KAIROS AEROSPACE

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Calibration and Demonstration of Aerial Methane Imaging for Efficient, Wide-Area Methane Emissions Detection

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Executive Summary

Kairos has developed a new methane detection solution, LeakSurveyor, which combines a patented aerial methane detection instrument with a proprietary data analysis pipeline to provide customers with clear, actionable information about where, and how big, their methane emissions are.

LeakSurveyor is designed to frequently survey wide areas for large leaks at low cost – a single instrument can cover 125 square kilometers (km^2) in one day. Surveying frequently for large leaks is more effective and efficient at reducing methane than the traditional paradigm of conducting infrequent ground surveys because the large emitters that cause most of the environmental and economic damage are found and fixed earlier. Based on our results In Alberta, Kairos believes LeakSurveyor can lead to reductions of ~80% of the fugitive methane emissions volume from upstream oil and gas wells and facilities by 2025, at a lower cost than alternative options, with potential applications in midstream and other industries as well.

Kairos' instrument measures the absorption of reflected sunlight that has passed through methane molecules and proprietary algorithms translate these measurements into an image of methane. Then in-house built software stitches these methane images. Simultaneously, aerially collected optical images and GPS data are combined into georeferenced maps with methane sources highlighted. Alberta presents unique challenges for the successful deployment of a system like LeakSurveyor – namely, colder temperatures, lower ambient light levels, and lower sun angle as compared to more favorable conditions in the oil & gas production areas of the United States.

Prior to this project, Kairos assessed that LeakSurveyor was at Technology Readiness Level 8 ("TRL-8", commercial-scale field demonstration) in the United States, based on having already conducted several commercial scale demonstrations of the technology in Texas, California, and Pennsylvania. However, based on Kairos' prior experience in Alberta during 2016, we believed that LeakSurveyor required further development before it will be at the same TRL for Alberta's more challenging operational environment. This project was designed to achieve TRL-8 for Alberta by its completion, with a demonstration of the system at commercially useful scale by the end of the project. To achieve that, we split the project into 3 phases: (i) collect calibration data in Alberta to use for testing and algorithm improvements, (ii) use that data to improve the system for the more challenging conditions of Alberta, and (iii) then return to Alberta to conduct another calibrated release test and to conduct a field demonstration of the improved system as an example of how LeakSurveyor would be used as part of a directed leak detection and repair program.

At the completion of this project, Kairos believes that we've successfully achieved TRL-8 for Alberta, through a successful field demonstration, in partnership with GreenPath and a Canadian oil and gas exploration and production company

("Operator")), and by exceeding most of the performance metric targets that we set for commercial readiness at the inception of the project. LeakSurveyor is also now at TRL-9 (commercial implementation and market roll-out) in the United States, having surveyed thousands of square kilometers of oil & gas fields and gathering lines and identified numerous large emissions sources for commercial customers since the inception of this project. In the coming years, Kairos aims to achieve a similar greenhouse gas reduction impact in Alberta.

Project Description

Technology description

The LeakSurveyor instrument consists of three parts: 1) an optical camera for visual verification of sites, 2) a GPS and inertial monitoring unit to record precise positions, and 3) a patented spectrometer that detects methane (see Figure 1). The spectrometer is sensitive to infrared sunlight that reflects off the ground. When this light passes through a plume of methane, the methane absorbs certain frequencies and lets others pass through. The spectrometer identifies those absorption features, and associates them with a particular position on the ground (see Figure 2). This makes our system highly specific for methane, as it is the only molecule that leaves this particular signature on the spectrum, and avoids signal confusion from other gases like propane. It is also specific to location; the resolution on the ground is well-matched to most gas plumes. As a result, we produce direct images of plumes, overlaid on simultaneously captured optical imagery. After reviewing the specifications and capabilities of other categories of methane sensing technologies we believe LeakSurveyor belongs to a new class of instrument, Aerial Methane Imaging (AMI).

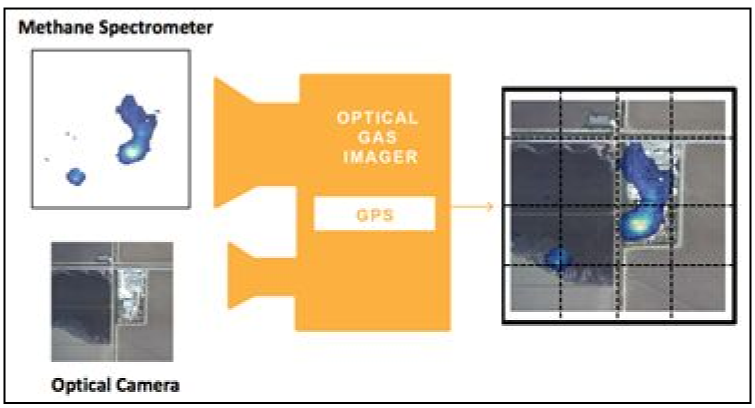


Figure 1: Conceptual diagram of LeakSurveyor pod, which synthesizes data from a methane spectrometer, GPS unit, and optical camera to create a single optical, georeferenced image of methane.

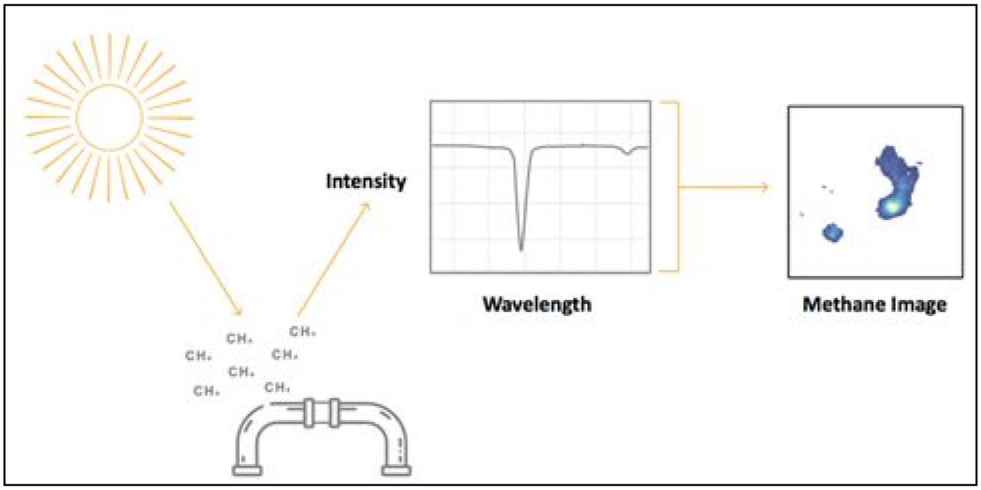


Figure 2: Sunlight reflects off the ground and passes through methane molecules, which absorb certain frequencies of the light and let others pass through. LeakSurveyor translates these absorption features into an image of methane.

