Aerial Survey Alternative Test Method (MATM-002)

January 10, 2025

1 Scope and Application

1.1 <u>Scope</u>

The subject method provides the user with a protocol for using airborne Gas Mapping LiDAR (GML) technology to identify and localize methane emissions emanating from equipment or other surfaces on the ground. The method may optionally provide other contextual information (e.g. aerial photography, equipment attribution, etc.) related to the identified emissions to facilitate investigative analysis of the emission sources or causes.

GML technology is based on the use of laser-based, beam-scanning, atmospheric light detection and ranging ("LiDAR") remote sensing instruments ("GML Instruments"). A GML Instrument is affixed to an aircraft (manned or unmanned) and scans one or more geographic areas below the aircraft, each of which may be defined by a polygon of geodetic coordinates enclosing possible methane emission sources ("Target Area", see Figure 1, left). The subject method may be applied to multiple Target Areas.

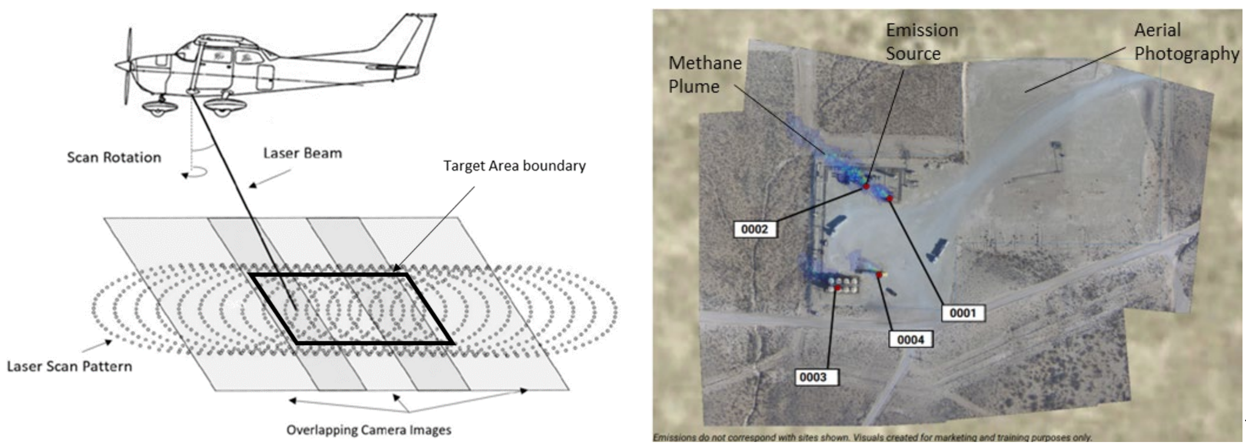

Figure 1. Left: Conceptual diagram showing laser beam scanning, Target Area, and overlapping camera images. Right: Example data showing Methane Plumes, Emission Sources, and aerial photography.

The GML Instrument scans a Target Area to gather data inputs, which are analyzed and processed to produce geo-registered, time/date-stamped, path-integrated methane gas concentration ("P-Concentration") plume imagery (see Figure 1, right). This plume imagery may be overlaid onto concurrently acquired geo-registered aerial photography and/or satellite imagery from the Target Area to provide contextual information (e.g. regarding the spatial location and/or equipment attribution of the emission location). Processing and analysis of the plume imagery and other data inputs may result in the determination that the emissions have emanated from certain geodetic coordinates within the Target Area. Certain equipment or operations occurring within the Target Area may be attributed to the source or cause of an emission.

The protocol described in this method achieves two principal measurement objectives. First, this method determines spatial regions where the GML Instrument identifies that P-Concentrations anomalously exceed the nominal background amounts ("Methane Plumes"). Second, this method determines whether there are identifiable spatial locations corresponding to emission sources of those Methane Plumes within the Target Area ("Emission Sources"), and provides Methane Plume imagery, Emission Source geodetic coordinates, and time/date information corresponding to such Emission Sources. See Figure 1 (right) for examples of Methane Plumes, Emission Sources, and aerial photography.

This method may provide, or receive from other data sources, any other auxiliary information (collectively, "Auxiliary Data") that may facilitate investigative analysis of the Emission Source. Such Auxiliary Data may include, corresponding to identified Emission Sources:

- digital photography or satellite imagery,
- emission rate quantification,
- a determination of intermittency or other temporal characteristics,
- an attribution of the emission to a piece of equipment or component,
- estimated height of an Emission Source,
- historical information indicating previous detections of an Emission Source,
- Supervisory Control and Data Acquisition (SCADA) data,
- information from other methane monitoring technologies, or
- any other data or information.

1.2 Application

The method is applicable to the oil and gas production sector including upstream and midstream. This method could also be applied to the segments of the energy sector as appropriate for detecting one or more emission sources emanating from within a defined Target Area. When approved for use through the applicable regulatory authority, this method can be used to comply with the applicable regulations (*e.g.,* 40 CFR part 60, subpart OOOOb) that require emissions monitoring.

The GML Instrument described in this method specifically detects methane plumes corresponding to elevated P-Concentrations of methane gas. In some circumstances, methane detection has been used as a surrogate for the detection of volatile organic compound ("VOC") emissions from the oil and gas sector, due to the high correlation with methane emissions.

1.3 Limitations to Applicability

The subject method may be limited in applicability by certain environmental, atmospheric, and operational conditions. These limitations include:

(a) Conditions for safe flight,
(b) High ground wind speed,
(c) Standing water,

(d) Low visibility to ground,
(e) Low ground surface reflectance,
(f) High flight altitude,
(g) Low measurement point density,
(h) Ambient temperature outside of instrument operating limits, and
(i) Interfering species.

The method addresses these limitations through prescriptive conditions in which GML data acquisition is performed as described in (see Section 4.) When data acquisition is performed, the ability of GML to overcome these limitations is assessed for each Target Area using the Detection Sensitivity Audit in Section 11.3. Limitation (i) has been mitigated by third-party laboratory testing confirming non-interference of other species common to oil and gas operations, as described in Section 4.9.

2 Summary of Method

2.1 Gas Detection Principle

The GML Instrument utilizes a form of laser absorption spectroscopy ("LAS") to detect and measure the P-Concentration in the parcel of air between the GML Instrument on the aircraft and the ground surface or equipment (see Figure 1).[1] The average wavelength of the transmitted laser beam is actively stabilized to match the center wavelength of a methane gas absorption line near 1651 nm with the use of a gas reference cell that is located within the GML Instrument (see Section 7.1). The wavelength-stabilized laser beam is then intentionally wavelength modulated at a pre-determined frequency and is directed toward the ground surface. The GML Instrument then receives a portion of the laser light that is scattered back from the terrain surface within the Target Area. Where the laser beam path propagates through methane gas, a portion of the laser light is absorbed by the methane gas. As a result of this absorption, the laser wavelength modulation causes an intensity modulation on the laser beam. This intensity modulation, along with the physical model outlined in Section 12.1, is used to compute the P-Concentration traversed by the beam.

A topographical LiDAR range measurement, coaligned with the LAS measurement, is performed from the GML Instrument to the ground surface, which is used in accounting for laser light absorption by ambient levels of background methane concentration throughout the beam path.

The scanning laser beam enables spatially distributed measurements throughout a "Scan Swath". On-board measurement systems, including a Navigation System and beam angle determination, are used to geo-register the LiDAR data points to a geodetic coordinate system.

Algorithms incorporating the spatial distribution of P-Concentration measurements are used to determine the existence, and generate imagery, of Methane Plumes, and to determine Emissions Sources. First, Methane Plumes are detected relative to background methane concentrations in an automated step with manual quality assurance oversight. Next, the identification and location of Emission Sources for the Target Areas is performed in an automated step that may be supplemented, refined, or replaced by manual processing, and with manual quality assurance oversight. This step may consider gas concentration gradients, Methane Plume shapes, ranging LiDAR data, aerial photography, and other factors. The performance of data processing protocols in terms of detection sensitivity and localization performance is described in Section 13 (Method Performance) and in Reference [2], respectively. In addition, processing protocol performance is verified during sensor qualification testing (Section 13.1). Scan data is time-stamped, and GML Instrument data is retained for at least five years following Target Area scans.

2.2 Data Collection

Under the subject method, the GML Instrument is affixed to an aircraft. During the aircraft flight, the Target Area is spatially scanned using the laser beam from the GML Instrument, as shown in Figure 1. The data acquired by the GML Instrument and other data inputs are used to detect and provide Methane Plumes that have identifiable Emission Sources within the Target Area. A minimum of one scan of the Target Area is conducted to gather data. Aerial photography of the Target Area may be gathered concurrently with the gas detection data by the GML Instrument to provide geographic/spatial context at the time of the LiDAR scan. LiDAR data is geo-registered to the geodetic coordinate system. Audits of scan coverage area and detection sensitivity are performed in automated protocols with manual input and quality assurance oversight.

Upon completion of gathering the initial data pertaining to the Target Area, a second scan may be performed (“Secondary Scan”), of those locations where preliminary data and analysis indicates identification of one or more Emission Sources. The purpose of the Secondary Scan may be to determine whether an Emission Source is intermittent (identifiable during the initial scan, but not on a second scan) or persistent (identified on both the initial and a Secondary Scan, “Persistent Emission Source”) for data quality assurance. Secondary Scans occur no more than 5 days after the initial scan is complete. A “Screening Event” constitutes completion of all scans of a Target Area within a monitoring interval (e.g., within a given quarter). Emissions monitoring plans must specify whether or not Secondary Scans will be performed as part of the subject method.

2.3 Data Delivery Principle

Once the Screening Event is completed for the Target Area, the acquired data is further processed and verified for quality. Both deployment parameters and processing thresholds may be used to align the Deliverables with the Detection Sensitivity Metric; i.e., to either increase or decrease the emission rate for which ≥90% of Emission Sources are identified. The resulting required method measurement deliverables (“Deliverables”) pertain to identified Persistent Emission Sources within a Target Area and include: (1) geo-referenced Methane Plume imagery, (2) Measured Coordinates of identified Emission Sources, (3) time and date that identifiable Emission Sources were detected on the final scan, and (4) time and date of data delivery. If a Secondary Scan is not performed to determine the persistence of an Emission Source, then the

Deliverables must pertain to Emission Sources identified in the first scan of the Target Area (i.e., may include both persistent and intermittent Emission Sources).

