REQUEST ID: ALTTECH-54

LONGPATH TECHNOLOGIES

Application

Alternative Test Method: Detect and Localize Methane Emissions using LongPath Emissions Sensing Network™ Technology

Detection Threshold: ≤10 kg/hr with 90% Probability of Detection

Submitted To: Environmental Protection Agency Emission Measurement Center

https://www.epa.gov/emc/oil-and-gas-alternative-test-methods

Submitted By: LongPath Technologies

https://www.longpathtech.com

Summary of Regulatory Requirements, from 40 CFR

Requirement Source	Requirement Summary	Demonstration of Compliance
§60.5398b(d)(2)(i)	The submitting entity must be located in or have representation in the United States.	LongPath is a Delaware C Corporation located in the United States. LongPath is headquartered in Boulder, Colorado with satellite offices in Texas and Colorado.
§60.5398b(d)(2)(ii)	If the submitting entity is an owner or operator of an affected facility regulated under this subpart or subpart OOOOa of this part or is the owner or operator of a designated facility under subpart OOOOc of this part, then the provisions of paragraphs §60.5398b (d)(2)(ii)(A) and (B) do not apply.	LongPath is not an owner or operator of affected or designated facilities.
§60.5398b(d)(2)(ii)(A)	The submitting entity must directly represent the provider of the measurement system using advanced methane detection technology.	LongPath is the provider of the advanced methane detection technology described in this ATM.
§60.5398b(d)(2)(ii)(B)	The measurement system must have been applied to methane measurements or monitoring in the oil and gas sector either domestically or internationally.	The LongPath Emissions Sensing Network™ Technology has been applied to methane measurements and monitoring in the oil and gas sector domestically and internationally.
§60.5398b(d)(2)(iii)	The underlying technology or technologies must be readily available for use, meaning it has been sold, leased, or licensed, or offered for sale, lease, or license to the general public, or has been developed by an owner and operator for internal use and/or use by external partners.	LongPath sells LongPath data products to oil and gas operators.
§60.5398b(d)(2)(iv)	The submitting entity must submit to the Administrator the information required in §60.5398b(d)(3).	The required information is provided in the ATM, as indexed and documented below.
§60.5398b(d)(3)	The ATM request must contain the information listed in §60.5398b(d)(3)(i) through (vii), as detailed below.	The required information is provided below and in the ATM where needed, as indexed and documented below.

§60.5398b(d)(3)(i)	The submitting entity's name, mailing address, phone number and email address.	Company and contact information are provided in the Oil and Natural Gas Advanced Methane Technology Alternative Test Method Portal: https://methane.app.cloud.gov/
§60.5398b(d)(3)(ii)	The desired applicability of the technology.	The LongPath Emissions Sensing Network™ System is broadly applicable across the sector, as detailed in Section 1.2 Applicability.
§60.5398b(d)(3)(iii)	Description of the measurement technology, including the information specified in §60.5398b(d)(3)(iii)(A) through (D).	The Description of Technology can be found in the Description of Technology documentation included in the application package.
§60.5398b(d)(3)(iv)	Description of how the measurement technology is converted to a methane mass emission rate or equivalent, including the information in §60.5398b(d)(3)(iv)(A) through (F).	The conversion of concentration data to mass emission rate data is captured in 13.4 Fugitive Emissions Screening Assessment.
§60.5398b(d)(3)(iv)(A)	Detailed workflow showing steps from measurement technology signal output to final emission rate, including how data is handled and stored, raw data processing procedures and manual/automated definitions, quality assurance checks to data.	A detailed workflow, including how raw data is handled and stored, can be found in Section 12.0 Procedure; description of raw data processing procedures can be found in Section 12.3 Data Collection & Processing Procedure; and quality assurance checks to data can be found in Section 10.0 Quality Control, Maintenance & Corrective Actions. The same information with greater detail of the measurement technology can be found in the Description of Technology document included in the application package.
§60.5398b(d)(3)(iv)(B)	Description of how meteorological data is used, collected or sourced.	Meteorological data is used and collected as described in Section 12.3 Data Collection & Processing Procedure.
§60.5398b(d)(3)(iv)(C)	Description of models used, including input variable determination or derivation.	A description of models used is found in Section 13.0 Data Analysis & Calculations.
§60.5398b(d)(3)(iv)(D)	Calculations used, including defined variables and description of their purpose.	Descriptions of calculations used are found in Section 13.0 Data Analysis & Calculations and Section 12.0 Procedure.

§60.5398b(d)(3)(iv)(E)	Description of a-priori methods and datasets used, including source and version numbers.	Descriptions of a priori methods and datasets used are found in Section 13.0 Data Analysis & Calculations and Section 12.0 Procedure.
§60.5398b(d)(3)(iv)(F)	Description of algorithms/machine learning procedures used in data processing, if applicable.	Descriptions of algorithms used are found in Section 13.0 Data Analysis & Calculations.
§60.5398b(d)(3)(v)	Description of data handling and storage, including the information in §60.5398b(d)(3)(v)(A) through (C).	Description of data handling and storage is found in Section 12.4 Data Delivery & Reporting Procedure.
§60.5398b(d)(3)(v)(A)	Description of data and metadata collection, maintenance and storage.	Description of data and metadata collection, maintenance and storage are found in Section 9.0 Sample Collection, Preservation & Storage.
§60.5398b(d)(3)(v)(B)	Description of raw data stream processing and manipulation, including how resultant data processing is documented and how version control is maintained.	Description of data processing and manipulation and version control are found in Section 12.3 Data Collection & Processing Procedure.
§60.5398b(d)(3)(v)(C)	Description of data streams provided to end-users and data delivery.	Description of data streams provided to end-users and data delivery is found in Section 12.4 Data Delivery & Reporting Procedure.
§60.5398b(d)(3)(vi)	Supporting information verifying that the technology meets the detection threshold defined in §60.5398b(c), including as applied in the field. Information provided must include items listed in §60.5398b(d)(3)(vi)(A) through (D).	Verification that the technology and method meet the detection threshold requirements, including in the field are found in Section 4.1 Verification of Detection Limits and Section 4.3 Verification of Performance in Field Conditions.
§60.5398b(d)(3)(vi)(A)	Independently evaluated published reports describing the submitted measurement technology.	A selection of independently evaluated reports describing the submitted measurement technology and method are found in Section 16.0 References.
§60.5398b(d)(3)(vi)(B)	Standard Operating Procedures including safety considerations, measurement limitations, personnel qualifications/responsibilities, equipment and supplies, data	Standard Operating Procedures (SOP) including safety considerations are listed in the SOP document submitted with this application and in Section 6.0 Safety; measurement limitations are described in Section 5.0 Interferences & Limitations of Applicability of the

	and record management, and quality assurance/quality control.	ATM, as well as in the Description of Technology and SOP documents submitted with this application; personnel qualifications/responsibilities are found in Section 6.0 Safety; data and record management are described in Section 12.4 Data Delivery & Reporting Procedure; and quality assurance/quality control are described in Section 10.0 Quality Control, Maintenance & Corrective Actions.
§60.5398b(d)(3)(vi)(C)	Description of the Alternative Testing Procedure, including objectives to ensure the detection thresholds required in §60.5398b(d)(3)(vi) are maintained.	All aspects of the procedure are described in Section 12.0 Procedure and specifics of detection threshold requirements being maintained are found in Section 10.1 Siting & Detection Threshold Metrics.
§60.5398b(d)(3)(vi)(D)	Documents provided to end-users of the data generated, including client products, manuals, and FAQ documents.	Documents provided to end-users can be found in the documents submitted with the application.
§60.5398b(d)(3)(vii)(A)-(C)	Supporting information verifying the spatial resolution of the technology.	Supporting documentation is provided that verifies the spatial resolution of the technology.

Table of Contents

1.0 Scope and Application

1.1 Scope

This method is an alternative test method (ATM) for determining compliance with the procedures in 40 CFR §60.5398b for fugitive emissions components affected facilities and compliance with continuous inspection and monitoring requirements for covers and closed vent systems, specifically demonstrating compliance through periodic screening per 40 CFR §60.5398b(b). This ATM is applicable for measuring gaseous concentrations of methane (CH_4) for the detection and localization of emissions of methane from oil and gas infrastructure.

1.2 Applicability

The LongPath Emissions Sensing Network™ technology is broadly applicable for use throughout the oil and natural gas sector. The LongPath measurement system has been applied across the full variety of geographies, climate types, and site types that accompany the designation of Broadly Applicable Across Sector.

The application of this technology is per the Environmental Protection Agency's 40 CFR part 60 Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and natural Gas Sector Climate Review. The test method is applicable to methane emissions from oil and gas infrastructure. This method can be used in lieu of the required fugitive monitoring and inspection and monitoring of covers and closed vent systems under 40 CFR part 60 subparts OOOOa, OOOOb and OOOOc to identify emissions, as defined in §60.5398b(c).

Applicable sites include single wellhead only well sites, small well sites, multi-wellhead only well sites, well sites with major production and processing equipment, centralized production facilities, and compressor stations.