LeakSurveyor's resolution allows us to distinguish between separate point sources of methane and differentiates us from air-sampling techniques. In Figure 3, for example, we separate the methane plume from natural gas production from the methane plume from the flooded rice field nearby, and would only report the former. What's more, we distinguish between the location and concentration of separate emissions within a single site, such that the ground crew following up on the emissions can go directly to a specific area to identify and repair a specific component.

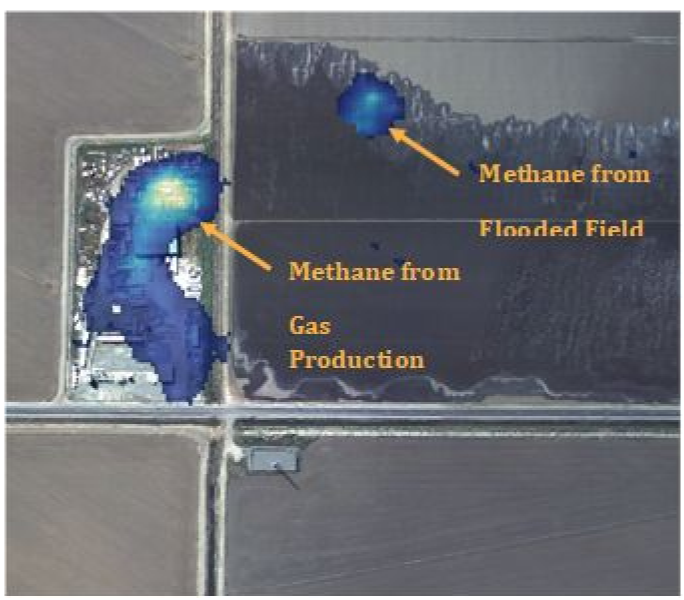


Figure 3: LeakSurveyor's direct point source methane imaging separates the gas production-related emission (on the left) from the nearby flooded field-related emission (on the right). This allows distinct attribution of methane between different sources.

The LeakSurveyor instrument is easily mounted on light aircraft and flown at standard general aviation altitudes of 3,000 feet (ft.), making it orders of magnitude faster than a ground crew and able to access terrain that would be difficult or dangerous to reach by car (see Figure 6). LeakSurveyor is also faster and safer than helicopters or low-flying aircraft. It can fly longer and farther than commercially available drones, which rarely have battery lives of more than 30 minutes, limiting their flight range and increasing their cost.

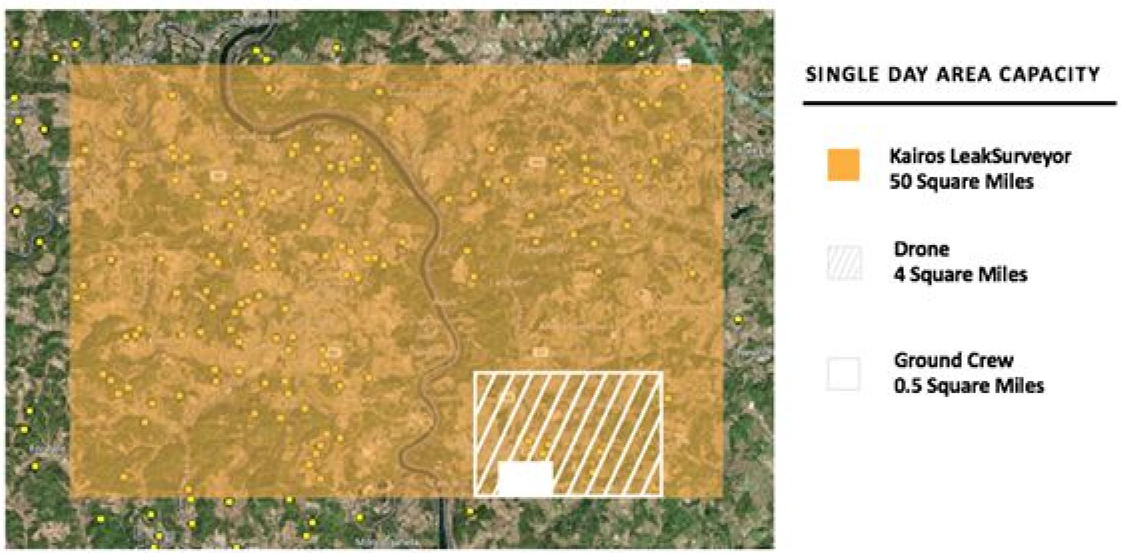


Figure 4: LeakSurveyor covers orders of magnitude more area than a ground crew, allowing frequent revisits.

Project goals

Kairos partnered with Emissions Reduction Alberta (ERA) to help LeakSurveyor achieve TRL-8 in Alberta by September 29th, 2018. To highlight the many milestone attainments, a demonstration of the system at commercially useful scale was conducted. More specifically, Kairos had two primary objectives for improving the technology for Alberta during this project. First, we wanted to improve our system's capability to separate the effects of ground absorption from changes in methane concentration that we measure. The amount of energy in spectral bands associated with methane depends on the background methane concentration in the atmosphere, the length of the path taken by light through the atmosphere, and on absorption by other things (such as clouds and ground materials). Kairos was already familiar with some of the ground features typical of West Texas, for example, that cause significant impact on methane bands and can cause false positive readings. Part of the goal of this project was to recognize ground conditions in Alberta which can confuse the results and address them through a combination of automated algorithms and human assessment of results. Phase 1 of the project was designed to collect data both in places with no excess methane and places with known amounts of excess methane (both in areas with a variety of ground features) to understand which types of ground features impact the raw data and attempt to tune our analysis process to this better. Second, lower lighting conditions (caused by higher latitude and less reflective ground features) requires a higher instrument sensitivity to identify methane plumes with the same level of confidence and with a similar detection threshold as when used under better lighting conditions. Kairos reports elevated methane concentration based on a confidence level metric that adjusts for the uncertainty in the measurement. Lower lighting (among many other factors) causes a lower signal-to-noise ratio for the same level of methane concentration and thus higher uncertainty and a lower confidence score. To achieve similar detection thresholds in Alberta, Kairos will need to improve its ability to correct for a variety of known sources of signal distortion to improve the overall signal-to-noise ratio of the system.

In addition to these general goals, we established some specific performance metric targets to assess the progress achieved during the project and LeakSurveyor's commercial readiness. These targets focused on the system's probability of detecting emissions of different sizes, false positive detections rate, and operational efficiency measures.

