Description of Technology: Methane Lidar Camera

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Scientific theory

The methane lidar camera is a continuous monitoring technology that detects and quantifies methane emissions from oil and gas facilities. In a typical deployment, the camera is mounted on a tall mast to get a vantage point above most of the equipment. The camera emits a laser beam to scan for emissions within finite fields of view and iterates through scan plans to cover all emission sources. For every scan, the camera creates images showing measurements of photon count (intensity), lidar range, computed path-integrated methane concentration, and a superimposed image of the methane concentration on the photon count. The camera uses a plume detection algorithm to detect emissions and identify continuous regions of elevated methane. Upon leak detection, the camera uses a mass balance algorithm to quantify the mass emission rate from the calculated path-integrated methane concentration and the local wind velocity obtained via the anemometer connected with the camera.

The methane lidar camera quantifies methane emissions using tunable diode lidar (TDLidar) technology, which combines aspects of tunable diode laser absorption spectroscopy (TDLAS) with differential absorption lidar (DIAL) and time-correlated single photon counting (TCSPC) to enable remote spectroscopy and ranging with low-power semiconductor diode lasers. The cameras use diode lasers with wavelengths around the methane absorption line at 1650.9 nm and Peltier-cooled single-photon avalanche diode (SPAD) detectors in a random modulation continuous wave (RM-CW) lidar system. By simultaneously tuning the laser wavelength and modulating the amplitude, it is possible to simultaneously and accurately determine both the range the laser light has travelled, as with typical lidar, and the amount of a particular gas that the laser light has passed through, as with typical TDLAS. A fundamental aspect of TDLidar is the use of the high-speed laser tuning, modulation, and detection that is enabled by modern semiconductor components. This enables the laser wavelength to be scanned at rates of 1 MHz or faster and enables the rapid acquisition of images of both gas spectra and structural distance data over extended fields of view. By modulating the wavelength back and forth across the methane absorption line at 1650.9 nm, the spectrum can be reproduced and spurious effects from ambient conditions can be negated. The camera uses a mechanically rotated Risley prism pair to rapidly scan the transmitted beam across the scene and build up an image (Titchener et al., 2022).

Figure 1 shows the schematic of the camera measurement system. The electronics (i.e., the spectrometer) control the frequency of the emitted laser beam via a modulator, while simultaneously modulating the output intensity. The transceiver is switched into the transmission mode during the pulse, enabling the beam to exit the camera and penetrate the plume of methane gas while blocking off the sensitive SPAD detector to protect it from saturation. Immediately following the end of the pulse, the transceiver switches into the detection mode and opens the path to the detector. The emitted laser beam traverses the gas plume, where it is partially absorbed, and reflects off background scattering objects. Common scattering objects include ground, buildings and structures, and vegetation; no mirrors or specialized reflectors are required. The camera can image, detect, localize, and quantify emissions for methane plumes that have a background scattering surface within 200 m along the camera's line of site; i.e., the laser emitted from the camera passes through the plume and reflects off a surface that is within 200 m from the camera. A small fraction of the scattered photons returns to the camera and enters the detector where they are counted, building up the raw spectrum to be used for further interpretation.

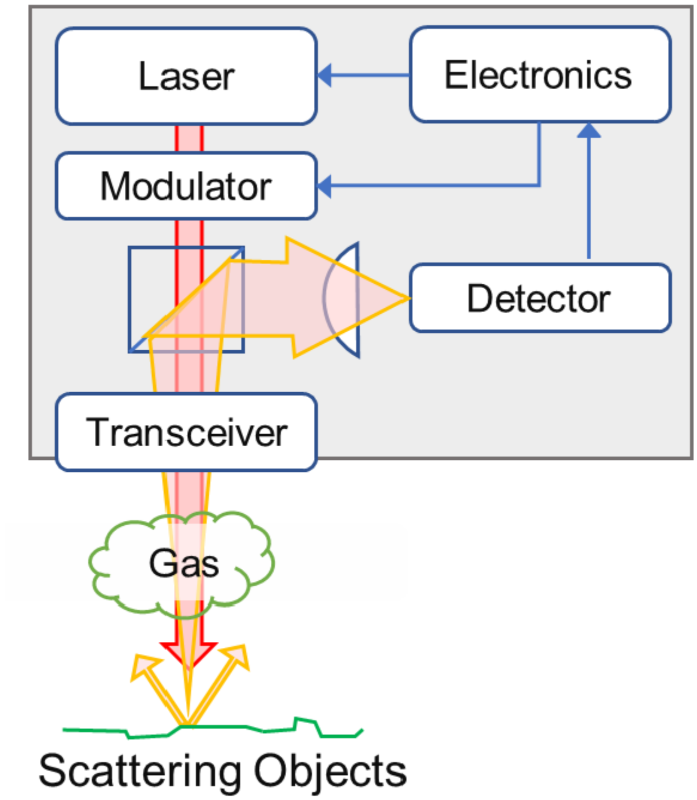


Figure 1: Schematic of the methane lidar camera (Titchener et al., 2022).

The camera uses the measured absorption curve to determine the path-integrated methane concentration, typically expressed in parts per million times meters (ppm-m). The camera hardware contains a sealed gas cell precalibrated at 500-800 ppm methane concentration to confirm that the laser is continuously locked in around the methane absorption wavelength of 1650.9 nm. The camera accumulates data points at a rate of 100 Hz while the beam is rapidly scanned around the environment. After accumulating several thousands of points, the data can be visualized in 2D and 3D images. The image of the methane plume can be overlain on the background image, enabling methane emissions to be allocated to a particular source (Titchener et al., 2022). The data are complex, containing signal intensity, lidar range, and spectral information. The methane plume is isolated by subtraction of the background due to an internal gas cell and ambient gas in the atmosphere, followed by applying a plume detection algorithm that simply identifies and separates out large, connected regions of elevated methane. Once a methane plume is identified, the camera uses a simple mass balance approach to calculate the methane mass emission rate. The mass balance approach aims to determine the mass emission rate by calculating the mass of gas flowing through a 3D surface enclosing a gas source. The principle of mass balance derives from the fundamental principle of conservation of mass, where the total amount that is emitted within a certain region of space must eventually flow out of that region, unless that region contains sinks of the emitted substance. The mass flux is defined as the mass of gas passing through a surface per unit area per unit time. By integrating the mass flux through a surface enclosing a volume, the total mass of gas entering or leaving that volume can be computed. If the net flux is greater than zero, this indicates that the region is emitting gas.

The mass balance equation, also known as Gauss' Law, can be generally expressed for any substance as

$$\left\langle \frac{dq}{dt} \right\rangle = \sum - \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle$$

where *q* is the total mass of that substance within the enclosing volume, *dq/dt* is its rate of change, $\boldsymbol{j}$ is the mass flux per unit area, the surface integral on the right-hand side is over a surface enclosing the volume, and $\sum$ is the sum total of sources and sinks of substance *q* within that volume. The brackets indicate a time average over a period longer than typical concentration fluctuations, which occur on the order of a minute. With the methane lidar camera, this time average window is fixed by the duration of a single image acquisition, which is generally 3 to 4 minutes. The signal is accumulated and binned as the beam rotates and sweeps through the gas plume multiple times; thus the data in the image do not represent an instantaneous snapshot but rather an average over the image acquisition time. This signal-averaging step is required for good signal-to-noise ratio and improved accuracy. It allows setting ⟨*dq/dt*⟩ to zero as any instantaneous pooling of methane behind structures found on-site is unlikely to persist for longer than the measurement time, eventually reaching the steady-state value after averaging over temporal fluctuations. As methane does not sediment, adsorb, or transform into another compound to a significant extent, it can be assumed that there are no sinks of methane (i.e., processes removing it from the atmosphere). Thus, $\sum$ is the mass emission rate and is equal to

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle .$$

Now the mass flux per unit area $\boldsymbol{j} = \boldsymbol{v}\,\rho$, where ρ is the gas concentration (g/m^3) and $\boldsymbol{v}$ is the wind velocity vector (m/s) measured by an anemometer connected to the camera at a frequency of 1 Hz; i.e., with a new wind measurement provided every second. Both ρ and $\boldsymbol{v}$ have spatial dependence. However, wind fluctuations will be averaged out both spatially and temporally over the methane image acquisition period of 3 to 4 minutes, such that a single mean wind value computed from the anemometer measurements over a corresponding methane image acquisition period can be used for the computation without loss of accuracy.

The methane lidar camera does not measure the concentration ρ directly, but rather a path-integrated methane concentration $\boldsymbol{\xi}$ (g/m^2); i.e., ρ integrated along the laser beam with direction $\hat{\boldsymbol{n}}$. To perform the double integration, the enclosing surface must be selected. Because methane flux follows the wind, ρ and hence $\boldsymbol{j}$ will be both zero upwind of the source. Thus, any surface can be used on the upwind side as the integral of $\boldsymbol{j}$ over it will be zero. Therefore, it can be ignored. For the downwind portion of the enclosing surface, a plane $\boldsymbol{S}$ is used which is defined by the vertical edge of the plane of the plume image $\boldsymbol{l}$ and the laser beam direction $\hat{\boldsymbol{n}}$. Then we can write $\rho d\boldsymbol{S} = \boldsymbol{\xi} d\boldsymbol{l} \times \hat{\boldsymbol{n}}$ (the crossproduct of $d\boldsymbol{l}$ and $\hat{\boldsymbol{n}}$) and for the total emission mass flux rate $\sum$,

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle = \left\langle \oiint \boldsymbol{v} \cdot \rho d\mathbf{S} \right\rangle = \left\langle \boldsymbol{v} \cdot \int \xi d\boldsymbol{l} \times \hat{n} \right\rangle$$

where again the bracket indicates the time averaging implicit in the measurement scheme. The mass balance approach to the quantitative mass emission rate computation is further discussed in Titchener et al. (2022).

Physical instrument

The key system components are illustrated in Figure 2 and described below, where the left image illustrates the connectivity diagram of components, and the right image shows the full system as assembled in the field. The components that make up the system are not limited to the descriptions below and can vary depending on the context of the installation. For example, masts can have different ranges of height, or the camera can be mounted to other structures such as I-beams with support brackets. Therefore, the descriptions and figures are for reference only:

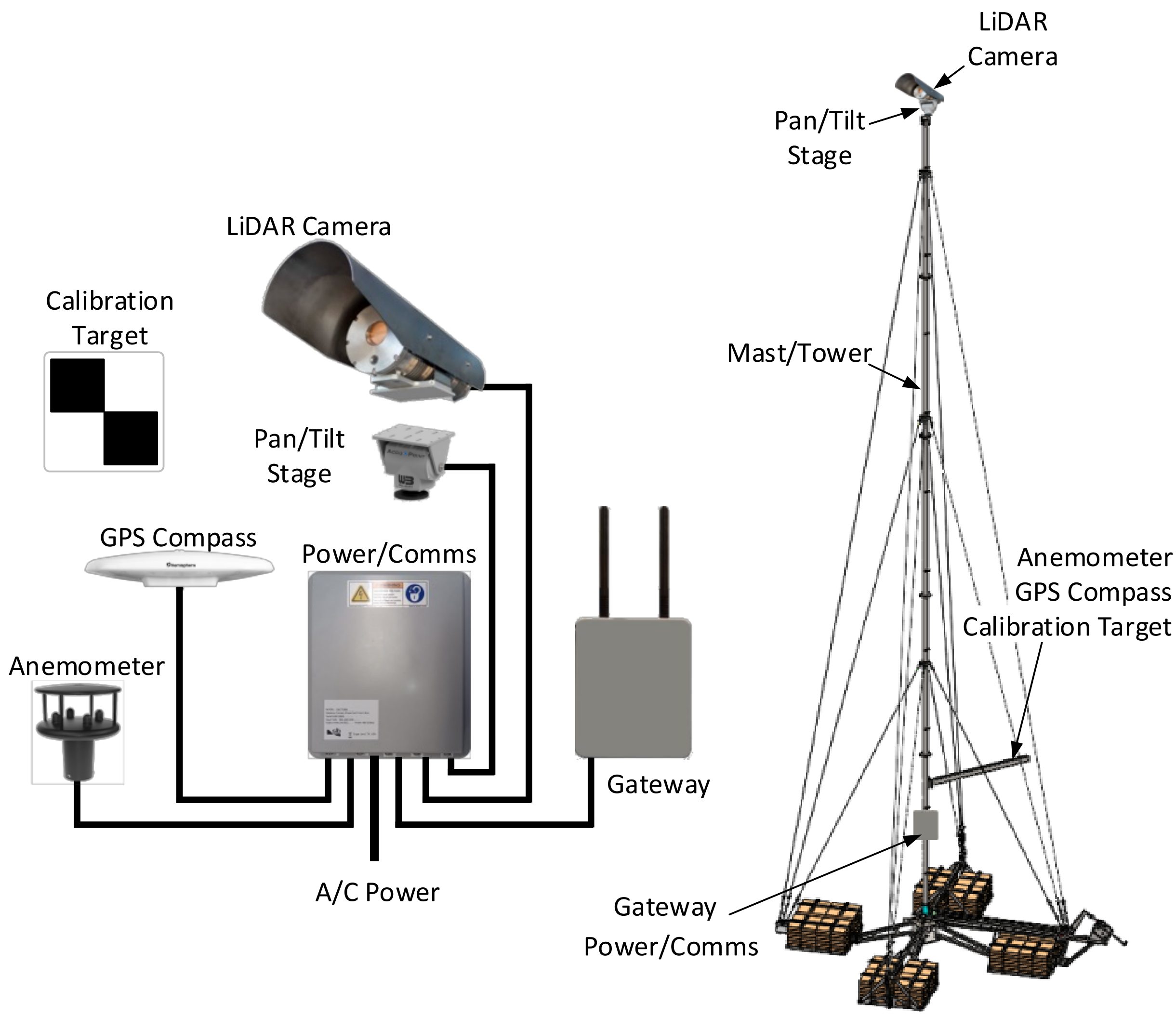


Figure 2: Acquisition system connection diagram and key components, and 3D view of the complete system.

- **Methane lidar camera**—Once directed to an emission source and stationary, the camera uses two prisms to scan a conical field of view while pulsing a laser. The laser return signal provides time of flight (for lidar range calculation), signal intensity, and path-integrated methane concentration. This information is used to detect and quantify methane leaks, and to produce images for leak evaluation.
- **Pan/tilt stage**—The camera sits on a pan/tilt stage that is used to control the nominal direction of the camera (i.e., center of field of view), directing the camera to the different emission sources. The camera is typically mounted above the emissions source, and the stage pans 360° degrees and tilts down to image the sources.

- **Power and communications enclosure**—This enclosure assembly serves as the power and networking hub for the acquisition system. The enclosure does not contain a central processing unit (CPU) or perform any local control, and all communication is through wired cables and connections. Features include LEDs to serve as diagnostic indicators, remotely operated relays to control camera and sensor power, ambient temperature measurement (outside enclosure), and dedicated grounding lug to ensure proper earth grounding.
- **Gateway**—The Delfi™ digital platform gateway includes a cellular modem, wifi, and ethernet connectivity to provide secure bidirectional communication with the cloud. The gateway is responsible for local control of the stage and camera, and data aggregation from the various sensors. Other connectivity options are available.
- **GPS compass**—The compass incorporates two GPS sensors that are used to provide location (i.e., latitude and longitude), as well as heading (referenced to true north). This information is combined with the location information of the monitored equipment to attribute leaks to the correct equipment. The heading data, in conjunction with the calibration target, also enable the system to automatically determine the orientation of the camera and anemometer.
- **Calibration target**—The target consists of a black-and-white grid on a metal plate. It is located on a sensor boom near the bottom of the tower. When the camera scans around the base of the tower, it can locate the target and determine the orientation of the sensor boom. This orientation then enables the system to determine the heading of the camera and wind data.
- **Anemometer**—The anemometer provides wind speed and direction, which is required to calculate the methane mass emission rate. The anemometer includes an internal heater to prevent ice buildup that would otherwise affect the measurement. The anemometer is typically mounted at the height of about 3 m, depending on the installation details. While this height may not correspond exactly to the elevation of the methane source, the wind variation with height will introduce only a small correction to the calculated mass emission rate that can be accounted for in the interpretation.
- **Mast/tower**— The tower (sometimes called mast) provides the support structure for the camera and acquisition system. It is typically 15 m high and capable of withstanding high wind speeds. The tower may incorporate guy wires that can be secured to the foundation of the tower to minimize the footprint and eliminate the need for ground penetrations. Other variations may be used to support the methane lidar camera, as well as existing structures in some cases.

Type of measurement and its application

The methane lidar camera quantifies methane emissions and can be used at all production and processing facilities and all natural gas transmission and storage facilities. The camera is a continuous-monitoring method deployed as a stationary remote sensor. It quantifies the methane mass emission rate, enabling rolling window averages of the mass emission rate to be determined. It is broadly applicable across the sector, including all onshore basins in the US. It can be used to monitor the collection of fugitive emissions components, covers, and closed vent systems at well sites, centralized production facilities, compressor stations, and other production/processing and transmission/storage facilities.

The camera is mounted above all the equipment to be monitored, and the laser beam directed toward the equipment images and quantifies any methane emission. This geometry results in a measurement that can be effective across a wide range of facility types and basins. Many environmental factors that affect other methane measurements do not significantly affect the methane lidar camera, including the following:

- Cloud cover—while clouds interfere with measurements based on sunlight, the methane lidar camera uses a laser rather than sunlight and therefore is not affected by cloud cover.

- Delta-T—the difference between the emitted gas temperature and the surrounding background temperature (delta-T) affects the signal from optical gas imaging (OGI) cameras that operate in the long wavelength region (US EPA, 2023) but does not affect the signal from the methane lidar camera.

- Topography—topographical features such as hills and forests that interfere with optical measurement requiring light to travel long distances do not interfere with the methane lidar camera where the laser travels a relatively short distances across facilities that are predominantly level and devoid of vegetation.

- Wind field—while wind impacts all methane measurements, the ability of the methane lidar camera to image the full plume of emitted methane makes the camera relatively insensitive to the wind field. Similar to OGI and Method 21, the sensitivity of the methane lidar camera decreases in strong winds where emitted methane is quickly blown away.

Although different basins can range widely in factors such as their prevailing cloud cover, delta-T, topography, and wind field, the methane lidar camera has similar performance across a wide range of basins because of its low sensitivity to those factors.

Potential limitations

The methane lidar camera operates under almost all conditions prevalent in US basins, including temperature ranges of -40°C (-40°F) to +50°C (122°F), -400 m to 3000 m altitude ranges, 0 to 95% noncondensing relative humidity, light fog, rain, and snow. Because the camera is an active system that emits a class 1, eye-safe laser, it can operate in the presence or absence of sunlight and under prevailing cloud cover. The laser wavelength is tuned to 0.1 nm around the methane absorption spectrum line at 1650.9 nm, so the camera is extremely selective to methane. At this wavelength, the response from ambient water vapor is 100 times lower, and from ambient carbon dioxide is 1,000 times lower, compared to the absorption of ambient methane. The lidar camera does not have cross-sensitivity or interference from other chemical species including C_2H_2, C_2H_4, C_2H_6, C_2N_2, C_3H_8, C_4H_{10}, C_3HN, C_4H_2, CF_4, CH_3Br, CH_3Cl, CH_3CN, CH_3F, CH_3I, CH_3OH, ClO, $ClONO_2$, $COCl_2$, COF_2, CS, CS_2, H_2, H_2CO, H_2O_2, H_2S, H_4Ge, HCN, HCOOH, HI, HO_2, HOBr, HOCl, NF_3, N_2, NO+, O, OCS, PH_3, SF_6, SO, SO_3, other larger monocular petrochemical gases, n-Heptane, liquid gasoline, crude oil, or diesel.

The following list of parameters can affect the detection and quantification capabilities of the cameras:

1. Line of sight: The camera measures the path-integrated methane concentration, typically expressed in parts per million times meters (ppm-m) along the laser beam. For such measurements, the laser beam must pass through the plume of methane and reflect off background scattering surfaces within 200 m of the camera. If the plume is completely obstructed from the camera's line of sight by equipment or structures, the beam will not pass through the gas. The camera can measure methane emissions that are at least partially in direct line of sight of the camera. The system need not have a fully unobstructed view of all parts of a facility in order to detect and accurately quantify emissions, as gas

plumes can be correctly measured as they emerge from behind an obstruction. To mitigate line-of-sight issues, the camera is mounted on a mast or existing equipment taller than the equipment to be monitored to get a vantage point. For facilities where direct line of sight to all equipment is not possible using one camera, multiple cameras are deployed to ensure total site coverage.

2. Highly reflective surfaces: For the laser beam emitted from the camera to return to the transceiver inside the camera, the beam needs to reflect off a diffusive scattering object. Any diffuse scattering surface works as a background scattering object. Common real-world surfaces including ground, buildings and structures, vegetation, etc. are diffuse scattering surfaces, so only a fraction of the photons in the emitted laser beam return to the camera. Highly reflective/mirrored surfaces at facilities, such as large water bodies can cause a significant portion of the emitted beam to reflect back to the transceiver, saturating the detector. Correspondingly, the beam may reflect completely away from the laser, causing insufficient photon returns. In general, onshore oil and gas facilities do not have standing water surrounding the equipment. Other mirrored surfaces can be avoided by adjusting the center and size of the camera's field of view.

3. Distance from reflecting surface: The camera has a range of 200 m. If the diffusive scattering surface behind the equipment is farther than 200 m from the camera, not enough signal may return to the camera, making it difficult to detect and quantify emissions. For large facilities, multiple cameras are deployed such that all pieces of equipment have a reflective surface within 200 m along at least one of the cameras' lines of sight.