1.3 Analytes

Compound Name	CAS No.
Methane	74-82-8

1.4 Method Range and Sensitivity

Demonstration of the method range and sensitivity can be found in Section 4.0 Verification of Test Method Quantification & Detection Limits, Section 13.2 Ongoing Detection Threshold Model, and Section 13.3 System Siting Detection Threshold Model.

2.0 Summary of Method

2.1 Emissions Quantification Principles

This method involves the measurement of atmospheric methane concentrations and collection of atmospheric meteorological parameters and combines these measurements with atmospheric inversion modeling to determine the presence and location(s) of methane emissions (see Section 3.2 Methodological Definitions) from the fugitive emissions components at a discrete oil and gas infrastructure site (see Section 3.2 Methodological Definitions). See Section 13.0 Data Analysis & Calculations for further detail.

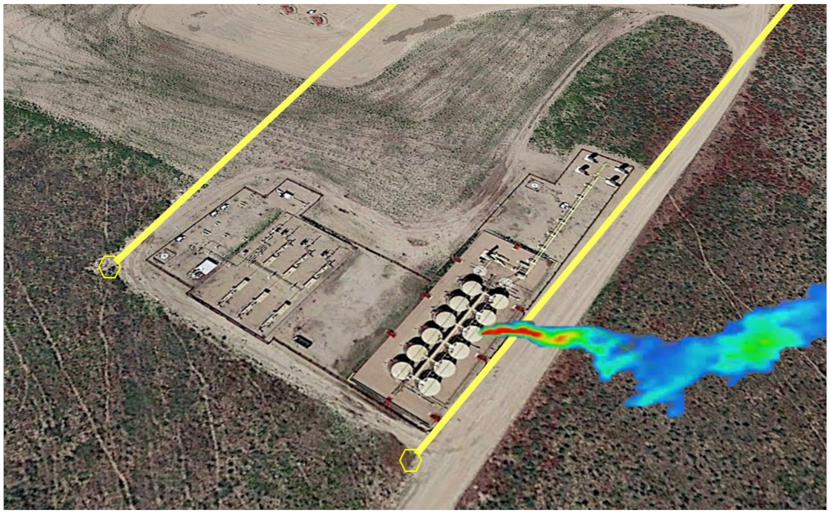


Figure 2.1 Example map (plan) view of two laser beam paths (yellow lines; see Section 3.1 Physical Location & Hardware Definitions) forming a geofence around one monitored centralized production facility. A graphic of a plume is shown to indicate wind direction and simulated plume dispersion and downwind advection. Plumes are not imaged in this approach. Rather, data that contributes to a valid quantified Emission Rate Reading are collected when a clean background is measured by an upwind beam path (left beam path) and an enhanced downwind beam path captures information about emissions from the monitored site (right beam path). Fugitive Emission Screening assessments are performed using this information (see Section 3.2 Methodological Definitions).

2.2 Data Collection

Atmospheric concentrations are measured using long-range open-path laser spectroscopy. A transceiver (see Section 3.1 Physical Location & Hardware Definitions) emits laser light, which travels across an open atmospheric path to a retroreflective mirror (see Section 3.1 Physical Location & Hardware Definitions), which returns the light to the transceiver, where the absorption of the laser light at wavelengths resonant with quantum transitions of methane is recorded and converted into an integrated methane concentration along the beam path (see Section 3.2 Methodological Definitions). See Section 12.0 Procedure for further detail.

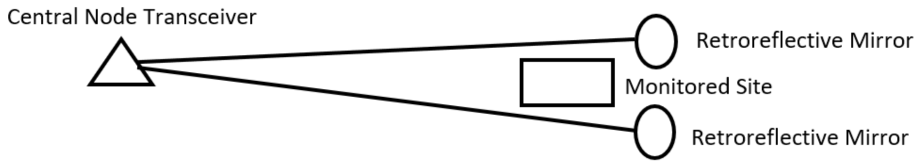


Figure 2.2 Example map (plan) view of central node transceiver (see Section 3.1 Physical Location & Hardware Definition), and two retroreflective mirrors (see Section 3.1 Physical Location & Hardware Definition) arrayed around one monitored site (see Section 3.1 Physical Location & Hardware Definition). A beam path is a line or narrow column between the central node transceiver and the retroreflective mirror (see Section 3.1 Physical Location & Hardware Definition).

2.3 Data Delivery and Storage

Fugitive Emissions Screening results are shared with the operator (see Section 3.2 Methodological Definitions). See Section 12.0 Procedure for further detail.

3.0 Definitions

3.1 Physical Location and Hardware Definitions

Anemometer means the commercial wind sensor used to measure the wind speed along different axes. Also provides measurement of wind direction and air temperature.

Beam Path means the pathway through the atmosphere of laser light between a *Transceiver* and a *Retroreflective Mirror*. Distances cited are one-way distances (not round-trip, although the laser light does perform a round trip, from *Transceiver* to *Retroreflective Mirror* and back).

Central Node means the location of the *Transceiver*, *Laser Spectrometer*, *Gimbal*, controls, computing devices and *Anemometer*. One *Central Node* can monitor one to many sites.

Gimbal means a device that rotates about two orthogonal axes enabling the controlled pointing of the laser transceiver toward retroreflective mirror targets.

Laser Spectrometer means a device that generates and detects laser light, including the laser control computer that converts raw laser energy to methane concentration data and QA/QC metrics.

Retroreflective Mirror means a corner-cube mirror that reflects light received back toward its source.

Transceiver means the optical componentry that sends eye-safe and invisible light through the atmosphere to a retroreflective mirror and then receives the reflected laser light for processing.

3.2 Methodological Definitions

Concentration Measurement means one sample, or measurement of the atmospheric concentration of methane gas along a *Beam Path* from *Transceiver* to *Retroreflective Mirror*.

Fugitive Emission Screening means an assessment of the presence of emissions from fugitive emissions components. See Section 13. Data Analysis & Calculations for more detail.

High-Rate Concentration Measurement means the concentration data collected at a >1Hz rate which is then averaged to produce one *Concentration Measurement*.

Meteorological Data includes wind and turbulence information for use in parameterization of atmospheric transport models.

Preliminary Real-Time Estimate means the total event of sample collection that occurs to gather concentration data at one site. One *Preliminary Real-Time Estimate* entails multiple atmospheric methane concentration measurements being taken along the two or more beam paths that are assigned to the measured site. Multiple such estimates are used in a Fugitive Emission Screening.

QAQC means quality assurance and quality control and is used to refer to metrics that assess whether the system is providing information within compliance. If QAQC metrics are not met, then corrective measures are triggered.

Site means an affected facility. Sites include single wellhead only well sites, small well sites, multi-wellhead only well sites, well sites with major production and processing equipment, centralized production facilities, and compressor stations.

4.0 Verification of Test Method Quantification & Detection Limits

The LongPath Emissions Sensing Network™ technology and methodology have been tested for quantification and detection limit at the Methane Emissions Technology Evaluation Center (METEC) test site and in the oil and gas field. LongPath underwent 3rd party blind testing at the METEC test facility managed by Colorado State University in Fort Collins, Colorado. LongPath went through the ARPA-E MONITOR program's Round 1 (R1) testing and Round 2 (R2) testing. The intent and test design for the ARPA-E MONITOR teams was to test whether monitoring solutions could achieve a target emission rate detection threshold of 0.115 kg/hr (6 scfh).

The following description of the METEC test site and blind test format is from the LongPath team's 2019 peer-reviewed publication describing the testing and results (Alden et al., 2019): "The METEC facility has three pads built to simulate those found in natural gas production. Pads 1 and 2 are 10 m × 10 m with a wellhead, separator, and storage tank located on each. Pad 3 is 60 m × 10 m, and has a 10 m × 10 m wellhead battery on the north end with three wellheads, a 10 m × 10 m separator battery in the middle with two separators, and a 10 × 10 m tank battery on the south end with two storage tanks. All equipment is plumbed to allow testers to remotely activate natural gas leaks, at known flow rates, at a variety of points on the equipment. Prior to testing, we were informed by METEC that methane leak rates could vary from 0 to any value. The composition of gas emitted was that of natural gas, and we reported rates of methane emissions. We examined the system's capabilities for pad-level or battery-level as well as equipment-level emissions monitoring."

During R1 tests, emission rates were continuous (sustained, or persistent emissions) and from a single leak point. During R2 tests, the emissions included multiple leak point locations (occurring simultaneously), and variable, intermittent emission rates (non-steady rates). The upper limit and range of emission rates chosen by METEC reflected two target goals. First, the METEC testers intended to assign leak rates to components that reflect measured "routine" oil and gas emission rates. Second, the testers chose a maximum limit for emissions that was equal to 5x the target emission rate of the ARPA-E program (6 scfh or 0.115 kg/hr). Compared to more recent estimates of emission rates from fugitive sources, (Omara et al., 2018; Rutherford et al., 2021) it is evident that these targets are extremely low and are below the detection limits of most all commercial monitoring systems (e.g., aircraft sensors, satellite sensors, drone-mounted sensors, and many ground-based sensors). Despite these aggressively low test rates, the LongPath system was able to accurately detect and quantify emissions all emissions in R1 and most emissions in R2.

4.1 Verification of Detection Limits & Time of Detection

In the first round of tests (R1), the LongPath measurement system had a 100% success rate in detecting the presence and absence of leaks. There were no “false positives” (the incorrect reporting of emissions when there were none) or “false negatives” (the incorrect reporting of no emissions when there were emissions) (Alden et al., 2019).