Overview of scope of work

The project included three distinct phases:

1. Training Data Collection - Collect calibration data from Alberta oil & gas production regions under a variety of operating conditions and ground reflection profiles with which to train our algorithms.
2. Data Analysis & System Calibration - Use the training data as test cases for algorithm improvements and improved data analysis tools.
3. System Validation and Demonstration - Field demonstration of the improved system as an example of how LeakSurveyor would be used as part of a directed leak detection and repair program. Also repeat calibrated release test to measure improvement in detection sensitivity and accuracy.

The results and learnings from each of these phases will be described in the following sections.

Outcomes and Learnings

Phase 1 - Training Data Collection

During Phase 1, Kairos spent three days (Oct 3-5, 2017) collecting data from multiple passes over calibrated leaks, set up by Carbon Management Canada at their Field Research Station, at different leak rates at different times of day and across different days. Each day, Kairos flew multiple passes over a given release rate ranging from 0 to 20 thousand standard cubic feet per day per mile per hour ("Mscf/day/mph of wind"), for a total of 40 passes per day and 120 over three days. Each pass was flown in a 6-mile-long path, with the release point at the center, in order to pick up adequate background. We captured near-ground wind speed at the leak locations using a weather station. On each of the three mornings, while the calibrated release equipment was being set up, we also flew over various patches with different backgrounds and no expected emissions, including bodies of water and the town of Brooks, to collect control data far away from the release point.

On October 9, 2017, after a few days of poor weather, we flew over 100 miles of oil and gas production in four (4) hours. This area comprised 895 wells and 26 batteries belonging to the Operator (as well as sites and facilities belonging to other producers in that region). This data, combined with the data taken from the calibrated release days, comprised our Alberta-specific training and testing data for Phase 2.

The image below displays the area of oil and gas production that was surveyed (outlined in red) and the site of the calibrated release, at CMC's Field Research Station site southwest of Brooks (indicated with a red star).

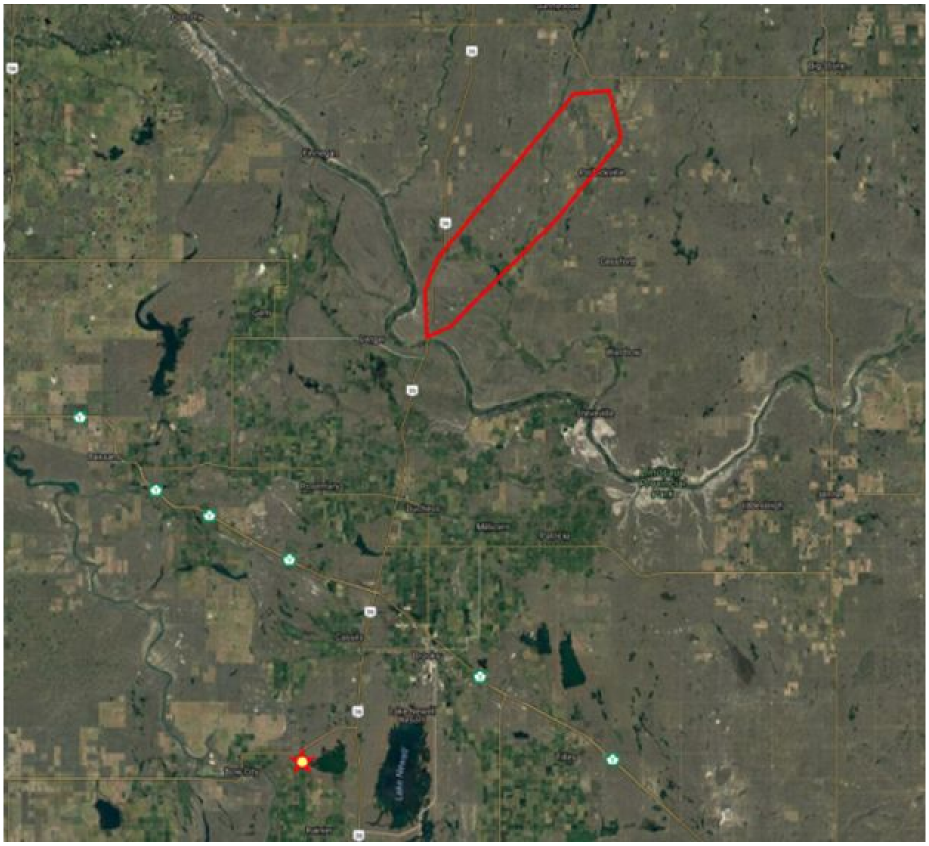


Figure 5: Operator operations. Survey region (red outline) and calibrated release location (red star).

Phase 2 - Data Analysis & System Calibration

During Phase 2, Kairos physicists, software engineers and data scientists used data from Phase 1 data sets as well as additional test flights and lab testing to identify a set of opportunities for system improvement and to test those improvements in preparation for demonstrating the enhanced system in Phase 3. During this phase, Kairos enhanced almost every aspect of the LeakSurveyor system, from certifying a newer generation spectrometer to developing software algorithm improvements and better tools for human analysis of the resulting data. In aggregate, we believe these enhancements have greatly improved the system's ability to collect data reliably and detect methane emissions more accurately for future service in Canada.

Opportunities for Improvement

Kairos identified some general areas where there was opportunity for improving the systems and processes used by LeakSurveyor. The section below describes these general areas first, and then following sections will describe specific technology improvements that were implemented in order to capture some of these opportunities.

Better adjustment to environmental conditions during data collection

Operating in Canada means operating under lower lighting conditions, lower temperatures, and with less optimal weather. Based on Phase 1 results, one area Kairos identified for improvement was the need for better instrument management tools during data collection to adjust better for environmental conditions and ensure we consistently collect high quality data. In order to reduce the costs of coordination, Kairos actively seeks reductions in the number of times when a flight produces low quality data and the region needs to be surveyed again. An area that we focused on was flight control software — the software used to manage the instrument during flights and for the data collection process, in general.

Reliable, hands-free operation

Two of the metrics that we highlighted in our project proposal were operational uptime and hands-free operations. Both of these are aimed at lowering the cost and time required for data collection. Prior to this project, operations engineers, operators who manage the instrument in the field, had only command-line tools to monitor the performance of the instrument, the quality of the data being collected, and to adjust the system during collection to troubleshoot problems. As noted above, this made it difficult for engineers to adjust the system to compensate for changes in the data collection environment (such as lighting). The system also suffered from reliability problems that often required an operations engineer to make changes or even reboot the system during flights. Our goals within this category were two-fold:

- Reduce reliability issues to ensure that good data is collected a higher percentage of the time that we are operating in the field. Of course, we are limited to operating during days and times of acceptable weather conditions, but within those windows of opportunity, we don't want to waste time and money with poor quality or missed data because of system problems.
- Reduce the need for expensive staff monitoring the instruments during flights. In the near term, the goal was to have the system run "hands-free" (i.e. without the need for engineers to intervene) most of the time. This will allow us to rely on less technically adept field staff in the short run and potentially eliminate that role entirely in the medium term, thus reducing the cost of providing leak detection services.