4. Heavy precipitation: As heavy precipitation (rain, snow, sleet, fog, etc.) can temporarily hinder a sufficient portion of the beam from returning to the transceiver when present, the sensitivity of the methane lidar camera may decrease during heavy precipitation events.

5. Extreme wind conditions: At extremely high wind velocities, the mast or tower that the camera is installed on can be lowered; however, the towers used are designed and independently certified to standard TIA-222 for a survival wind speed of at least 105 mph. In addition, at high wind speeds, some smaller releases are sufficiently diluted by the air flow to make them more difficult for the camera to detect, resulting in less obvious visualization and higher uncertainty in the flow rate calculation. The effect of wind speed is reduced for objects shorter distances from the camera. Table 1 indicates how the limit of detection is influenced by the combined effects of distance and wind speed.

Table 1: Limit of detection (at 90% probability of detection) as a function of distance and wind speed.

Limits of Detection (typical, 90% PoD)

Distance	Wind Speed		
	<1 m/s	<5 m/s	<10 m/s
<100-m (<328-ft)	0.2 kg/h	1.0 kg/h	2.0 kg/h
<200-m (<656-ft)	0.4 kg/h	2.0 kg/h	4.0 kg/h

6. Cellular connectivity: The system provides many different methods of connectivity to ensure a large geographical coverage. The primary network connection solution is through

LTE cellular, but if that is unavailable, the system can be connected to a local network via ethernet or wifi. It is also possible to extend the wireless connectivity using satellites or cellular boosters.

Mass Emission Rate Calculation Procedure

Procedure to determine camera placement

For optimal camera placement, a 3D model of the site is created. This can be done using elevation data from publicly available information, operator-provided lidar surveys, or other methods such as photogrammetry, computer-aided design (CAD) data, by extruding equipment located on an aerial image to a defined height, or other means. Using such a model of the site, equipment of interest for monitoring and areas where the camera is allowed to be positioned are identified. These allowed areas reflect places where the ground is acceptable to install a mast, power is available, and it will not interfere with operations on the site. The footprint size of the selected mast type is considered when defining the spatial extent of an allowed installation. A series of possible camera position points are then identified. For each allowed camera position, each potential leak source is considered in sequence to check that no other equipment/building on the site significantly obscures it and it is also within the maximum range of the camera. As an example, the top and middle images in Figure 3 represent equipment level coverage for two camera locations shown by star markers. The location in the top image only covers 77% of the equipment in the facility and is unacceptable. The location in the middle image covers 100% of the equipment and is allowable for camera installation. To identify the best location, the facility is discretized into hexagons where each hexagon is a potential camera location and the equipment level coverage for each location is computed. As shown in the bottom image of Figure 3, some locations provide 100% coverage (yellow hexagons) while other locations do not (nonyellow hexagons). Acceptable locations include those that achieve 100% coverage of all required sources. If no single location is acceptable, the methodology is repeated by adding a second camera location and optimizing both locations to achieve 100% coverage. This methodology may be performed manually or digitally.


Overall Coverage: 77.3%
coverage (%)
100
80
60
40
20
0


Overall Coverage: 100.0%
coverage (%)
100
80
60
40
20
0


coverage (%)
100
80
60
40
20
0

Figure 3: (top and middle) Lidar camera planning showing equipment level coverage for two proposed camera locations on the same site. The star indicates a proposed camera location, and the color scale shows coverage for each equipment unit for a camera installed at the starred location. In the top and middle images, only the equipment to be monitored by the camera is colored, and the color represents the ability of a camera at the starred location to detect and quantify emissions at the equipment unit. The camera location in the top image only covers 77% of the equipment in the facility and is unacceptable. The camera location in the middle image covers 100% of the equipment and is allowable for camera installation. (bottom) Each hexagon is a potential camera location while the color of the hexagon indicates overall coverage of all sources on the site from a camera installed at that location.

Procedure to install camera

The camera and its ancillary equipment can be mounted on many different support structures. The camera is typically mounted at an elevated position, resulting in good line of sight over the facility. Most commonly, the camera is mounted on a mast that can be installed by two people without any special heavy equipment (no crane required). Health and safety considerations have been the main driver to ensure safe installation and operation of the system. A complete installation manual is available and has separately been uploaded as confidential business information in the supporting documentation.

Procedure to image plume of path-integrated methane concentration

The camera uses the measured absorption curve to determine the path-integrated methane concentration typically expressed in parts per million times meters (ppm-m). To enhance the accuracy of methane concentration measurements, the system employs a sophisticated curve-fitting process. This process involves comparing the collected spectral data against a reference absorption curve, typically derived from known methane absorption characteristics. By employing statistical techniques such as least-squares optimization, the system adjusts the curve parameters, including the peak position, width, and amplitude, until the model closely fits the observed data (Titchener and Ai, 2021). The camera accumulates data points at a rate of 100 Hz while the beam is rapidly scanned around the environment. After accumulating several thousands of points, the data can be visualized in 2D and 3D images. The data are complex, containing signal intensity, lidar range, and spectral information. The methane plume is isolated by subtraction of the background due to an internal gas cell and ambient gas in the atmosphere, followed by applying a plume detection algorithm that simply identifies and separates out large, connected regions of elevated methane. The image of the methane plume can be overlain on the background image, allowing methane emissions to be allocated to a particular source (Titchener et al., 2022).

The methane lidar camera employs the innovative use of dual rotating prisms to manipulate the optical beam to scan across the field of view in various patterns, including a flower pattern and a spiral pattern shown in Figures 4 and 5, respectively (Ai et al., 2023). The described system uses a pair of rotating prisms, referred to as a Risley pair, and a novel, synchronous control schema for them. This synchronization of the two rotating prisms enables the system to steer the laser beam and to perform a true optical zoom. This manipulation is achieved by varying the amplitude and rate of superimposed oscillations of the prism-to-prism angle relative to the synchronous rotation rate of the prism pair, as the system continues to rotate the prisms. This patented method allows for continuous and dynamic adjustment of the beam's trajectory, enabling comprehensive coverage of the designated field of view while maintaining a high resolution of detection throughout the area and at the same time, can typically achieve >20x true optical zoom while maintaining high scanning speed.

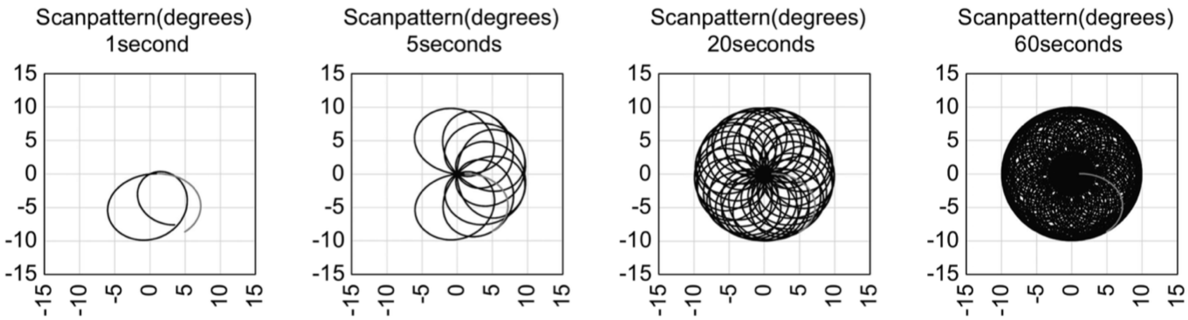


Figure 4: Flower pattern created using dual rotating prisms to manipulate the optical beam to scan across the field of view. The laser beam scan pattern develops over time. The x- and y-axes represent angle of the beam in horizontal and vertical directions, respectively.

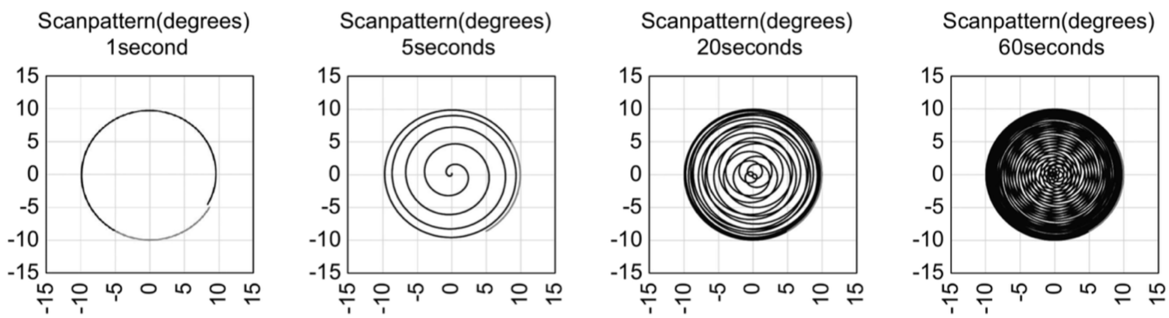


Figure 5: Spiral pattern created using dual rotating prisms to manipulate the optical beam to scan across the field of view. The laser beam scan pattern develops over time. The x- and y-axes represent angle of the beam in horizontal and vertical directions, respectively.

Figure 6 shows a typical grid of images created for every frame acquired by the camera. The top left plot is for the methane concentration along the laser's path in ppm-m. The bottom left plot shows the signal level returning to the detector in the camera. The top right image is an overlay of the methane concentration along the laser path on the signal count. Such an overlay provides an unambiguous source identification for the emission. The bottom right image shows a plot of the distance measured by the lidar in meters. This image shows a methane plume originating at a wellhead at the Methane Emissions Technology Evaluation Center (METEC) facility at Colorado State University as measured by our methane lidar camera.

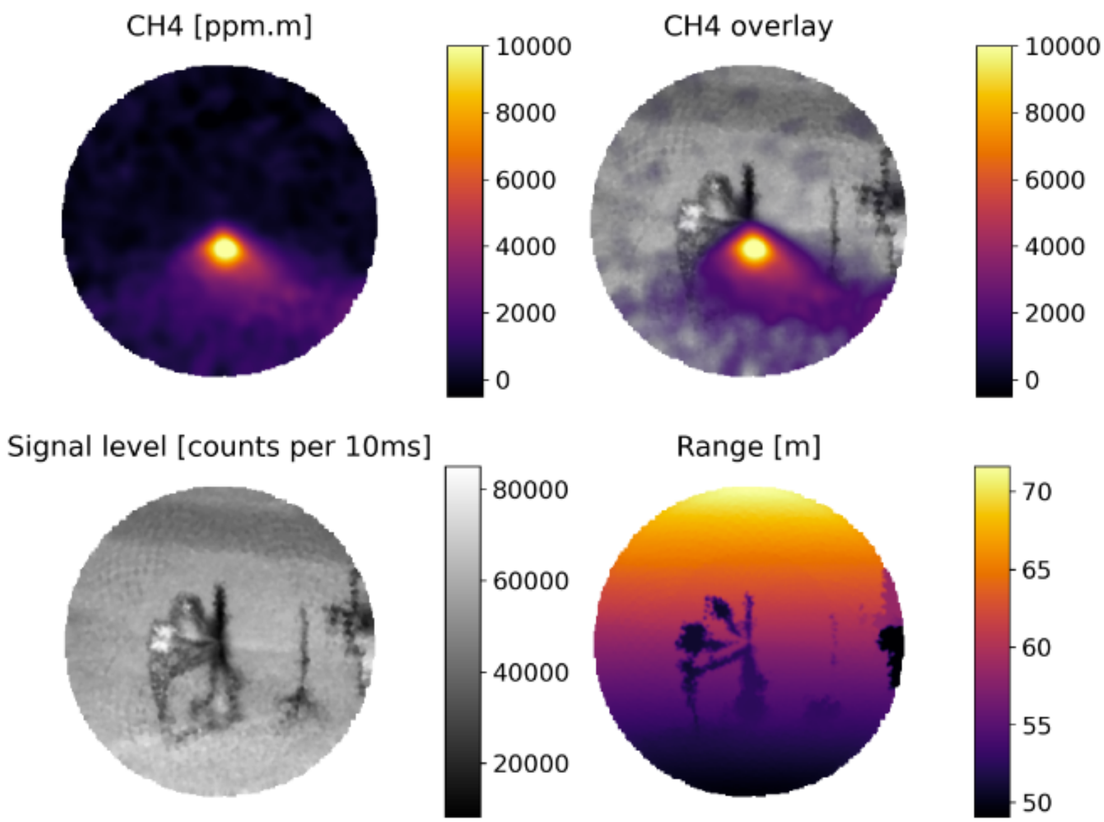


Figure 6: A typical image showing the signal level (bottom left) and lidar range (bottom right) measured by the camera for an acquisition frame at METEC. Computed methane concentration along the laser's path is on top left and an overlay image of the methane concentration on the signal level is on top right.

Procedure to measure environmental factors

As described in the equations in the Scientific Theory section, the main environmental factor that influences the detection and quantification of the methane emissions is the wind, and its speed and direction are monitored once per second by the system's anemometer. These wind data are used in the detection and quantification algorithms. The system has a variety of internal measurements including various temperatures and humidity levels, but these are only used for system health monitoring and do not relate to the emissions measurements.

When measuring the wind speed and direction, it is important to have the system properly oriented. To mitigate the risk of improper camera and/or anemometer orientation, and also to simplify the edge installation process, the reference system described in the previous sections (using the example mast and acquisition system) is designed to be self-detecting of orientation. This is illustrated in Figure 7, which is a top-down view of the tower showing the placement of the anemometer and GPS compass sensors.

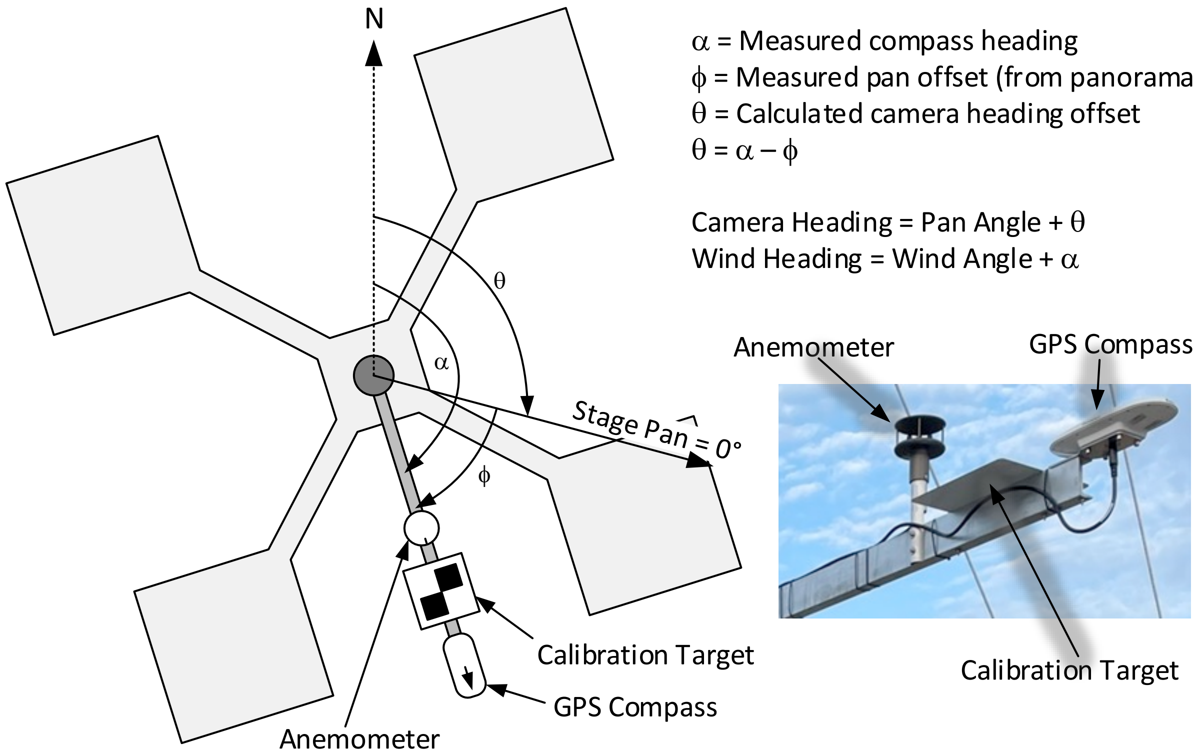


Figure 7: On the left is a top view of the mast system showing hardware to enable automatic detection of orientation. On the right side shows a photo of the ancillary equipment installed on the sensor arm.

After installation, the pan/tilt stage will rotate the camera to scan around the base of the tower until it locates the pan angle (ϕ) associated with the calibration target. A GPS compass mounted in line with the calibration target allows for the camera heading offset (θ) (relative to true north) to be determined. By forcing the default orientation of the anemometer to be in line with the calibration target and GPS compass, the anemometer heading (α) is also easily calculated. The camera and anemometer heading values are then used to properly quantify the leak and attribute it to the correct equipment.

The anemometer is mounted on an arm approximately 3 m above the ground. This helps ensure that the wind measurement is representative of both high (e.g., on top of equipment) and low (e.g., ground level) equipment. The anemometer is located far enough from the tower so that the tower will not disrupt the measurement if the wind comes from behind it. While this height may not correspond exactly to the elevation of the methane source, the wind variation with height will introduce only a small correction to the calculated mass emission rate, which can be accounted for in the interpretation.

In addition to the wind speed and direction measured by the anemometer, the system also measures the ambient temperature. This measurement is taken outside the power and communications enclosure, at the bottom of the enclosure where it will not be affected by direct sunlight; however, it is only for reference and is not required for the methane quantification and localization interpretation.

Procedure to identify emission beginning and end times

The system uses a concept similar to that of the METEC protocol wherein an "emission ID" is assigned to any uniquely identified leak point in space and time. These are defined as emission sources. In other words, if an emission is seen at a specific location (within the spatial resolution of the lidar) its start time, 3D location on the site, and emission rate are recorded and assigned a unique ID. As the lidar cycles through the site measuring each targeted piece of equipment, and upon returning to where it saw a leak before, if that leak is still emitting, its measured rate is again recorded against that same, existing ID. This continues until the leak is no longer observed, at which point that ID number is retired, allowing the full measurement sequence over the lifetime of that leak to be referenced by that ID number and for its start/end time and total emissions to be summed over the leak's lifetime. A new leak at that location would be assigned a new ID, and so on.

Measurement

The lidar camera is set up with a scan plan, designed to cover all user-defined sources at the site, and will cycle through the scan plan repeatedly. Each scan taken is saved as a scan frame and can either contain a positive identification of a methane plume or a zero-methane-detected indicator.

Methane detection (observation)

When a positive detection is made, the lidar camera will automatically be tasked to do a follow-up scan of the same frame to get a confirmed second detection. This is done automatically as defined in the operational configuration of the system and is done for every first positive detection. A data product called "observation" will be created, including both the absolute, temporal, and spatial information of the methane plume detected.

Source attribution

When setting up the system, all methane sources to be monitored are defined in the system, based on a polygon defining the boundaries of the source. The observation will be automatically attributed to a single source and the system keeps track of the status of all sources defined in inventory.

The location of a detected leak is characterized by the orientation of the camera (stage pan and tilt angles) when detecting the leak and the location of maximum integrated methane concentration within the plume image. This direction is converted to heading and pitch angles with respect to a ground-fixed coordinate system using parameters that were previously computed during calibration of the pan-tilt stage immediately after the camera was installed. The direction of line of sight to the leak is compared to the positions of labelled potential leak sources that were previously defined.

The attribution algorithm returns a list of potential sources and an attribution confidence level for each. The highest confidence is assigned to potential sources that are directly in the line of sight to the leak. For other sources, the attribution confidence is a monotonically decreasing function of the smallest angle between the line of sight to the leak and any line of sight to the source. All potential sources with an attribution confidence level below a cutoff value are discarded, so that only sources considered to be likely causes of the leak remain. For example, a leak that is observed between two closely spaced units of equipment and very far from a third, would return the labels of the first two corresponding potential sources, each with about 50% attribution confidence.

Source emission tracking (event)

If the attributed source already has an emission event active, meaning there has been previous positive observations made for this source, the new observation will be appended to the same emission event. If there are no active emission events for the attributed source, a new event will be created, defining the start time of the emission.

If the scan frame is detecting zero methane, this will then be associated to all sources in field of view of the scan frame. If any of these sources has an active emission event, the observation of confirmed zero will be appended to it and the event will be closed. This gives the end time of the emission.

For both active and closed events, the system calculates the average emission rate for the event, the duration of the event, and the total emitted methane in kilograms.

Procedure to quantify mass emission rate

The camera uses the measured absorption curve to determine the path-integrated methane concentration, typically expressed in parts per million times meters (ppm-m). The camera accumulates data points at a rate of 100 Hz while the beam is rapidly scanned around the environment. After accumulating several thousands of points, the data can be visualized in 2D and 3D images. The data are complex, containing signal intensity, lidar range, and spectral information. The methane plume is isolated by subtraction of the background due to the internal gas cell and ambient gas in the atmosphere, followed by applying a plume detection algorithm that simply identifies and separates out large, connected regions of elevated methane. The image of the methane plume can be overlain on the background image, enabling methane emissions to be allocated to a particular source (Titchener et al., 2022).

Once a methane plume is identified, the camera uses a simple mass balance approach to calculate the methane mass emission rate. The mass balance approach aims to determine the mass emission rate by calculating the mass of gas flowing through a 3D surface enclosing a gas source. The principle of mass balance derives from the fundamental principle of conservation of mass, where the total amount that is emitted within a certain region of space must eventually flow out of that region, unless that region contains sinks of the emitted substance. The mass flux is defined as the mass of gas passing through a surface per unit area per unit time. By integrating the mass flux through a surface enclosing a volume, the total mass of gas entering or leaving that volume can be computed. If the net flux is greater than zero, this indicates that the region is emitting gas.