The below figure demonstrates the detection success across emission rates ranging from 0 kg/hr to 0.6 kg/hr (0 scfh to 30 scfh). The testing of a 0 scfh emission rate confirmed the ability of the system to accurately determine a true negative (no emissions) result.

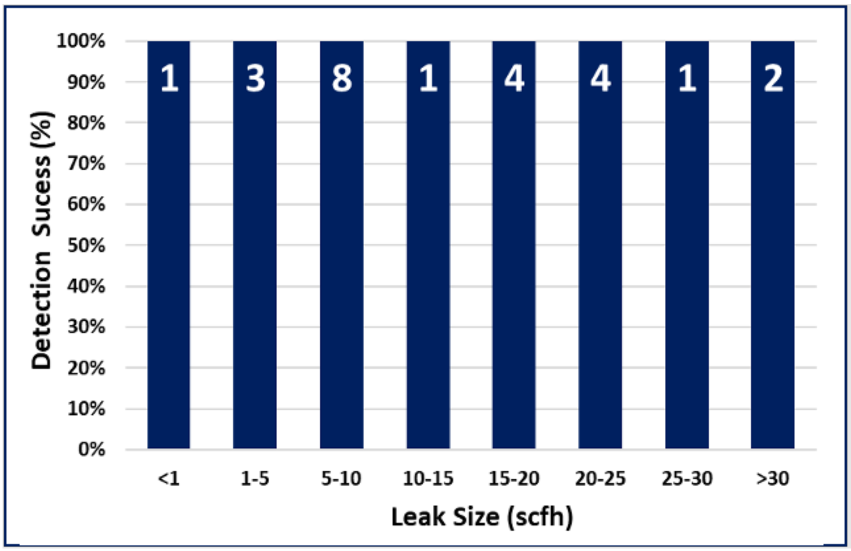


Figure 4.1 Detection results for blind METEC testing of emission rates above, at, and below the target minimum detection threshold of 0.4 kg/hr (20.8 scfh).

In the second round of tests (R2), which tested more complex combinations of multiple and intermittent emissions sources, the system had a 100% success rate in detecting the presence and absence of leaks greater than 0.096 kg/hr (5 scfh).

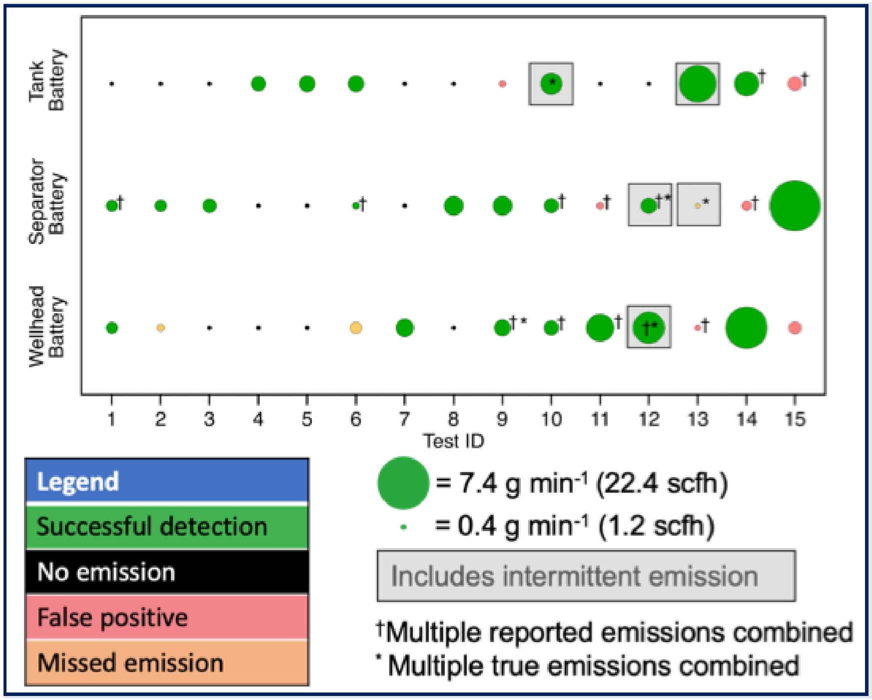


Figure 4.2 Detection results for blind METEC testing of intermittent and complex (multi-source) emission rates above, at, and below the target minimum detection threshold of 0.4 kg/hr (20.8 scfh).

This 3rd party blind test data from METEC was used to create a probability of detection curve using a confusion matrix of blind test results for true positive and false negative outcomes for each controlled release rate. A 90% probability of 0.06 kg/hr is found, including all levels of emissions complexity: steady, intermittent, single point, and multiple point emission sources. The confusion matrix data (colorful dots), and model with uncertainties (blue line and shaded area) are shown below.

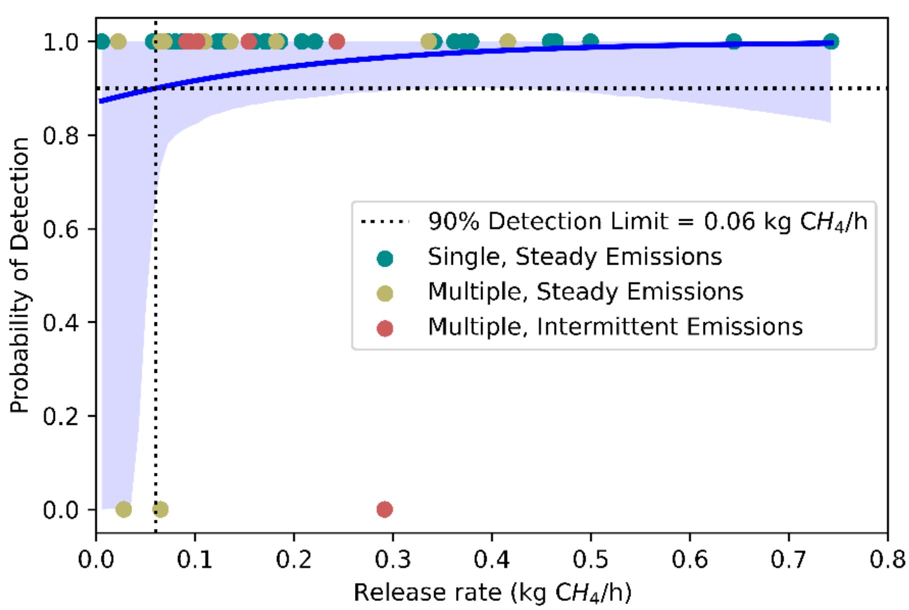


Figure 4.3 Probability of detection curve showing a 90% probability of detection limit of 0.06 kg/hr, more than 6x below the target minimum detection threshold of 0.4 kg/hr.

In this method, the minimum detection threshold is, in practice, the minimum detection limit above the site-specific baseline emission rate. The METEC results above show that many of the tests used to determine the LongPath Emissions Sensing Network™ involved multiple emissions sources. The probability of detection is re-assessed for only those emission sources that are tested while another emission source is also active (site-specific baseline). The results demonstrate that a minimum detection limit below 0.4 kg/hr is also achieved (0.09 kg/hr) when tested as an above-baseline detection.

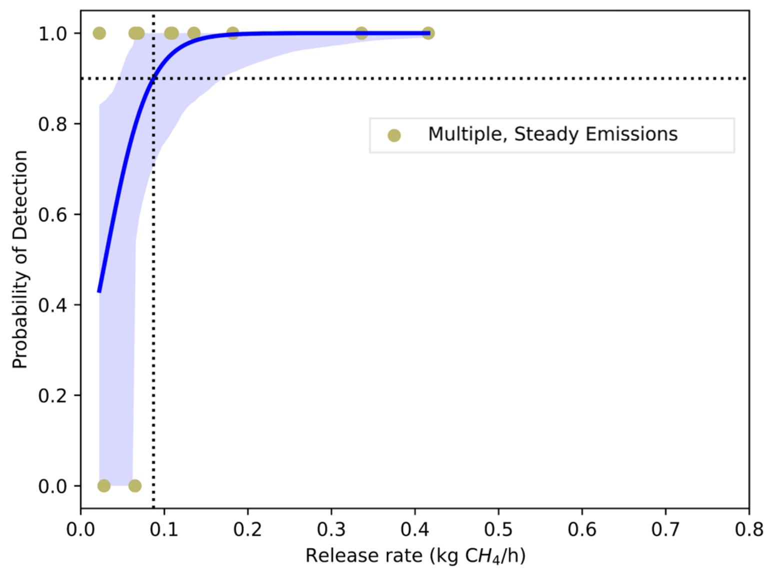


Figure 4.4 Probability of detection curve showing a 90% probability of detection limit of 0.09 kg/hr, when multiple emissions sources are detected and quantified simultaneously from the same site.

The detection thresholds demonstrated at METEC were for test durations of 3.5 hours on average. A Fugitive Emissions Screening therefore requires at least 3.5 hours duration of emissions information is collected at each site prior to use in assessing detections.