Adjustment for lower lighting conditions

As noted above, one of the big differences for operating in Canada is consistently lower lighting levels. Kairos LeakSurveyor uses reflected sunlight to measure the absorption of light by atmospheric gases at specific wavelengths. Lower lighting levels create a number of challenges, including increasing the level of noise vs. methane signal in the data. To address these challenges, we worked on adjustments to the instrument that would allow us to capture more light with longer exposure times and handle a wider range of acceptable lighting. We also improved the information available to human analysts to understand what light we actually received, as a factor in assessing the reliability of potential detections.

Identifying and suppressing areas with unreliable data to avoid false positives

From experience, we've found that that certain factors, such as bodies of water, cause LeakSurveyor to receive data that does not lead to reliable results. One area of improvement was to identify cases where the data processing algorithms can recognize data points whose source data is not reliable enough and exclude those data points from final results. In addition, we added to the output data available to human analysts to show where those excluded data points were spatially aligned with visual images of the ground.

Better separation of methane signal from other confounding signals

Another area for improvement was to enhance the signal processing algorithms to target methane more precisely and distinguish it better from other causes that have similar impacts on the portion of the spectrum measured by our instrument. Some of these confounding signals, such as bright reflections off tanks or shiny roofs and gases with absorption lines that are close to those of methane, are not exclusively problems in Canada. Other challenges, such as operating with frequently cloudy skies, appear to be more common in Canada than in sunnier regions to the south. A major focus of Phase 2 was to try different signal processing techniques to detect and correct for signal bias caused by these confounding signals.

Adjustment for geo-location at higher latitudes

After each individual data point has been analyzed by the signal processing algorithm, its geo-location (latitude and longitude) is determined in order to display results on maps relative to ground features (wells, roads, buildings, etc.). We found that the geo-location algorithm was not as accurate for high latitude data, relative to prior data taken in California or Texas, and we improved the algorithm to handle higher latitudes better.

Consistency of human analysis of resulting data

In addition to the significant automated data processing improvements, we've also improved the process by which our Analysts review results and apply judgement to potential detections. More data has been made available to analysts for decision-making such as locations of excluded data and improved lighting maps. Further, new tools were developed that allow for the consistent capture of potential detections and to add a quality control check prior to finalizing what or what not to report to end users.

Specific Improvements

The table below provides a categorized list of specific technology enhancements that were implemented during Phase 2. In the following section, each improvement is discussed briefly to provide more detail.

Improvement	Category	Targeted Opportunity Area(s)
System monitoring, dashboards, simplified controls	Flight control software	● Reliable, hands-free operation
Automatic exposure time and gain adjustment	Flight control software	● Reliable, hands-free operation ● Better adjustment to environmental conditions during data collection ● Adjustment for lower lighting conditions
Automated dark frame capture	Flight control software	● Reliable, hands-free operation ● Better adjustment to environmental conditions during data collection
Improved build & configuration management	Flight control software	● Reliable, hands-free operation
Instrument performance vs. temperature characterization	Hardware improvement	● Better adjustment to environmental conditions during data collection
Power reliability	Hardware improvement	● Reliable, hands-free operation
Characterization and tuning of instruments' dynamic range	Hardware improvement	● Better adjustment to environmental conditions during data collection ● Adjustment for lower lighting conditions
Second generation spectrometer	New instrument: calibration and certification	● Reliable, hands-free operation ● Better separation of methane signal from other confounding signals
Brightness maps showing captured light and true scene brightness	Automated data processing	● Adjustment for lower lighting conditions ● Consistency of human analysis of resulting data
Excluded data points	Automated data processing	● Identifying and suppressing areas with unreliable data to avoid false positives

Principal component analysis	Automated data processing	● Better separation of methane signal from other confounding signals
Forward model	Automated data processing	● Better separation of methane signal from other confounding signals ● Identifying and suppressing areas with unreliable data to avoid false positives
Improved map placement algorithm	Automated data processing	● Adjustment for geo-location at higher latitudes
Automated analysis workstation set-up	Data analysis tools	● Consistency of human analysis of resulting data
Emission detection data capture and review tools	Data analysis tools	● Consistency of human analysis of resulting data

System monitoring, dashboards, simplified controls

Kairos developed a flight control system that runs on a laptop connected over a local wifi network (inside the plane) to the LeakSurveyor instrument. The system continuously monitors the instrument during data collection and outputs key performance indicators via a graphical user interface to allow operations engineers to easily monitor the instrument health and troubleshoot problems. The system provides simple controls to easily troubleshoot problems while limiting the scope of changes to ensure fixes are within acceptable ranges. This has been a big improvement over the prior tools that required operations engineers to be highly technical and trained to ensure errors that occured weren't a result of operator troubleshooting errors. Now, operations engineers can simply launch the system and let it run for most of the flight without intervention. These improvements are getting us closer to the day when the systems can collect data unattended with only a pilot in the plane.

Automatic exposure time and gain adjustment

When Kairos operates in locations with bright, consistent lighting (as is often the case in Texas or California), it is possible to leave the values for the camera's exposure time and gain relatively constant over a day of data collection. When the environment is more challenging (e.g. collecting under cloudy conditions and adjusting for the lower light penetration while avoiding overexposure) the system must be much more reactive to the brightness of scene being measured, changing the exposure time frequently. Unfortunately, we cannot rely on the camera's stock auto-exposure capabilities as Kairos's standards for what constitutes "good imagery data" differ significantly from the exposure baselines set by our camera suppliers. Therefore, one of the important additional capabilities built into the flight control system was continuous monitoring of the lighting levels in spectral data we are capturing and a control algorithm to adjust exposure time and gain to optimize these variables.

Automated dark frame capture

An important aspect of signal processing is to measure and subtract out the signal that is received from the detector even when there is no light at all (a “dark frame”). To the extent that the dark frame changes due to different ambient temperature conditions (e.g., potentially significantly colder in Canada) or drifts over time, it is more accurate to measure the dark frame each day. Another feature that we built into the flight control system is a set of tools for the instrument operator to quickly capture dark frames at the beginning and end of each day and automatically add them to the data set that is uploaded for processing.

Improved build & configuration management

One potential source of unreliability was in getting all the details right when deploying hardware and software updates to instruments as the engineering team made rapid improvements to the tools that were being used in the field. Getting a mismatched version of updated software with an older configuration file caused operational problems that led to errors that reduced time available collection time. We made a number of improvements to configuration management tools, automated system testing, and deployment protocols to reduce the field problems and downtime that this type of problem can cause.