Auxiliary Data may also be provided under the subject method to assist in causal or investigative analysis including: (5) geo-referenced and orthorectified aerial photography or satellite imagery, (6) equipment attributed to identified Emission Sources, (7) persistence of identified Emission Sources, (8) emission rate quantification, (9) height estimate of Emission Sources, and (10) historical data indicating previous identification of an Emission Source.

Deliverables and Auxiliary Data may be represented in varying documents and file formats (e.g. .pdf, .xls, .kml, .kmz, web/app interface, etc.), and delivered through varying mechanisms (via email, file transfer protocol (FTP), SharePoint, web/app interface, application programming interface (API), or other means.). Example Deliverables, including Methane Plumes and Emission Sources, are shown in Figure 1 (right), which are accompanied by tabular data with geodetic coordinates and time/date of Emission Sources.

2.4 Test Method Performance Metrics

The use of a GML Instrument within the subject method must achieve the following required performance metrics ("Performance Metrics")

a. Identification of Emission Sources with an average detection sensitivity of no greater than the applicable regulatory detection sensitivity tier [*e.g.,* ≤10 kg/hr with 90% Probability of Detection ("POD")] ("Detection Sensitivity Metric") as controlled and determined by a Detection Sensitivity Test described in Section 9.1.1 during GML Instrument qualification and by maintaining the calibration and standardization described in Section 10, and as verified for the group of Target Areas to which the subject method is applied using quality assurance protocols described in Sections 10 and 11, including the Detection Sensitivity Audit for field operations; and

b. Determination of an Emission Source geodetic coordinates ("Measured Coordinates") with a statistical uncertainty (average bias plus one standard deviation) not greater than 2 meters ("Localization Metric") from the true Emission Source geodetic coordinates ("True Coordinates"), as determined by a Localization Test described in Section 9.1.2 during GML Instrument qualification, and by using the calibration and quality assurance protocols in Sections 10 and 11 for field operations.

c. Quantification of an Emission Source emission rate with an average ratio of the Estimated Rate divided by the Metered Rate ("Relative Error Ratio") of between 0.7 and 1.3 ("Quantification Metric") as determined by a Quantification Test described in Section 9.1.3 during GML Instrument qualification, and as ensured using the calibration and quality assurance protocols in Sections 10 and 11 for field operations.

The Detection Sensitivity Metric must be achieved for the deployment of the method at the collection of sites identified in the applicable monitoring plan.

Note: If the monitoring plan specifies that 40 centralized production facilities will be scanned with an average aggregate detection sensitivity of ≤3 kg/hr (90% POD), then the Detection Sensitivity Metric for the 40 scans of those facilities in a given quarter must be achieved at ≤3 kg/hr (90% POD), as verified by the Detection Sensitivity Audit.

3 Definitions of Method

3.1 Actual Wind Speed

The averaged anemometer wind speed measurement during controlled release testing. The wind speed measurement is taken by an anemometer located within 30 meters of the geodetic coordinates, and within ±0.5 m of the height, of the controlled release aperture.

3.2 AGL

Above Ground Level. The height above ground level.

3.3 Auxiliary Data

Information other than the Deliverables that may facilitate investigative analysis of an Emission Source.

3.4 Deliverables

The resulting processed measurement data compiled and delivered from use of this method, as defined in Section 2.3.

3.5 DER

Designated Engineering Representative. A DER is a qualified individual who has been appointed in accordance with the FAA regulations at 14 C.F.R. §183.29.

3.6 Detection Sensitivity Audit

A quality assurance step used to ensure the detection sensitivity performance of the GML Instrument applied to collection of Target Areas scanned under the subject method.

3.7 Detection Sensitivity Metric

See Section 2.4.

3.8 Detection Sensitivity Model

The framework for determining GML Instrument detection sensitivity performance under operational or environmental conditions during field operations for scanned Target Areas, detailed in Section 12.3.

3.9 Emission Source

The identifiable spatial location from which a Methane Plume originates.

3.10 Estimated Rate

The emission rate estimated by GML processing during controlled release testing as part of GML Instrument Qualification protocols (Section 9.1).

3.11 FAA

United States Federal Aviation Administration. The FAA is responsible for the regulation and oversight of civilian aviation within the United States.

3.12 FDA

United States Food and Drug Administration. The FDA regulates lasers to ensure the protection of public health and compliance with federal standards.

3.13 Gas Concentration Noise (GCN)

The parameter that, in addition to wind speed, is used to determine detection sensitivity performance for GML Instruments based on the Detection Sensitivity Model.

3.14 GML Instrument

The laser-based, beam-scanning, remote sensor instrument used to scan an area for the purpose of detecting and locating sources of methane emissions.

3.15 GPS

Global Positioning System. A navigational system using satellite signals to fix the location of a radio receiver on or above the Earth’s surface.

3.16 HRRR Model

High-Resolution Rapid Refresh model that is updated from The National Oceanic and Atmospheric Administration (“NOAA”) and that may be used to determine wind speed at a geographic location and time.

3.17 <u>IFR</u>

Instrument Flight Rules. Instrument flight rules are rules and regulations to govern flight under conditions in which flight by outside visual reference is not safe, as defined by the U.S. Federal Aviation Administration's (FAA).

3.18 <u>IMU</u>

Inertial Measurement Unit. A device that measures and reports acceleration, orientation, angular rates, and other gravitational forces.

3.19 <u>Kg/h</u>

Kilogram per hour. Unit for measuring mass emissions rates.

3.20 <u>Km/h</u>

Kilometer per hour. Unit for measuring speed.

3.21 <u>LAS</u>

Laser Absorption Spectroscopy. Techniques that use lasers to assess the concentration or amount of a species in gas phase by absorption spectroscopy.

3.22 <u>LDAR</u>

Leak Detection and Repair. The set of federal regulations which require subject facilities to identify and repair leaking components to minimize the emission of fugitive methane, VOCs, and/or hazardous air pollutants.

3.23 <u>LiDAR</u>

Light Detection and Ranging. A remote sensing method that uses laser light to measure remote quantities, such as the distance to an object or the concentration of a gas species between the LiDAR device and a remote object or surface.

3.24 <u>Localization Metric</u>

See Section 2.4.

3.25 <u>Maximum Spectral Deviation</u>

The maximum allowable amount of deviation for the frequency of the transmitted laser beam from the target optical frequency as referenced against the on-board reference gas cell.

3.26 Measured Coordinates

The geodetic coordinates of an Emission Source determined by data from a GML Instrument.

3.27 Metered Rate

The emission rate determined by a flow meter for a controlled methane release during controlled release testing as part of GML Instrument Qualification protocols (Section 9.1).

3.28 Methane Plumes

Regions of identified anomalous P-Concentrations that exceed the nominal ambient background amounts of methane gas concentrations.

3.29 MHz

Megahertz. A unit of frequency equal to one million hertz.

3.30 m/s

Meters per second. A unit of speed.

3.31 Nm

Nanometer. A unit of wavelength.

3.32 Navigation System

A subsystem of the GML Instrument that is responsible for determining the instrument location, altitude, pitch, roll, and inertia.

3.33 NOAA

National Oceanic & Atmospheric Administration. NOAA maintains the HRRR atmospheric model.

3.34 Pa

Pascal. A unit of pressure equal to one newton per square meter.

3.35 Performance Metrics

Specific metrics that must be achieved during application a GML Instrument within the subject method. The Performance Metrics are inclusive of the Detection Sensitivity Metric, Localization Metric, and Quantification Metric. See Section 2.4.

3.36 P-Concentration

Path-integrated methane gas concentration. A measurement of the concentration of methane gas.

3.37 Ppm

Parts per million. Unit for measuring gas mixing ratios.

3.38 Ppm-m

Parts per million – meter. Unit for measuring P-Concentrations.

3.39 Persistent Emission Source

The same Emission Source identified on both an initial and Secondary Scan.

3.40 Probability of Detection (POD)

The probability of identifying an Emission Source that is emitting methane at a particular emission rate.

3.41 Procedure

The protocols performed by the method user to acquire, process, and deliver data (Section 11).

3.42 Quantification Metric

See Section 2.4.

3.43 Relative Error Ratio

Ratio of the Estimated Rate divided by the Metered Rate.

3.44 RPM

Revolutions per minute. Unit of measure for the rate at which an object rotates.

3.45 Scan Coverage Audit

A quality assurance step indicating the scan coverage performance of the GML Instrument applied to collection of Target Areas scanned under the subject method.

3.46 Scan Swath

The geospatial region of the ground surface within which measurements are acquired during a single GML Instrument pass.

3.47 Screening Event

The collection of scans within a monitoring interval (e.g., within a given quarter) for a given Target Area. A Screening Event may include either just an initial scan, or both an initial and a Secondary Scan, the selection of which must be made prior to beginning the Screening Event and specified within the emissions monitoring plan. The Screening Event for a given Target Area is completed after all scans of that Target Area are completed.

3.48 Secondary Scan

GML instrument scan of those locations where preliminary data and analysis indicates identification of one or more Emission Sources. Occurs no more than 5 days after the initial scan is complete. May be used to determine if an Emission Source is a Persistent Emission Source. Secondary Scans are performed with the same GML Instrument deployment guidelines and processing parameters as the other Target Area scans performed under the subject method.

3.49 STC

Supplemental Type Certificate. STC is defined by the U.S. Federal Aviation Administration (FAA).

3.50 Target Area

The defined geographic area containing possible methane Emission Sources, which is scanned by the GML Instrument.

3.51 United States Geological Survey (USGS)

The USGS maintains the USGS spectral library, used to identify materials by their spectral fingerprints.

3.52 Test Setup

The test setup for controlled release testing (Section 9.1).

3.53 True Coordinates

The actual geodetic coordinates of an Emission Source.

3.54 VFR

Visual Flight Rules. Visual flight rules are defined by the U.S. Federal Aviation Administration (FAA).

3.55 VOC

Volatile Organic Compound. As defined in 40 CFR Part 51.100(s) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides, or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions.

3.56 WMS

Wavelength Modulation Spectroscopy. WMS is a derivative form of laser absorption spectroscopy applied, in this case, to detect methane gas emissions.

4 Interferences and Limitations to Applicability

Certain operational and/or environmental factors or conditions may limit the ability of a user to implement the subject method or may otherwise interfere with the GML Instrument's ability to achieve the Performance Metrics under the subject method. Achievement of the Detection Sensitivity Metric in the field is verified as part of the detection sensitivity quality assurance protocols in Section 11.3.