4.2 Verification of Quantification

In the first round of tests (R1), the quantification of emission rate was accurate, on average, to ±27%. In the second round of tests (R2), the quantification of emission rate was accurate, on average, to ±40%, including for multiple, and very low-rate intermittent emissions occurring at once. Single, steady sources were quantified, on average, to ±21%.

Blinded field trials on active oil and gas pads provide further demonstration of quantification capabilities. Across 29 tests, spanning metered rates from 0.6 to 243 kg/hr and across 4 different basins in the US, the LongPath Emissions Sensing Network™ system demonstrated an average quantification accuracy of ±10% with an average relative error ratio of 1.1. Across all (METEC and active oil and gas) blind tests, the average quantification was ±20% with an average relative error ratio of 1.1. The slightly higher overall quantification error from including METEC tests is because small errors in testing of very low rates are amplified.

Finally, in addition to the above blinded tests in the controlled METEC setting and field demonstrations at production facilities and compressor stations, LongPath has performed long-term measurements at an underground natural gas storage facility (midstream). This year-long campaign included cross-validation of results with repeat aircraft mass balance measurements, as well as cross-validation of emissions variation with changes in operations according to logs maintained by the site manager. In this study, it was demonstrated that, while the independent LongPath (ground-based) and aircraft-based methods found the same statistical distribution of emissions (or size and range of routine emission rates), only the LongPath continuous monitoring consistently identified high-emitting outlier events. These top 10% of the largest emissions events accounted for a vast proportion (40%) of total emissions from the site and were not captured by aircraft flyovers because of the short duration and infrequent cadence (monthly) of the aircraft flights, compared with the continuous (3-hourly) measurements. That work was published in a peer-reviewed journal (Alden et al., 2020).

The finding of a 0.06 kg/hr minimum detection threshold (at the 90% probability of detection level) will be used as the empirical anchor point as we build out a framework for accurate fugitive emissions screening.

4.3 Verification of Performance in Field Conditions

We leverage atmospheric modeling tools to link performance in controlled release and uncontrolled settings. Atmospheric transport influence functions (ratios of atmospheric enhancements in methane to emission rates) allow for the replication of 1) the conditions and configuration for the METEC field validation tests; and 2) the range of conditions/configurations that are represented in field deployments of the system. Note that 'configuration' refers to the modeled layout and relative locations of the laser transceiver, the retroreflectors (which when combined with the laser transceiver location establish the beam path), and the assumed emission source. Beam path sensitivity due to placement and instrument precision metrics - based on both laboratory (controlled) and field data are used to generate a bottom-up sensitivity value for the system.

An empirical-to-field sensitivity factor is calculated to enable a bridge from empirical METEC data which was collected as part of a controlled, blind testing experiment to any field or test site data where it is not possible to conduct such studies. This scaling factor is required to translate the sensitivity of a single concentration measurement to an ensemble of concentration values, which is used in both the METEC studies and field inversions for source rates. We calculate the scaling between the model-estimated detection threshold and the empirically determined value based on the METEC tests of 0.06 kg/hr.

The calculated empirical-to-field sensitivity value is 0.25 kg/hr. This yields an empirical-to-field sensitivity factor of 0.24 that can be applied to any bottom-up sensitivity matrix to bridge field sensitivity to the empirically measured 0.06 kg/hr detection threshold. That is, 0.25 kg/hr x 0.24 = 0.06 kg/hr:

Bottom-Up Sensitivity x 0.24 = *Empirically-Derived Detection Threshold*

To demonstrate that detection thresholds are met in an ongoing manner during operation, bottom-up sensitivity is calculated for each measurement and the empirical-to-field sensitivity factor is applied an empirically-based minimum detection threshold. Additional detail regarding the calculation of the empirically-derived minimum detection threshold on an ongoing basis is found in Section 13.2 Ongoing Detection Threshold Model.

4.4 Verification of the Representativeness of Sampled Meteorology

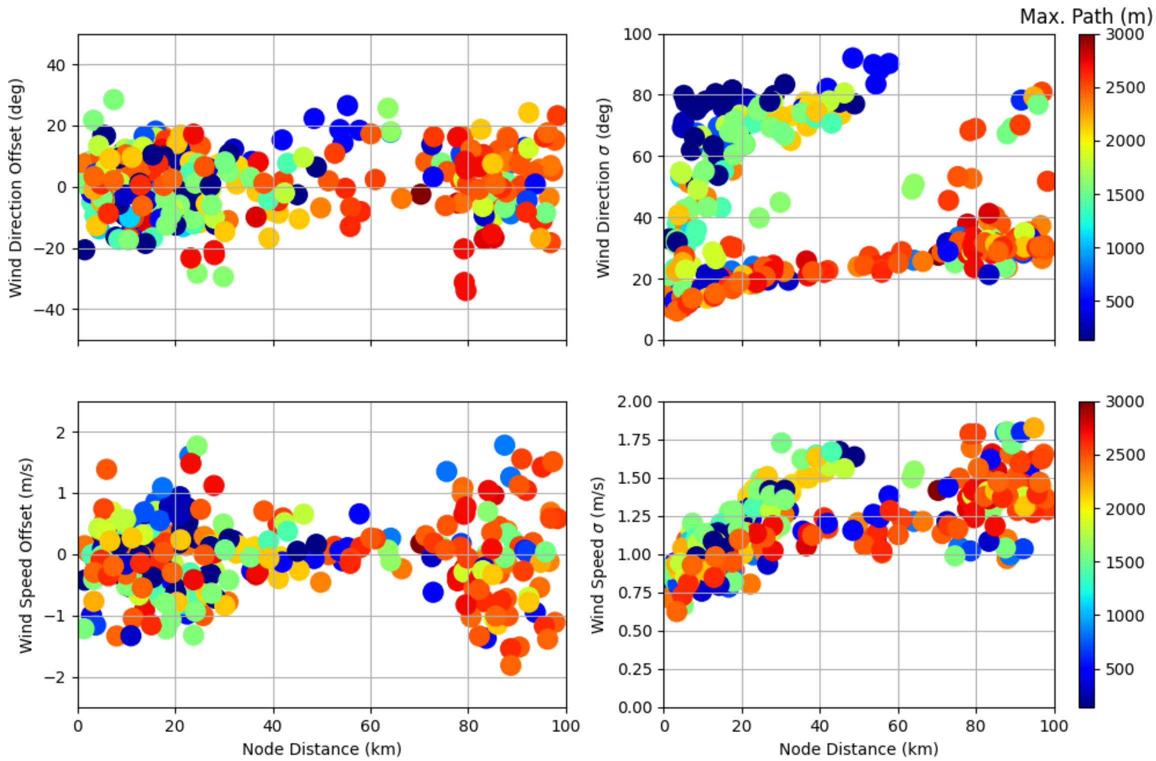
The LongPath Emissions Sensing Network™ System uses one anemometer at the central node location for parameterizing the meteorology at all sites monitored by that node. Therefore, for sites with only short Beam Path lengths, the anemometer is representative of a smaller diameter area. For sites with longer Beam Path lengths, the anemometer is representative of a larger geography. The geographic extent to which the anemometer measurements are expected to be representative is therefore directly correlated to the Beam Path lengths or distances of each site to the central node.

The concept of networked monitoring therefore both enables and requires the use of a single anemometer for the monitoring of multiple sites, since the factors driving limitations in the proximity of sites to the central node (see Section 5.2.8 Proximity of Sites to Transceiver) directly scale with differences in local-scale micrometeorology.

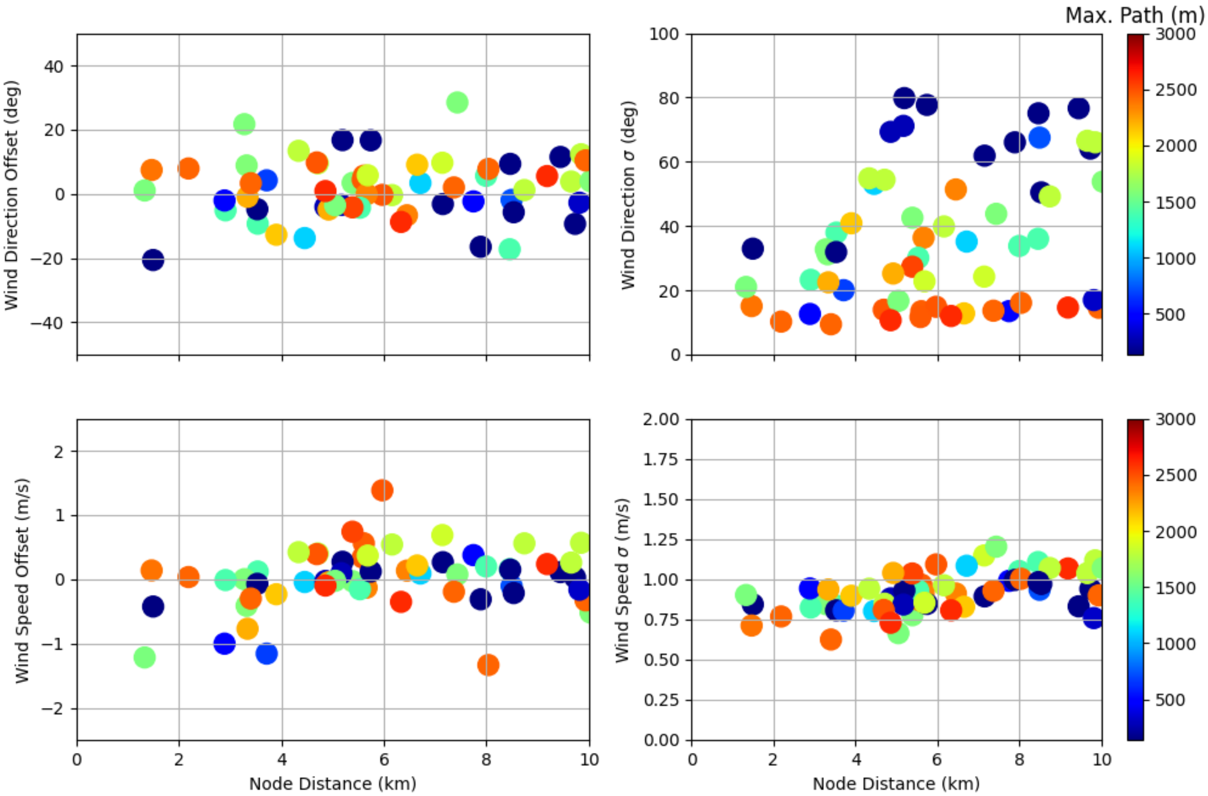
We explore the relationships between adjacent anemometers on LongPath nodes. Specifically, we demonstrate that, in areas for which longer pathlengths are made possible by topography, the agreement between neighboring anemometers' data prove that a networked approach is appropriate.