Instrument performance vs. temperature characterization

There are a number of aspects of the system, such as the dark frame signal or the quantum efficiency of the detector to different wavelengths of light, that vary with temperature. As temperature varies more in Canada, especially at the colder extremes, than in other areas in which we have operated, we thought temperature issues were more likely to be a problem there. We did both lab and flight testing to understand and characterize how these instrument behaviors change with temperature. We also took steps to improve our control of the instruments’ temperature and to monitor when it deviates from normal temperature ranges so that can feed into both our assessment of the data for those time periods and into longer term system improvements.

Power reliability

Another source of lost data collection time and unreliable operation in Alberta was camera drop-outs or other system hiccups that have mostly been related to subtle unreliability in the power circuits. In part, this is related to power connectors that jiggle around under airplane turbulence and lead to brief power degradations. As the weather is often less ideal in Canada than in California, we experienced more problems of this type than usual during Phase 1. We took a number of steps to address these problems in our original first generation instrument and paid particular attention to better power circuitry in the second generation instrument, which seems to have improved reliability significantly.

Characterization and tuning of instruments' dynamic range

An important aspect of getting clean data is operating the instrument so that the amount of light received falls within the "dynamic range" at which each pixel of the camera has a linear response. That means that you want to control the exposure time and camera gain so that the number of photons received by the camera and converted into electrical signal falls within the good range. The flight control software attempts to adjust those variables to maintain good data, and when lighting is steady and bright, it is not very difficult to control for this. However, when lighting levels are lower and especially where they vary more dramatically from dark to bright areas (e.g., with patchy clouds), it helps if you can increase the acceptable range. During this phase, we put a lot of effort into characterizing the detectors' gain at varying configuration settings and lighting levels in order to optimize the settings that would give us wider dynamic range at the lighting levels we've seen in Canada and elsewhere.

Second generation spectrometer

One of our internal development efforts during this period was to test, calibrate, and ultimately certify for production operations a new second generation spectrometer. As well as simply adding to our capacity to run multiple surveys in parallel, the new instrument has a number improvements that will be relevant to future projects in Canada. It makes use of improved, more resilient power circuitry that has been proven to have vastly fewer in-flight problems requiring instrument operator attention. It also measures light across a slightly wider range of wavelengths than the first generation instrument, which gives us some additional information about other gases that have absorption features in that part of the spectrum and can help to separate those signals from methane. Many of the improvements described in this document apply to both instruments, but a number of improvements were specifically aimed at testing and certifying this new instrument. We did controlled release data collection in Phase 1 with both instruments so that we would have good Canadian test data with which to tune this second generation instrument.

Brightness maps showing captured light and true scene brightness

One of the important considerations for human analysts reviewing the data is how much light we had available for measurement in an area. More light usually means less noise in the raw data and a more reliable signal. Big swings in lighting can warn us of clouds, which can cause problems with the signal processing algorithms. We put less confidence in potential detections in areas of marginal light or areas where clouds could have biased the results, so making it easy for analysts to check this information is valuable. During Phase 2, we altered the way that we present this lighting information to analysts. We now provide two different views of "how much light" that each help answer a different question about our data. First, we provide a map showing the amount of light we actually measured. Since the exposure time is changing to adjust for different lighting levels, a longer exposure of a darker area might capture the same amount of light as a shorter exposure of a bright area. Since noise and other aspects of the instrument response are related to the total amount of light *captured*, this measure tells us how good the signal-to-noise ratio should be in the data. Second, we provide a map of the true brightness of the scene. In other words, if all of the data had been captured at the same exposure length, how would the brightness of each area compare? This view of the data gives analysts a better indication of where the system was working harder to get enough light or where overall brightness was changing rapidly, which is a good indication of cloud cover. Combined, these new views of the lighting situation are valuable tools for the analysts to use when determining how to rate our confidence in each potential methane emission detection.

Excluded data points

One of the goals for improvement was to detect and remove causes of false positive detections automatically. We determined that many false positive situations were caused by individual data points containing unreliable data that then skewed the statistical results for an entire area around them. By detecting that these data points were flawed and excluding them from the statistical analysis of the area maps, we could greatly reduce the number of false positives. A data point can be excluded for a variety of reasons. For example, areas over water usually receive insufficient light to achieve a minimum signal-to-noise ratio. In other areas, an especially bright spot may receive so much light that the data is outside the dynamic range of the system (where instrument response is linear to light received). The signal processing algorithms now do a better job detecting these out-of-bounds cases and excluding those data points from the results. We also created a new map layer for human analysts showing where data points were excluded, which can be viewed in relation to features on the ground and to the location of potential detections. This helps analysts understand why the exclusion may have happened and whether exclusions may have impacted our results in an area of interest.

Principal component analysis

PCA is a signal processing technique and a type of unsupervised machine learning. It allows a sample (a spectrum in our case) to be measured over a large number of attributes and then, using statistical techniques, finds correlations among the attributes that indicate common root causes for the variations. Methane might be the common root cause for a set of absorption lines changing, for example, but the reflection characteristics of a dirt road might cause some overlapping, but different, attribute changes. PCA can be used to separate true methane signal from other confounding signals that cause absorption in some of the same wavelength bands as methane. We developed an alternative methane metric based on PCA that can be used by analysts as a second opinion (to our original methane metric) on whether a potential detection is likely to be real. We find that the PCA metric out-performs the original metric under some circumstances (mostly by removing some false positive cases), but is not consistently superior.

Forward Model

We also developed a model of what we expect to receive at the instrument based on a detailed understanding of the solar spectrum, the absorption bands of all common gases in our wavelength region of interest, how our instrument measures the incoming light, and a variety of assumptions about the column density of gases in the atmosphere, for example. This type of model is commonly referred to as a forward model, predicting what data we should measure given possible values for unknown input variables (i.e. column densities). Using this model, we can solve for the most likely values of column density that explain the data we are receiving, which provides another method for estimating the amount of methane detected. This forward model is thus a third way to cross-compare algorithmic results to increase our confidence in potential detections or to avoid false positives that register in only one version of the metric.

The forward model also detects cases where the shape of the spectrum received simply is not a very good match for any realistic set of assumed column densities and thus is probably unreliable data that should be excluded. While these situations are uncommon, it provides another good way to remove outliers that might otherwise cause false positive detections.

Improved map placement algorithm

Our initial results from the Phase 1 data collection seemed not to be as well aligned with visible ground features (such as roads) as we normally see in other collection regions. Upon investigation, we determined that at higher latitudes there is a much bigger difference between a degree of longitude and a degree of latitude (in terms of meters) than at lower latitudes, and this was causing the projection of the instrument's view for each pixel to a ground lat/lon location to be inaccurate. While not a major change, this is a good example of a fix to the system that is particularly relevant to making the system ready for usage in Canada.