4.1 Conditions for Safe Flight

As the GML Instrument is operated from an aircraft, atmospheric visibility or other adverse weather conditions may limit the ability to safely fly the aircraft, thereby limiting the applicability of the subject method. Flights and scans for the subject method must only be conducted when the aircraft and the flight conditions fall within all pertinent safety regulations, including, for example, Visual Flight Rules (VFR)[3] and/or Instrument Flight Rules (IFR)[4] of the United States Federal Aviation Administration ("FAA"). The aircraft operator has complete authority to cease or limit flight operations for safety purposes under the subject method.

4.2 High Ground Wind Speed

High wind conditions at the Target Area may dilute and disperse the methane gas concentration through transport by the wind. High winds therefore reduce the ability of the GML Instrument to meet the Detection Sensitivity Metric under the subject method. For this reason, and for flight roll stability purposes, which are needed to enable Target Area coverage, the subject method must not be conducted during times if the High-Resolution Rapid Refresh ("HRRR") model from the National Oceanic and Atmospheric Administration (NOAA)[5], or a regional weather service with equivalent or better wind speed accuracy (as compared to HRRR as of January 1, 2023), forecasts average wind speeds exceeding 15 m/s.

For wind speeds below this limit, but still high (e.g. 14 m/s) the unfavorable impact of high wind speed may be offset by favorable values of other operational or environmental conditions (e.g. that impact gas concentration noise (see Section 13.2)) to enable achievement of the Detection Sensitivity Metric. Therefore, assuming the Detection Sensitivity Metric is achieved (and verified using the detection sensitivity quality assurance protocols in Section 11.3), there is no other specific operational limitation for ground wind speed.

4.3 Standing Water

The GML Instrument's laser light typically reflects off standing water in a single direction away from the GML Instrument, rather than scattering diffusely back to the GML Instrument for measurement. Standing water can therefore result in insufficient returning laser light and can prevent the GML Instrument from detecting Methane Plumes to meet the Detection Sensitivity Metric. Therefore, the subject method is not applicable to portions of Target Areas comprising oceans, lakes, ponds, flooded regions, or rivers.

4.4 Low Visibility to Ground

Even if the conditions for aircraft flight are safe, and therefore the method safety requirement in Section 4.1 is met, smoke or other atmospheric conditions may limit the GML Instrument's laser light from reaching surfaces on the ground. Such atmospheric conditions may inhibit the GML Instrument's ability to achieve the Detection Sensitivity Metric under the subject method. However, degraded visibility to the ground may be offset by favorable values of other operational or environmental conditions (see Section 13.2) to enable achievement of the Detection Sensitivity Metric. Therefore, assuming the Detection Sensitivity Metric is achieved (and verified using the detection sensitivity quality assurance protocols in Section 11.3), the only visibility limitations to application of the subject method are to ensure safe flight operations (Section 4.1).

4.5 Low Ground Reflectance

Low ground reflectance can inhibit scattered laser light from returning to the GML Instrument from the ground surface and may therefore reduce the ability of the GML Instrument to meet the Detection Sensitivity Metric under the subject method. Typical dry ground surfaces encountered within Target Areas for the oil and gas industry (soil, concrete, grass, vegetation, etc.) exhibit reflectance greater than 20% at optical wavelengths near 1651 nm.[6] Moisture has been shown to decrease surface reflectance compared to dry surfaces (e.g. by <10%, ~40%, and ~80%, for vegetation, soil, and hard surfaces, respectively).[6] Snow cover has been shown to exhibit surface reflectance of between 3% and over 20%, depending on the grain size of the snow, at optical wavelengths near 1651 nm.[6] However, unfavorable ground reflectivity may be offset by favorable values of other operational or environmental conditions (see Section 13.2) to enable achievement Detection Sensitivity Metric. Therefore, assuming the Detection Sensitivity Metric is achieved (and verified using the detection sensitivity quality assurance protocols in Section 11.3), there are no explicit ground reflectivity limitations to applicability of the subject method.

4.6 High Flight Altitude

The GML Instrument detection sensitivity decreases with increasing flight altitude due to reduced laser light received by the GML Instrument back from the ground surface (i.e. radiometric LiDAR considerations), and due to decreased LiDAR data point density on the terrain being scanned (see Section 4.7). High flight altitude may therefore reduce the ability of the GML Instrument to achieve the Detection Sensitivity Metric under the subject method. However, high flight altitude may be offset by favorable values of other operational or environmental conditions (see Section 13.2) to enable achievement of the Detection Sensitivity Metric. Therefore, assuming the Detection Sensitivity Metric is achieved (and verified using the detection sensitivity quality assurance protocols in Section 11.3), there are no explicit flight altitude limitations beyond those to ensure safe flight operations.

4.7 Low Measurement Point Density

The GML Instrument detection sensitivity decreases with decreasing measurement point density on the terrain being scanned. Such decreases in measurement point density may be caused by higher flight altitude (see Section 4.6), increased flight speed, decreased measurement update rate, decreased laser beam scan rate, increased sensor field of view, or other factors. These factors may therefore reduce the ability of the GML Instrument to meet the Detection Sensitivity Metric under the subject method. Such causes of decreased point density may be offset by favorable values of other operational or environmental conditions (see Section 13.2) to enable achievement of the Detection Sensitivity Metric. Therefore, assuming the Detection Sensitivity Metric is achieved (and verified using the detection sensitivity quality assurance protocols in Section 11.3), there are no explicit limitations on factors that impact measurement point density.

4.8 Unacceptable Ambient Temperature Outside the GML Instrument

The GML Instrument is constructed and tested to operate properly within a specified temperature range. For this reason, the subject method requires that the GML Instrument is operated only within the operational temperature range (external to the GML Instrument) defined by calibration and standardization testing in Section 10.

4.9 Interfering Species

Different forms of LAS may be susceptible to interference from non-target species (e.g. common species or volatile compounds in oil and gas operations). The GML technology has demonstrated immunity to interference from carbon dioxide, carbon monoxide, ethane, ethene, propane, n-butane, iso-butane, and water vapor.[7]

5 Safety

The subject method requires activities governed by other categories of regulations, including requirements of the Occupational Safety and Health Administration and the FAA. Applicable requirements and regulations from these, and other relevant jurisdictional administrative authorities, must be followed to properly conduct the subject method. Because the subject method may be adopted by a variety of industries, site-specific hazards may be identified, understood, and accounted for prior to conducting the subject method.

5.1 Risks Associated with Aviation

Flight providers operating the aircraft to which the GML Instrument is attached have rules, regulations, and safety policies and procedures which must be followed for internal and general aviation compliance. The aircraft operator therefore has complete authority to cease or limit flight operations for safety purposes. The GML Instrument must be secured to the aircraft by a Supplemental Type Certificate ("STC") mount. Notwithstanding the broad discretion concerning safety granted to the aircraft operator, unidentified general aviation flight hazards may still exist.

5.2 Laser Safety

The United States Food and Drug Administration ("FDA") regulates the use of laser beams. Each GML Instrument with which the subject method is applied must comply with all applicable FDA regulations, including those regulating the maximum amount of laser light that may reach the ground surface in order to protect human eyesight.

6 Equipment and Supplies

6.1 GML Instrument

The subject method requires the use of a laser-based beam-scanning remote sensor instrument capable of detecting and imaging the anomalous P-Concentration between the instrument on the aircraft and the ground surface, as described herein.

6.2 GML Instrument Mount

The GML Instrument is attached to the aircraft by a mount that complies with FAA regulations. All external mounts to the aircraft must be certified by a STC and/or a Designated Engineering Representative ("DER"), and the sensor must be installed by an FAA-certified mechanic.

6.3 Computer Software or Firmware

Computer software or firmware capable of processing the data acquired from scans is necessary for the use of this method.

6.4 GPS Antenna

A GPS instrument is required to measure and record the coordinates of the GML Instrument for the acquired data points. The GPS must have the capability to meet the geolocation accuracy requirements of the subject method in latitude and longitude. The GPS Antenna is a component of the Navigation System.

6.5 IMU System

An Inertial Measurement Unit ("IMU") is required to determine the orientation of the GML Instrument. The IMU system is a component of the Navigation System.

7 Reagents and Standards

7.1 Methane Gas Reference Cell

The subject method includes the use of a methane gas reference cell internal to the GML Instrument. As a necessary requirement for acceptance of the corresponding data, the optical frequency of the transmitted atmospheric LiDAR laser beam must be actively stabilized to a methane gas reference cell absorption line during the acquisition of data (see Section 9.2).

7.2 Satellite Data

The subject method requires receiving GPS satellite data that is used to geo-reference methane data acquired during application of the subject method. Adequate GPS status must be maintained (see Section 9.2).

7.3 Wind Data

Wind data may be used at the time of the scan of the Target Area to enable the detection sensitivity quality assurance protocols in Section 10 and Section 11.3. Wind speed and direction at the Target Area for the subject method may be calculated, measured, or interpolated by (a) a calibrated on-site anemometer, (b) the HRRR model from NOAA, or a regional weather service with equivalent or better wind speed and direction accuracy (maximum one-hour temporal resolution), (c) using a validated model to estimate wind speed based on Methane Plume imagery, or (d) any combination of these.

8 Sample Collection, Preservation, and Storage

8.1 General Collection and Storage of Data

The GML Instrument measures and records data including the intensity of the portion of the laser beam that returns to the GML Instrument from the Target Area, GPS coordinates, temperatures, and pressures. The data may be partially (or fully) processed onboard the GML Instrument firmware in real time. The data may be stored on memory resources available internal to the GML Instrument. The data may be removed from the memory resources for post-processing and delivery purposes external to the GML Instrument. The procedures for collection, processing, and delivery of data for the subject method include the following, which are described in more detail in Section 11:

(a) Planning Procedure, see Section 11.1
(b) Data Collection and Processing Procedure, see Section 11.2
(c) Quality Assurance and Reporting Procedure, see Section 11.3

Data from the GML Instruments that is used to produce the Deliverables is stored by Bridger Photonics, Inc. for a minimum of five years from the date of delivery.

9 Quality Control

Quality assurance includes GML Instrument Calibration and Standardization as described in Section 10 in addition to the following measures:

(a) GML instrument qualification
(b) Quality checks in GML Instrument during data acquisition
(c) Continuous monitoring of GML Instrument status during data acquisition
(d) Data quality verification

9.1 GML Instrument Qualification

Each GML Instrument used under the subject method must be suitable to meet or surpass the required Performance Metrics as measured by successful completion of three qualification tests:

(a) Detection Sensitivity Test,
(b) Localization Test, and
(c) Quantification Test.