The mass balance equation, also known as Gauss' Law, can be generally expressed for any substance as

$$\left\langle \frac{dq}{dt} \right\rangle = \sum - \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle$$

where q is the total mass of that substance within the enclosing volume, dq/dt is its rate of change, $\boldsymbol{j}$ is the mass flux per unit area, the surface integral on the right-hand side is over a surface enclosing the volume, and $\sum$ is the sum total of sources and sinks of substance q within that volume. The brackets indicate a time average over a period longer than typical concentration fluctuations, which occur on the order of a minute. With the methane lidar camera, this time average window is fixed by the duration of a single image acquisition, which is generally 3 to 4 minutes. The signal is accumulated and binned as the beam rotates and sweeps through the gas plume multiple times; thus the data in the image do not represent an instantaneous snapshot but rather an average over the image acquisition time. This signal-averaging step is required for good signal-to-noise ratio and improved accuracy. It allows setting $\langle dq/dt \rangle$ to zero as any instantaneous pooling of methane behind structures found on-site is unlikely to persist for longer than the measurement time, eventually reaching the steady-state value after averaging over temporal fluctuations. As methane does not sediment, adsorb, or transform into another compound to a significant extent, it can be assumed that there are no sinks of methane (i.e., processes removing it from the atmosphere). Thus, $\sum$ is the mass emission rate and is equal to

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle .$$

Now the mass flux per unit area $\boldsymbol{j} = \boldsymbol{v}\,\rho$, where ρ is the gas concentration (g/m^3) and $\boldsymbol{v}$ is the wind velocity vector (m/s) measured by an anemometer connected to the camera at a frequency of 1 Hz; i.e., with a new wind measurement provided every second. Both ρ and $\boldsymbol{v}$ have spatial dependence. However, wind fluctuations will be averaged out both spatially and temporally over the methane image acquisition period of 3 to 4 minutes, such that a single mean wind value computed from the anemometer measurements over a corresponding methane image acquisition period can be used for the computation without loss of accuracy.

The methane lidar camera does not measure the concentration ρ directly, but rather a path-integrated methane concentration $\boldsymbol{\xi}$ (g/m^2); i.e., ρ integrated along the laser beam with direction $\hat{\boldsymbol{n}}$. To perform the double integration, the enclosing surface must be selected. Because methane flux follows the wind, ρ and hence $\boldsymbol{j}$ will be both zero upwind of the source. Thus, any surface can be used on the upwind side as the integral of $\boldsymbol{j}$ over it will be zero. Therefore, it can be ignored. For the downwind portion of the enclosing surface, a plane $\boldsymbol{S}$ is used which is defined by the vertical edge of the plane of the plume image $\boldsymbol{l}$ and the laser beam direction $\hat{\boldsymbol{n}}$. Then we can write $\rho dS = \boldsymbol{\xi} d\boldsymbol{l} \times \hat{\boldsymbol{n}}$ (the crossproduct of $d\boldsymbol{l}$ and $\hat{\boldsymbol{n}}$) and for the total emission mass flux rate $\sum$,

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle = \left\langle \oiint \boldsymbol{v} \cdot \rho d\mathbf{S} \right\rangle = \left\langle \boldsymbol{v} \cdot \int \xi d\boldsymbol{l} \times \hat{n} \right\rangle$$

where again the bracket indicates the time averaging implicit in the measurement scheme. The mass balance approach to the quantitative mass emission rate computation is further discussed in Titchener et al. (2022).

The principle of mass flow balance derives from the fundamental principle of conservation of mass. Provided the substance under investigation does not sediment, pool, adsorb, or transform into another compound due to chemical reactions, the total amount that is emitted within a certain region of space must eventually flow out of that region. While there may be instantaneous pooling of methane behind structures found on site, it is unlikely to persist for longer than the measurement time of several minutes, eventually reaching the steady-state flux, after averaging over temporal fluctuations. Thus, measuring the total flux of methane issuing from the emission source provides a direct measure of the average emission rate.

Improving image accuracy through optical zoom

The lidar camera also has the capability to “zoom in” on a leak point to get a more detailed image of the plume and to maximize the accuracy of the mass flow rate quantification. This ability relies on the lidar’s patented (Ai et al., 2023) synchronized Risley prism scanner. This true optical zoom enables the lidar to obtain more accurate images of the gas plume especially at distance. By zooming in, the sensor can capture finer details within the target area, which improves the quality of the 3D mapping and at the same time enables more precise identification of gas concentration pathlengths and the exact location of the leak. Higher zoom results in higher spatial resolution imaging, which is crucial when analyzing complex areas where the gas plume might be interacting with various structural obstacles at extended distance, thereby affecting the local wind flow and the subsequent modeling of the gas emission rate. With the ability to zoom, the system can adjust the field of view to focus on specific areas, ensuring that the data collected are as accurate and informative as possible for effective emission detection and quantification.

The camera beam scans a predetermined field of view in angular space at 100 Hz. By tuning the motion of the Risley prisms, the angular field of view of the camera can be changed. Because the camera beam measures the path-integrated methane concentration at discrete points, by tuning the field of view, we can control the density of data points in real space. Through such tuning, the camera can accurately detect and quantify extremely low leak rates below 0.4 kg/h.

The camera scans a specific field of view for 3 to 4 minutes to acquire sufficient data for interpretation. The field of view can be as large as a cone with 24° cone angle. Depending on the distance of the camera from various equipment in the facility, a single field of view can span tens to hundreds of meters. Within 12 hours, the camera acquires 180 unique fields of view. The camera takes about 9 hours to scan a hemisphere of space below horizon from the camera's location. Since most of this space is plain ground, a typical facility with multiple emissions sources can be scanned within a few hours by creating a scan plan where the camera focuses only on areas with potential emission sources and does not spend time scanning plain ground with no potential to emit.

Whenever possible, a scan plan is created for the camera such that each field of view contains exactly one fugitive source. Even if multiple sources are emitting simultaneously, each emission is detected and quantified individually to get an accurate measurement of total emissions across the facility. If multiple pieces of equipment are emitting simultaneously in the same field of view with sufficient distance between emission points to distinguish the plumes, more zoomed-in scans with smaller fields of view are acquired to unambiguously distinguish the separate emissions. If multiple emission points produce plumes that merge into a single plume, the total rate quantification will be cumulative for all the nearby emissions and will not affect total site-level emissions. Additional example images demonstrating the camera's ability to identify component-level emissions are included in attachment 1 to this document.

Procedure to determine median mass emission rate

Each methane emission detected by the camera will be attributed to a single source, where a source is defined by the user as an area of possible fugitive, closed vent, or cover emissions. Each periodic screening event requires the capture of 3 scan frames per field of view. The median mass methane emissions from each possible fugitive, closed vent, or cover in each scan frame will be calculated to determine if the emissions in that scan frame exceed the applicable alerting threshold. A periodic screening report is generated and each emission (defined as a median mass emission rate) is reported as either an alert (exceedance of alerting threshold) or no alert (emissions below alerting threshold). All emissions resulting in an alert require follow up monitoring by the operator.

See Figure 8 for a description of the workflow.

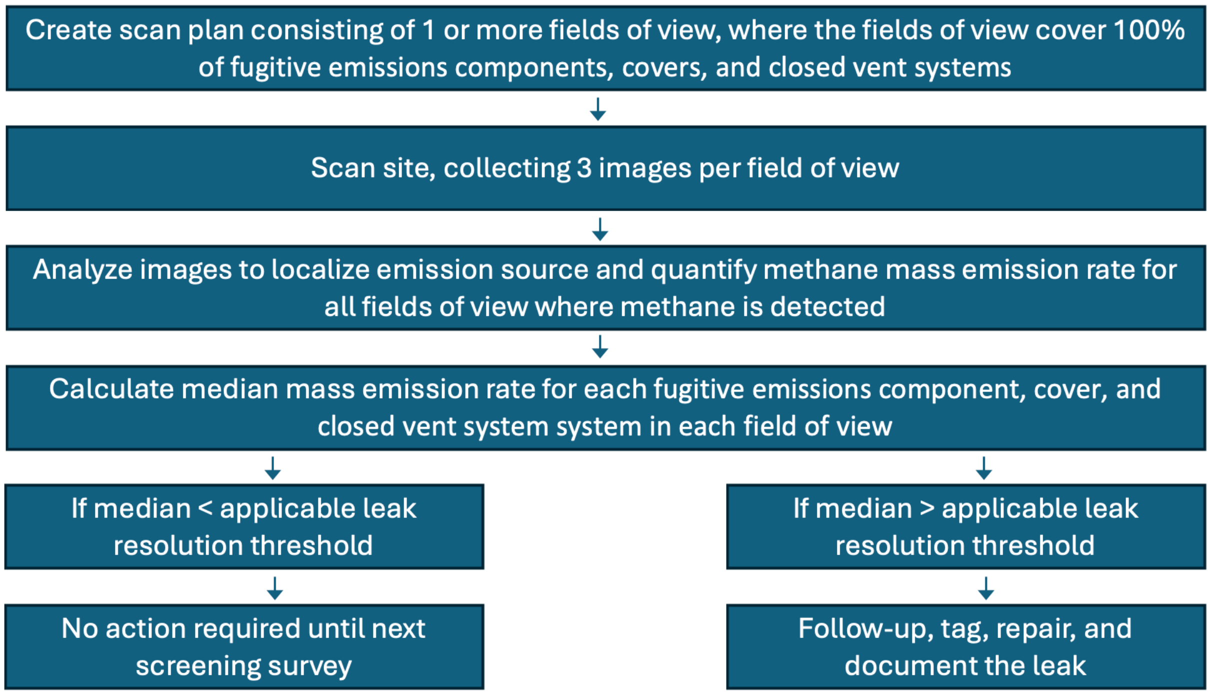


Figure 8: Workflow for detecting and repairing methane emissions

Summary of how meteorological data are collected and used

The camera is used in conjunction with an anemometer that collects wind speed and direction information at 1-Hz frequency. In general, the camera scans a specific field of view for 3 to 4 minutes to acquire sufficient data for interpretation. Wind speeds and directions acquired over this duration are vector averaged and the vector standard deviation of wind direction is calculated using a unit vector average and directional/circular statistics methods. The vector average of the wind speed is used as a representative wind realization over the camera acquisition duration. The component of wind speed along the plume length is used to compute emission rate as described below.

After accumulating several thousands of points, the data can be visualized in 2D and 3D images. The data are complex, containing signal intensity, lidar range, and spectral information. The methane plume is isolated by subtraction of the background due to an internal gas cell and ambient gas in the atmosphere, followed by applying a plume detection algorithm that simply identifies and separates out large, connected regions of elevated methane.

Once a methane plume is identified, the camera uses a simple mass balance approach to calculate the methane mass emission rate. The mass balance approach aims to determine the mass emission rate by calculating the mass of gas flowing through a 3D surface enclosing a gas source. The principle of mass balance derives from the fundamental principle of conservation of mass, where the total amount that is emitted within a certain region of space must eventually flow out of that region, unless that region contains sinks of the emitted substance. The mass flux is defined as the mass of gas passing through a surface per unit area per unit time. By integrating the mass flux through a surface enclosing a volume, the total mass of gas entering or leaving that volume can be computed. If the net flux is greater than zero, this indicates that the region is emitting gas.

The mass balance equation, also known as Gauss' Law, can be generally expressed for any substance as

$$\left\langle \frac{dq}{dt} \right\rangle = \sum - \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle$$

where q is the total mass of that substance within the enclosing volume, dq/dt is its rate of change, $\boldsymbol{j}$ is the mass flux per unit area, the surface integral on the right-hand side is over a surface enclosing the volume, and $\sum$ is the sum total of sources and sinks of substance q within that volume. The brackets indicate a time average over a period longer than typical concentration fluctuations, which occur on the order of a minute. With the methane lidar camera, this time average window is fixed by the duration of a single image acquisition, which is generally 3 to 4 minutes. The signal is accumulated and binned as the beam rotates and sweeps through the gas plume multiple times; thus the data in the image do not represent an instantaneous snapshot but rather an average over the image acquisition time. This signal-averaging step is required for good signal-to-noise ratio and improved accuracy. It allows setting $\langle dq/dt \rangle$ to zero as any instantaneous pooling of methane behind structures found on-site is unlikely to persist for longer than the measurement time, eventually reaching the steady-state value after averaging over temporal fluctuations. As methane does not sediment, adsorb, or transform into another compound to a significant extent, it can be assumed that there are no sinks of methane (i.e., processes removing it from the atmosphere). Thus, $\sum$ is the mass emission rate and is equal to

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle .$$

Now the mass flux per unit area $\boldsymbol{j} = \boldsymbol{v}\,\rho$, where ρ is the gas concentration (g/m^3) and $\boldsymbol{v}$ is the wind velocity vector (m/s) measured by an anemometer connected to the camera at a frequency of 1 Hz; i.e., with a new wind measurement provided every second. Both ρ and $\boldsymbol{v}$ have spatial dependence. However, wind fluctuations will be averaged out both spatially and temporally over the methane image acquisition period of 3 to 4 minutes, such that a single mean wind value computed from the anemometer measurements over a corresponding methane image acquisition period can be used for the computation without loss of accuracy.

The methane lidar camera does not measure the concentration ρ directly, but rather a path-integrated methane concentration $\boldsymbol{\xi}$ (g/m^2); i.e., ρ integrated along the laser beam with direction $\hat{\boldsymbol{n}}$. To perform the double integration, the enclosing surface must be selected. Because methane flux follows the wind, ρ and hence $\boldsymbol{j}$ will be both zero upwind of the source. Thus, any surface can be used on the upwind side as the integral of $\boldsymbol{j}$ over it will be zero. Therefore, it can be ignored. For the downwind portion of the enclosing surface, a plane $\boldsymbol{S}$ is used which is defined by the vertical edge of the plane of the plume image $\boldsymbol{l}$ and the laser beam direction $\hat{\boldsymbol{n}}$. Then we can write $\rho d\boldsymbol{S} = \boldsymbol{\xi} d\boldsymbol{l} \times \hat{\boldsymbol{n}}$ (the crossproduct of $d\boldsymbol{l}$ and $\hat{\boldsymbol{n}}$) and for the total emission mass flux rate $\sum$,

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle = \left\langle \oiint \boldsymbol{v} \cdot \rho d\mathbf{S} \right\rangle = \left\langle \boldsymbol{v} \cdot \int \xi d\boldsymbol{l} \times \hat{n} \right\rangle$$

where again the bracket indicates the time averaging implicit in the measurement scheme. The mass balance approach to the quantitative mass emission rate computation is further discussed in Titchener et al. (2022).

Summary of how models/calculations are used and how inputs are determined

Once a methane plume is identified, the camera uses a simple mass balance approach to calculate the methane mass emission rate. The mass balance approach aims to determine the mass emission rate by calculating the mass of gas flowing through a 3D surface enclosing a gas source. The principle of mass balance derives from the fundamental principle of conservation of mass, where the total amount that is emitted within a certain region of space must eventually flow out of that region, unless that region contains sinks of the emitted substance. The mass flux is defined as the mass of gas passing through a surface per unit area per unit time. By integrating the mass flux through a surface enclosing a volume, the total mass of gas entering or leaving that volume can be computed. If the net flux is greater than zero, this indicates that the region is emitting gas.

The mass balance equation, also known as Gauss' Law, can be generally expressed for any substance as

$$\left\langle \frac{dq}{dt} \right\rangle = \sum - \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle$$

where *q* is the total mass of that substance within the enclosing volume, *dq/dt* is its rate of change, $\boldsymbol{j}$ is the mass flux per unit area, the surface integral on the right-hand side is over a surface enclosing the volume, and $\sum$ is the sum total of sources and sinks of substance *q* within that volume. The brackets indicate a time average over a period longer than typical concentration fluctuations, which occur on the order of a minute. With the methane lidar camera, this time average window is fixed by the duration of a single image acquisition, which is generally 3 to 4 minutes. The signal is accumulated and binned as the beam rotates and sweeps through the gas plume multiple times; thus the data in the image do not represent an instantaneous snapshot but rather an average over the image acquisition time. This signal-averaging step is required for good signal-to-noise ratio and improved accuracy. It allows setting ⟨*dq/dt*⟩ to zero as any instantaneous pooling of methane behind structures found on-site is unlikely to persist for longer than the measurement time, eventually reaching the steady-state value after averaging over temporal fluctuations. As methane does not sediment, adsorb, or transform into another compound to a significant extent, it can be assumed that there are no sinks of methane (i.e., processes removing it from the atmosphere). Thus, $\sum$ is the mass emission rate and is equal to

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle .$$

Now the mass flux per unit area $\boldsymbol{j} = \boldsymbol{v}\,\rho$, where ρ is the gas concentration (g/m^3) and $\boldsymbol{v}$ is the wind velocity vector (m/s) measured by an anemometer connected to the camera at a frequency of 1 Hz; i.e., with a new wind measurement provided every second. Both ρ and $\boldsymbol{v}$ have spatial dependence. However, wind fluctuations will be averaged out both spatially and temporally over the methane image acquisition period of 3 to 4 minutes, such that a single mean wind value computed from the anemometer measurements over a corresponding methane image acquisition period can be used for the computation without loss of accuracy.

The methane lidar camera does not measure the concentration ρ directly, but rather a path-integrated methane concentration $\boldsymbol{\xi}$ (g/m^2); i.e., ρ integrated along the laser beam with direction $\hat{\boldsymbol{n}}$. To perform the double integration, the enclosing surface must be selected. Because methane flux follows the wind, ρ and hence $\boldsymbol{j}$ will be both zero upwind of the source. Thus, any surface can be used on the upwind side as the integral of $\boldsymbol{j}$ over it will be zero. Therefore, it can be ignored. For the downwind portion of the enclosing surface, a plane $\boldsymbol{S}$ is used which is defined by the vertical edge of the plane of the plume image $\boldsymbol{l}$ and the laser beam direction $\hat{\boldsymbol{n}}$. Then we can write $\rho d\boldsymbol{S} = \boldsymbol{\xi} d\boldsymbol{l} \times \hat{\boldsymbol{n}}$ (the crossproduct of $d\boldsymbol{l}$ and $\hat{\boldsymbol{n}}$) and for the total emission mass flux rate $\sum$,

$$\sum = \left\langle \oiint \mathbf{j} \cdot d\mathbf{S} \right\rangle = \left\langle \oiint \boldsymbol{v} \cdot \rho d\mathbf{S} \right\rangle = \left\langle \boldsymbol{v} \cdot \int \xi d\boldsymbol{l} \times \hat{n} \right\rangle$$

where again the bracket indicates the time averaging implicit in the measurement scheme. The mass balance approach to the quantitative mass emission rate computation is further discussed in Titchener et al. (2022).

Additional detail on how models involving machine learning procedures is submitted separately as confidential business information.

Summary of any a priori methods and dataset

For optimal camera placement, a 3D model of the site is created using either elevation data from publicly available or operator provided lidar surveys or other methods such as photogrammetry, CAD data, or else by extruding equipment located on an aerial image to a defined height. Historic wind data from public sources can be used to determine predominant wind directions to optimize camera placement. No other a priori methods or datasets are involved in this method.

Summary of any machine-learning procedures

Additional detail on how models involving machine-learning procedures is submitted separately as confidential business information.

Data Management and Processing Steps

The following section intends to give an overview of the completeness of the connected and integrated system, from the Lidar Camera doing the measurements, to the edge device collecting and communicating measured data to be ingested in the cloud solution for processing, interpretation and delivering actionable information to the end user through our user interfaces.

Software architecture overview of connected system

Figure 9 depicts the overall software architecture of the connected system between edge (device connected to the methane lidar camera) and cloud (the software application for collecting all data from the lidar camera, data interpretation and user interfaces), which is designed with a focus on data quality, performance, and security. The gateway running at the edge includes the required modules for a containerized Internet of Things (IoT) edge deployment. Containers include:

- **Ingestion**—Container to connect to the camera and receive topics of interest, such as methane spectral data. The ingestion process includes first-level data acquisition (from camera and sensors), manipulation, and enhancement, then standardizes and compresses the data and sends to the local storage. This is done with synchronization from the control module to make sure the boundaries of the data are represented correctly.

- Control—This process handles the camera scanning plan. A scan plan is essentially a list of frames that the camera is instructed to scan. Each frame contains required information, including:
    - Pan/tilt coordinates
    - Zoom level
    - Measurement duration

The local storage is an option from Microsoft® that allows for robust automated synchronization of the data placed in the local storage to a storage account on the cloud. Using the module predefined options, the developer sets how the data can be removed after it has been synchronized to the cloud. This module also handles sync issues in case of network connection loss. The cloud is able to access the data in the storage account using preexisting Microsoft APIs and events. There is enough storage at the edge to cope with many weeks of connectivity loss.

In addition to handling connectivity issues without data loss, the methane lidar camera reports on its own health status, and the edge gateway combines this with additional metrics regarding the ancillary edge equipment. These health metrics provide the framework for a continuous health monitoring and notification system, whereby problems are detected using algorithms and then addressed automatically and/or reported through flags and notifications.