Automated analysis workstation set-up

Each day's worth of data collection results in a large amount of data that needs to be set up within a geographical information system (GIS) for review by a human analyst. As we prepared to scale up operations to handle new data sets every day and to deliver those results to customers quickly, we needed to make this faster and easier. We developed tools to launch a workstation automatically and set up all the relevant data with default analysis color mappings so that an analyst can immediately begin reviewing the results. Previously, the effort of getting all of the right things in place to begin the actual analysis work could take hours of analyst time for each day's worth of data. This improvement drives down our cost of analysis and reduces the turn-around time for providing conclusions to our clients and is thus a key part of commercial readiness. Also, by making the set-up of the data and choice of color mappings consistent, we expect to achieve more consistent analysis results across analysts.

Emission detection data capture and review tools

As human analysts identify detections while reviewing each day's data set, we want to capture the data leading to that assessment in a central database that can track detections over time and make the core data easily available to others without the need to pull up the entire day's data set. This leads to a more consistent analysis process across different human analysts and also facilitates a quality control process where the nominated detections can be reviewed by a group of analysts before finalizing the Kairos confidence rating for each detection.

Phase 3 - System Validation and Demonstration

Results of controlled releases

On September 18th, 2018, Kairos performed a controlled release at Delta Bluegrass, approximately 10 miles west of Stockton, CA. Kairos collected data during 50 flight passes over the release point, with methane being released at rates ranging from 2 to 100 Mscf/day/mph of wind. Each pass was flown in a 6-mile-long path, with the release point at the center, in order to pick up adequate background. Test flow rates were set based on the desired flow rate (in Mscf/day/mph wind) and the measured wind speed (mph). Wind speed (average speed over 1 minute intervals) was collected by a portable weather station set up at approximately 3 meters above ground near the release point. At 3 different times during the day, we flew a total of 6 passes with no methane being released to serve as an experimental control where (as expected) we detected no excess methane above the background level.

The images below provide a sample of the plumes detected by LeakSurveyor during the calibrated release.

Relatively small plume from lower release rate

Stronger plume from mid-size release rate

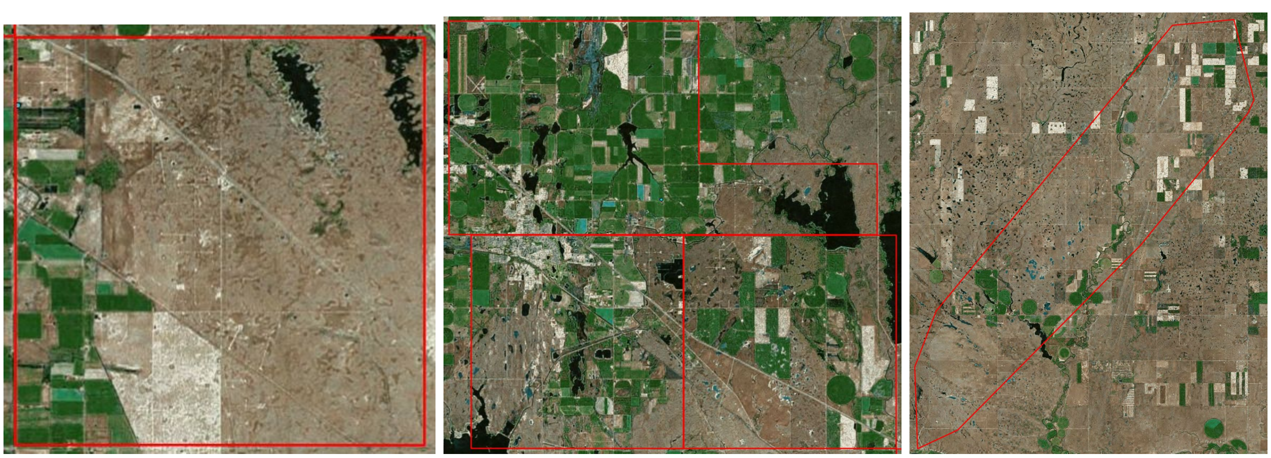
We also detected methane (unexpectedly) at another location about 2 miles south of the calibrated release point. Plumes were detected at this location during several of the flight passes. On further inspection, we believe this is surface equipment related to a nearby underground gas storage facility.

Plume near underground gas storage facility

Using the data points from this calibrated release test, we can estimate a probability of detection curve for different release rates, and this was used to assess Kairos' progress against the probability of detection performance metrics we had set for the project. We also used the data from the calibrated release day to assess the system's false positive rate at the end of the project relative to the false positive rate during the data collection in Phase 1.

Field Demonstration

Kairos collected live system data over the Operator's assets in the Brooks region of Alberta (outlined below in orange). Imagery was collected over a period of 3 days between August 6th and August 10th, 2018. The aerial surveys covered approximately 676.2 Km^2 and took 11.92 hours to complete.



Live system demonstration areas

Overall, Kairos identified five (5) sites with potential emission sources; 4 of the identified sites were confirmed via a ground follow-up study. Kairos partnered with GreenPath to complete the ground follow-up study.

Project outcomes

Kairos believes that we have achieved our goal of getting LeakSurveyor to TRL-8 and readiness for commercial operations in Alberta. LeakSurveyor significantly exceeds the project targets on all performance metrics, including reducing the false positive rate by >99% and having a 96% probability of detection for a mid-range emission rate of 10 Mscf/day/mph wind.

Environmental Impact: Greenhouse Gas

Qualitative findings

Alberta is an important oil and gas producing region in Canada and as such has fugitive methane emissions of raw or associated gas. There is substantial uncertainty in the estimates of fugitive and vented emissions from the oil and gas industry. Furthermore, upstream activities in the region are characterized by remote facility locations, which are difficult to travel between and require equipment that can be powered without access to electrical grids. LeakSurveyor aims to address these challenges by remotely detecting and quantifying fugitive emissions in Alberta, both to guide repairs that will reduce the amount of methane emitted and to provide the longitudinal data needed to gain a better understanding of the problem of fugitive emissions.

Detecting and repairing fugitive methane emissions also leads to co-benefits from reducing conventional, non-GHG pollutants – because volatile organic compounds and hazardous air pollutants are associated with methane emissions from the oil and gas industry – that can harm public health and the environment.