In the below image, we show the mean offset in wind direction and wind speed (left panels, top and bottom) and the standard deviation of the offsets in wind direction and wind speed (right panels, top and bottom) for neighboring anemometers whose distance apart is denoted by "Node Distance (km)" on the x-axis.

In these plots, longer pathlengths are shown with warm colors (yellow, orange and red), whereas shorter pathlengths are shown with cool colors (green and blue). A clear relationship is seen, in which Node Distance (or distance between adjacent anemometers) has a direct impact on the 1-sigma variation in wind direction and wind speed between the two datasets. This demonstrates that, as two anemometers are geographically closer, they capture more similar wind dynamics.



Zooming in on just anemometer or node distances of 10 km and below, the mean offsets between wind direction and wind speed data are very low and the standard deviations between systems are also low.



The statistics for anemometers that are located within 5 km of one another show a mean and standard deviation offset of 0.12 +/- 0.85 m/s in wind speed and 3.4 +/- 29 degrees in wind direction. The finding that these offsets center strongly around zero and have high R values (0.88 and 0.95, respectively) indicates that any two anemometers within 5 km of one another are appropriate for parameterization of meteorological information. The table below shows statistics for all anemometers within 5 km of one another.

Wind Speed Average Offset (m/s)	0.12	Wind Direction Average Offset (deg)	-3.43
Wind Speed Std of Offset (m/s)	0.85	Wind Direction Std Offset (deg)	28.65
Wind Speed R Value	0.88	Wind Direction R Value	0.95

It is further clear that nodes that have longer maximum path lengths (orange and red points in the above graphs) center more tightly around zero in terms of mean offset, particularly for wind direction, and also have much lower standard deviations of wind direction offset and wind speed offset. The below table shows statistics for all anemometers within 5 km of one another and with maximum Beam Paths >2 km. Filtering for areas where long Beam Paths are possible demonstrates improvement in the standard deviation of both the wind speed and wind direction, and improvements in the R values for each, as well as negligible changes in the already very low offsets for average wind speed and wind direction.

Wind Speed Offset (m/s)	0.08	Wind Direction Offset (deg)	-4.54
Wind Speed Std of Offset (m/s)	0.82	Wind Direction Std of Offset (deg)	18.38
Wind Speed R Value	0.91	Wind Direction R Value	0.98

When we look at the same subset of >2 km Beam Path nodes for anemometer data agreement across distances up to 10 km, we find an even better agreement, suggesting that the correlations hold but that more data offers a larger sample size.

Wind Speed Offset (m/s)	-0.02	Wind Direction Offset (deg)	-1.91
Wind Speed Std (m/s)	0.89	Wind Direction Std (deg)	18.45
Wind Speed R Value	0.91	Wind Direction R Value	0.98

This analysis confirms that the topographic features that enable longer Beam Paths to be installed are associated with geographies across which meteorological information is highly correlated. We therefore establish that meteorological information for up to 1 km away may be used for parameterization of atmospheric transport models for individual oil and gas sites.

5.0 Interferences and Limitations to Applicability

5.1 Interferences

There are no spectroscopic interferences, for example from atmospheric water vapor or other trace gas molecules. There are also no known interferences from heat signals that affect the signal processing to calculate a concentration from the laser signal.

Optical attenuation from rain, snowfall, fog, and high winds can occlude the laser signal resulting in lower signal from the retroreflective mirrors. Similarly, dirt, mud, or other substances covering the retroreflective mirrors can block or reduce the signal. Normally the power of the laser light more than overcomes attenuation and there is sufficient received laser power (meeting the SNR threshold specified in Table 10.1) to continue making measurements through these conditions. During intense rain, heavy snowfall, or heavy fog the laser light will become fully occluded and Concentration Data are not taken. QAQC metrics and corrective actions are included for both potential sources of interference in Section 10.0 Quality Control, Maintenance & Corrective Actions.

5.2 Limitations to Applicability

The method is not impacted by sky cover, cloud cover, snow cover, equipment accessibility, or time of day or night. The following potential limitations are known.

5.2.1 Wind Direction and Speed

For data collected in low wind speed conditions (<1 m/s), quantification of emission rates is not performed, following literature recommendations (De Visscher, 2013). At high wind speeds (e.g., >> 15 m/s), the shape of an emitted plume can become narrow enough that it may not intersect a beam path. Under these conditions, the monitored area coverage may become zero percent, leading to no data being processed for emission rates. The parameterization of site coverage depends on site and equipment geometry and meteorology, so a specific maximum wind speed is not definable. Hurricane conditions can result in the temporary lowering of the tower per operator safety specifications.

Modeling during site setup informs the specific wind direction limitations for quantification of each monitored area (see Section 12.1 Planning Procedure).

5.2.2 Environmental Disturbances

Environmental disturbances may include very high or very low temperatures. The current range of tested environmental operating conditions of the method includes temperatures of -34 °C to 44 °C, however these limitations are not inherent.

Disturbances from dust, rain, snow and other weather events require no intervention. Occlusive precipitation or fog that temporarily reduces visibility to less than the distance from transceiver retroreflective mirror will automatically pause measurements until retroreflected signal returns to the transceiver. Dirt and dust on the retroreflective mirrors and optical window may partially occlude the laser light, leading to lower signal strength. The power of the laser light more than overcomes occlusion of reflected light by particles, but in rare cases, dirt or dust accumulate on the retroreflective mirrors or transceiver windows in heavy enough deposits to prevent the system from performing measurements (see Section 10.0 Quality Control, Maintenance & Corrective Actions).

5.2.3 Number of Sites and Coverage

The number of sites that can be monitored by one transceiver is a function of topography, geographic layout, and vegetation canopy heights, and is established during the planning phase using models with available site visit data, historical data and satellite data (see Section 12.1 Planning Procedure).

5.2.4 Density and Proximity of Sites

A minimum angular distance between adjacent retroreflective mirrors is maintained to match gimbal pointing accuracy and eliminate the possibility of unintentional signal acquisition from neighboring retroreflective mirrors.

5.2.5 Topography

Because topography dictates retroreflector and central node placement to achieve line-of-sight, assessment of line-of-sight is undertaken before and during installation of systems (see Section 12.1 Planning Procedure and Section 12.2 Installation Procedure).

5.2.6 System Uptime

System uptime is tracked continuously in real-time by the system and monitored by remote technicians who receive hourly alerts if any system or subsystem fail operational checks and are automatically alerted if the weekly average system uptime falls below 90% (see Section 10.0 Quality Control, Maintenance & Corrective Actions). The metrics that are combined for system uptime include system power and the gimbal actively working to achieve signal from retroreflective mirrors.

5.2.7 Solar Power Uptime

System uptime relies on solar power unless the system is powered by line or generator power. System uptime for solar powered systems is maintained by using sufficient backup battery power (7 days reserve) to maintain the uptime requirements of §60.5398b(c) (see Section 5.2.6 System Uptime above).

5.2.8 Proximity of Sites to Transceiver

The maximum allowable, minimum allowable and optimal distance of the monitored site to the transceiver is determined as described in Section 13.2 Ongoing Detection Threshold Model.

6.0 Safety

Outside of installation procedures, this method is fully automated and does not require personnel on site except in cases in which manual maintenance is required.

Installation procedures incur the safety risks inherent to working in proximity to oil and gas equipment. Specifically, this method targets methane gas, which is a fire hazard. Standard precautions should be taken.

During installation of equipment, the following safety considerations are made. System design is approved by a professional engineer to mitigate the risk of collapse or falling of the equipment holding the transceiver, anemometer and retroreflective mirrors. Equipment is installed and located so that an ample fall radius prevents possible collisions with on-site equipment. Equipment is located out of the way of oil and gas equipment, including the transceiver, which is not intrinsically safe and requires power, for example from a solar panel and/or battery. The retroreflective mirrors are intrinsically safe and do not require power.