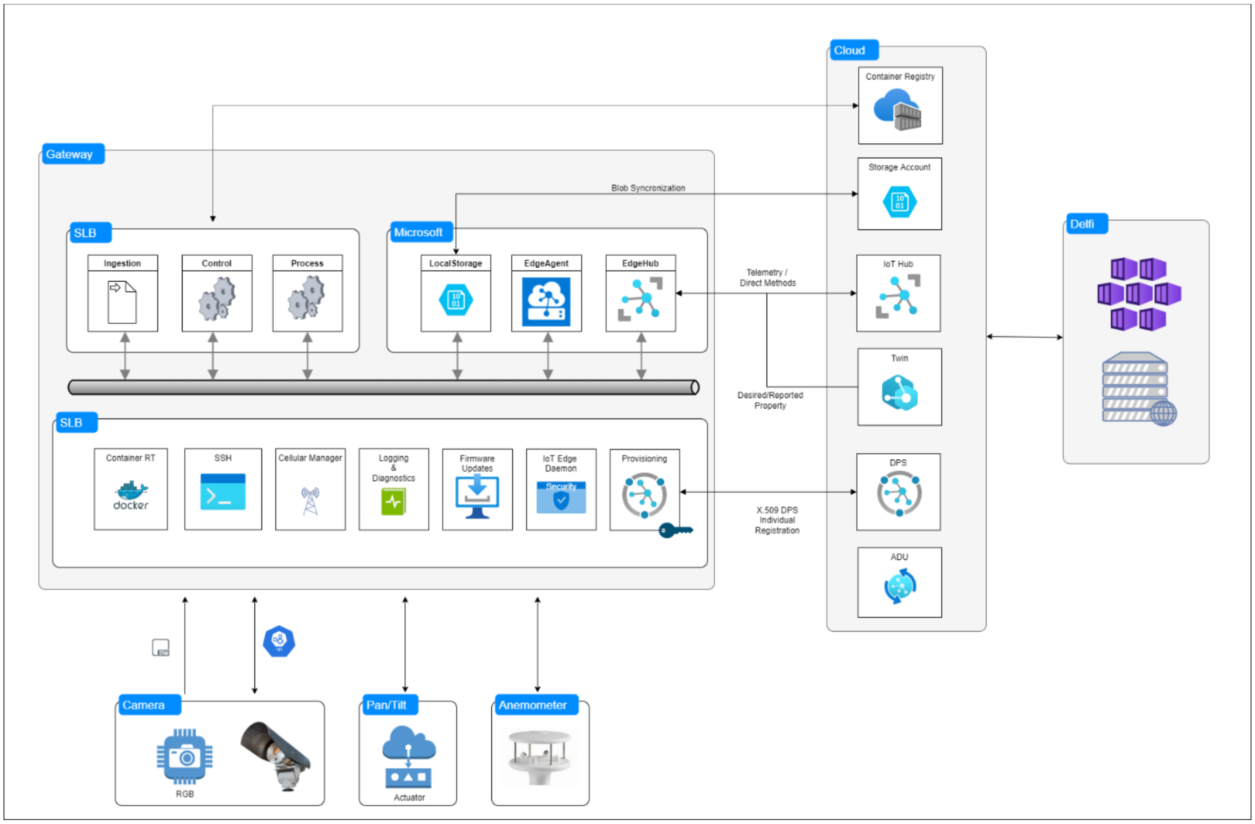


Figure 9: Software architecture managing data quality, security, and storage.

Procedure to collect/generate data

The methane lidar camera is commissioned to continuously scan all possible methane emission sources. This is done in the form of a scan plan that takes snapshots (frames) of possible emission source at regular intervals. A frame is generated approximately every 5 minutes, which is the time it takes the laser to scan the area of interest (camera field of view). In order to scan a whole facility, a scan plan is created containing sets of targets specified in 3D coordinates such as tilt, heading, and zoom. Once a scan plan has been activated, the camera will loop through each of the targets (frames), looking for methane plumes and if detected, then it will quantify and attribute the origin of the plume to a known source. Every time a frame is acquired, environmental data are also measured, appended, and transmitted to the cloud. In the cloud, data integrity and quality are verified and then passed to interpretation algorithms that detect, quantify, and attribute emissions to sources. The processing is done at a faster rate than the time it takes to acquire each frame.

In addition to gas concentration data, system health metrics such as CPU load, memory consumption, auxiliary systems health (anemometer, GPS, etc.), among others, are collected. Diagnostic data are transmitted regularly to the cloud and used to detect issues at the edge, enabling remote troubleshooting and sending alarms in case of system degradation.

Procedure to maintain/store data

Raw data containing methane concentration, photon count, distance, wind speed, and wind direction are serialized and packaged in a strongly typed structured format. The file structure defines the communication schema between the edge and the cloud, and it is version controlled to trace the evolution of the schema, enabling backward-compatibility. The payload is compressed and encrypted before being transmitted over a secured channel to the cloud using the industry-standard transport layer protocol.

Data are transmitted on demand, every time a frame is generated, which is usually every 5 minutes. When data are received in the cloud, files are routed to separate tenants per operator and persisted in file stores that are encrypted using a symmetric block cypher with 256-bit key lengths (AES 256). Raw data are immutable, which allows recovery from downstream failures in the processing pipeline and provides traceability. All raw data are periodically backed up several times a day to at least two regions. Multiple copies of past backups are retained, providing a layered approach to restore to predetermined points in time in the past for up to several days.

Procedure to process/manipulate data

Data processing is done automatically every time a new frame is received in the cloud from the edge. In the case of communication failures, the edge can buffer data for several days and when communications are restored, buffered data are transmitted in order.

After raw data from the edge systems are ingested, it is unmarshalled and passed to a processing pipeline that checks for data integrity and applies quality checks such as data out of range, outliers, missing data, and sensor data. If data quality checks are passed, data are fed to interpretation algorithms that will detect if a plume is present in the image. If so, it will estimate the flow rate of the emission and attribute the plume origin to a known emission source at the site. The processing pipeline also creates 1) images showing methane concentration, photon count, range and 2) a compound image overlapping the photon count and the methane concentration. These enable users to confirm the interpretation from algorithms and are kept as evidence of the raw data. The overlapping of methane concentration over intensity and range are useful information for identifying where a gas plume originated.

Connectivity and system health metrics such as data transmission frequency and data quality are computed regularly, aggregated at site level, and used for determining system availability as per the EPA requirements for continuous monitoring systems. Data quality checks analyze data feeds and validate that data are arriving at the required frequency, data are changing and within expected ranges, and checks for invalid data. These checks are used to confirm power and function of the system and calculate health indicators several times a day.

This provides an easy way to demonstrate system compliance with regulatory requirements.

Summary of how the data processing is documented

Data processing is done automatically every time a new frame arrives in the cloud. As data are processed, final and intermediate results are populated in operational stores that are continuously backed up and allow data recovery to any point in time in the last 30 days. Every time a transformation is done to the data, an entry is captured in a system log, providing end-to-end traceability on the processing of the data.

Interpretation algorithms are versioned and stored in a version control system. Changes to algorithms follow a strict change management process where each change is peer reviewed by at least two experts, thoroughly tested and documented before being deployed into production. All changes to production are also documented and approved. Material changes to interpretation algorithms are communicated to users via release notes published in the system.

The system is operated according to the Service Organization Control Type 2 (SOC 2) standard that provides controls that cover key areas such as: security, availability, processing integrity, and confidentiality. Compliance to the SOC 2 standard is verified annually by external auditors.

Description of Final Product Returned to the End User

Information is delivered in real time to users via an intuitive, cloud-hosted solution. In addition to providing access to independent measurements, diagnostic details, and fugitive emissions statistics, the solution also provides intuitive user interfaces to meet the required functionality for managing emissions as per EPA specification.

Emissions are tracked from individual sources and totals are aggregated on individual sites or group of sites in an area, providing a summary overview and historic trending of emission events. For each site, the system identifies the areas and sources that require immediate attention above the operator-specified applicable alerting threshold, previous measurements, and trends.

Dashboards with actionable insights enable users to track emission trends and abatement performance. In-app and email alerts notify users when emissions above a configured threshold are detected or expected. In particular, the system computes median mass emission rates based on 3 scan frames per field of view during a periodic screening event and issues alerts when those medians exceed the alerting threshold chosen for compliance by the operator. If the system is operated continuously, the system also notifies operators when emissions are identified that may exceed alerting thresholds during a periodic screening event, providing operators an early opportunity to abate those emissions.

The cloud solution is divided into three main groups:

1. Measurement services: Independent measurements from the lidar camera, such as images showing gas concentration, photon intensity and range, mass emission rates time series, location of emissions, environmental data, and system health information.

2. Locations: Site-level emission dashboards provide details such as individual emission events per source (area or component), events tracking information, including start/end times, average rates, total emitted volume, emission category (venting, fugitive, etc.) and additional support information. There are also site-level dashboards showing daily emission trends, baseline, rolling averages, and action levels.

3. Dashboards: Global overview of all monitored sites and summary with historic trends.

Summary of information provided to the end user

The following sections include screen shots and descriptions of the user interface of the cloud-based software application used to support the methane lidar camera.

Continuous emission monitoring system user interface

Figure 10 shows the user interface of the methane lidar camera where each observation can be viewed on the timeline, and for any selected observation exploring the scan frame image taken.

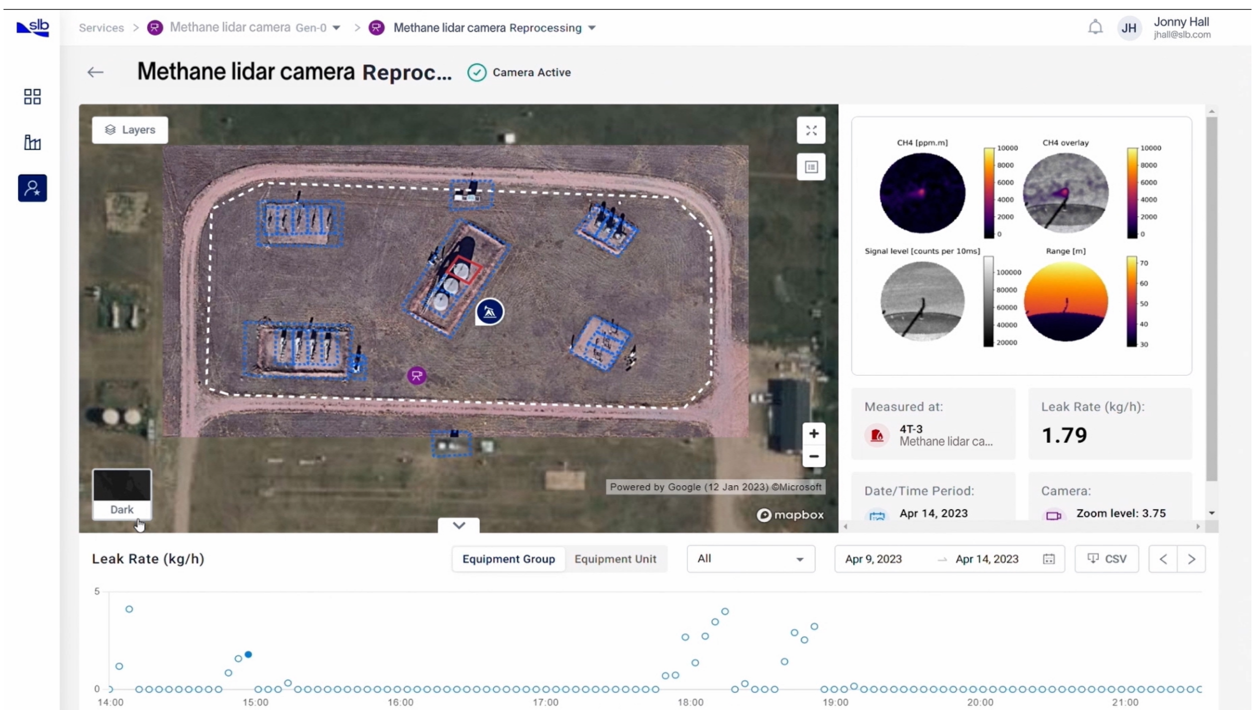


Figure 10: Methane lidar camera user interface.

Locations—Site-level emission dashboards

Site-level dashboards showing median mass emission rates, daily emission trends, emission baseline,s rolling averages, and action levels are provided to the user to understand methane emission behavior, identify anomalies, and trigger actions to reduce emissions (Figures 11 and 12).

The dashboard is configured to provide multiple leak definitions and reporting methods, including approaches consistent with the requirements for periodic scanners, requirements for continuous monitors, and user-configurable reports and alarms.

For operators who use the methane lidar camera to comply with the requirements for periodic scanners, the dashboard presents the median methane mass emission rate for each possible fugitive, closed vent, or cover in each field of view, evaluated over three images collected per field of view. If that median exceeds the applicable leak resolution threshold, the system issues an alert. The alert contains a variety of information regarding the detected leak, including the date of the emission, the time of the emission, the location of the emission, and the measured mass emission rate.

For operators who use the methane lidar camera to comply with the requirements for continuous monitors, the dashboard presents the site baseline emissions (over 30 days), the site-level rolling window average mass emission rate (for 1 day, 7 days, and 90 days), and the action levels (7 days and 90 days).

For operators who use the methane lidar camera for voluntary purposes, the dashboard offers user-configurable alert based on factors such as the emission rate and duration.

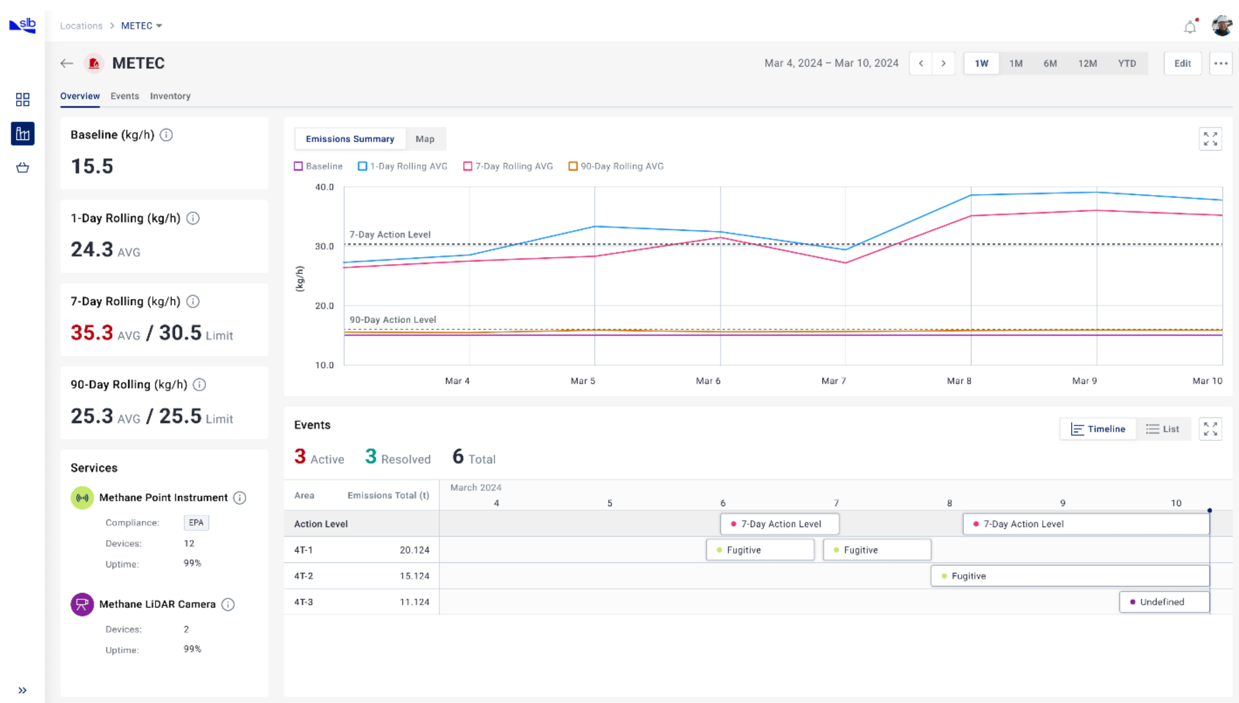


Figure 11: Location dashboard for site-level emissions, representing the requirements for continuous monitors.

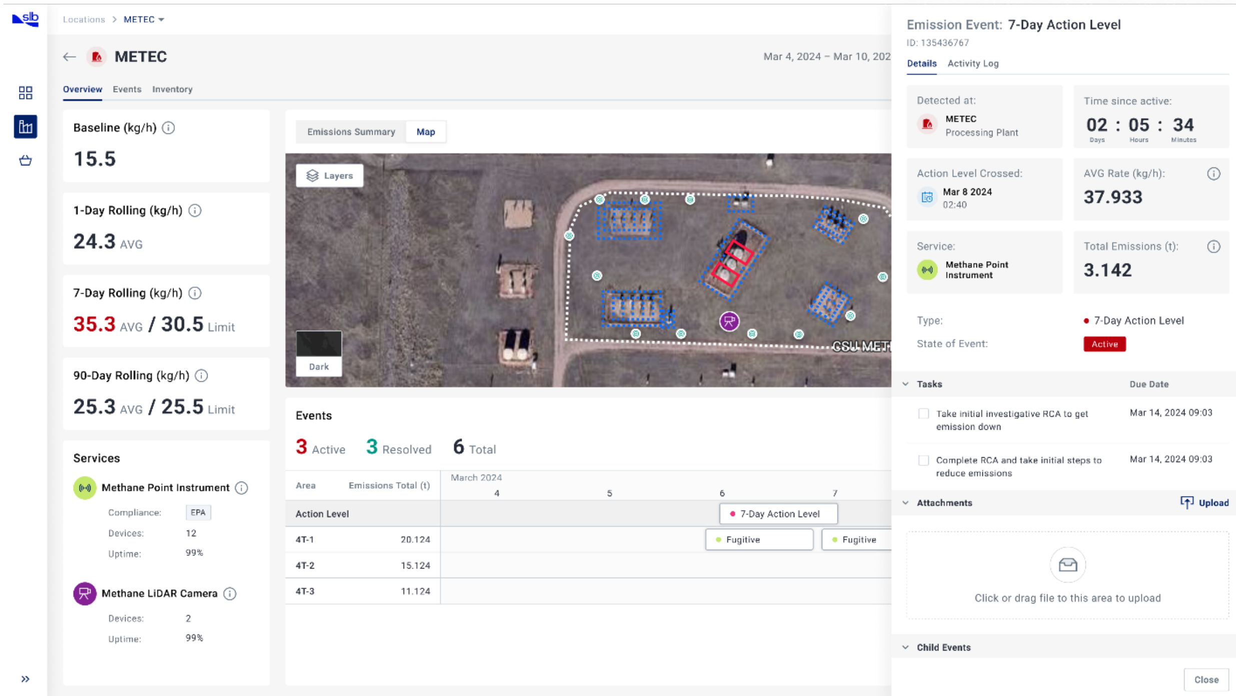


Figure 12: Location dashboard for site-level emissions—detail view.

Also, system uptime trends are provided to the user to ensure and demonstrate compliance with continuous monitor availability requirements.

The uptime visualizes the percentage of system uptime per day, where 100% indicates the successful generation of a minimum of two observations every 12 hours. This forms the basis to compute the average uptime per month and finally the moving average over a 12-month period.

It displays the data on a device-by-device basis, providing a detailed view of each unit's performance (Figure 13).

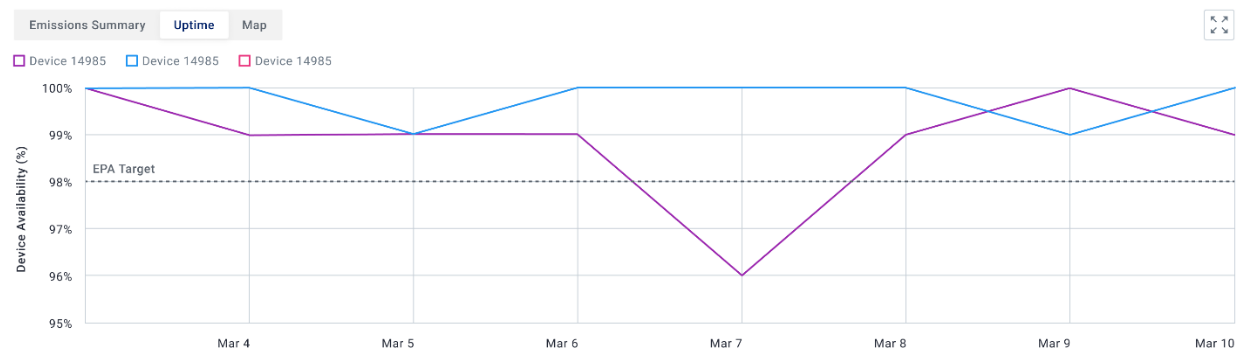


Figure 13: System uptime monitoring.

Dashboards

Global dashboards aggregate information from all monitored sites and provide a convenient way to understand overall trend of emissions.

The following information is available for the last month, quarter, or year (Figure 14):

- Daily totals for all sites or individual sites
- Number of emission events
- Distribution of emission events per type and source
- Average emission duration.