These tests must be performed under semi-blind conditions using controlled methane emission releases from a ground-based location. Therefore, the data acquisition and processing are performed without knowledge of the presence of emission, the True Coordinates, or the Metered Rate. No artificial or cooperative reflectance materials may be used to enhance reflectivity for any portion of testing.

For each GML Instrument, a controlled methane emission source must be placed pseudo randomly at a different location within the central 100 m x 100 m of the test site for issuance of various metered emission rates (“Metered Rates”) in accordance with each test protocol. The emission source must emit a gas composition consisting of >80% purity methane, with methane composition fraction known to better than ±5%, from an aperture located at a height of between 1.0 meters and 3.0 meters above ground level (“AGL”). A NIST-traceable, calibrated gas flow meter must be used to quantify the Metered Rates during testing. The flow meter must have a flow rate uncertainty of less than ±10% for all Metered Rates issued during testing, have automated time-stamped data logging capabilities.

The Test Setup must include an on-site NIST-traceable, calibrated anemometer, with automated time-stamped data logging capabilities for local wind measurements at the time of testing. The anemometer must be located horizontally within 30 meters laterally, and at a height within ±0.5 meters, of the controlled release aperture.

The following data corresponding to the test site must all be time-stamped within thirty (30) seconds of one another and documented:

(a) a binary "detect" or "no detect", and the Metered Rate, for each consecutive valid scan of the test site;

(b) the Measured Coordinates and the True Coordinates of each Emission Source detected;

(c) the averaged (up to one minute) wind speed measured by the anemometer used during testing ("Actual Wind Speed") for each consecutive valid scan of the test site; and

(d) the GCN for each consecutive valid scan of the test site.

For each test, qualifying conditions must be met for valid measurements. For the Detection Sensitivity Test and Quantification Test, the Actual Wind Speed during controlled release testing must be ≥1 m/s, the Emission Source must be within the Scan Swath, and the Methane Plume must be well developed at the time of measurement as described in Reference [13]. If the Actual Wind Speed for a given scan during a test is below 1 m/s, the Emission Source is not within the Scan Swath, or the Methane Plume is not sufficiently developed, then that scan is invalid.

During all controlled release testing, no data processing advantages and no use of information from the Test Setup, may be used to artificially improve the test results compared to field application of the subject method. For example:

(a) No knowledge of the Test Setup controlled release aperture location, height, or tendencies may be used during processing to artificially improve test results compared to field application of the subject method;

(b) No knowledge of Metered Rates or tendencies may be made available or used to artificially improve test results compared to field application of the subject method;

(c) Identification of Methane Plumes must be automated;

(d) No reduced threshold resulting in an increased probability of false positive rate, for identified Methane Plumes may be used relative to those used during field application of the subject method in meeting the Performance Metrics;

(e) All algorithms that impact test performance must perform the same or worse as those used during field application of the subject method in meeting the Performance Metrics; and

(f) No reduced processing field of view or reduced spatial analysis region may be used as compared to that used during field application of the subject method.

Each GML Instrument must successfully complete the following Detection Sensitivity Test, Localization Test, and Quantification Test at least once before use under the subject method and then at least once every two years thereafter. Calibration records are available on request to Bridger Photonics, Inc. The specifics of each test follow.

9.1.1 Detection Sensitivity Test

The goal of the Detection Sensitivity Test is to ensure that each GML Instrument's detection sensitivity performance (emission rate with POD) is consistent with the Detection Sensitivity Model (Section 12.3), which then ensures that achievement of the Detection Sensitivity Metric can be assessed during field operations. The testing is designed, through semi-blind controlled releases, to generate a sample of both true positive and false negative detection events with Metered Rates targeting between the GML Instrument's 50% and 98% POD based on the Detection Sensitivity Model. The false negative and true positive measurement results are compared to predictions from the Detection Sensitivity Model and consistency is assessed relative to a percent deviation metric. This approach accounts for the possibility that a GML Instrument detection sensitivity performance may be tested under conditions that are more favorable than during field application of the subject method. The approach also allows the testing to be performed within a broad range of environmental and operational conditions under which the Detection Sensitivity Model has been experimentally validated.

The controlled releases for the Detection Sensitivity Test must include scans by the GML Instrument of at least twelve valid measurements of controlled releases, at least six of which must be in the range of 50% to 98% POD as predicted by the Detection Sensitivity Model based on the Metered Rate, the Actual Wind Speed, and the measured GCN for the testing. The controlled releases are designed to use Metered Rates within a range intended to produce detection events with a 90% probability of detection to allow for robust comparison with predictions from the Detection Sensitivity Model (see Section 12.3). A typical range of Metered Rates for a Detection Sensitivity Test may be 0.3 kg/hr to 3.0 kg/hr. The range of Metered Rates used for testing is selected to probe the partial detection to full detection range of the GML instrument and will therefore depend on environmental and operational conditions at the time of testing (e.g. wind speed and GCN) to generate both true positive and false negative detection events. Using the known Metered Rate, Actual Wind Speed, and GCN for each detection event, the detection statistics are compared to predictions of the Detection Sensitivity Model.

Test Success Metric: For a GML Instrument to successfully pass the Detection Sensitivity Test, the count of false negative detections must not have less than 10% probability of observation based on the Detection Sensitivity Model (configured to calculate POD, see Section 12.3).

9.1.2 Localization Test

The goal of the required Localization Test is to ensure that each GML Instrument is capable of localizing an Emission Source's geodetic coordinates to meet the Localization Metric. The metric is useful for assessing the ability of GML Instruments to accurately determine the location of an Emission Source.

The controlled releases for the Localization Test must include at least nine valid measurements by the GML Instrument of issued controlled releases for which a true positive detection event is registered. This testing may share the use of true positive detection events from the Detection Sensitivity Test. A typical range of Metered Rates for a Localization Test may be 1 kg/hr to 40 kg/hr. The True Coordinates used for testing a given GML Instrument must be pseudo randomly selected within the test site.

For each valid true positive Methane Plume detection event during testing, the Measured Coordinates of the Emission Source must be determined and recorded. A priori knowledge of the True Coordinates must not be used in determining the Measured Coordinates. The absolute value of the distance between the True Coordinates and the Measured Coordinates is determined to calculate the average distance and standard deviation for all valid consecutive Emission Sources.

Test Success Metric: For a GML Instrument to successfully pass the Localization Test, the average of valid Measured Coordinates plus one standard deviation must be within 2 meters of the True Coordinates.

GML Instruments successfully completing this Localization Test may be used with "Area-level" spatial resolution, meaning the GML Instrument has demonstrated the ability to determine Measured Coordinates relative to the True Coordinates of Emission Sources to meet or surpass the Localization Metric.

9.1.3 Quantification Test

The goal of the Quantification Test is to ensure that each GML Instrument accurately quantifies emission rates corresponding to identified Emission Sources to meet the Quantification Metric.

The controlled releases for the Quantification Test must include scans by the GML Instrument of at least eight valid issuances of controlled releases for which a true positive detection event is registered and the metered release rate is greater than 3 kg/hr, which represent additional requirements for a valid measurement for the Quantification Test. This testing may share the use of true positive detection events from the Detection Sensitivity Test and/or the Localization Test. A typical range of Metered Rates for a Quantification Test may be 3 kg/hr to 40 kg/hr.

For each valid true positive Methane Plume detection event during testing, the Relative Error Ratio must be computed and recorded. A priori knowledge of the Metered Rate must not be used in determining the Estimated Rate.

Test Success Metric: For a GML Instrument to successfully pass the Quantification Test, the average of all valid Relative Error Ratios for that sensor must fall between 0.7 and 1.3.

9.2 Monitoring of GML Instruments During Data Collection

The following instrument data quality indicators must be monitored in flight during data collection to ensure proper performance of the instrument:

Table 1. Continuously Monitored Data Quality Indicators

Parameter	Acceptable Deviation	Measurement Conditions
Beam Scanner	≤ 400 RPM	LiDAR beam scanner rotation rate monitor must indicate a deviation from the target rotation rate no greater than 400 RPM.
GPS Status	≥ 8 satellites ≤ 2 m position uncertainty	The GPS satellite monitor must indicate communication with no less than 8 satellites and average position uncertainty must indicate no greater than 2 m.
Gas Laser Stabilization	≤ 200 MHz	The gas laser stabilization monitor must indicate no greater than 200 MHz deviation from the target optical frequency as referenced against the on-board reference gas cell (Section 7.1) and must be logged with a time resolution of no greater than 0.1s.

10 Calibration and Standardization

For application of the subject method, the GML Instrument must be properly calibrated and maintained in accordance with this section. At a minimum, the parameters in Table 2 must be calibrated and/or verified for each GML Instrument for which the subject method is used prior to its first use and repeated no less frequently than once every two years thereafter. Further descriptions of calibration and verification procedures are provided in Sections 10.1-10.6.

Table 2. GML Instrument Calibration Parameters

Parameter	Value	Measurement Conditions
Chemical species detected	Methane (CH_4)	Methane absorption line.

Parameter	Value	Measurement Conditions
P-Concentration Measurement Uncertainty	≤ 10%	Calibrated in the laboratory using external gas cells containing a calibrated P-Concentration of methane gas. Calculation of P-Concentrations based on absorption measurements and LAS model must agree to calibrated P-Concentration to within ≤ 10%.
LiDAR Range Measurement Uncertainty	< 3 parts in 10^3	Verified by direct comparison with an external range measurement system with <1 part in 10^3 uncertainty.
Thermal operation range	> 0°C and < 40°C minimum range.	All critical subsystems must operate properly during thermal cycling for no less than 10 minutes at low and high temperature limits. Broader allowed operating temperature ranges may be established for individual GML Instruments.
LiDAR Geo-Registration Uncertainty	≤ 2 m	Verified during airborne testing by determination of the discrepancy between GML Instrument-measured and ground-calibrated geodetic coordinates of the same object.
Aerial Photography Geo-Registration Uncertainty	≤ 2 m	Verified by direct comparison with geo-registered 3D topographic LiDAR imagery or Google Earth imagery.

10.1 Chemical Species Detected

Each GML Instrument is configured and calibrated to detect the primary isotope of methane gas ($^{12}CH_4$).

