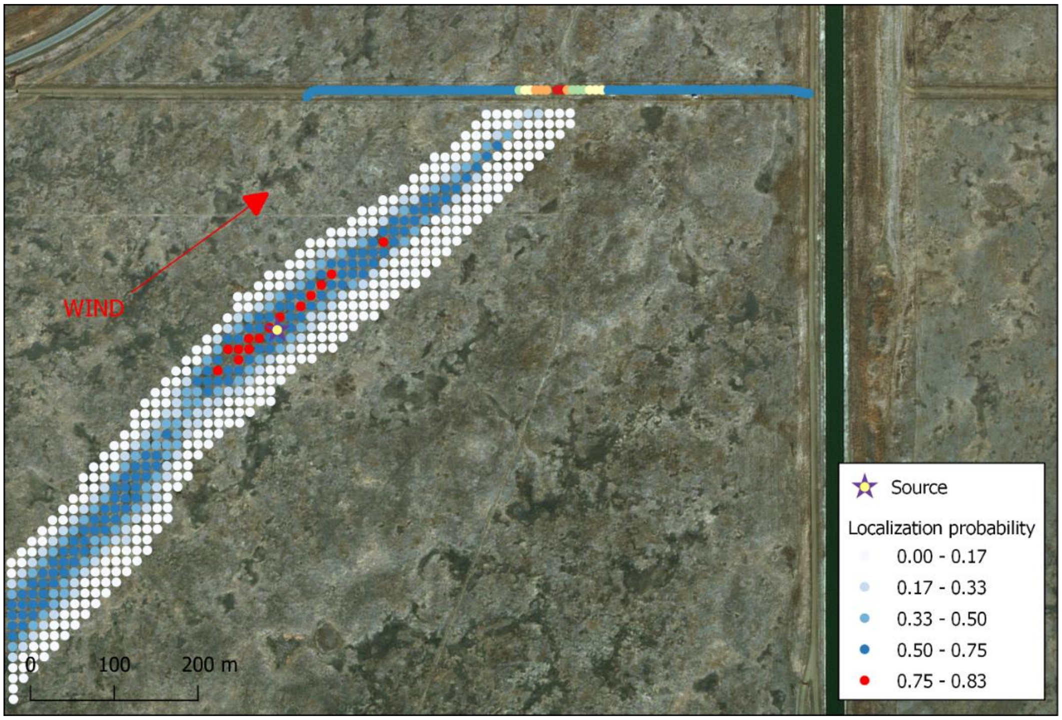

Fig. 8: *The localization results. The most promising estimates of location are shown in red. Less promising results are shown by blue to white colors.*

6.4. Source Quantification

Source quantification with the ATLAS Emissions Toolbox is performed at a screening-grade accuracy level. We deliberately calculate source flux with less data to provide an inaccurate number. More data can be collected, but typically the increase in accuracy is not warranted when the cost of driving back and forth or performing longer surveys is considered.

For this experiment, the algorithm estimated the flux at 1.533 g s^{-1}, which is slightly lower than the real flux at 2.556 g s^{-1}. This magnitude of error is quite low considering that this flux was calculated from one pass of data and compares favorably to other much more intensive screening experiments such as the approach used in the US EPA's Other Test Method 33.

Improving low data density flux estimates is an emerging research priority and we are devoting considerable resources to optimizing and understanding the sources of error in the present set of algorithms. We are also working on improving the speed of calculation. The speed of calculation can range from seconds to minutes, depending on data density and quantity.

7. NEXT STEPS

PoMELO is undergoing continuous improvement and testing. The main hardware/software improvements are in active development and mainly target automation and intelligent screening. The automation upgrades focus on real-time localization and quantification. The goal is to transition from data to information in real time so that decisions can be made on-the-fly. This could allow for digital 'tagging' of emissions sources in a manner analogous to OGI-based LDAR surveys. Fig. 9 shows an example of digital tagging from a survey of a facility during the Alt FEMP Project in November 2018. Within minutes of arriving on site, the emission source can be identified and tagged, and used to immediately direct the application of close-range techniques for component-level identification. This approach could be part of an alternative LDAR program and greatly accelerate the LDAR surveys.