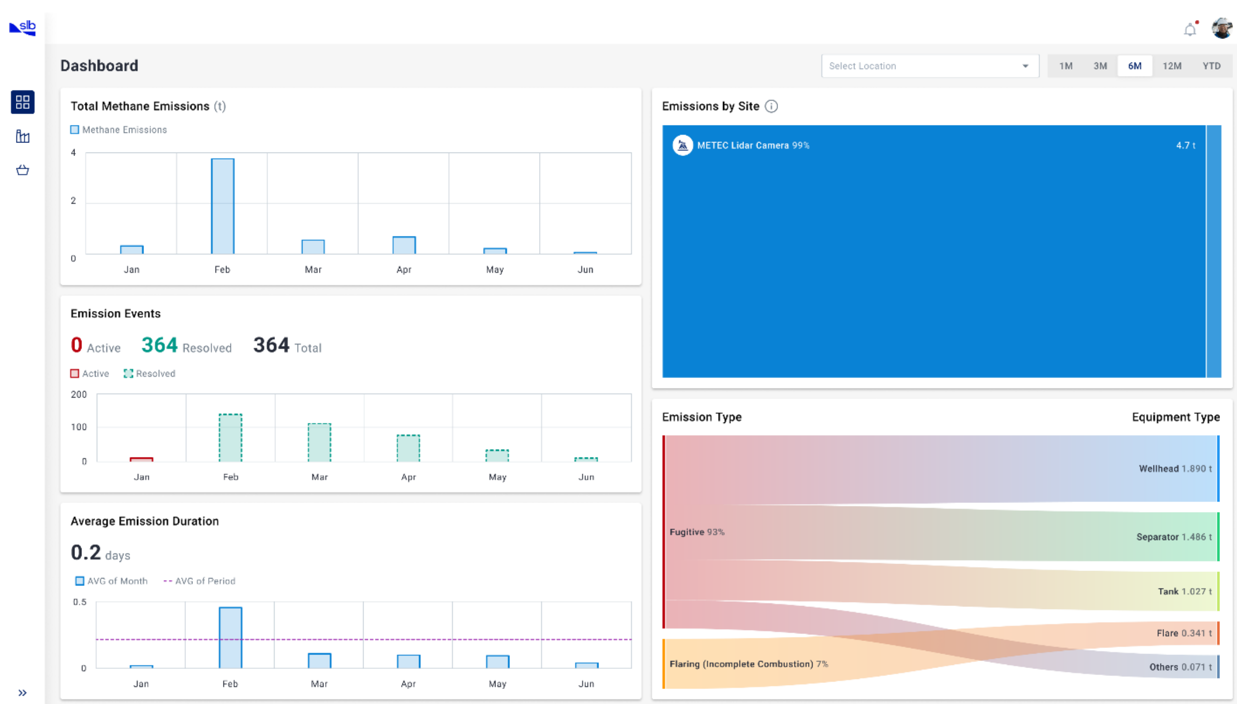


Figure 14: Summary dashboard for all locations monitored.

Notifications

The software platform supports two types of notifications: in-app and email. Users can create customized rules to determine when and how they receive these notifications. Notifications are customizable using rules. Rules enable us to set up notifications for all sites or individual sites based on exceeding emission thresholds (Figures 15, 16, and 17).

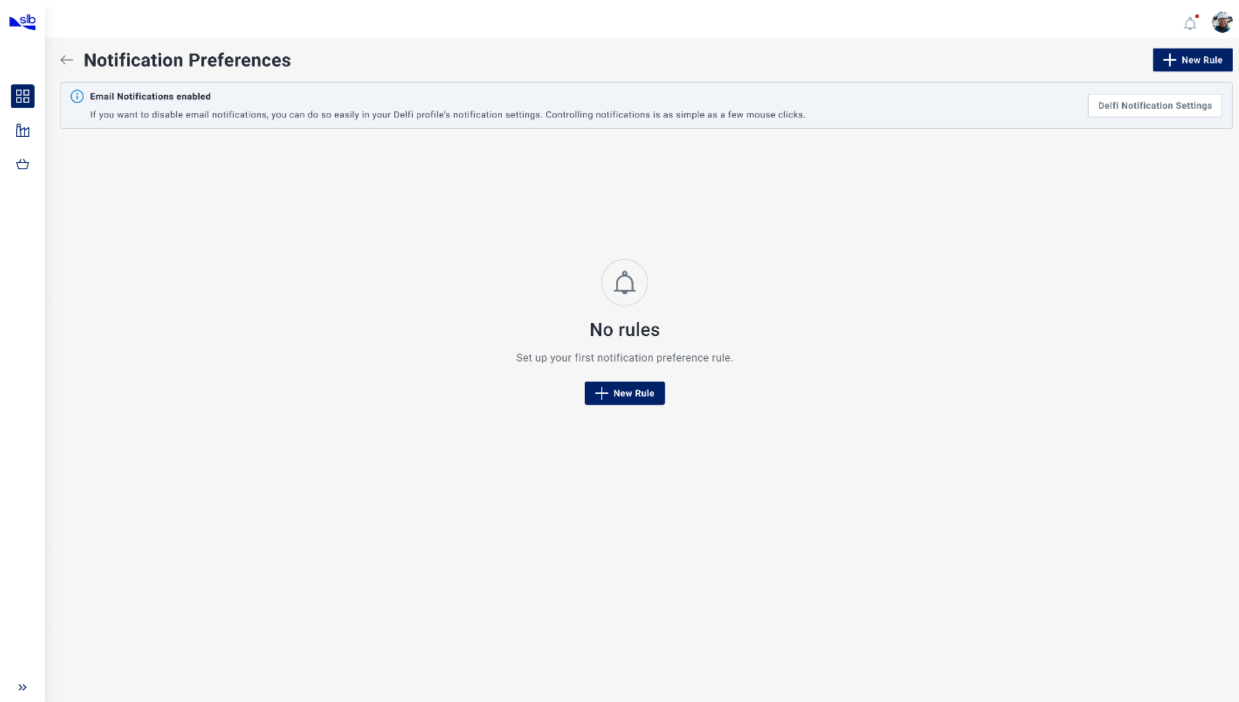


Figure 15: User-defined notifications.

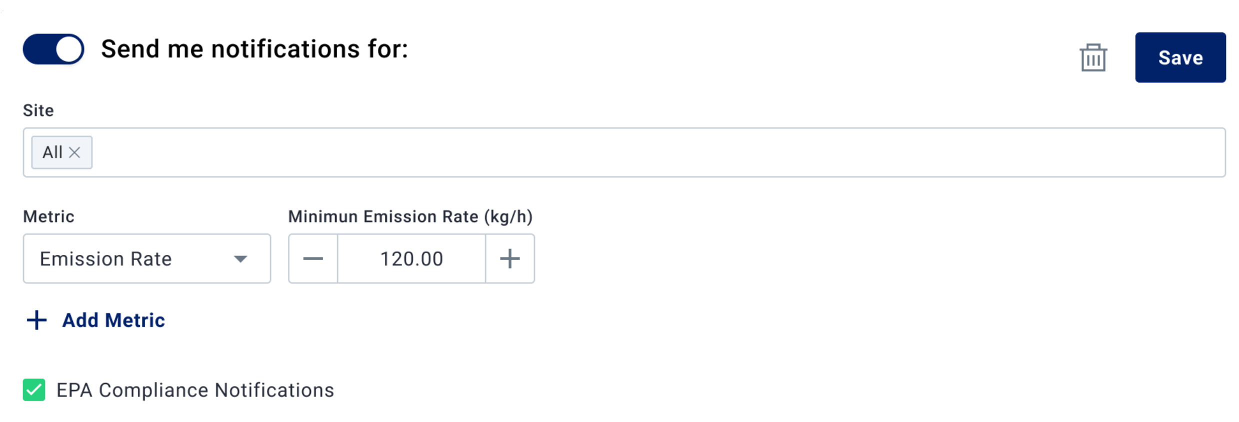


Figure 16: User can define threshold-based notifications, including those corresponding to the requirements for periodic screeners and for continuous monitors

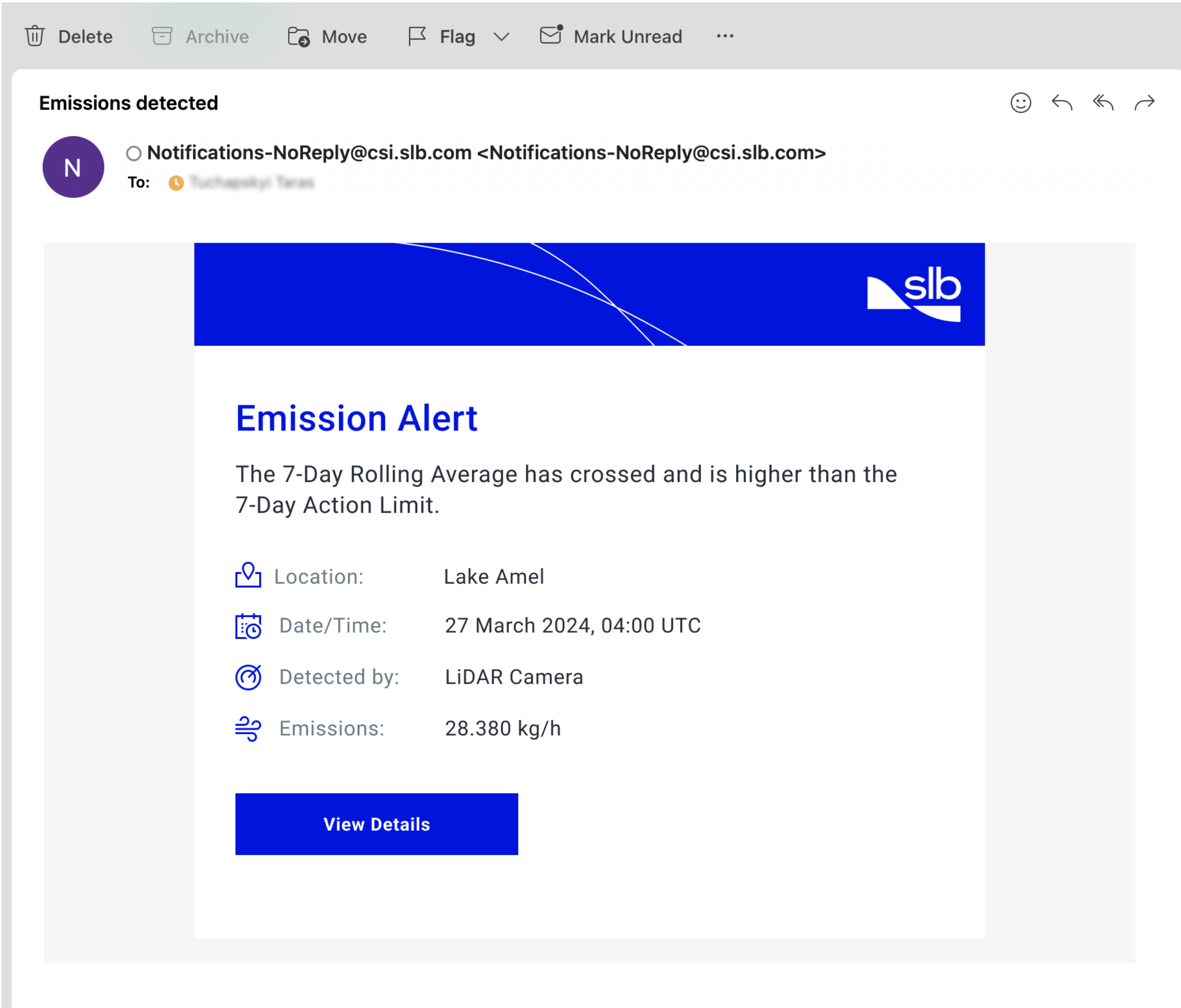


Figure 1710: Email notification as received by the user.

Procedure to deliver/supply information to the end user

Information is delivered in real time to users via an intuitive cloud-hosted solution. In addition to providing access to independent measurements, diagnostic details, and fugitive emissions statistics; the solution also provides intuitive user interfaces to meet the required functionality for managing emissions as per EPA specification. Emissions are tracked from individual sources and totals are aggregated on individual sites or group of sites in an area, providing a summary overview and historic trending of emission events.

For each facility, the system identifies the areas and sources that require immediate attention above the periodic screening alerting threshold, previous measurements, and trends.

Dashboards with actionable insights enable users to track emission trends and abatement performance.

In-app and email alerts notify users when emissions above a configured threshold are detected. This provides an effective way to manage by exception, ensuring timely intervention when emissions deviate from normal.

References

Ai, X., Titchener, J., and Dunning, A.: "Method of Operating a Lidar System for Detection of Gas," US Patent No. US11644576B2 (May 9, 2023).

Reed, M. K. and Ai, X: "Measurement of Gas Flow Rate," US Patent Application Publication No. 2023/0324430 A1 (October 12, 2023).

Titchener, J., Millington-Smith, D., Goldsack, C., Harrison, G., et al.: "Single Photon Lidar Gas Imagers for Practical and Widespread Continuous Methane Monitoring," *Applied Energy* (2022) 306 (Part B), 118086. https://doi.org/10.1016/j.apenergy.2021.118086.

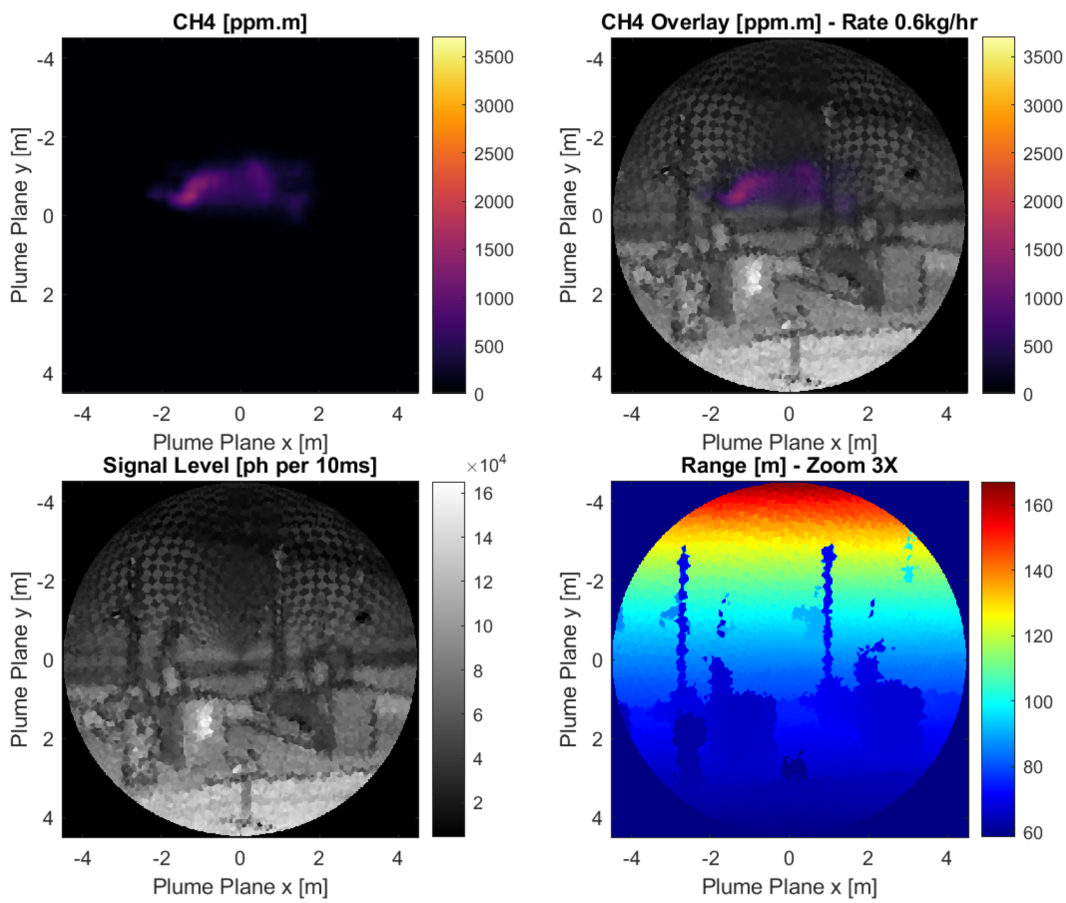
Titchener, J. and Ai, X: "Rapidly Tuneable Diode Lidar," UK Patent No. GB2586075A (July 28, 2021).

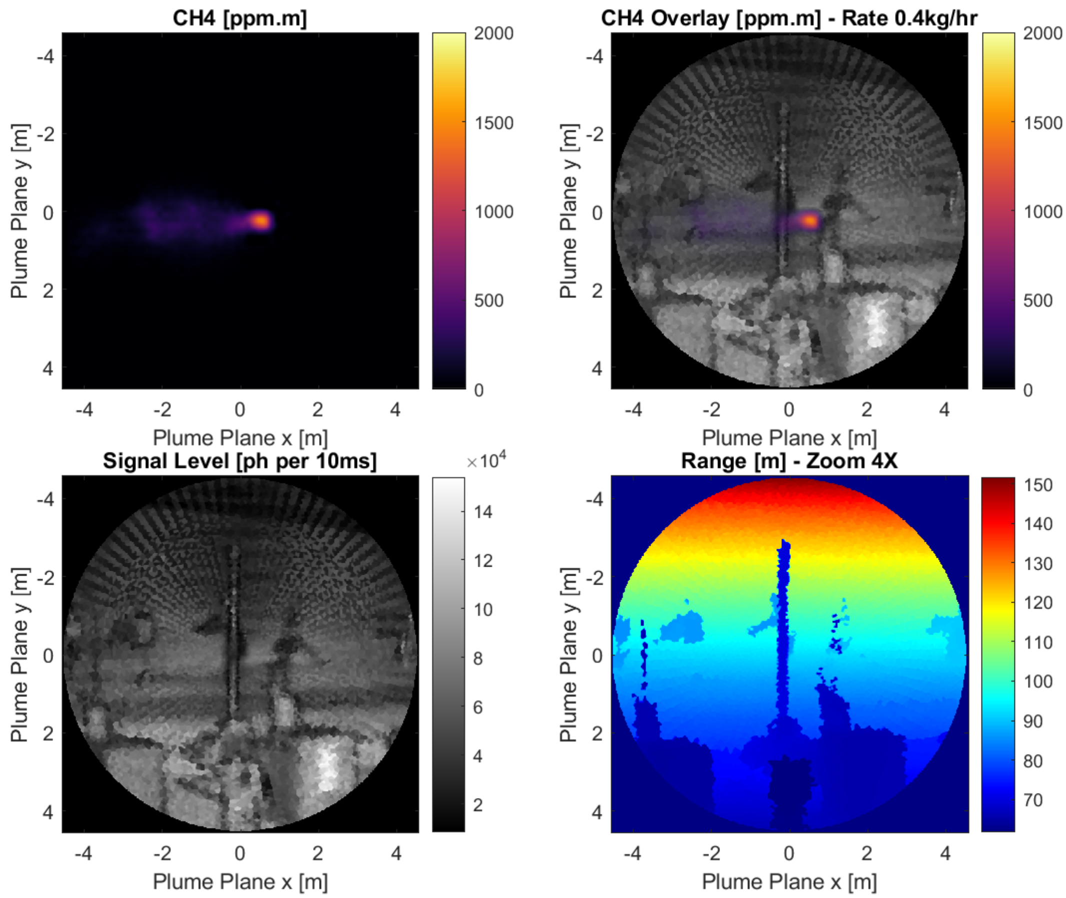
US Environmental Protection Agency (EPA): "EPA Issues Final Requirements for Using Optical Gas Imaging in Leak Detection (Appendix K)," https://www.epa.gov/system/files/documents/2023-12/technical-fact-sheet.-using-optical-gas-imaging-in-leak-detection-appendix-k_0.pdf (December 1, 2023).

Attachment 1:

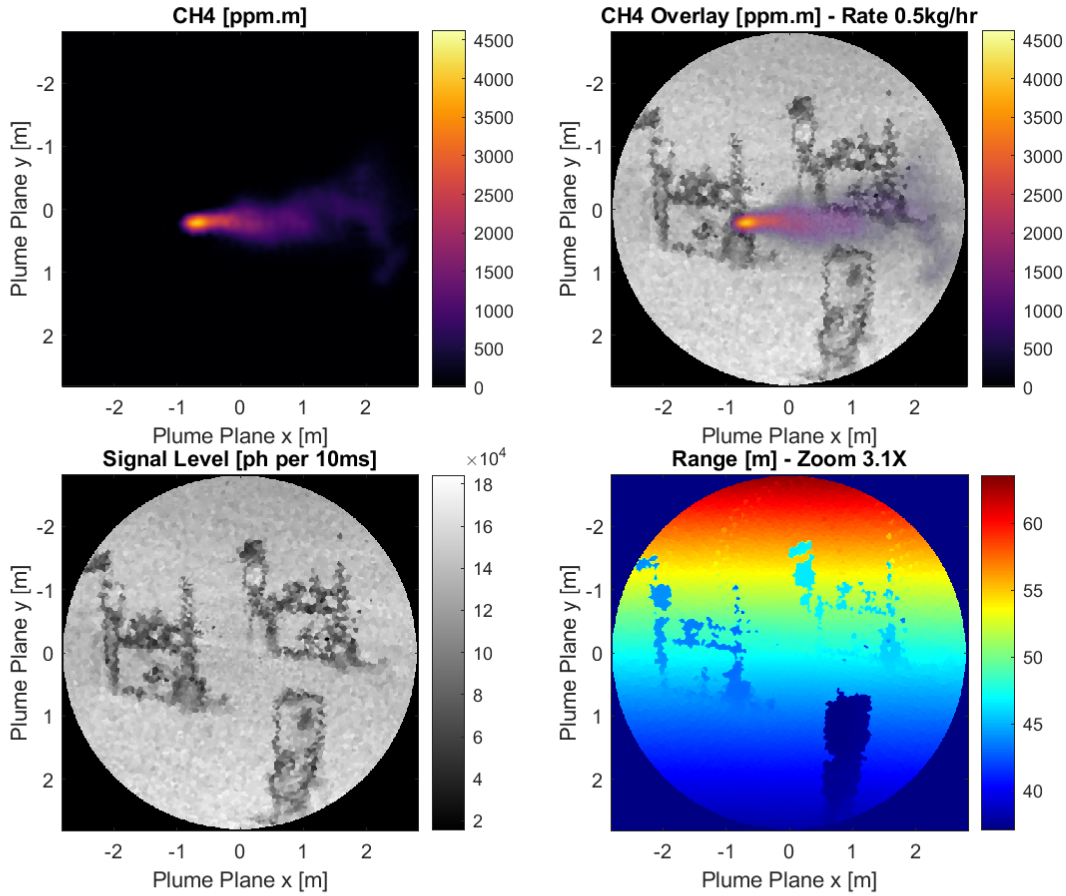
Example Images of Component-Level Leaks

The images included in this attachment demonstrate the methane lidar camera's ability to identify emissions at the component-level spatial resolution as defined by 40 CFR 60.5398b(d)(3)(vii) as "a technology with the ability to identify emissions within a radius of 0.5 meter of the emission source."