After installation, maintenance predominantly occurs remotely and is only on an as-needed basis, which minimizes on-site exposure to potential risks.

All personnel who install or maintain equipment have appropriate Safety Certifications, use personal protective equipment, and observe standard oilfield safety protocols for gases and liquids.

The laser light leaving the transceiver is Class 1, meaning it is safe for the human eye. The laser light is invisible and does not pose a risk of distracting personnel from other duties. The laser light has been approved by the FAA for use near an airport.

7.0 Equipment and Supplies

The following equipment and supplies are required for this method. All equipment is owned, installed, and maintained by LongPath.

Tower to mount laser spectrometer and transceiver, rated to local standards for wind and hazardous conditions. The height of the laser transceiver determined as described in Section 12.1 Planning Procedure and Section 13.3 System Siting Detection Threshold Model.

Laser transceiver that transmits and receives laser light from central node to reflective mirrors.

Laser spectrometer that generates laser light and signals required to perform laser absorption spectroscopy and measure methane concentrations in ambient temperature ranges. The spectrometer can measure methane concentrations in the range from ambient atmospheric concentrations (1.9 ppm methane) and differences (i.e., Δ ppb) above background to +10s of ppm. The sensitivity of the laser system should be at least 10 ppm*m.

Gimbal steers the laser light towards the reflectors. The required pointing accuracy is determined by the transceiver design and is independent of distance to the reflector.

Retroreflective mirrors (small, specialized mirrors) reflect laser light back towards the transceiver. Two or more reflectors are used per monitored site. The location and height of a retroreflective mirror is determined as described in Section 12.1 Planning Procedure and Section 13.3 System Siting Detection Threshold Model.

Anemometer to accurately measure local meteorological data such as: wind speed (with precision of ±5%); wind direction (with precision of ±5%); air temperature (with a precision of ±0.5 °C over 5 seconds and sensor drift <0.1 °C over 30 seconds); and air pressure (with a precision of ±0.1 mbar over 5 seconds and sensor drift <0.05 mbar over 30 seconds).

Power source such as solar panel and batteries or stable power connection from the grid to provide constant source of DC voltage. Off-grid solar power system has sufficient reserves to last 7 days without sunlight.

Software and firmware to autonomously operate system and process data.

Computing and storage equipment to autonomously operate full system, aggregate data from various sensors, process data in real time, and store data to later sync with off-site database.

Network connectivity equipment to transmit and receive data over existing network infrastructure.

GPS device to measure initial geospatial locations of tower and reflector. This is used by deployment personnel during installation and is not part of normal system operation.

8.0 Reagents and Standards

8.1 Methane Gas Reference Cell

The precision of each laser system is validated during the manufacturing process at three conditions using commercially available static optical reference cells containing a sealed mixture of 50 Torr pure methane and 690 Torr pure nitrogen (resulting total pressure of 740 Torr). The length of the reference cells was selected to represent measurements at column densities of 20, 3, and 0.6 ppm-km, which span the measurement ranges necessary to achieve the continuous monitoring requirements.

9.0 Sample Collection, Preservation and Storage

The collection of samples pertains to the collection and processing of data. Physical samples are not procured or necessary for this method.

The initial planning, placement and installation of the equipment needed to collect samples (data) is described in Section 12.1 Planning Procedure and Section 12.2 Installation Procedure.

The operation of equipment, collection of samples (data) and sample (data) processing is described in Section 12.3 Data Collection & Processing Procedure.

Data handling and storage of samples (data) is described in Section 12.4 Data Delivery & Reporting Procedure.

All elements related to the ascertaining that performance metrics and quality control of sample collection, preservation and storage are followed are found in Section 10.0 Quality Control, Maintenance & Corrective Actions.

10.0 Quality Control, Maintenance & Corrective Actions

A series of metrics are used to ensure data collection and processing meet required criteria, as described in this section.

Once installed, the equipment does not require regularly scheduled maintenance. Systems are monitored continuously with automated remote data checks. Cross-check methods include automated QAQC flags for key data and parameters as well as automated detection of sensor downtime for immediate re-initiation of measurements as needed. Table 10.1 summarizes several key metrics and corresponding acceptance criteria that assure the system is operating in a nominal state.

Each subsystem performs automated diagnostics to detect critical failures at the frequency specified in Table 10.1 below. At the end of each hour the Data Analytics team is notified of systems where QAQC have failed for periods exceeding one hour and automated self-correction was not successful. The Data Analytics team uses diagnostic logs and system information to triage the failure mechanism. Frequently subsystem failures can be addressed remotely, but in the case of hardware failure a field maintenance visit is requested by the Data Analytics team. Response time to critical failures is dependent on the install location and access to the premises. On average critical failures are addressed with on-site maintenance within 48 hours of the request from the Data Analytics team.

Instrument	Measurement	Acceptance Criteria	Frequency Checked	Corrective Action
Anemometer	Wind speed accuracy	± 5% at 10 m/s	Manufacturer	Do not deploy
Anemometer	Wind direction accuracy	± 3° at 10 m/s	Manufacturer	Do not deploy
Anemometer	Temperature accuracy	± 1°C	Manufacturer	Do not deploy
Anemometer	Wind speed bounds	ϵ [0 m/s, 50 m/s]	Every measurement (5 seconds)	Filter measurement; service if persistent
Anemometer	Wind direction bounds	ϵ [0°, 360°]	Every measurement (5 seconds)	Filter measurement; service if persistent

Anemometer	Temperature bounds	ϵ [-60°C, 60°C]	Every measurement (5 seconds)	Filter measurement; service if persistent
Anemometer	Firmware error code	No error code	Every measurement (5 seconds)	Filter measurement; service if persistent
Spectrometer	Concentration precision	± 2ppb over 10 seconds	In-house manufacturing	Do not deploy
Spectrometer	Concentration accuracy	< 5% from reference methane cells	In-house manufacturing	Do not deploy
Spectrometer	Model fit error	< 5% at column densities > 2 (ppm-km)	In-house manufacturing	Do not deploy
Spectrometer	Concentration bounds	ϵ [1.8 ppm, 50 ppm at 2.5 km]	Every measurement (>10X an hour)	Filter measurement
Spectrometer	Optical interference	< 5% model fit error	Every measurement (>10X an hour)	Filter measurement
Spectrometer	Laser intensity SNR	SNR > 25 based on baseline noise intensity	Every measurement (>10X an hour)	Filter measurement, service telescope or retroreflective mirror if persistent
Emission rate algorithm	Wind Direction	< 20^o off parallel from site heading from tower	Every concentration measurement (>10X an hour)	Emission measurement is not reported
Emission rate algorithm	Wind Speed	> 1 m/s	Preliminary Real-Time Estimate (>1X an hour)	Emission measurement is not reported
Emission rate algorithm	Measurement density	>1 concentration measurement per bounding retroreflective mirror at site	Every Preliminary Real-Time Estimate (>1X an hour)	Emission measurement is not reported

Power system	Fault indicators	No critical faults present	Every minute	Field service required
Power system	Charging history	Has charged >20% daylight hours	Daily	Data Analytics team triage
Gimbal	Movement	Movement detected	Every measurement (>10X an hour)	Software or field service required
Networking system	Data upload to cloud	Data upload success	Hourly	Wait for cell service to return; field service required if persistent

Table 10.1: QAQC metrics, acceptance criteria, and corrective actions.

10.1 Siting & Detection Threshold Metrics

Three criteria must be met for siting and detection threshold metrics to be deemed acceptable.

First, a system installation is planned so that it will meet the minimum detection threshold requirements, which are assessed on an ongoing basis during monitoring. The minimum detection threshold requirements can be found in Section 13.3 System Siting Detection Threshold Model and Section 13.2 Ongoing Detection Threshold Model.

Second, beam angle and line-of-sight must be ascertained per Section 5.2.4 Density & Proximity of Sites and Section 5.2.5 Topography.

Third, all target equipment must be monitorable by the installed equipment, as assessed during the planning, installation, and monitoring phases.

10.2 Meteorological Data Quality Checks

Meteorological data is collected using an anemometer. Each anemometer comes validated and calibrated by the manufacturer, meeting the specifications detailed in Table 10.1.

During normal operation, every measurement of wind data is checked for error flags provided by the manufacturer's firmware and to be within reasonable bounds (see Table 10.1). If either of these checks fail, the data is discarded. If the failed state persists (> 10% readings are failing), a field service event is triggered. Per §60.5398b(c)(ii), at least twice every six-hour block, the anemometer is confirmed to be receiving valid data.

10.3 Laser Spectrometer Quality Checks

10.3.1 In-house Manufacturing Validation

Each laser spectrometer is manufactured in-house by LongPath Technologies. Prior to deployment, the precision and accuracy of each spectrometer is validated using three methane gas reference cells described in Section 8.1 Methane Gas Reference Cell. Spectrometers which fall outside of the bounds for precision, accuracy and spectroscopic fit error specifications set in Table 10.1 are not deployed.