10.2 P-Concentration Calibration

The ability for each GML Instrument used for the subject method to accurately measure P-Concentration is verified through a calibration procedure. This calibration procedure compares P-Concentration determined by the GML Instrument to a known P-Concentration in multiple physical reference standards of known path length, tested for methane purity, and each having pressure ≤ 10% from specification. The comparison is based on (a) empirical laser absorption measurements performed by the GML Instrument, and (b) a physical model of the methane absorption measurement that includes laser modulation parameters, spectroscopic properties of the absorption line, and environmental variables to convert the absorption signals recorded by the GML Instrument into P-Concentration. Details of the physical model for the case of Wavelength Modulation Spectroscopy (WMS) are presented in Section 12.1.

The output laser beam from the GML Instrument (when the laser beam is not spatially scanned) is passed through external gas reference cells (fixtures) with known P-Concentrations. Laser light is transmitted through the gas reference cell(s) to a target and scattered back to the GML Instrument, and the attenuation of the laser light due to the gas absorption is measured by the GML Instrument. The P-Concentration values calculated by the GML Instrument due to the attenuated laser light are calibrated so that they agree with the known gas cell P-Concentration values to within ±10% for each of at least two gas cells, each with a different P-Concentrations, spanning (roughly logarithmically) the P-Concentration measurement range of the GML Instrument. For example, gas cell P-Concentrations of 500 ppm-m, 5,000 ppm-m and 50,000 ppm-m may be appropriate for a GML Instrument with a P-Concentration range of 0-50,000 ppm-m.

10.3 LiDAR Range Measurement Calibration

The LiDAR range measurement is calibrated by comparing the result of a GML Instrument range measurement to a separate calibrated test range reference measurement system. The reference measurement system must have a range uncertainty of <1 part in 10^3. Comparisons are made using a test target at a distance of >50 meters. The GML instrument must have a difference from the test range reference measurement system equal to or less than three parts in 10^3.

10.4 Temperature Operation Range Standardization

The acceptable operating temperature range for the GML Instrument is established by thermally cycling the GML Instrument in a thermal chamber. During this test, critical subsystems of the GML Instrument including laser systems, beam scanner, and Navigation System are activated. The GML Instrument ambient temperature is controlled to the limits of the operating temperature range and then allowed to reach thermal equilibrium for at least 10 minutes. During the test, critical GML Instrument subsystems must not flag anomalous behavior relative to established subsystem performance at temperatures of 0ºC and at 40ºC for a minimum of 10 minutes at each temperature extreme. GML Instruments functioning properly over larger temperature ranges may be used under the subject method over the larger temperature ranges.

10.5 LiDAR Geo-Registration Calibration

LiDAR geo-registration performance is calibrated and verified using flight test data. One or more objects are selected as physical references for airborne testing. GML Instrument data is recorded for flight passes over the reference object at more than one flight altitude and from roughly perpendicular flight pass directions. 3D point clouds of the reference object are generated from the GML Instrument data for each flight pass. The GML Instrument spatial calibration parameters are adjusted to achieve alignment of the 3D point clouds from all passes to within 2 m. The absolute position of 3D point clouds from all flight passes must agree with a GPS (RTK) location measurement to within 2 meters.

10.6 Aerial Photography Geo-Registration Calibration

The aerial photography is ortho-rectified and geo-registered using the GML Instrument range data or aerial or satellite imagery. The GML Instrument spatial calibration parameters are adjusted to achieve alignment between references features (structures, roads, etc.) in the 3D point cloud or aerial or satellite imagery with the corresponding features in the aerial photography to within 2 m.

11 Procedure

The overall procedure for the subject method ("Procedure") includes Planning, Data Collection and Processing, and Data Quality Assurance and Reporting. Each of these procedures is described below.

11.1 Planning Procedure

Prior to scanning, one or more Target Areas are identified as geographic areas that enclose equipment or other assets to which the subject method is applied. Once a Target Area is defined, a flight plan may be established with the intention that the Target Areas fall within the "Scan Swath" extent of the GML Instrument. A flight plan may include multiple passes of a single Target Area (e.g. to enable adequate spatial coverage of a Target Area) and multiple Target Areas.

The planning procedure may include consideration of flight hazards and may be designed to avoid operational and environmental conditions that may inhibit successful completion of the subject method. Method performance is confirmed in the posterior using the Scan Coverage Audit and Detection Sensitivity Audits (see Section 11.3). Planning may therefore begin with assessment of weather, flight crew status, and other conditions to ensure the scans of Target Areas may be performed in a safe manner.

11.2 Data Collection and Processing Procedure

During a scan of a Target Area, a flight plan may be followed. Data collection by the GML Instrument occurs during overflight of the Target Area. The critical GML Instrument functionality listed in Section 9.2 must be confirmed during scanning operations.

An initial scan of the Target Area is performed to detect Methane Plumes. Multiple flight passes may be required to achieve adequate scan coverage and therefore to successfully pass the Scan Coverage Audit described in Section 11.3.

A Secondary Scan of the Target Area may be performed in locations within the Target Area where initial data and analyses indicate identification of one or more Emission Sources. The data collected from scans after the initial scan may be used to verify identification of Emission Sources as a quality assurance step.

Data collected of the Target Area may be processed on-board the GML Instrument, or elsewhere, to generate, the Deliverables and, optionally, the Auxiliary Data.

11.3 Data Quality Assurance and Reporting Procedure

For quality assurance and control purposes, each identified Emission Source within the Target Areas must be verified to have the appropriate attributes assigned for the Deliverables.

In addition to these quality assurance and quality control measures, two internal audits are performed to confirm adequate spatial scan coverage and detection sensitivity for the Target Areas under the subject method:

(a) Scan Coverage Audit: To ensure adequate spatial scan coverage by the GML Instrument, the average percent coverage of Target Areas under the subject method must be greater than 90% ("Scan Coverage Audit") for the collection of Target Areas under the subject method.

(b) Detection Sensitivity Audit: To ensure adequate detection sensitivity performance, the Detection Sensitivity Metric must be met for the Target Areas scanned under the subject method. The Detection Sensitivity Model (configured to calculate emission rate for 90% POD, see Section 12.3) is used to confirm that the GML Instrument(s) detection sensitivity meets or surpasses the Detection Sensitivity Metric for the collection of Target Areas under the subject method.

Spatial coverage and detection sensitivity reports (e.g., histograms similar to Figure 8) are available on request to Bridger Photonics, Inc.

Incremental delivery of the Deliverables is acceptable (e.g. the Deliverables need not be delivered all at the same time) and can promote expedited emissions reduction. If one or more Target Areas preclude passage of either audit above, then scans for those Target Areas must be repeated to achieve regulatory compliance for those Target Areas under the subject method. The disqualification of a Target Area for regulatory compliance under the subject method for a given time period does not affect such qualification of any other Target Area or any other time period.

11.4 Training Procedure

Training is required if flight planners have less than 1 year of existing experience. The training protocol for flight planning (see Section 11.1) requires successful completion of established projects that introduce the trainee to the method objectives and metrics. During this course, trainees are exposed to datasets on our special training database that have been previously analyzed by our teams. The metric for qualification as a planner is achievement of similar results to recognized planning quality, and approval by an authorized planner expert with at least one year of planning experience pertaining to field operations.

The training protocol for data processing and analysis (see Section 11.2) includes a 6-8 week internal course, mentored by experienced processors and analysts, to establish a strong understanding and ability to utilize internal software, data analysis methods, and workflows. At the end of this course, trainees are tested using multiple testing data sets that have been previously analyzed by established processing and analysis experts. The testing data sets include varying degrees of complexity and geographical location to ensure a well-rounded understanding of processing and analysis under different circumstances. Upon completion of the course and testing, a qualified processing and analysis expert reviews the test results to approve or deny the trainees ability to perform processing and analysis for the subject method.

Records of employment start and date that individuals transition from training to operations are retained and available on request to Bridger Photonics, Inc.

12 Data Analysis and Calculations

12.1 LiDAR Laser Absorption Spectroscopy Physical Model

This subsection describes the mathematical framework used for the WMS technique under the subject method to calculate P-Concentration based on a laser absorption measurement and other parameters. It is used in generating Methane Plume imagery and in the calibration and standards checks to confirm that the absorption measured by each GML Instrument yields the correct P-Concentration (see Section 10.2).

For the case of WMS, the P-Concentration traversed by the laser beam is calculated by Eq. 12-1:

$$C_{PI} = \frac{mP_{2f}}{P_{1f}}\,\gamma\left(T, p, \frac{mP_{2f}}{P_{1f}}, \eta, \xi\right)$$

Eq. 12-1

Where:

P_{1f}	=	the measurement of received optical power
P_{2f}	=	proportional to the methane concentration
m	=	the intensity modulation depth that relates P_{1f} to the total average received laser power
γ	=	coefficient that relates the ratio $\frac{mP_{2f}}{P_{1f}}$ to the P-Concentration
η	=	laser modulation parameters of the transmitted lidar beam
ξ	=	methane spectroscopic parameters
T	=	atmospheric temperature
p	=	atmospheric pressure

The LiDAR equations to calculate the signal power received by the sensor are calculated as follows (Eq. 12-2 through Eq. 12-4):

$$P_{DC} = \frac{A\chi\rho}{R^2} S_{DC} \,,$$

Eq. 12-2

$$P_{1f} = \frac{A\chi\rho}{R^2} S_{DC} m \,,$$

Eq. 12-3

$$P_{2f} = \frac{A\chi\rho}{R^2} S_{DC} \frac{C_{PI}}{\gamma} \,.$$

Eq. 12-4

Where:

S_{DC} = DC component of the LiDAR beam transmitted power, W
P_{DC} = DC component of the LiDAR received power, W
A = area of the receiver, m^2
χ = receiver optics collection efficiency, unitless
ρ = terrain reflectivity per steradian, sr^{-1}
R = distance from sensor to terrain, m
C_{PI} = P-Concentration, in units of ppm-m

12.2 Environmental Parameter Data

The environmental parameters outlined in Table 3 are measured to provide appropriate inputs for P-Concentration referenced elsewhere in the subject method.

Table 3. Environmental Parameters

Parameter	Uncertainty	Measurement Conditions
Ambient temperature	≤ 4.0° C	Measured and logged at a rate of at least once per ten seconds.
Ambient pressure	≤ 1,000 Pa	Measured and logged at a rate of at least once per ten seconds.

12.3 Detection Sensitivity Model

This subsection describes the mathematical framework (“Detection Sensitivity Model”) used under the subject method to determine the detection sensitivity performance of a GML Instrument under operational and/or environmental conditions that may be experienced during field operations.