Because this project was focused on improving the technology to the point of commercial demonstration, the direct methane reduction benefits from this project were very minor. During Phase 3, we detected 4 fugitive emissions sources from the demonstration survey, which we estimate could lead to a reduction of 16 metric tons of methane emissions, if repaired.[1]

Kairos' primary impact will come from broad usage of the system to find and repair fugitive methane emissions more rapidly than would be done by other inspection methods. Based on U.S. data, widespread commercial implementation

[1] In these estimates, we assume that facilities are inspected annually, on average, and fugitive emissions will go on for 6 months, on average, before being discovered and repaired.

of LeakSurveyor could lead to the reduction of fugitive methane emissions in Alberta by ~80% over five years, at a lower cost than alternative solutions. While LeakSurveyor is conducting commercial-scale operations in the United States, we estimated the technology was only ready for near-commercial pilot demonstration in Canada when this project started. This project has helped us to progress on the path toward technical readiness. We believe the system is now ready for market rollout and ultimately wide-spread commercial implementation in Alberta.

Quantification of emissions reduction potential

To estimate GHG reductions with widespread, long-term deployment of LeakSurveyor, we first estimate a baseline scenario of the volume methane emitted when no detection technology is used but leaks are still randomly mitigated, whether through detection during normal operations (i.e. via audio, visual, or olfactory signals) or repair during routine maintenance activities. This is a reasonable baseline because, while Alberta currently has a Best Management Practice for Fugitive Emissions Management, it is not required and operators are unlikely to voluntarily use the expensive instruments that are currently on the market in Alberta to conduct surveys in a systematic manner. If, however, a leak is detected in the normal course of operations, it is reasonable for the operator to fix the leak as it presents a waste of product and in some cases a safety hazard.

The data for our baseline scenario reflects "top-down" measurements of ambient methane concentration in the atmosphere, which are generally larger than "bottom-up" estimates of methane emissions from direct measurements of emissions from individual sources.[2] This discrepancy has been partly attributed to under-measurement of super-emitters,[3] which are rare and therefore unlikely to be captured in the direct measurement campaigns that have been performed due to their small sample sizes. "If emissions distributions have 'heavy tails'…small sample sizes are likely to underrepresent *[sic]* high-consequence emissions sources," writes Brandt et al. (2014). Zavala-Araiza et al. (2015) were able to reconcile bottom-up and top-down estimates in part by accounting for the influence of large emission sources ("two percent of oil and gas facilities in the Barnett account for half of methane emissions at any given time, and high-emitting facilities appear to be spatiotemporally variable.") We have therefore modeled a baseline leak rate distribution based on sample data from a direct measurement campaign in Texas[4], extended with a power law distribution, which is usually used to model data whose frequency of an event varies as a power of some attribute of

[2] Miller, Scot, et al. "Anthropogenic Emissions of Methane in the United States." *Proc. Natl. Acad. Sci. U. S. A.* Dec. 10, 2013. URL: http://www.pnas.org/content/110/50/20018

[3] Zavala-Araiza, Daniel, et al. "Reconciling Divergent Estimates of Oil and Gas Methane Emissions." *Proc Natl. Acad. Sci. U. S. A.* Dec. 22, 2015. URL: http://www.pnas.org/content/112/51/15597 and
Allen, David, et al. "Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements." *Current Opinion in Chemical Engineering*. August 2014. URL: http://www.sciencedirect.com/science/article/pii/S2211339814000525

[4] City of Fort Worth Natural Gas Air Quality Study. Eastern Research Group et al. for the City of Fort Worth, 2011. URL: http://fortworthtexas.gov/uploadedFiles/Gas_Wells/AirQualityStudy_final.pdf

that event – in this case the event is a leak and the attribute is leak size. The power law distribution we used has an upper bound of 500 Mscf/day (meaning the simulation never generates a leak larger than that.) Our research scientists selected -1.75 for the power, or exponent, in the power law formula , in order to match national U.S. top-down estimates of petroleum-sector methane emissions.[5] We do not have a similar data set on which to base an Alberta-specific analysis, due to the lack of such in-depth studies on other sectors and geographies, but our U.S.-based analysis provides a reasonable baseline scenario for comparison.

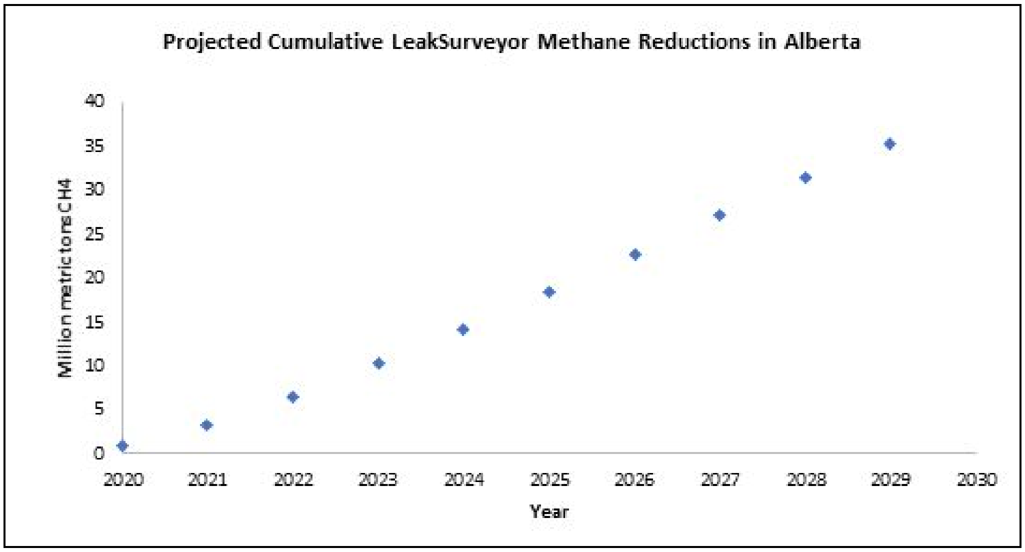
Finally, we use an open-source computer model called the Fugitive Emission Abatement Simulation Testbed[6] (or FEAST) to perform Monte Carlo simulations of natural gas leakage over time under different LDAR programs, based on the leak distribution data set described above and the detection capabilities of different instruments and monitoring frequencies. The baseline scenario is the "null" scenario in this program, which is modeled as operators randomly finding and fixing leaks in the normal course of operations. In this way, we arrive at our estimates that monthly LeakSurveyor surveys lead to an ~80% reduction from null in fugitive methane emissions volume from oil and gas operations. LeakSurveyor's detection capabilities were modeled as being approximately equal to this project's release rate targets. We've shown during this project that LeakSurveyor now meets (and likely exceeds) that level of sensitivity, which adds confidence to these projections.

For initial commercial implementation of the LeakSurveyor technology, our model assumes rolling out a monthly LeakSurveyor program to a few select natural gas producers with sites in one area. If this initial implementation surveys 5,000 well sites and associated facilities monthly, the model predicts annual reduction in the first year of approximately 110,000 metric tons of methane (~6 billion cubic feet) relative to a "null" scenario.