10.3.2 Operational Checks of Concentration Data

The raw laser data are obtained on the data acquisition unit and sent to the central processing computer at a high temporal rate. The high-frequency data are down-sampled to periods of time where the detected laser signal intensity exceeds a minimum signal-to-noise ratio (SNR) threshold as shown in the table above. Note this SNR is the laser intensity SNR and does not correspond to the absorbance noise of the measurement. Concentrations are calculated for each of the remaining laser signal data points using a HITRAN based spectroscopic model. Concentrations from the fitting process are then filtered to remove data points where the fit error between the model and the measured data exceeds 5% fit error based on integrated absorbance area to remove spurious results caused by potential optical interference or signal noise. The high-temporal resolution concentration data are averaged for the window of time in which the gimbal continuously points toward a single retroreflector. Measurement time is on the order 10s of seconds, depending on the atmospheric conditions (e.g., turbulence) and the resulting return power.

The resulting averaged concentration value is assigned a series of quality assurance indicators, which include checks for averaged fit error, measurement signal-to-noise ratio, and out of bound concentration values that have failed QAQC checks as described in Table 10.1 above. If any of these values fall outside of the specified measurement range, the measurement is flagged as 'low-quality' and is not used in the emission rate calculation. Further information on the concentration processing and QA/QC procedure can be found in the Standard Operating Procedures (SOPs), Quality Control (QC) and Internal Guidance document. If system-wide concentration measurements fail QAQC checks for greater than 1 hour or retroreflector specific concentration measurements fail for greater than 1 day the Data Analytics team is notified to diagnose and triage.

Optical attenuation from rain, snowfall, fog, and high winds can occlude the laser signal resulting in lower signal from the retroreflective mirrors. Normally the power of the laser light more than overcomes attenuation, but during intense rain, heavy snowfall, or heavy fog the laser light will become attenuated to the extent that the laser SNR drops below the acceptable level specified in Table 10.1. During these events the system will not produce concentration measurements until the weather conditions improve. The Data Analytics team is notified of time windows where concentrations are not reported, but no corrective action is required. Similarly, dirt, mud, or other substances covering the retroreflective mirrors can block or reduce the laser signal or retroreflective mirrors can be damaged in the field. If concentration measurements of specific retroreflective mirrors continuously fail SNR QAQC checks specified above for greater than one day, the Data Analytics team is notified to diagnose the failure mechanism. If the failure mechanism is identified to be poor signal SNR, a field service event is triggered to either clean or replace the retroreflective mirror.

10.4 Emission Rate Data Quality Checks

Preliminary Real-Time Estimates must pass three QAQC checks, summarized in Table 10.1 and detailed below.

10.4.1 Wind Speed Input to Emission Rate Data

If wind speed falls below 1 m/s, those measurements are not used for quantification, because of standard recommendations regarding dispersion models' ability to accurately parameterize atmospheric pollutant transport at wind speeds less than 1 m/s (De Visscher, 2013). If wind speeds go above a certain level (this is dynamically determined and is specific to each individual instance), then site coverage may be dynamically reduced to 0% because no plume would intersect a beam, and those measurements are not used.

10.4.2 Wind Direction Input to Emission Rate Data

Upon installation each site is designated a fixed range of wind directions under which Preliminary Real-Time Estimates may be considered successful (Section 12.2 Installation Procedure). Concentration measurements that occur during wind directions that are not in the allowable range for the site are not used in the emission rate calculation. If all measurements during the Preliminary Real-Time Estimate are outside of the acceptable bounds, then a Preliminary Real-Time Estimate is not reported.

10.4.3 Concentration Measurement Input to Preliminary Real-Time Estimate Data

A minimum of one concentration reading per bounding retroreflective mirror at a given site is required to produce a Preliminary Real-Time Estimate, meaning a minimum of one upwind and one downwind sample must be collected. If this threshold is not met, a Preliminary Real-Time Estimate is not logged.

10.5 System Status Checks

In addition to the quality checks detailed in the above sections, the overall system performance and current state is constantly and automatically monitored by custom software. Table 10.1 lists acceptance criteria and corrective actions for the power, gimbal, and networking subsystems.

10.6 Operational Downtime

Defined as any state which prevents the gimbal from actively working to achieve signal from retroreflective mirrors. This metric encompasses the below System Power (Section 10.6.1 System Power Checks) and System Function (Section 10.6.2 System Function Checks) requirements of necessary subsystems. Systems are continuously checked for operational downtime, with hourly alerts pushed to the data analytics team if a system is in an operational downtime state. A Fugitive Emissions Assessment period must have <90% downtime to be considered valid.

10.6.1 System Power Checks

Automated system checks are performed every hour. If the system has lost communication for a period exceeding one hour, a notification is sent to the data analyst team. When communication to the device has been restored, the cause of the communication lapse is determined by the Data Analytics team.

In the case of power failure, the timestamp when the device last logged a measurement is used as the beginning of the 'power failure' window. In the event of internet failure, the system will continue to independently operate until the internet has been restored, at which point the system will sync any measurements recorded during the internet service lapse.

10.6.2 System Function Checks

Function for the LongPath system is defined as operation of the system where the subsystems components are drawing power and able to communicate to the central processing computer. Log files and diagnostics information from all the subsystems are synced on the order of minutes to the cloud server, allowing for functionality of the subsystems to be confirmed remotely. In this way, the function of the system is checked on a continuous basis.

Functionality of specific subsystems are described below:

Gimbal: The gimbal must be provided with power and able to receive commands and send feedback to the central processing computer. In a functional state the gimbal should be able to undergo a self-calibration process as requested by the system or upon power up.

Anemometer: Outside of adverse weather conditions (e.g., components iced over), the anemometer is considered functional if it is provided power and can stream wind speed, wind direction, and temperature data continuously to the central processing computer.

Spectrometer: The laser system must be drawing power and temperature compensation active. Data acquisition must be able to receive and transmit commands from the central processing computer.

11.0 Calibration and Standardization

The laser system used in this method does not require standardization, calibration, or on-site visits for tuning once deployed in the field. Similarly, bump-tests and baseline adjustment are not required. The technique of absorption spectroscopy is inherently calibration-free.

The anemometer is calibrated by manufacturer per manufacturer specifications.

12.0 Procedure

12.1 Planning Procedure

Once sites are identified by the owner/operator for monitoring, a site survey is scheduled to locate equipment groups and to measure equipment heights. This information is used along with any available satellite imagery or other map products to generate a geodatabase of planned locations and heights of tower and retroreflectors. This is generated by taking the 3D site survey locations and heights and running an optimization algorithm to produce ideal and feasible locations and heights. Retroreflective mirrors must bound all applicable fugitive emissions sources. Siting and detection threshold metrics must be cleared per Section 10.1 Siting & Detection Threshold Metrics. Heights of all equipment are also confirmed to be within county and state regulations for structure heights and permits are acquired if necessary.

Once a siting plan has been produced for which acceptable siting criteria are met (Section 10.1 Siting & Detection Threshold Metrics), a deployment file is created that specifies the GPS coordinates for the equipment that will be installed according to the Installation Procedure (Section 12.2 Installation Procedure).

12.2 Installation Procedure

The installation process begins with verifying the central node location using GPS coordinates from the deployment file. The following installation procedures are example procedures but may change as needed for different locations and tower heights. All installation procedures must be approved by engineers and meet all necessary siting and sensitivity metrics as described elsewhere in this document. A concrete slab is placed where the tower will be located. Anchoring involves drilling holes into the concrete base, inserting wedge anchors, and securing them with impact drivers. The tower is then attached to the anchored base, and guy lines are connected to stabilize it. Additional tasks include securing cables, mounting the gimbal and telescope, installing the cell antenna, and setting up the anemometer. Concrete blocks are stacked for mounting the solar panels. The battery box is mounted to the tower base, and batteries are installed following precise wiring instructions. Solar panels are mounted and wired, ensuring they are positioned for optimal sun exposure. The system is then powered on. Cement blocks are placed on site locations based on the deployment file and reflectors are mounted and line of sight is then verified. The system is checked to confirm proper installation and performance per Section 10.1 Siting & Detection Threshold Metrics. Any failures of siting and detection threshold metrics result in an iteration of planning and install steps until metrics have been met.

After installation, final "as built" deployment waypoints are used to generate the "as built" geodatabase. This geodatabase is then used to initialize model parameters in the atmospheric inversion.

The allowable wind direction for a site and for a Preliminary Real-Time Estimate is defined as any wind direction where the beam path of at least 1 retroreflective mirror on a site has a concentration response to a theoretical emission from a location on the site and less than or equal to 1 beam path of the bounding reflectors for the site has a concentration response to a theoretical leak from a location on the site. The acceptable wind directions for a site are determined by modeling the concentration response to a methane leak in intervals of 5 degrees from 0 to 360 degrees on all retroreflector beam paths and selecting wind directions that have a sensitivity of at least 0.01 ppb increase in concentration per 1 scfh of leak rate. This information is stored in software configuration files.

12.3 Data Collection & Processing Procedure

During a Fugitive Emissions Screening, Preliminary Real-Time Estimates are collected until at least 3 hours of measurements have been obtained (measured as the sum of the duration of individual Preliminary Real-Time Estimate data collection periods) since the start of the screening period. Screening frequency is as stated in the compliant monitoring plan for use.