This section describes how the Detection Sensitivity Model is applied to the subject method. To ensure consistent and predictable detection sensitivity performance of GML Instruments during sensor qualification, the Detection Sensitivity Model is solved for POD (as described below) for use with the Detection Sensitivity Test (see Section 9.1.1). Alternatively, to ensure consistent and predictable detection sensitivity performance of GML Instruments during field operations, the Detection Sensitivity Model is solved for emission rate (as described below) to directly confirm the actual field performance of GML Instruments for data quality assurance as part of the Detection Sensitivity Audit (see Section 11.3).

Developing and validating a model to determine the detection sensitivity performance (an emission rate with a POD) of a methane detection technology or instrument can be intractable due to the high dimensionality of the parameter space involved (i.e. many conditions can impact the detection sensitivity performance). However, it has been found that the detection sensitivity performance of GML Instruments can be consolidated to depend on just two independent variables: GCN and wind speed. Importantly, all operational and environmental parameters *except* for wind speed (e.g. flight altitude, flight speed, LiDAR transmitter/receiver characteristics, LiDAR point density, terrain reflectivity, etc.) affecting the detection sensitivity performance of a GML Instrument (see Section 4.1 - 4.7) are represented by the measurable GCN variable.

For the subject method, the dependence of the detection sensitivity performance on these two independent variables (wind speed and GCN) has been robustly tested under semi-blind controlled release conditions and the Detection Sensitivity Model has been developed and validated to confidently determine the detection sensitivity performance of GML Instruments under field operational and environmental conditions (see Reference [13]). During testing and validation, true positive and false negative detections were plotted within the range of operational and environmental conditions that may be experienced during field operations to construct a generalized POD function that describes detection sensitivity as a function of GCN and wind speed.

While wind speed may be acquired separately from the GML Instrument data (e.g. from a remote wind model, such as NOAA HRRR, in-situ anemometer data, or using a validated model to estimate wind speed based on Methane Plume imagery), a calibrated noise model is used to determine the GCN for each GML P-Concentration measurement. The model used to determine GCN includes contributions from incoherent noise sources (n_{in}) and coherent noise sources (n_{cn}) and has the functional form described in Eq. 12-5:

$$GCN = \sqrt{n_{in}^2 + n_{cn}^2}\,,$$

Eq. 12-5

where n_{in} may include shot noise, Johnson noise, relative intensity noise, and other incoherent noise sources, and n_{cn} may include speckle noise[8] and other coherent sources.

An example equation to calculate the incoherent noise is provided in Eq. 12-6:

$$n_{in} = \frac{-m\gamma NEP}{2P_{1f}\sqrt{\Delta T}},$$
Eq. 12-6

Where:

NEP	=	Photodetector noise equivalent power (including shot noise)
ΔT	=	LiDAR gas concentration measurement duration.

The detection system *NEP* and the LiDAR transmitter/receiver speckle noise (n_{cn}) are calibrated during manufacturing and validated through flight testing. Flight test validation is performed by computing the observed GCN using statistical analysis of sets of measured LiDAR gas concentration values and comparing them against the GCN values produced for each individual LiDAR gas concentration measurement by the model.

To account for detection sensitivity effects related to the spatial distribution and density of individual LiDAR gas concentration measurements and to create gas plume imagery, the geo-registered GCN values are interpolated onto a raster grid having fixed pixel size. An example of the spatial distribution of LiDAR points and raster grid are shown in Figure 2.

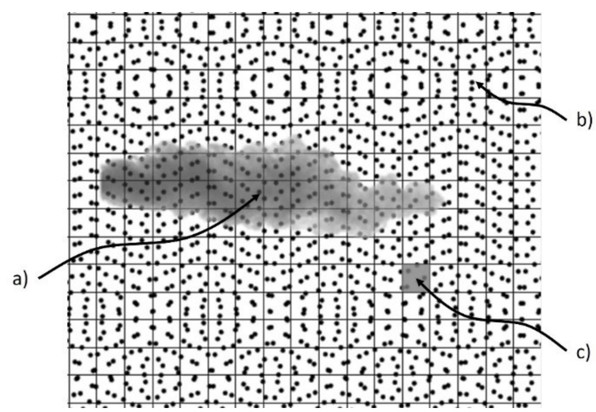

Figure 2. Procedure diagram for the subject method with example responsible parties.

The raster image P-Concentration pixel values are computed by a weighted average of the individual LiDAR P-Concentration values within each pixel, where the weighting factors for the individual P-Concentration LiDAR measurements are derived from the GCN values. Specifically, the pixel P-Concentration and GCN values are computed using Eq. 12-7 through Eq. 12-9:

$$c_j = \frac{\sum w_i c_i}{\sum w_i},$$
Eq. 12-7

$$w_i = \frac{1}{GCN_i^2},$$
Eq. 12-8

$$GCN_j = \frac{1}{\sqrt{\sum w_i}}.$$
Eq. 12-9

Where:

j	=	the j^{th} pixel in the raster grid
i	=	the i^{th} LiDAR point in the j^{th} raster pixel
c_j	=	the weighted average P-Concentration for the j^{th} raster pixel
w_i	=	the weighting factor for the i^{th} LiDAR point in the j^{th} raster pixel
GCN_j	=	the weighted average *GCN* for the j^{th} raster pixel

Details of the Detection Sensitivity Model may be adapted with other wind speed determinations (e.g. local) and the actual emission rate. The probability of detection *POD* is modeled using the Bernoulli distribution with a 'predictor' function g(**x**;α) with variables **x** = [*GCN*, *u*, *Q*] and coefficients β and 'inverse link' function F(g(**x**;α);β) with coefficients β, such that the probability of GML detecting an emission of rate *Q* at a location with wind speed *u*, and gas concentration noise *GCN* is given by Eq. 12-10:

$$POD \stackrel{\text{def}}{=} \mathrm{F}(\mathrm{g}(\mathrm{x};\alpha);\beta).$$
Eq. 12-10

Maximum likelihood estimation (MLE) is used to optimize the coefficient values for candidate pairs of predictor and inverse link functions using the negative logarithm of the likelihood function for the Bernoulli distribution. The corrected Akaike Information Criterion is used to compare the MLE optimization outcomes for various functional forms for predictor and inverse link functions to determine the predictor and inverse link functions that best represent the controlled release data. The controlled release detection data using the GCN model input was found to be best represented by the predictor function, Eq. 12-11:

$$g(Q,u,GCN) = \frac{\beta_1 Q^{\beta_2}}{GCN^{\beta_3} u^{\beta_4}}.$$
Eq. 12-11

As new controlled release data is acquired, and over a broader range of environmental and operational conditions, the POD model may be refined using the optimization process described above, and the functions and coefficients that best represent the data are used to compute POD. Currently, the optimized Detection Sensitivity Model is configured to calculate POD for a given emission rate, provided in Eq. 12-12:

$$POD = 1 - \left(1 + \left[\frac{\beta_1 Q^{\beta_2}}{GCN^{\beta_3} u^{\beta_4}}\right]^{\alpha_1}\right)^{-\alpha_2},$$

Eq. 12-12

Where:

α = [2, 1.5]
β = [0.0241, 1.9505, 2.0836, 1.5185]

The Detection Sensitivity Model solved for POD as above may be used to determine success of the Detection Sensitivity Test (see Section 9.1.1).

The Detection Sensitivity Model can alternatively be solved for the emission rate *Q* as a function of wind speed *u*, *GCN*, and POD, yielding an equation that describes iso-POD surfaces (i.e. surfaces of fixed POD). The Detection Sensitivity Model, when configured to calculate an emission rate detection sensitivity for a fixed POD, is Eq. 12-13:

$$Q_{POD} = \left(\left[(1 - POD)^{\frac{-1}{\alpha_2}} - 1\right]^{\frac{1}{\alpha_1}} \left[\frac{GCN^{\beta_3} u^{\beta_4}}{\beta_1}\right]\right)^{\frac{1}{\beta_2}}.$$

Eq. 12-13

In this form, the Detection Sensitivity Model is used to verify the performance of GML Instruments in the field using the Detection Sensitivity Audit (see Section 11.3).

Other methods or models that have been experimentally validated by comprehensive measurements to perform equally or better than those presented here, and published in reputable peer-reviewed journals, may also be used to determine the dependence of detection sensitivity performance (emission rate and POD) on operational and environmental conditions.

With regard to the Detection Sensitivity Test, the POD is calculated for each valid measurement of a controlled release. The PODs are then used to create a Bernoulli probability generating function, and subsequently a cumulative distribution function (CDF). Figure 3 shows the Bernoulli CDF for a test flight with nine valid issuances of controlled releases. For a GML Instrument to successfully pass the Detection Sensitivity Test, the count of false negative detections must not have less than 10% probability of observation. For example, as shown in Figure 3, four or more detections are required to pass the Detection Sensitivity Test for this case. The test flight resulted in seven detections, which represents success in passing the test.

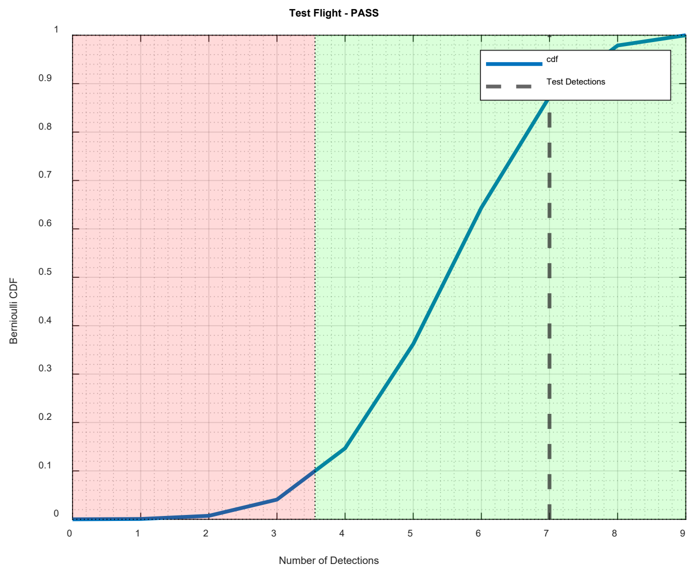

Figure 3. Shows an example Bernoulli CDF as a function of observed detections.