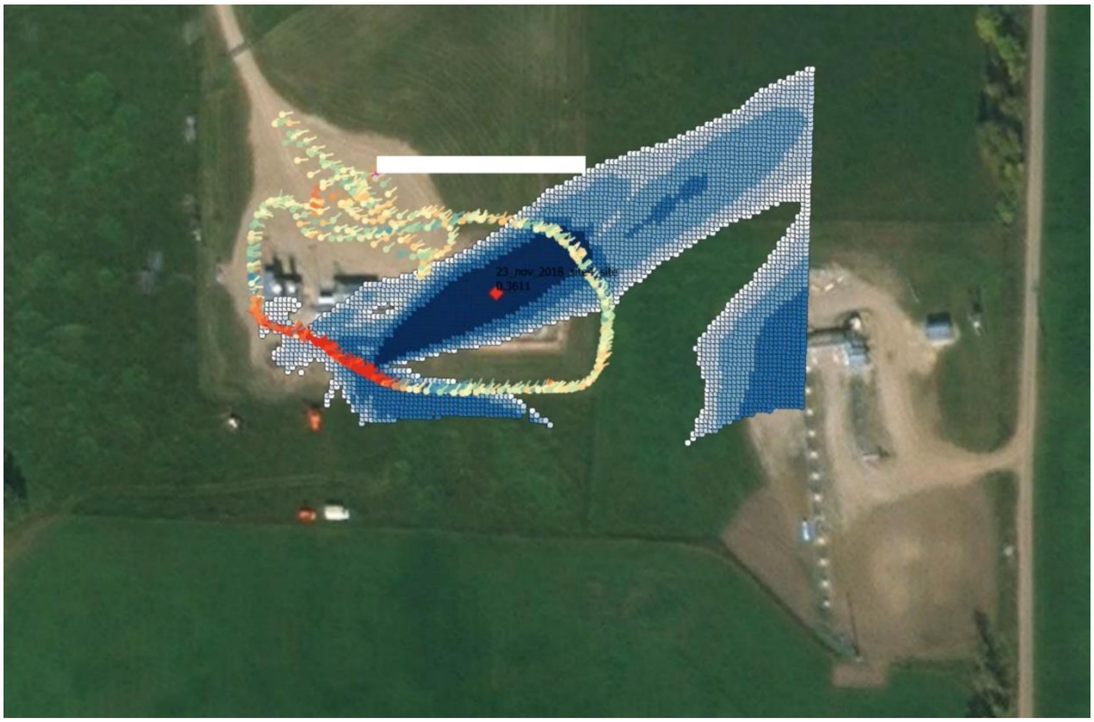

Fig. 9: *Map showing methane concentration and wind direction during a survey of a facility in November 2018. Wind direction was from the northeast. The name and location of the facility has been redacted. The colored points with lines are the methane concentrations (red denotes higher concentration) and wind directions. The colored area shows the emissions source probability map, with the candidate source denoted by the red diamond. In this case the source identified by our localization algorithm corresponded to a tank.*

We are also developing an improved flux estimation method using artificial intelligence (AI). We know from experience that our current flux estimation method tends to under-estimate actual emissions, so the goal is to close the gap by incorporating AI and our growing library of emissions data.

We envision two deployment modes of our hardware/software system: *passive sensing* and *targeted sensing*. In passive mode the system collects emissions data opportunistically while operators drive to sites for other tasks. In targeted mode, the system is strategically deployed to screen and triage emissions. The current system is ready for deployment in targeted mode, but to enable the passive mode we need to make some changes to the hardware and software. The main changes are to develop an enclosed, portable pod for the hardware and a cloud system for data storage, analytics, and reporting. These upgrades are in development and the first prototype is expected at the end of 2019.