During a Preliminary Real-Time Estimate (see Section 3.0 Definitions), the gimbal pivots to direct the laser light at the two (or more) retroreflective mirrors assigned to the monitored site. The laser transceiver collects data for one monitored site by directing the laser light to each retroreflective mirror in sequence, thereby collecting multiple concentration readings. A site is monitored until at least one concentration measurement has been made on each bounding retroreflective mirror associated with the site, meaning at least one upwind and one downwind value must be collected.

The laser spectrometer produces and detects eye-safe laser light autonomously and continuously through time. The laser data are obtained on the data acquisition unit and sent to the central processing computer at a high temporal rate. Each data packet is stamped with: UTC time of measurement, unique measurement ID number corresponding to retroreflector visit, and embedded software version number.

Once received by the central processing computer, the high-frequency data are filtered for SNR and optical interference described in Section 10.3.2 Operational Checks of Concentration Data. Each of the remaining laser signal data points is automatically processed to produce a path-integrated methane concentration measurement using modeled absorbance signals (Section 13.1 Laser Absorption Spectroscopy Physical Model). The high-temporal resolution concentration data are then further averaged for the window of time in which the gimbal continuously points toward a single retroreflector.

Prior to use in the emission rate calculation a second round of QAQAC metrics are assigned to the averaged concentration value calculated from the high-frequency data. QAQC checks and metrics and corrective actions are as described in Section 10.3.2 Operational Checks of Concentration Data. The processed concentration data and quality metrics are stamped with a unique identifier of the software version (traceable and backed up with the 3rd party software) and saved to the computer for further processing by the emissions algorithm.

The anemometer collects data continuously through time. Additionally, high-resolution real-time or forecast data from weather models may be used to supplement anemometer data, including for instances of anemometer downtime or for anemometers that do not produce the required frequency or data fields for accurate modeling of turbulence parameters. The temporal resolution of information needed is hourly and the spatial resolution of information needed is 12 km horizontal grid. The variables include wind speed, wind direction, boundary layer height, sensible heat flux, temperature, and friction velocity.

The raw data from the anemometer includes high-frequency directional wind speeds and temperature. The high-frequency data are sent from the anemometer to the central processing computer where QAQC checks are applied as described in Section 10.2 Meteorological Data Quality Checks. If forecast or real-time data from a weather model is used, it is uploaded to the central processing computer from a remote server. At the central processing computer, these data are processed to produce wind direction, wind speed and turbulence parameters (De Visscher, 2013), time stamped with the UTC time of measurement and saved to the central processing computer for further processing by the emissions quantification algorithm. QAQC checks and corrective actions are as described in Section 10.2 Meteorological Data Quality Checks. The high-frequency raw data is subsequently averaged to a lower frequency for long-term storage in the database.

At the central processing computer, final as-built GIS data, wind speed, wind direction and turbulence parameters, and temperature data are processed to produce Preliminary Real-Time Estimates, as described in 13.4 Fugitive Emissions Screening Assessment. These data are also processed to produce bottom-up sensitivity values and detection thresholds as described in Section 13.2 Ongoing Detection Threshold Model. QAQC to determine whether the Preliminary Real-Time Estimate that was obtained by the inversion should be logged as successful or flagged as unusable are described in Section 10.4 Emission Rate Data Quality Checks. All processed data are stored as a data packet with UTC time of measurement, site ID and meteorological data. Processed data are synced to a central server every minute.

Data that has been synced to the central server is then further processed on the central server platform. The following data processing steps occur at the central server platform.

Preliminary Real-Time Estimates are processed to generate Emission Rate Reading, which are the daily average mass emission rate in kg/hr of methane for each calendar day of screening. Emission Rate Readings for each day of screening are used in the Fugitive Emissions Assessment (see 13.4 Fugitive Emissions Screening Assessment).

12.4 Data Delivery and Reporting Procedure

As described above, data logging occurs locally at the central processing computer. Data is securely transferred to a server via communications on the central node tower. Once raw data from the edge hits the initial Extract, Transform and Load (ETL) point, a secondary gateway instance is used to further ETL data as a security measure to ensure data is contained. Once raw data from the edge is delivered to the initial ETL point, a secure backup of the data is created. The results of the Fugitive Emissions Screening assessment are provided to the operator web application.

Samples, which are digital data, are stored for a minimum period of 5 years at primary and secondary locations for data security and maintenance. Records are provided to the owner or operator for reporting.

12.5 Operational Downtime Reporting Procedure

Operational downtime checks are performed as described in Section 10.6 Operational Downtime. The start time for each Operational Downtime period will begin at the first hourly notification of the system no longer meeting the Operational Downtime requirements and ends when the first Preliminary Real-time Estimate is reported by the system. The daily Operational Downtime percentage is calculated as the total hours of Operational Downtime divided by 24 hours.

13.0 Data Analysis and Calculations

13.1 Laser Absorption Spectroscopy Physical Model

The absorption signal, $\alpha(\lambda)$, is modeled using the Beer-Lambert law as described by the equation below, where I_o represents the incident intensity of the light source and I_t represents the laser intensity after passing through an absorbing gas. The right-hand side of the equation below is calculated for each molecular transition (j) within the bandwidth of the measurement. The temperature dependent linestrength S_j describes how the strength of the given transition changes with temperature; this parameter is calculated using terms taken from the HITRAN database. The lineshape function $\phi_j(\nu)$ describes how the shape of the given transition responds to changes in pressure, concentration, and temperature. The lineshape function for each transition is modeled using a Voigt profile described below and is also calculated using parameters from the HITRAN database. Finally, P represents total atmospheric pressure, X the mole fraction of the absorbing gas, and L the path length of the sample.

$$\alpha(\nu) = \left(\frac{I_t}{Io}\right)_\nu = \Sigma_j \exp\left(-S_j\phi_j(\nu)PXL\right)$$

The lineshape function used for calculating the modeled absorbance is a standard Voigt profile defined by as ϕ_V in the equation below. The Voigt lineshape is a convolution of a Gaussian lineshape ϕ_D)￼ and a Lorentzian lineshape ϕ_C￼).

$$\phi_V(v) = \int_{-\infty}^{\infty} \phi_D(u)\phi_C(v-u)du$$

For signals with pronounced wavelength dependent intensity variations across bandwidth the baseline normalization described by Cole et al. (2019) is applied.

13.2 Ongoing Detection Threshold Model

A minimum detection threshold is calculated for each Emission Rate Reading produced by the LongPath Emissions Sensing Network™ System to ensure that thresholds required in the relevant monitoring plan are met.

The bottom-up sensitivity value for each Preliminary Real-Time Estimate multiplied by the Empirical-to-Field Sensitivity Factor yields the minimum detection threshold for each Preliminary Real-Time Estimate (Section 4.3 Verification of Performance in Field Conditions). Per §60.5398b(d)(3)(vi), for the purpose of this subpart the average aggregate detection threshold is the average of all site-level detection thresholds from a single deployment of a technology. Therefore, the final aggregated minimum detection threshold value for an Emission Rate Reading is the node-wide average of the Preliminary Real-Time Estimate minimum detection thresholds values used in the calculation of the Emission Rate Reading value.

A failure of the Emission Rate Reading for a site to consistently meet the required minimum detection threshold values is checked and corrected as described in Section 10.1 Siting & Detection Threshold Metrics.

13.3 System Siting Detection Threshold Model

For assessment of the initial layout of a LongPath Emissions Sensing Network™ system, it is possible to model indicators that the siting is adequate. However, the final as-built locations must be used with ongoing real-time data for an accurate assessment of siting. While initial siting is performed for the best possible outcome, the model described in Section 13.2 Ongoing Detection Threshold Model is ultimately what is used to assess site performance and make changes if quality criteria are not met.

13.4 Fugitive Emissions Screening Assessment

To identify gas emissions from oil and gas operations, indirect methods are required. For example, OGI cameras do not directly measure or detect emissions, but rather they detect the signatures of emissions present in the atmospheric concentration of gasses proximal to potential source locations. This method follows the same principles.

The below equation shows that the atmospheric concentration of methane gas measured at a sensor downwind of a site, $CH_{4\ ATM}$, is influenced by methane emissions occurring on the site, including the contributions of fugitive emissions, x_{FUG}, and non-target (non-fugitive) emissions, x_{NTE}, as well as the contribution of incoming background methane molecules, $CH_{4\ BG}$. The term A denotes the influence function linking each source, x, to a change in atmospheric concentrations, ΔCH_4.

$$CH_{4\ ATM} = A(x_{NTE} + x_{FUG}) + CH_{4\ BG}$$

In this method, the background is measured, and the non-target emissions are calculated, so that the fugitive emissions contributions can be solved for directly (Coburn et al., 2018; Alden et al., 2019).

Once at least 3.5 hours of Preliminary Real-Time Estimates of rate have been accumulated by the system, a daily Emission Rate Reading value is compiled and compared against the target detection thresholds to determine the presence or absence of fugitive emissions sources.

14.0 Pollution Prevention

Physical samples are not produced or collected in this method such that pollution prevention measures are not needed.

15.0 Waste Management

Physical samples are not produced or collected with this method such that waste management measures are not needed.

16.0 References

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