12.4 Emission Rate Quantification

Determination of an Estimated Rate for the subject method is described in Reference [9] and includes: (a) using Methane Plume imagery to define a gas flow direction from the Emission Source, (b) combining the Methane Plume profile in up to three spatial dimensions with the gas flow speed (e.g. wind) profile in up to three spatial dimensions to determine flow rates, and (c) averaging over flow rates pertaining to a region of the Methane Plume that is less perturbed (e.g. by turbulence, local structures, foliage, or topography), to determine an Estimated Rate. This process is partially automated and partially manual.

Third-party proof of performance of determining Estimated Rates for the subject method is shown in Figure 4. The figure shows results from three separate controlled release data sets, performed by three separate entities (Carleton University [12], Colorado State University [7], and Bridger Photonics, Inc. [10]) comprising Methane Plume detections from approximately 1,300 controlled release test scans.

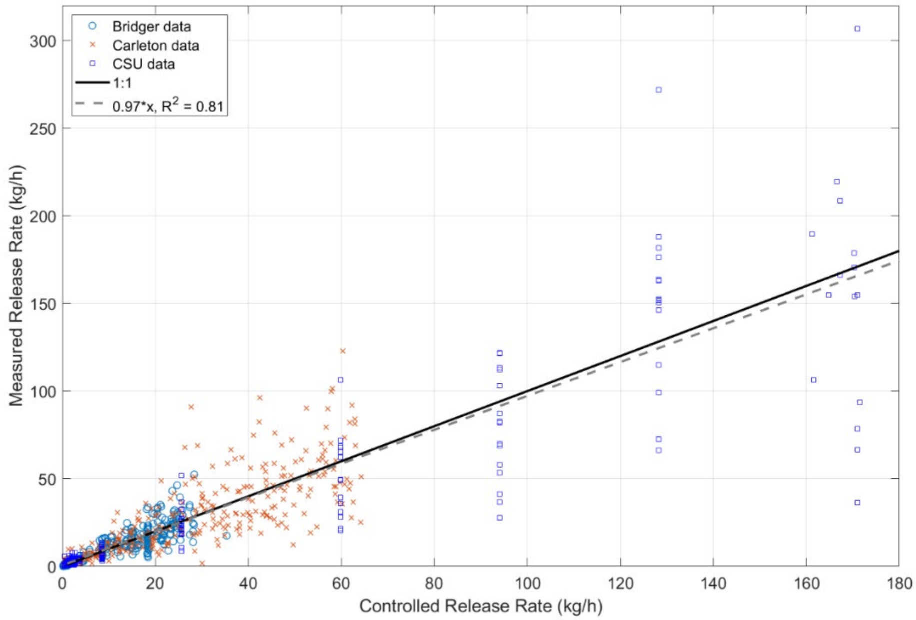

Figure 4. Plot of Estimated Rate versus Metered Rate for three controlled release test data sets – Bridger sensor QA data, Carleton single- and double- blind release data (Reference 12), and CSU single blind controlled release data (Reference 7). The black solid line represents 1:1 parity and the gray dashed line represents an ordinary least squares linear regression with slope = 0.97 and R^2 = 0.81.

13 Method Performance

Semi-blind controlled release testing (i.e. where the sites and/or locations, but not the emission rates, of the controlled emissions are known to the party under test) can be a useful step in assessing a methane detection technology's detection sensitivity performance during field operations. However, it is known that the operational and environmental conditions under which semi-blind controlled release testing is performed can represent a very limited (and typically favorable) subspace of those conditions under which field operation are performed. Therefore, it is acknowledged that semi-blind controlled release testing is inadequate to establish a technology's detection sensitivity performance during field operations unless it is performed comprehensively over the range of variables experienced during field operations that can affect detection sensitivity.

Also, knowledge of the sites and/or locations of the releases during controlled release testing can be used to artificially enhance detection sensitivity performance under semi-blind controlled release conditions. For example, a signal-to-noise threshold for identification of Methane Plumes may be relaxed during controlled release testing because there is limited negative consequence of false positive Methane Plume identifications, particularly when the emission source is known a priori. Therefore, it is acknowledged that controlled release testing must be performed using the same, or more stringent/selective, data processing as used during field operations, which must include automated Methane Plume detection and must not produce a higher false positive rate as during field operations, to constitute valid controlled release test results and prevent artificial enhancement of performance.

Acknowledging these challenges, the following three controlled release tests establish evidence of the detection sensitivity performance and emission rate quantification error of GML technology achieved during field operations: (1) fully-blind controlled release testing in the field, and (2) parameter-based performance determination that is validated over the variables that affect detection sensitivity and emission rate quantification. Such a determination may be used to establish detection sensitivity performance and emission rate quantification error during field operations.

13.1 Fully-Blind Controlled Releases

13.1.1 Detection Sensitivity

Controlled release testing was performed by Carleton University on GML technology (first-generation sensors) in 2019 and 2020/2021 during actual field operations under fully-blind conditions (i.e. without any knowledge of those acquiring or processing the data).[11,12] Those affiliated with GML therefore had no prior knowledge of the controlled release location, site, region, height, emission rate, or even that the testing was taking place, until after the scan results were delivered. Such fully-blind testing performed during field operations ensures that no artificial processing advantages are used for the controlled release testing, and that actual field conditions are present. The key results of the 2020/2021 testing are provided in Figure 5, which shows the controlled source emission rate as a function of wind speed for numerous releases and for the first-generation of GML sensors.[12]

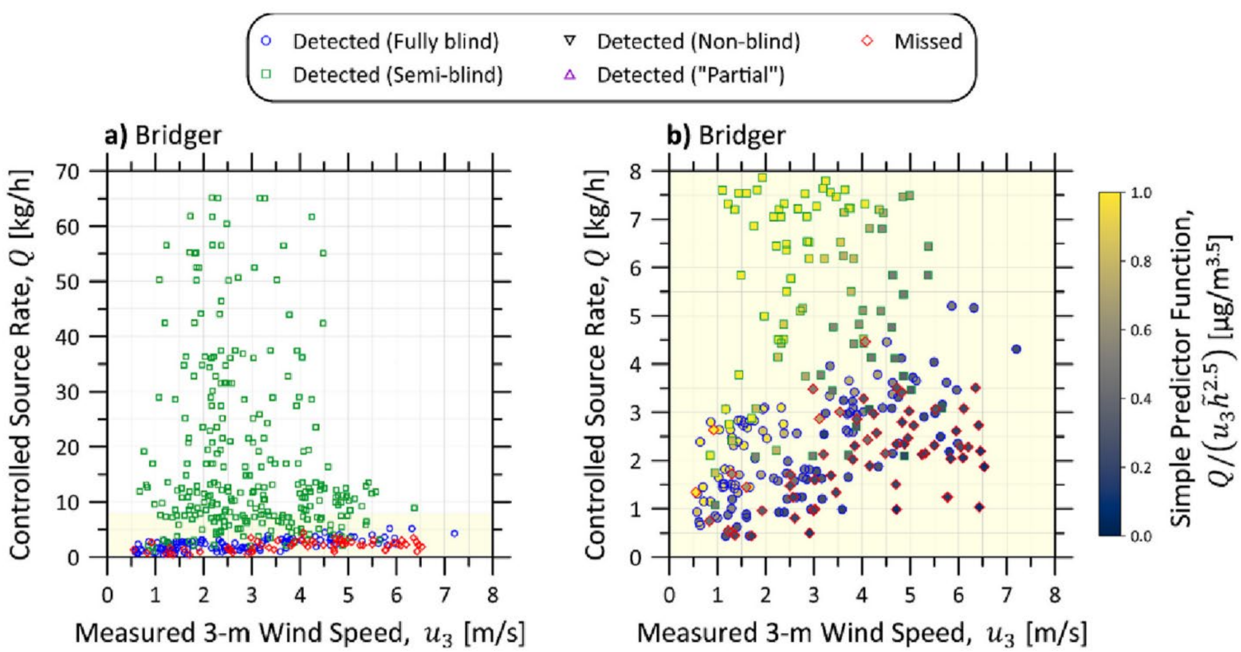

Figure 5. Key results from controlled release testing performed by Carleton University of GML technology (first-generation sensors) taken during field operations in 2020/2021.[12] Blue-outlined circles are fully-blind true positives, green-outlined squares are semi-blind true positives, and red-outlined diamonds are false negatives.

In the figure above, blue-outlined circles indicate true-positive detections of fully-blind controlled releases, and red-outlined diamonds represent false-negative detections, during the testing. While the semi-blind and fully-blind false negatives are not distinguishable in this figure, the data indicate that the first-generation GML sensor detected 120 (out of 182) fully-blind controlled releases ranging from 0.4 kg/hr to 5.2 kg/hr during standard operations. The data also indicate that the first-generation GML achieved no false negative detections at all above 4.5 kg/hr for any wind speed experienced during the testing (up to 7.5 m/s).

Using the combined detection data (fully-blind and semi-blind), a generalized mathematical model was generated in reference [12] that represents the POD achieved by the first-generation GML sensor for a given emission rate (Q) at a given wind speed (u) and flight altitude (h), as provided in Eq. 13-1:

$$\mathrm{POD} = \exp\left(-\left(\frac{0.224\, Q_{[\mathrm{kg/h}]}^{1.07}}{\left(\frac{\tilde{h}_{[m]}}{1000}\right)^{2.44} \left(u_{3[\mathrm{m/s}]} + 2.14\right)^{1.69}} \right)^{-2.53} \right)$$

Eq. 13-1

The detection sensitivity observed by the first-generation GML sensor at the common reference wind speed of 3 m/s and at GML's then-standard operational flight altitude of 175 m was determined to be 2.3 kg/hr with 90% POD. Second generation GML has improved performance, and the detection sensitivity can be improved further by restricting flight altitude and wind speed within GML operations. It is acknowledged that the above model only accounts for wind speed and flight altitude, while other operational and environmental factors also impact detection sensitivity. Section 12.3 extends the formalism established in Reference [12] to create a generalized model that accounts for all operational and environmental factors to enable determination of detection sensitivity in any field condition, as summarized in Section 13.2, below.

13.1.2 Emission Rate Quantification

The Carleton University controlled release data described in the previous section and a single-blind controlled release data from two separate tests administered by Colorado State University (CSU) in Midland, TX in October 2021 and Stanford University in Ehrenberg, AZ in November 2021 are used to demonstrate performance of GML emission rate estimates. Both third-party tests show similar performance for the quantification error bias and variance associated with Estimated Rates by GML Instruments. Results from the Carleton University controlled release test are shown in Figure 6.