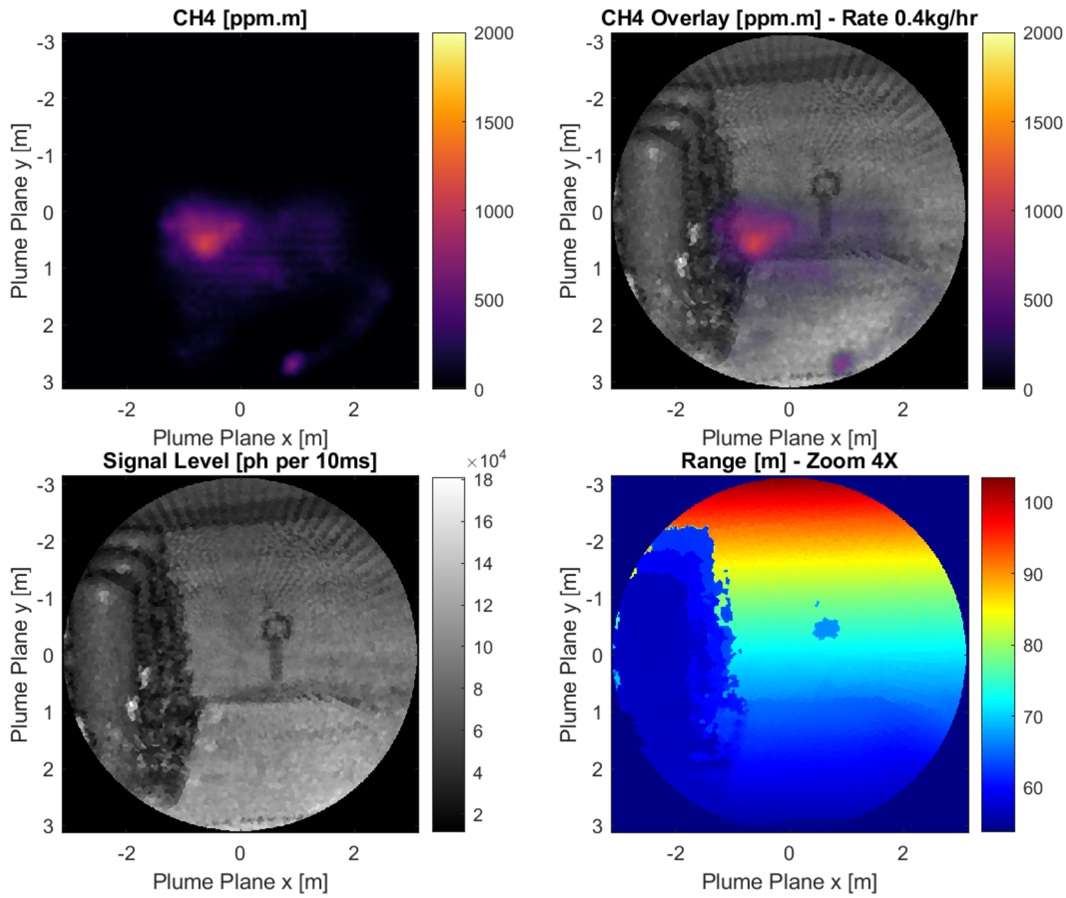


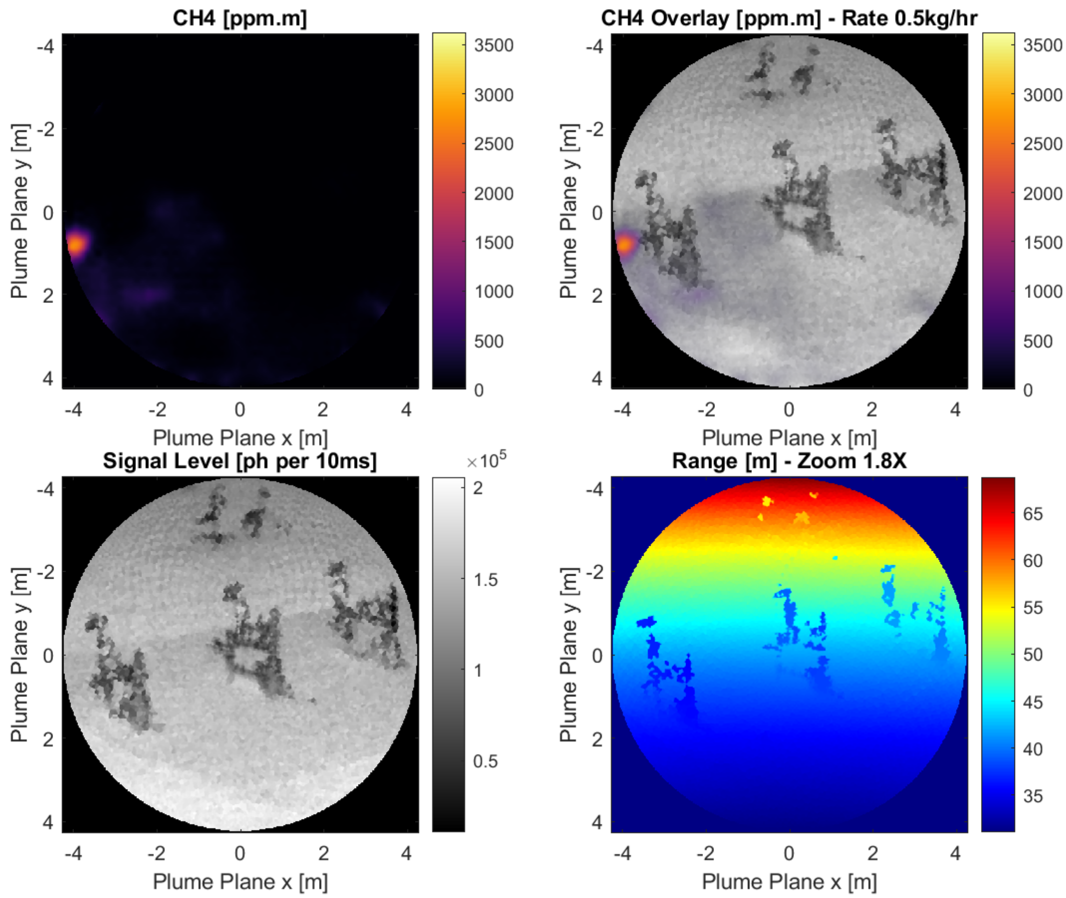


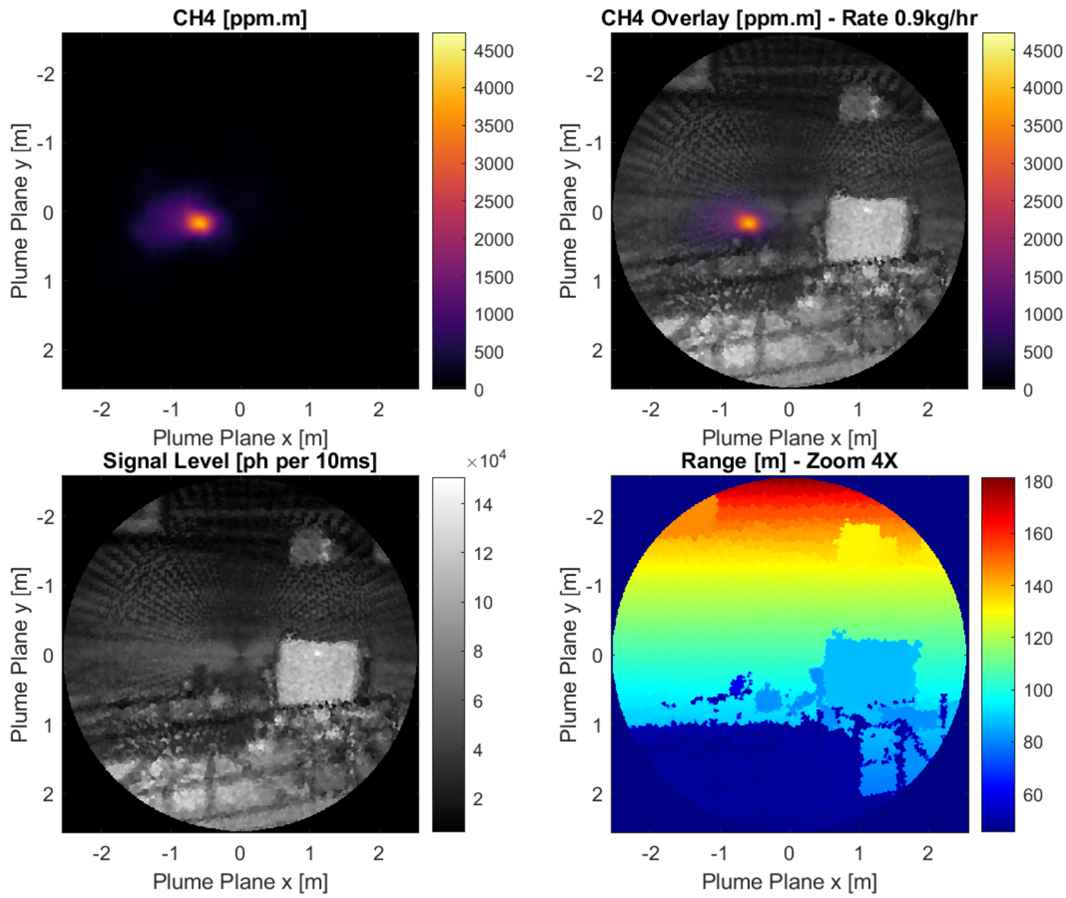
CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.4kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane y [m]
Plume Plane x [m]

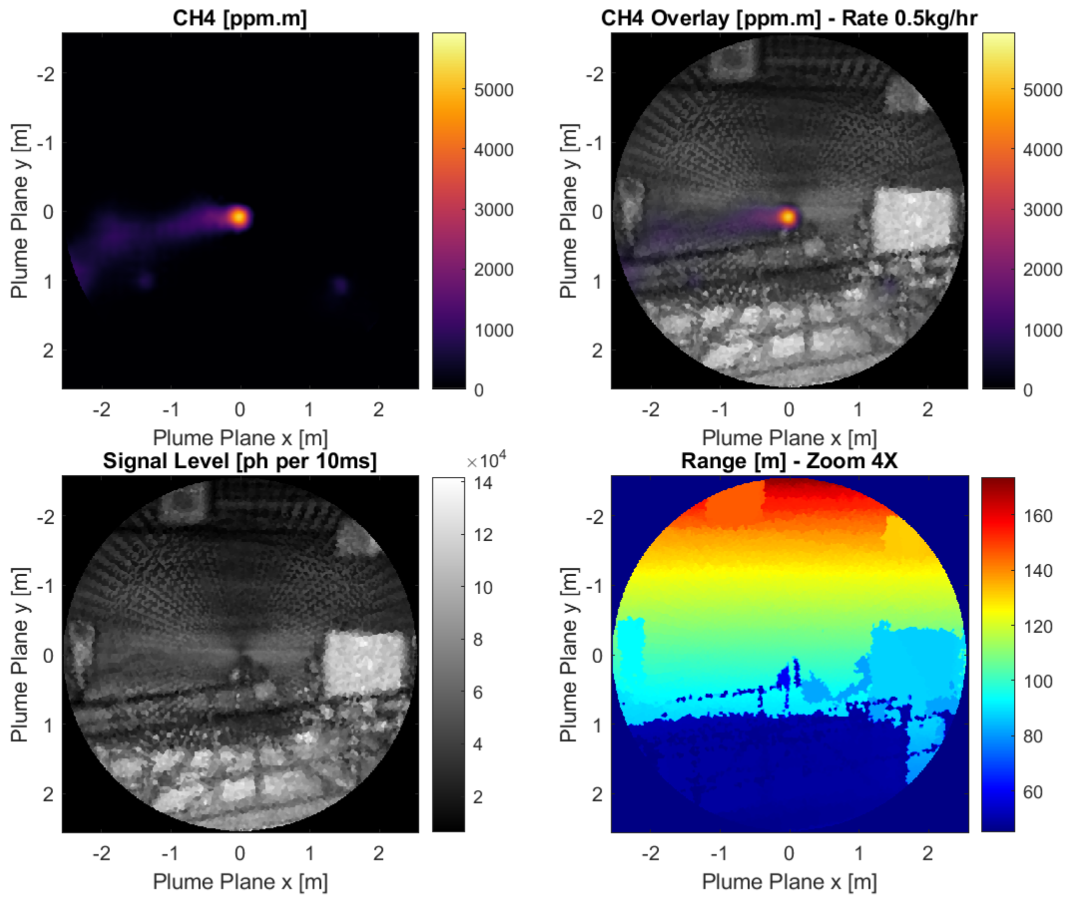


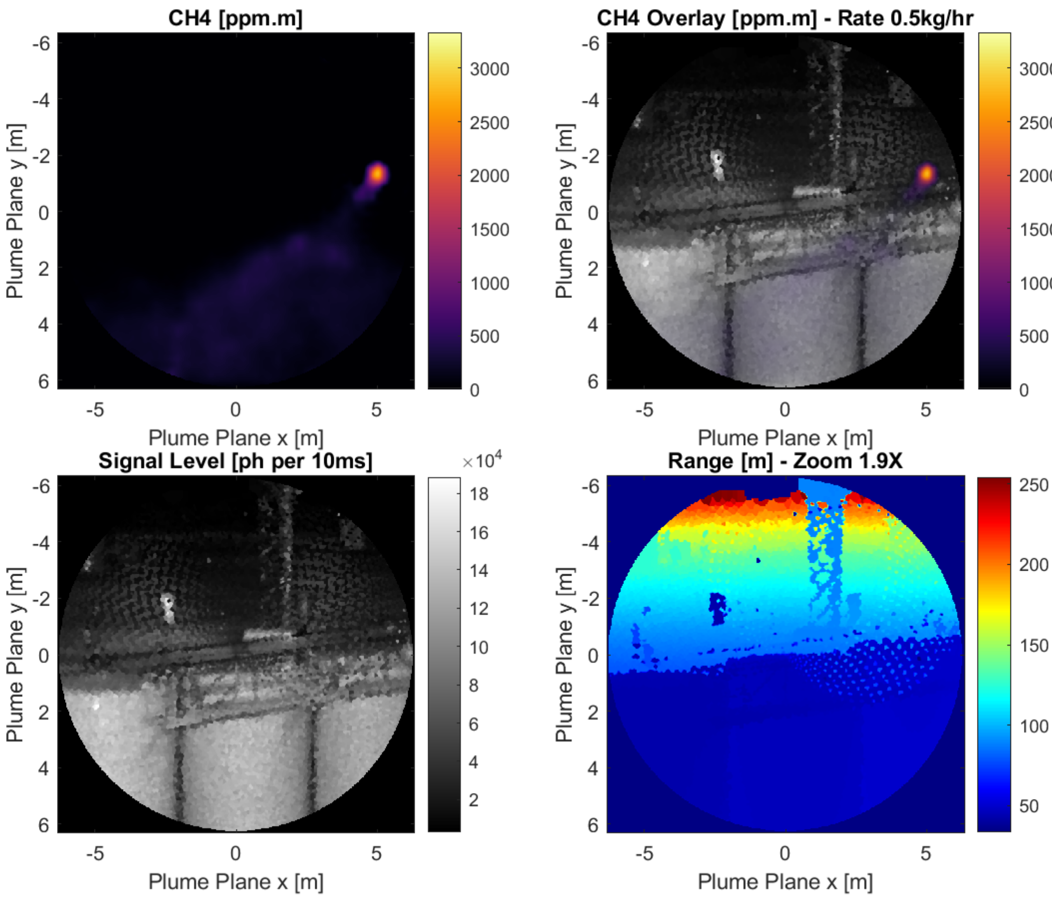
CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 3.1X
Plume Plane x [m]
Plume Plane y [m]
×10^4


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.4kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane x [m]
Plume Plane y [m]
×10^4

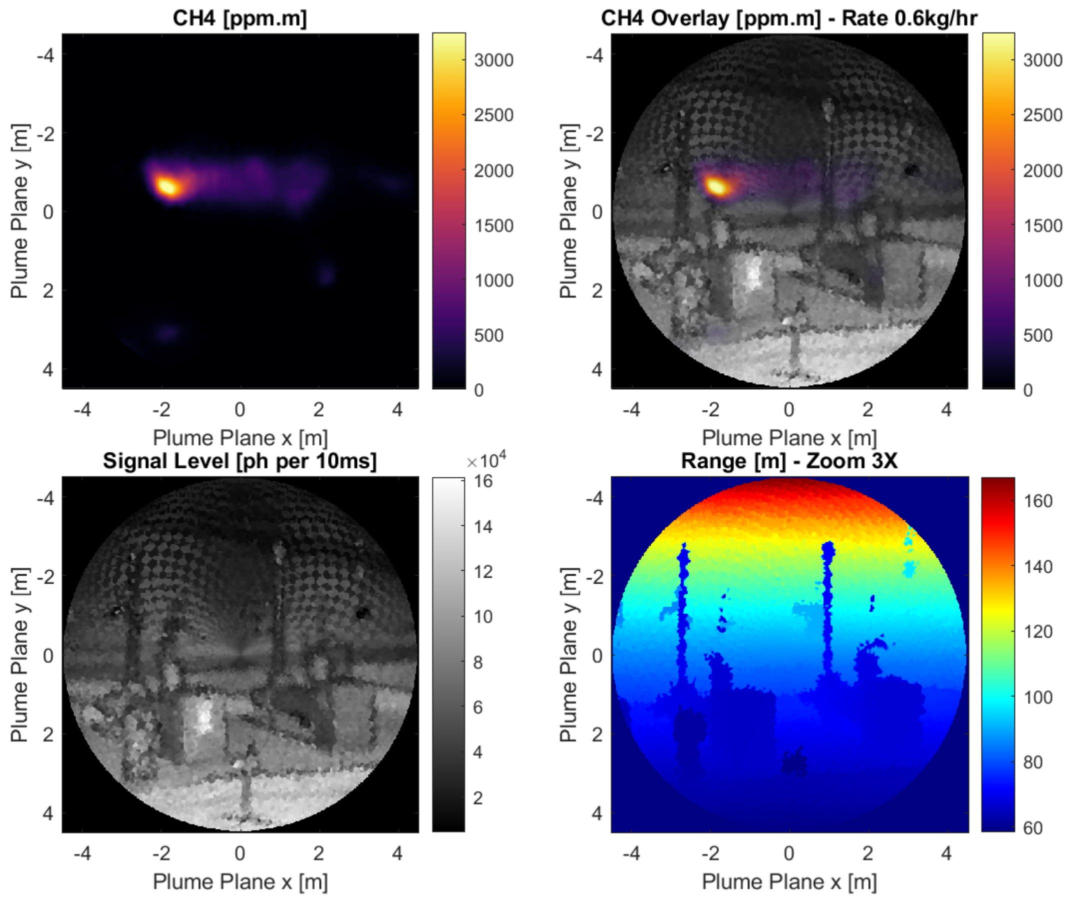

CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 1.8X
Plume Plane y [m]
Plume Plane x [m]
×10^5


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.9kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane y [m]
Plume Plane x [m]
×10^4

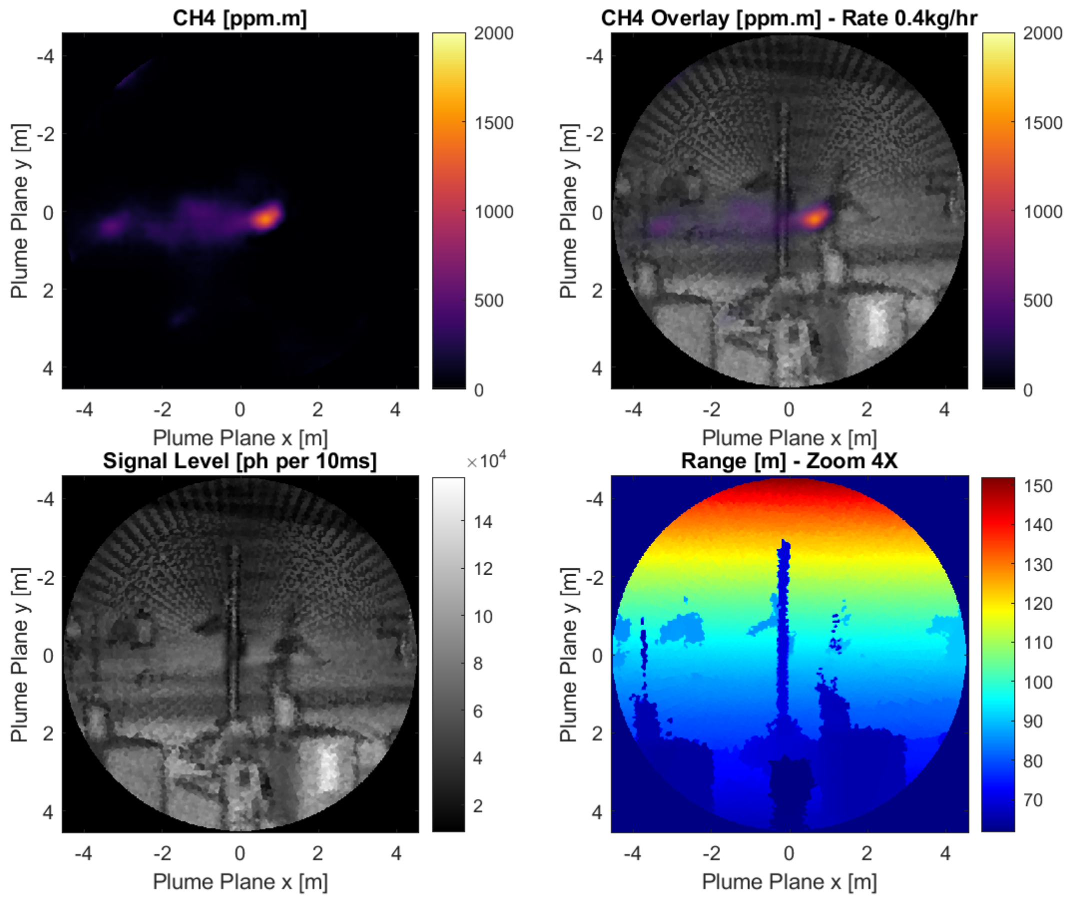

CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane x [m]
Plume Plane y [m]
×10^4