Our projections then assume a growth rate in our market penetration that is rapid in the first few years and then levels off (these projections are based on current active well counts in Alberta, thus ignoring future production growth as well as impacts from surveying inactive wells). In our first fully commercialized year, 2020, we project to be performing monthly surveys for 25% of the market, or 40,000 wells, with a cumulative methane reduction over that year of roughly 1 million metric tons of methane. By 2025, we project having roughly 75% of the market, and will have reduced roughly 18 million metric tons of methane cumulatively. At this pace, by 2030, we will have reduced roughly 35 million metric

[5] If the exponent is more negative, excessive numbers of tiny leaks are required to produce the methane from the top-down estimates. This results in many more leaks than wells, such that the typical well would have three to five leaks. This is out of sync with reality, as many wells and facilities are not leaking at all. If the exponent is less negative (closer to zero), then more of the methane comes from truly enormous emissions. We don't have enough data to support that, although it could still be true.
[6] http://www.ngecenter.org/feast.htm

tons of methane over 10 years. The chart below shows our projected reductions over time as we scale up our market penetration.



Conclusion

This project succeeded in achieving its goal of advancing the technology readiness level of the LeakSurveyor system to the point of commercial demonstration and preparedness to be rolled out for widespread commercial use. Over the course of the project, we made numerous improvements to the system to improve reliability, reduce operating costs, enhance signal processing algorithms, and improve the tools used by our analysts, with many of these improvements targeted at providing good results in the more challenging operating environments we've experienced in Alberta. By the end of the project, we had significantly exceeded all of our performance metric goals for the project. Kairos appreciates Emission Reduction Alberta's support, and the support of our project advisors and partners, in making these advances possible.

Scientific Achievements

As noted in our project proposal, the primary goal for this project was to improve our understanding of the characteristics of data gathered in Alberta and improve our analysis of that data for methane detection. The resulting learnings have been incorporated into better flight control software, more detailed and accurate characterization of our instruments, and improved data analytics algorithms that are all incorporated into the LeakSurveyor systems and services. We treat this intellectual property as trade secrets. At the time of this report, Kairos does not intend to publish our results in any books, papers or present outcomes at academic conferences.

Business and Technology Roadmap

Technology Roadmap

Kairos is proud of the advancements in technology described in this report, and will continue to advance our core technology and service offerings. We're continuing to think creatively about hands-free operation, factors that impact collection conditions across seasons and varying environments, and are designing solutions where the LeakSurveyor system is robust enough to work autonomously, with the pilot able to fulfill the small number of tasks required for operation. Further, resources have been allocated to improve and ease data uploads.

We're also making continued investments in improving data analysis. We're building tools that further automate the detection and recording of methane plumes. With these advancements we estimate that our data processing pipeline will be able to support 10 times more data while only increasing overall workloads by an estimated 25%. Further, to meet these higher capacity needs, we working to increase computing and storage mechanisms.

Finally as driven by customer requests, we are working to support a variety of delivery formats. To meet these customer needs, we're developing tools that provide fully featured GIS layers.

Commercialization Plans in Alberta

Product-Market Fit

Kairos is working directly with our Operator partner to inform our commercialization strategy in Alberta and across Canada. In the United States, we've found oil and gas exploration and production companies along with pipeline operators to be our primary commercial end-users. We believe the same will hold true in Canada, but we plan to test this assumption using customer feedback about product-market fit. Along with this feedback, we plan to share the publicly available findings from this study with other operators to gauge interest in our offerings. Customer feedback will be integral in our commercialization strategy. We anticipate we'll have the Operator's feedback gathered and analyzed by the end of 2018.

We also collaborated with GreenPath on this project to do follow-up ground analysis, which could be a combined services opportunity. We plan to evaluate Kairos methane survey product offerings both with and without ground follow-up services. At this point, we are still determining exact offerings that are attractive to end-users as we continue to understand data needs. We anticipate completing a review of possible product offerings within the next six months.

Based on our discussions with potential customers, we plan to design future pilot projects to further refine product-market fit in Alberta. Our goal is to conduct additional pilot projects in Alberta within the next nine months.

Regulatory Approval

Another key to our commercialization strategy in Alberta is gaining regulatory approval for fugitive emission monitoring requirements. While we believe aerial imaging can cost-effectively reduce emissions through increased gas capture in a non-regulatory context, using aerial imaging to also meet compliance requirements will further strengthen the commercial value proposition for industry clients. We've already engaged with AER to promote aircraft-based surveys as an approved monitoring method, and once the Provincial regulations are finalized, we plan to formally apply for regulatory approval. We expect this to be a key component of our commercialization strategy. We anticipate regulatory approval will take 9 to 12 months from when the Alberta regulations are finalized

Partnerships

For a more extensive discussion of our planned partnerships, see the Communications section. We plan to use the partnerships with the organizations we've already identified, along with any others we identify, as a tool to increase awareness of our product and find potential customers.

Communications Plan

We plan to use a multifaceted approach to communicate the commercial readiness of our technology to our primary stakeholders: the oil and gas industry and regulators at the Provincial and Federal levels. In order to communicate with industry, we will use direct B2B outreach to identify potentially interested operators to explore further commercialization efforts. We will also work through industry trade groups, conferences, technology events, and other relevant forums to discuss our commercial capabilities. Currently, we plan to work with the Petroleum Technology Alliance Canada (PTAC), the Methane Leadership Alliance (MELA), and other relevant workgroups. As our understanding of companies' needs and involvement in groups evolves, so will our list of groups we work with. Partnerships with industry organizations will provide us with methods to vet, refine, and ultimately promote our aerial methane imaging products.

Part of our effort will involve direct interaction with Canadian operators in Canada; we intend to also continue working with multinational companies, many of which have operations in Canada but significant operations in the U.S. and Europe. We believe there is significant potential for cross-pollination between our efforts elsewhere in North America and the potential for the adoption of our technology in Canada.

We also plan to continue engaging with regulators at the Provincial and Federal levels. Most recently, we provided comments to the Alberta Energy Regulator (AER) on the commercial readiness of our technology along with several suggested rule changes that would facilitate implementation of new technologies. We plan to remain engaged in any subsequent rulemakings through the public comment process. We also plan to engage directly with regulators to share the current status of our technology and make them aware of our capabilities. This may be done through direct meetings, teleconferences, webinars, event participation, etc.

As Canada's methane emission strategy evolves, we'll remain active and constructive participants in the process. With presentations, media placement in key outlets, event participation, and other strategies we identify going forward, we'll ensure that both industry and the regulatory agencies are informed about Kairos Aerospace's capabilities.