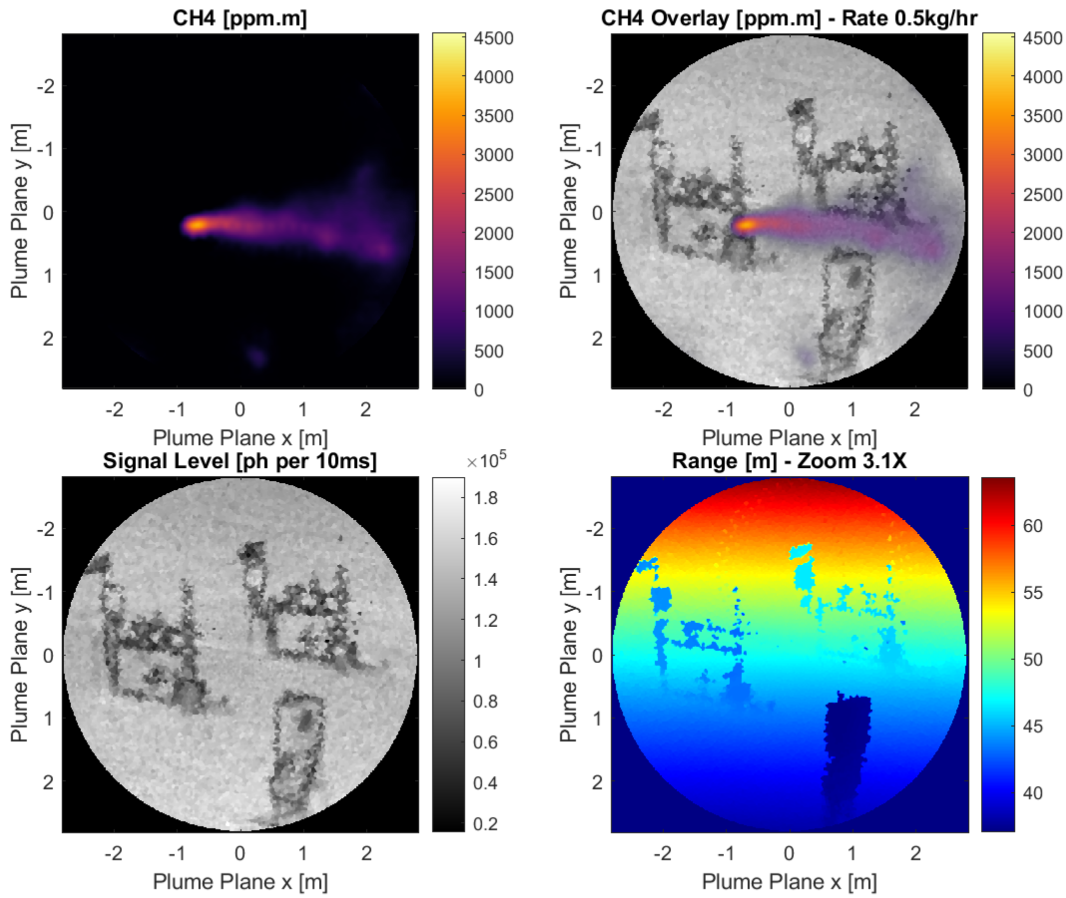
CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 1.9X
Plume Plane x [m]
Plume Plane y [m]
×10^4

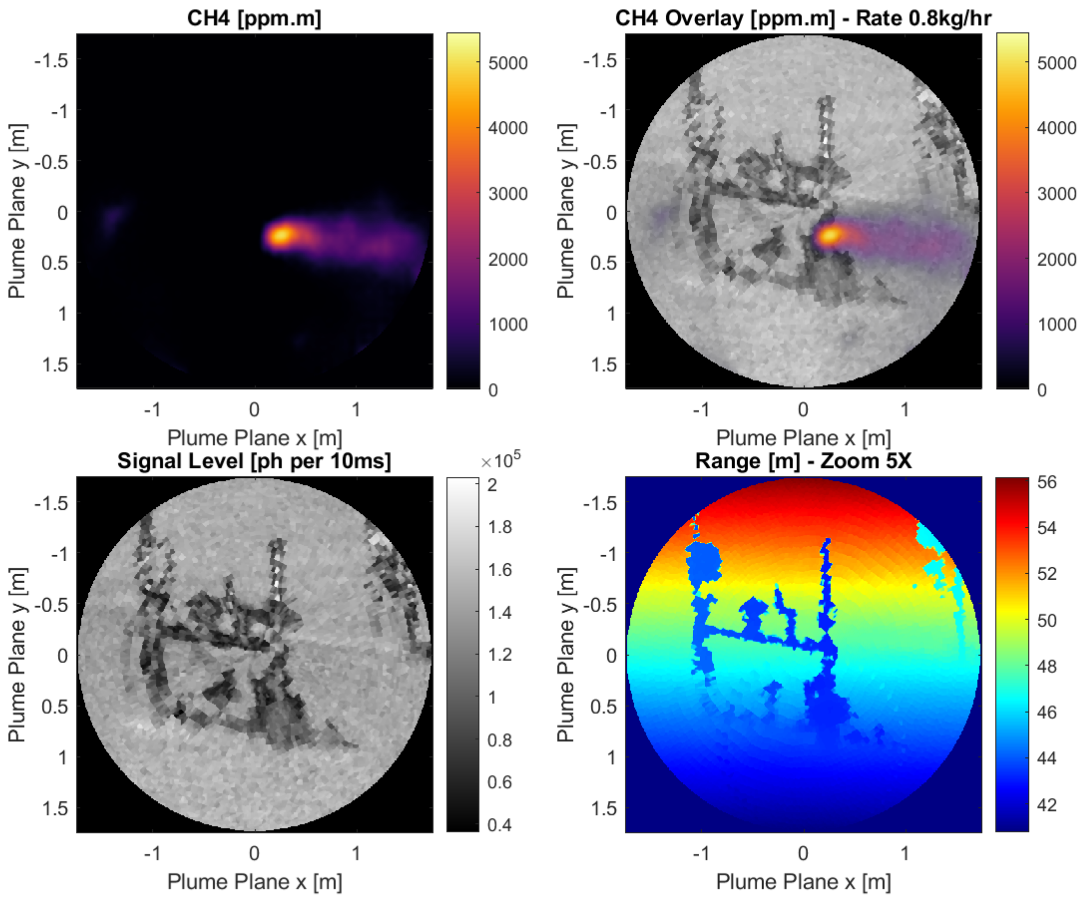


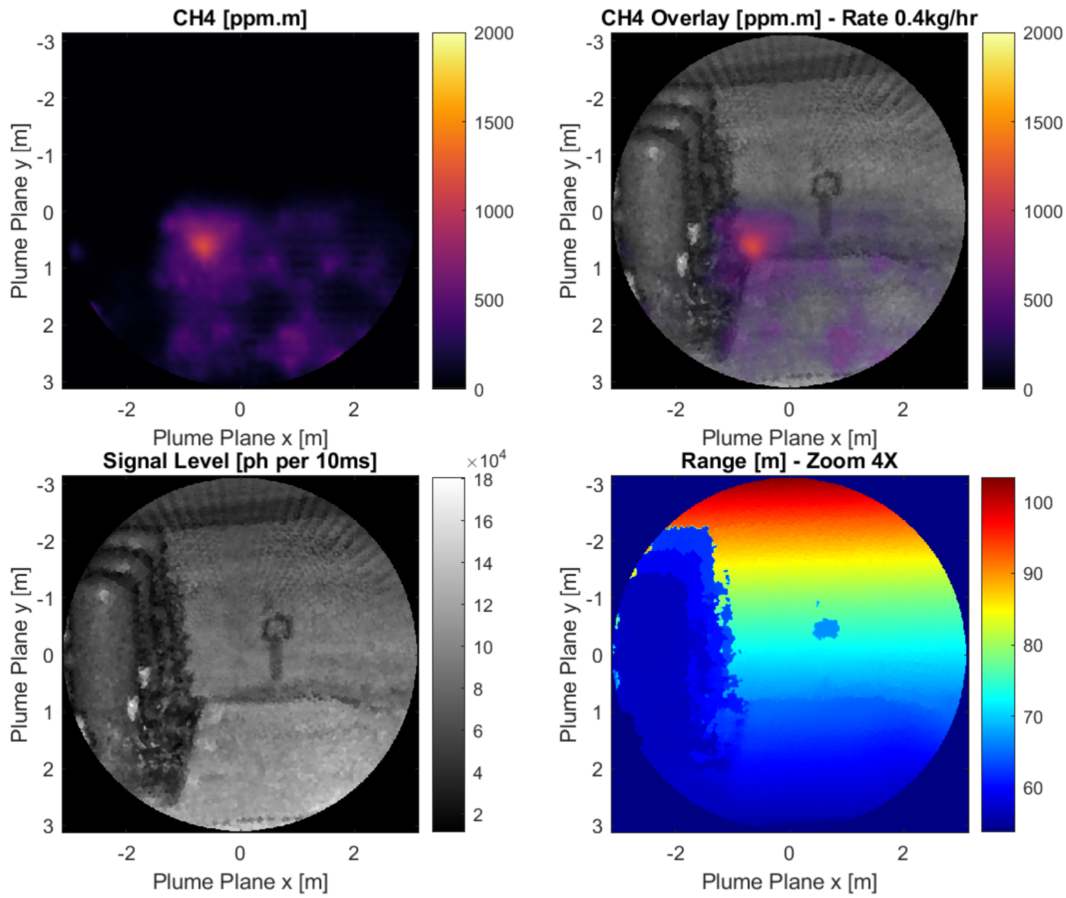
CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.6kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 3X
Plume Plane x [m]
Plume Plane y [m]
×10^4

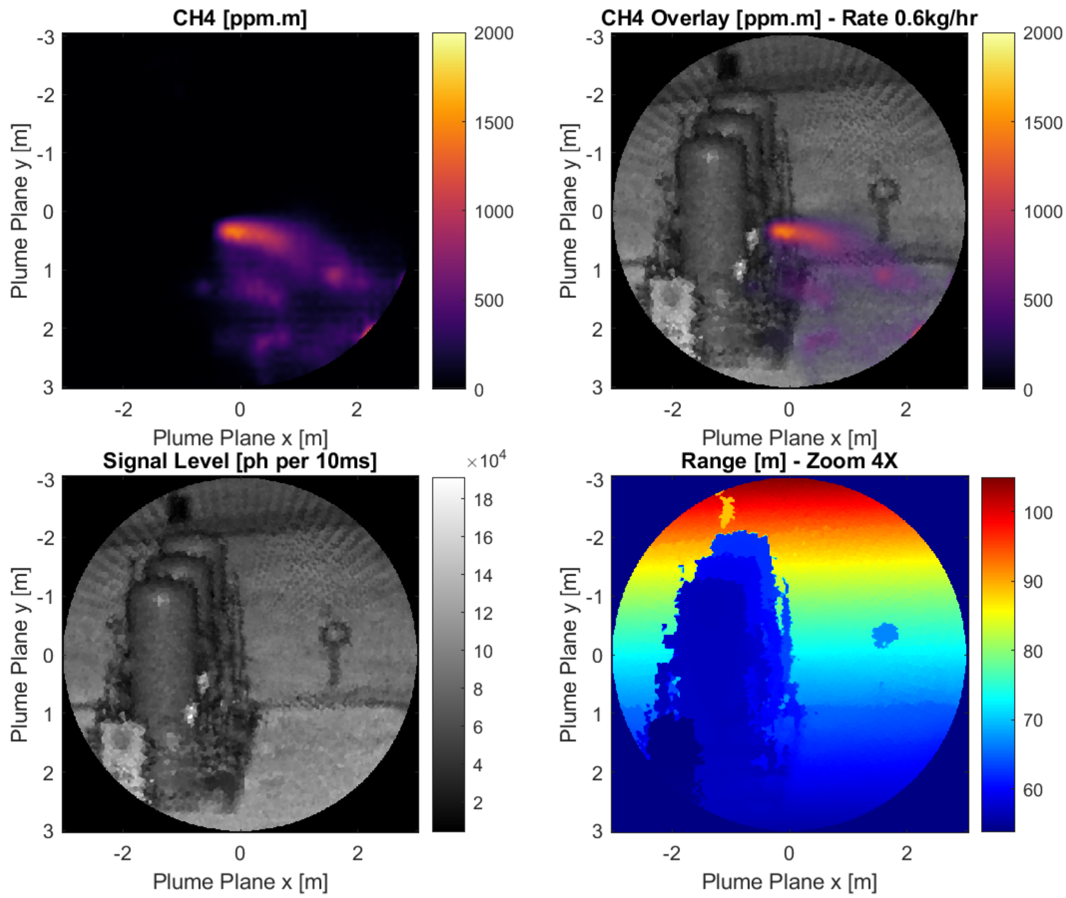


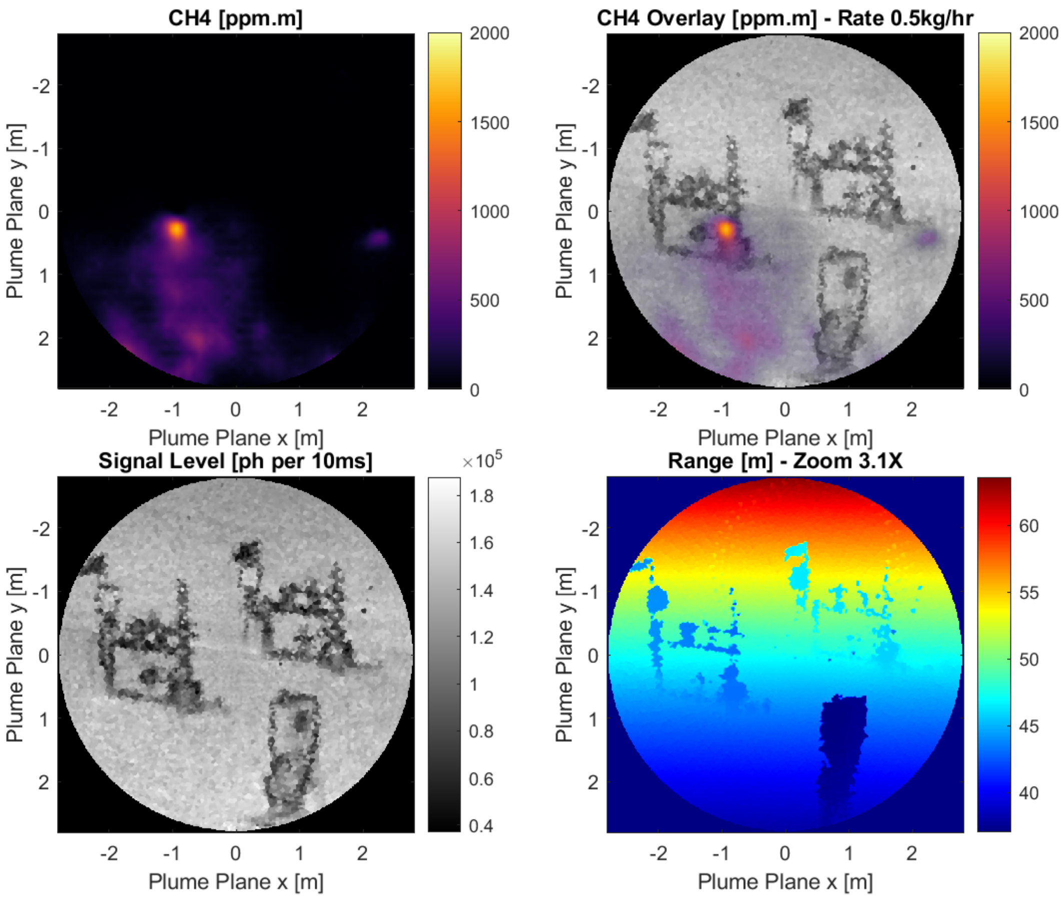
CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.4kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane y [m]
Plume Plane x [m]


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 3.1X
Plume Plane x [m]
Plume Plane y [m]
×10^5

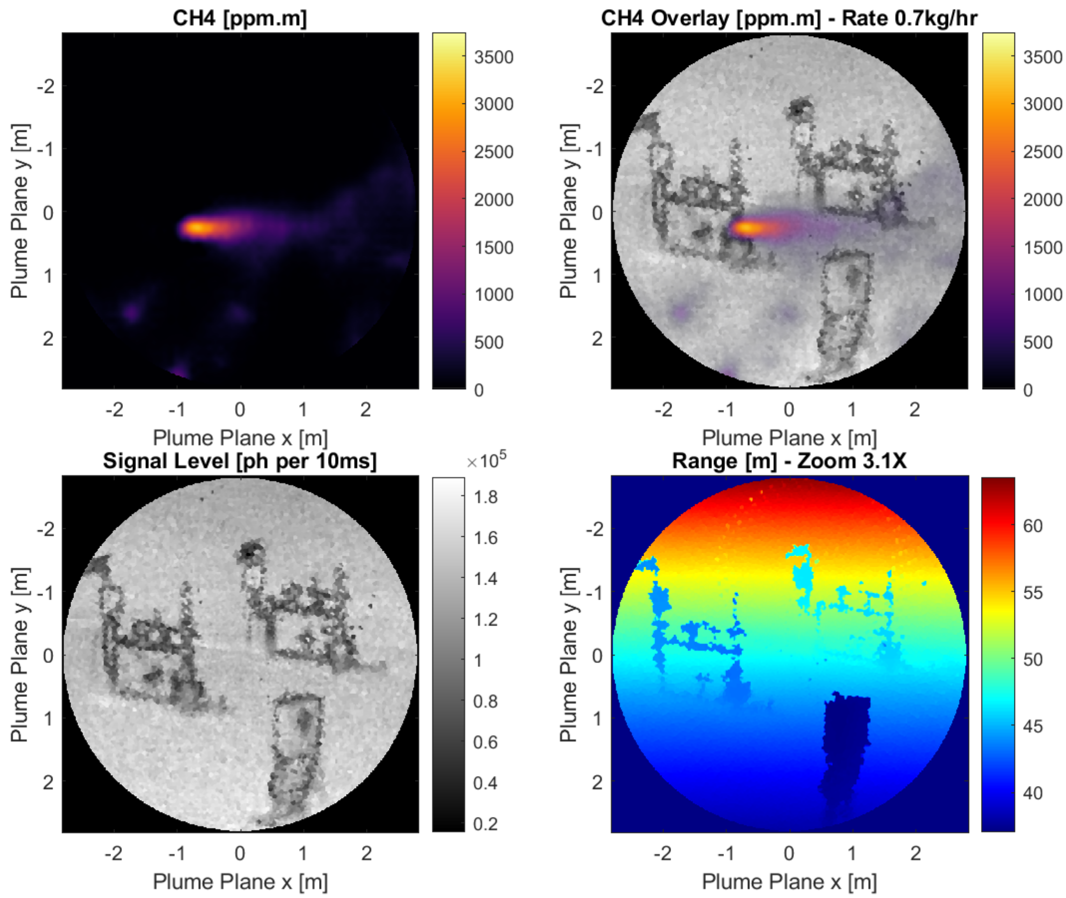

CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.8kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 5X
Plume Plane x [m]
Plume Plane y [m]
×10^5


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.4kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane x [m]
Plume Plane y [m]
×10^4

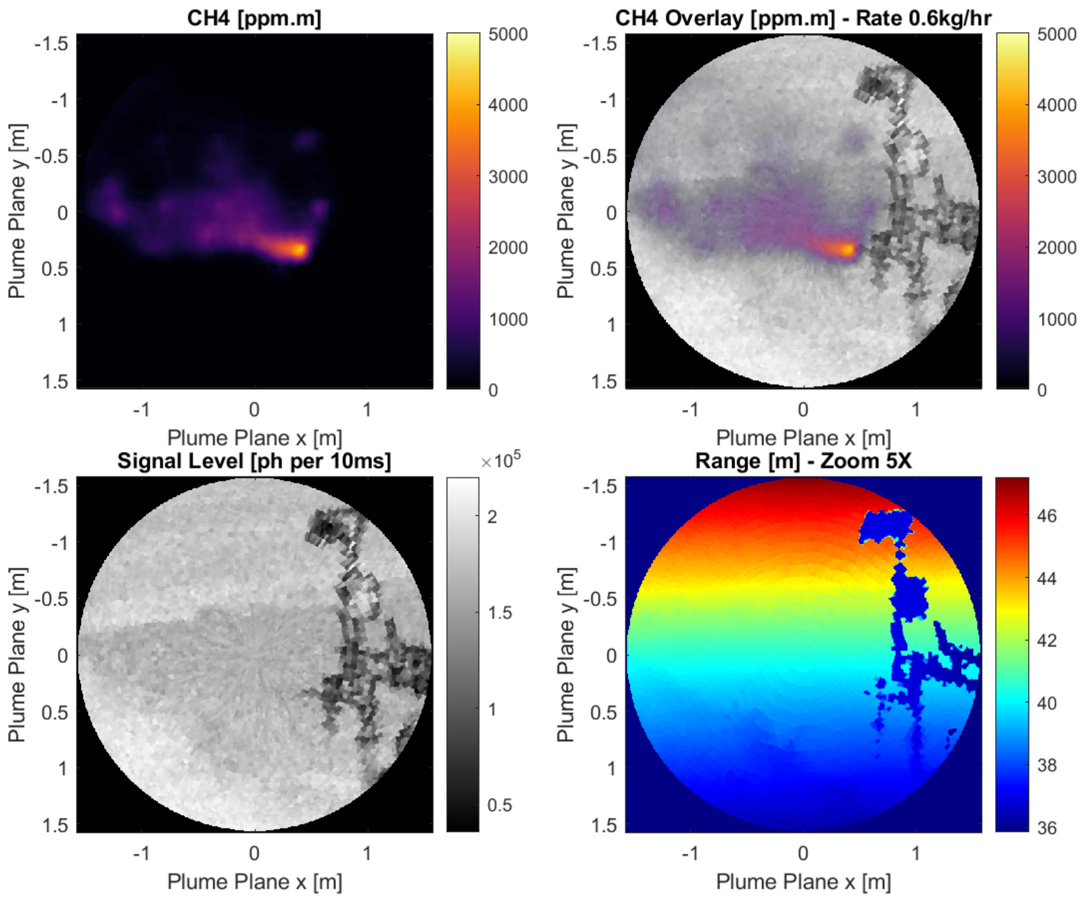

CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.6kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane y [m]
Plume Plane x [m]
×10^4

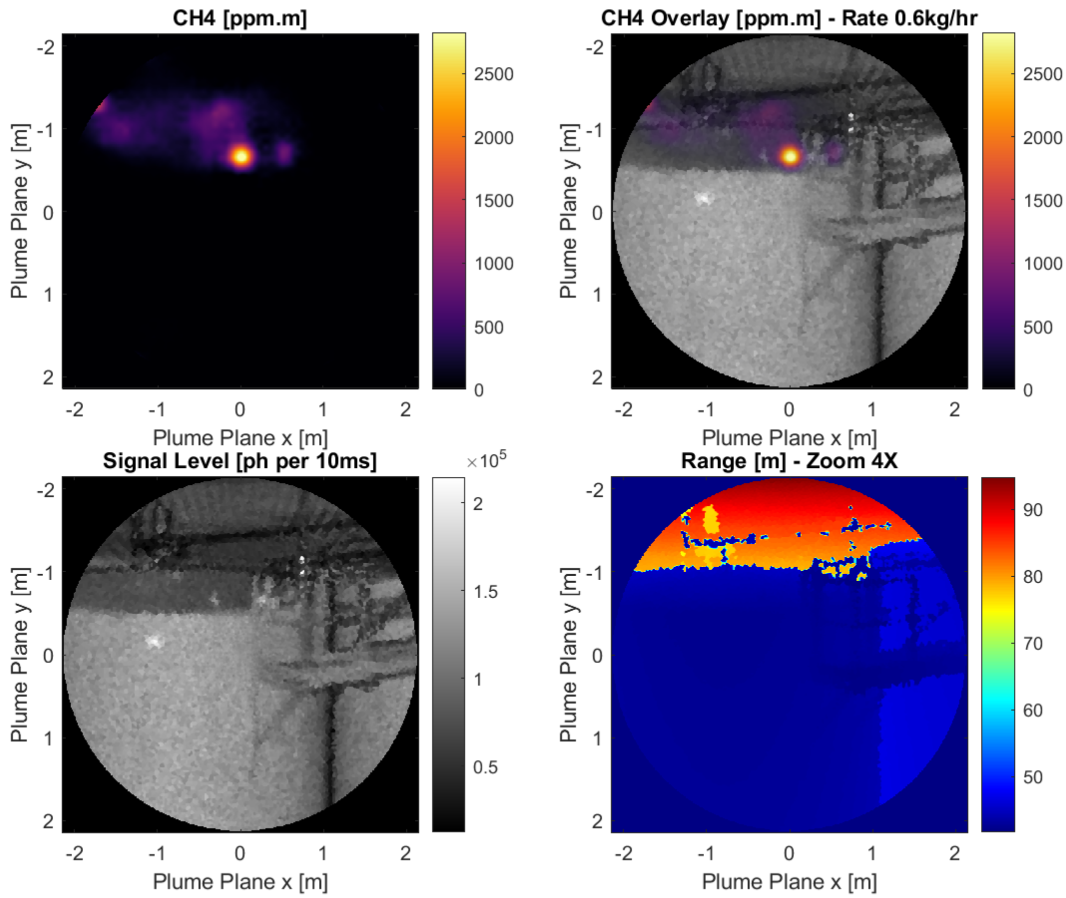


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 3.1X
Plume Plane x [m]
Plume Plane y [m]
×10^5

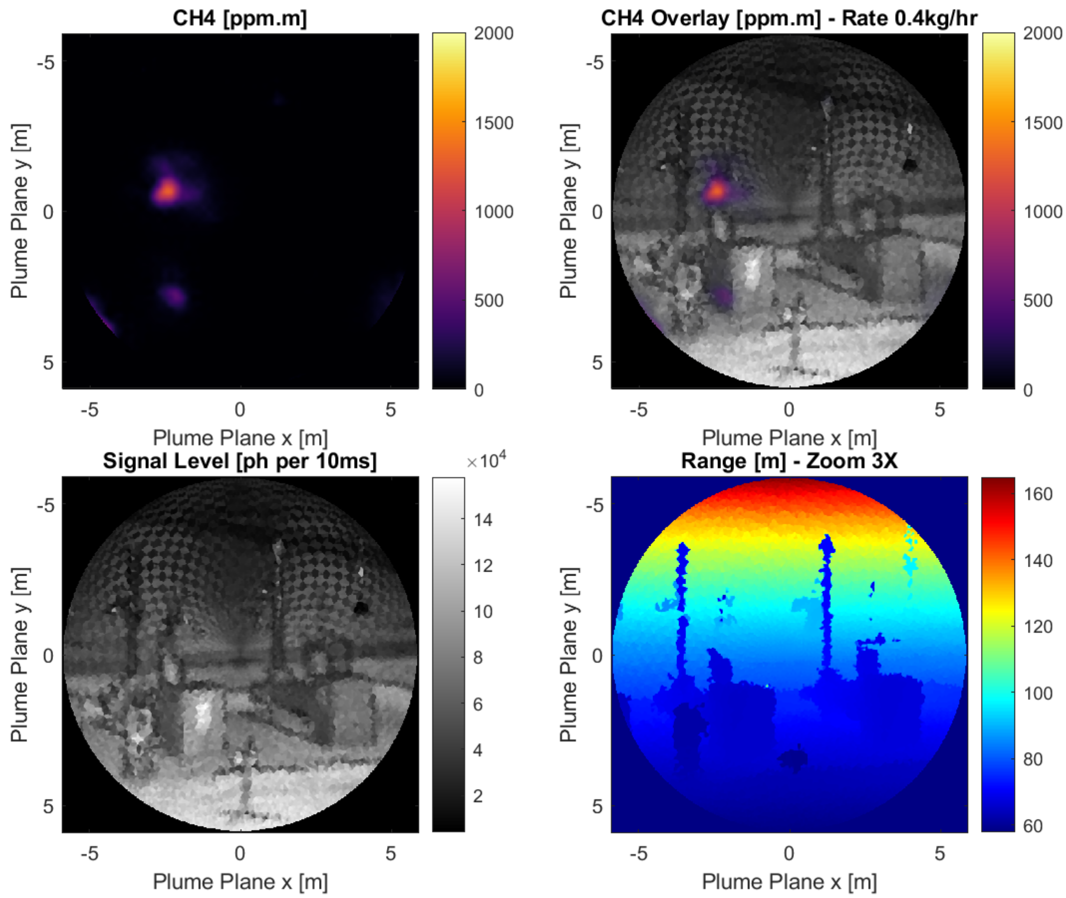


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.7kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 3.1X
Plume Plane x [m]
Plume Plane y [m]

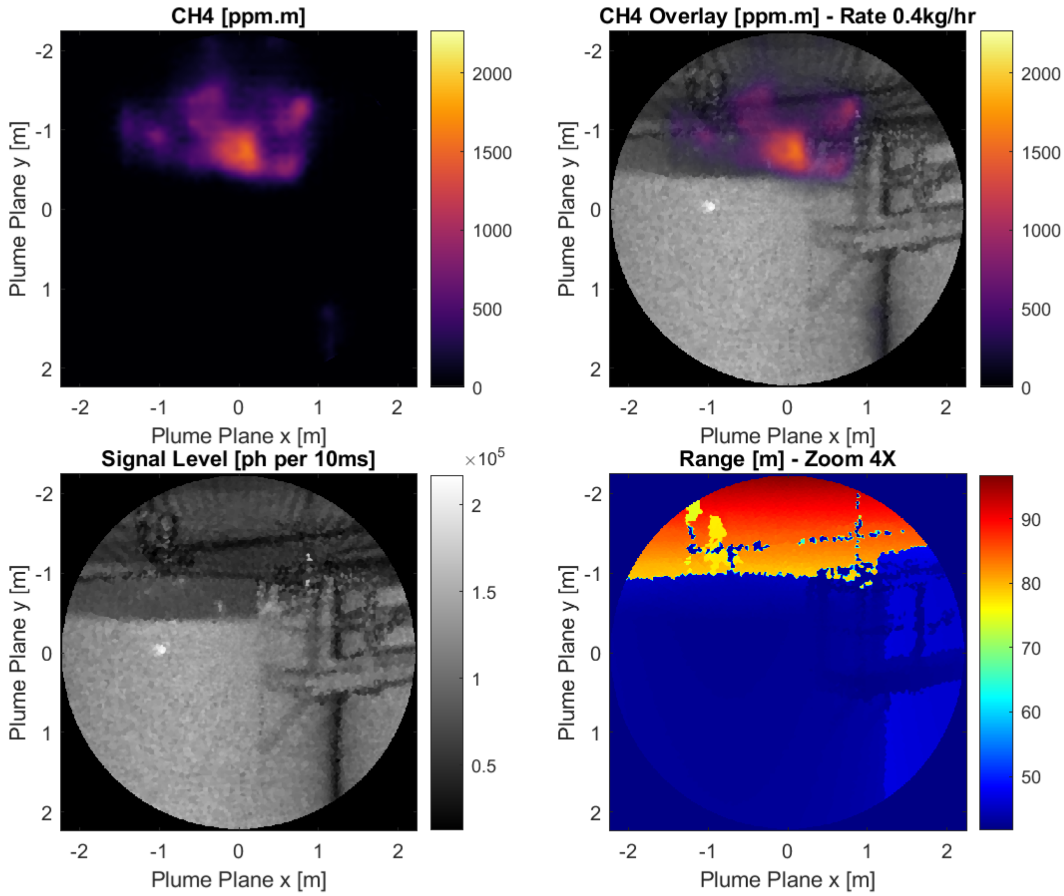

CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.6kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 5X
Plume Plane y [m]
Plume Plane x [m]
$\times 10^5$

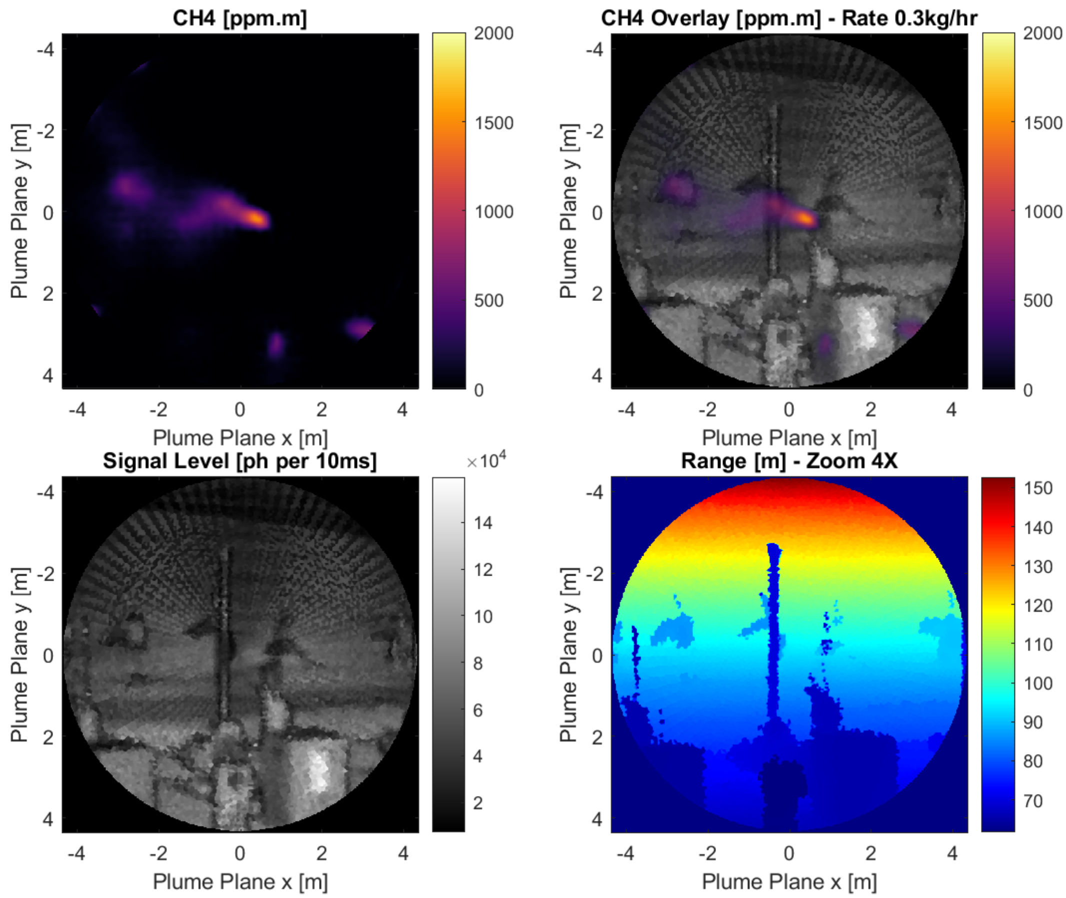


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.6kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane x [m]
Plume Plane y [m]
×10^5

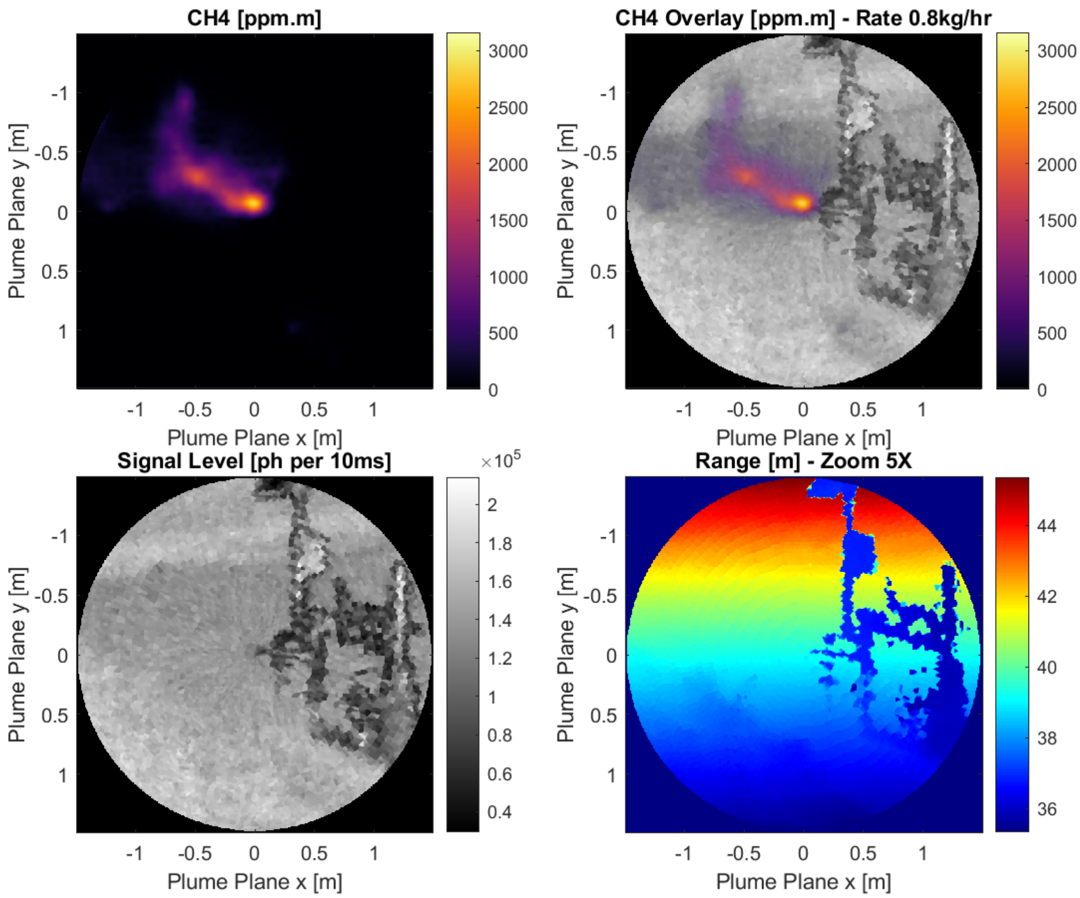


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.4kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 3X
Plume Plane x [m]
Plume Plane y [m]

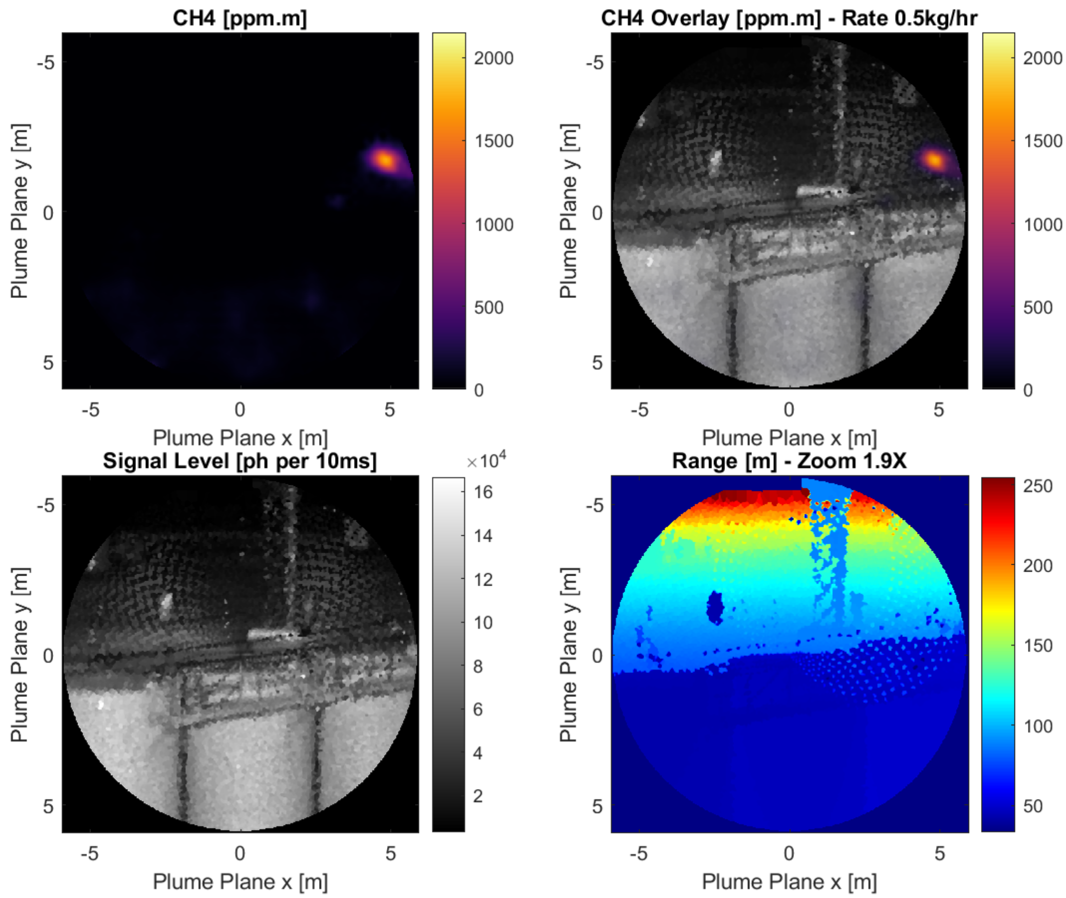

CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.4kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane y [m]
Plume Plane x [m]
×10^5



CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.3kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 4X
Plume Plane x [m]
Plume Plane y [m]



CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.8kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 5X
Plume Plane x [m]
Plume Plane y [m]
-1
-0.5
0
0.5
1
3000
2500
2000
1500
1000
500
0
×10^5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
44
42
40
38
36


CH4 [ppm.m]
CH4 Overlay [ppm.m] - Rate 0.5kg/hr
Signal Level [ph per 10ms]
Range [m] - Zoom 1.9X
Plume Plane x [m]
Plume Plane y [m]
$\times 10^4$