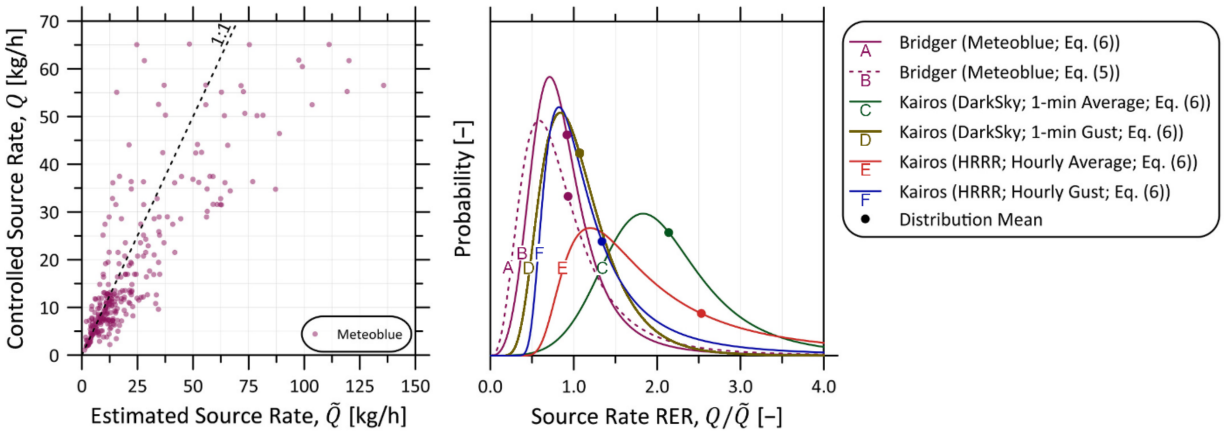

Figure 6. Emission rate quantification results from controlled release testing performed by Carleton University of GML technology (first-generation sensors) taken during field operations in 2020/2021. (Left) Plot of the GML estimated source rate against the controlled release rate for each GML Estimated Rate (dashed gray line indicates 1:1 parity line). (Right) Distributions of the Relative Error Ratio for emission rate estimates analyzed by Carleton University in the study (curves A and B are Bridger GML results). Note that RER is defined as Metered Rate divided by Estimated Rate in Carleton study whereas it's defined as Estimated Rate divided by Metered Rate for the subject method described herein.

Results from the Carleton test show an overall +8% bias of the Estimate Rate indicated by the Distribution Mean marker shown in Figure 6 (Right). Similar results are observed from the CSU and Stanford controlled release tests, shown in Figure 7. In this data set an 8% positive bias of the Estimated Rates is observed, based on the slope of the linear regression shown in Figure 7 (Top). Further analysis of this data shows a positive bias and larger variance for GML Estimated Rates for small Metered Rates, Figure 7 (Bottom). Despite the larger variance of Estimated Rates for smaller Metered Rates the low-side percent error for Metered Rates below 1 kg/h is smaller than the low-side error for Estimated Rates corresponding to Metered Rates larger than 1 kg/h.

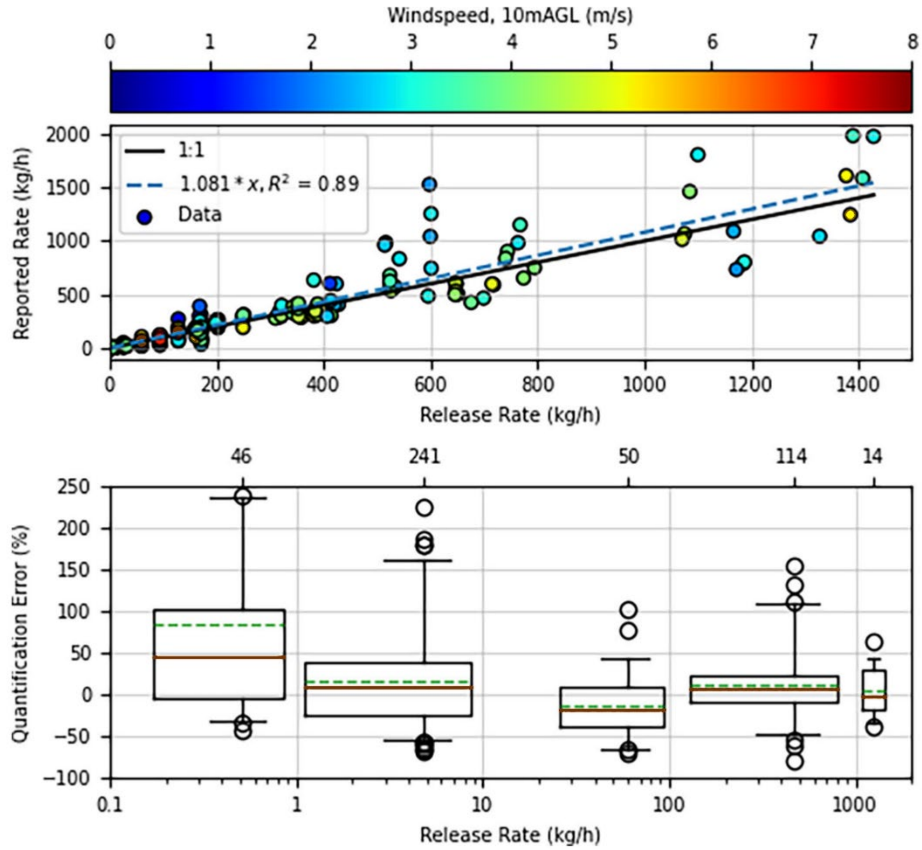

Figure 7. Results from the CSU and Stanford controlled release tests. (Top) Plot of the estimated release rate versus the controlled release rate with the 1:1 parity line (black) and a liner fit of the data (dashed line). (Bottom) Box and Whisker plot of the % error defined as Estimated Rate/Metered Rate for different Metered Rate bins. The mean error for each bin is indicated by the solid horizontal line showing a positive bias in the Estimated Rate for small emission rates.

13.2 Parameter-Based Detection Sensitivity Determination

The second technique for establishing a technology's detection sensitivity performance during field operations is to develop a parameterized detection sensitivity model, informed and validated by controlled release testing with automated plume detection algorithms, across the variable ranges of conditions experienced during field operations that can affect detection sensitivity performance. Bridger developed and validated a detection sensitivity model ("Detection Sensitivity Model", see Section 12.3 and Reference [13]) based on controlled release testing, that consolidates all operational and environmental conditions (e.g. wind speed, flight altitude, flight speed, ground reflectivity, measurement point density, etc.) into two measurable independent variables: wind speed, and gas concentration measurement noise. During field operations, both of these variables, and therefore the detection sensitivity performance, are determined for each Target Area scanned in the field. This information is used to verify that GML achieves the Detection Sensitivity Metric during field operations, as part of the Detection Sensitivity Audit described in Section 11.3.

In this section, the results of the model described in Section 12.3 are applied to second-generation GML Instrument data to establish the performance during example past field operations. The controlled release data, tested across the two independent variables of wind speed and gas concentration noise, can be represented by the general Detection Sensitivity Model form as provided in Eq. 12-13, where Q_{POD} is the emission rate detected for a given probability of detection (*POD*), gas concentration noise ("*GCN*"), and wind speed (*u*). The model parameters (α_1, α_2, β_1, β_2, β_3, β_4) are determined by repeated controlled release testing (with automated Methane Plume identification and zero false positive identifications) under varying operational and environmental conditions that may be experienced in the field. The parameter values may be continually refined over time to more accurately represent the GML Instrument fleet performance as more controlled release testing is performed (see Section 12.3).

Using this formalism, Figure 8 shows a histogram of emission rate detection sensitivities (90% POD) achieved for individual scanned Target Areas during standard field operations in the Marcellus production basin. The figure indicates an average detection sensitivity of 0.9 kg/hr (90% POD) is achieved by second-generation GML sensors in the Marcellus basin under standard operating conditions for that basin, and no Target Areas were scanned with a detection sensitivity poorer than 2.5 kg/hr (90% POD). Target Areas were not pre-arranged for testing and there was no selection or de-selection of Target Areas to influence the results.

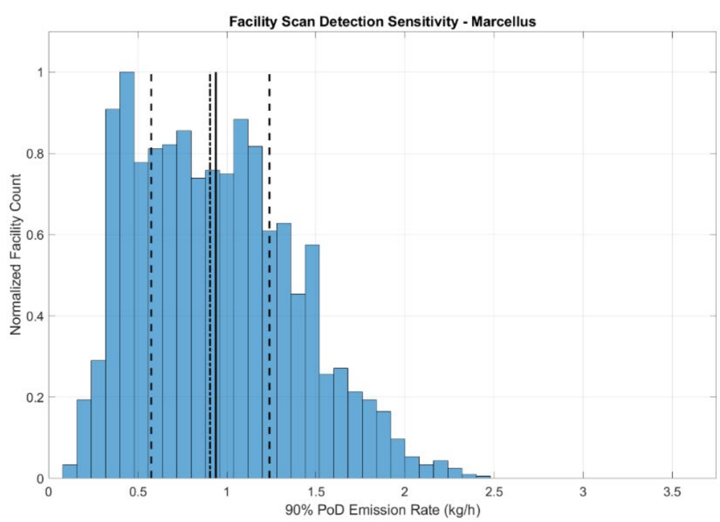

Figure 8. Example histogram of detection sensitivity (90% POD) achieved for numerous Target Areas scanned during field operations in the Marcellus Basin. The dot-dash vertical line represents the median emission rate for 90% POD, and the solid vertical line represents the mean emission rate for 90% POD. The black dashed lines bound the interquartile of the sample set.

The results shown in Figure 8 establish that GML Instruments can achieve a Detection Sensitivity Metric better than 1 kg/hr (average, with 90% POD) during standard field operations. To accommodate *less* restrictive regulatory detection sensitivity tiers under the subject method, (a) acceptable wind speeds for operations may be increased, (b) GCN may be increased by any means (e.g. increased acceptable flight altitude or speed) or, (c) the acquired data may be processed to align Deliverables with aa higher emission rate Detection Sensitivity Metric. For all cases, the Detection Sensitivity Audit shall be used to validate field instrument performance (See Section 11.3).

14 Pollution Prevention

A discussion of pollution prevention issues is not relevant, as no physical samples are collected under this method.

15 Waste Management

Because no physical samples are collected with the laser-based remote sensor, there are no waste management concerns.

16 References

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17 Method Flowchart

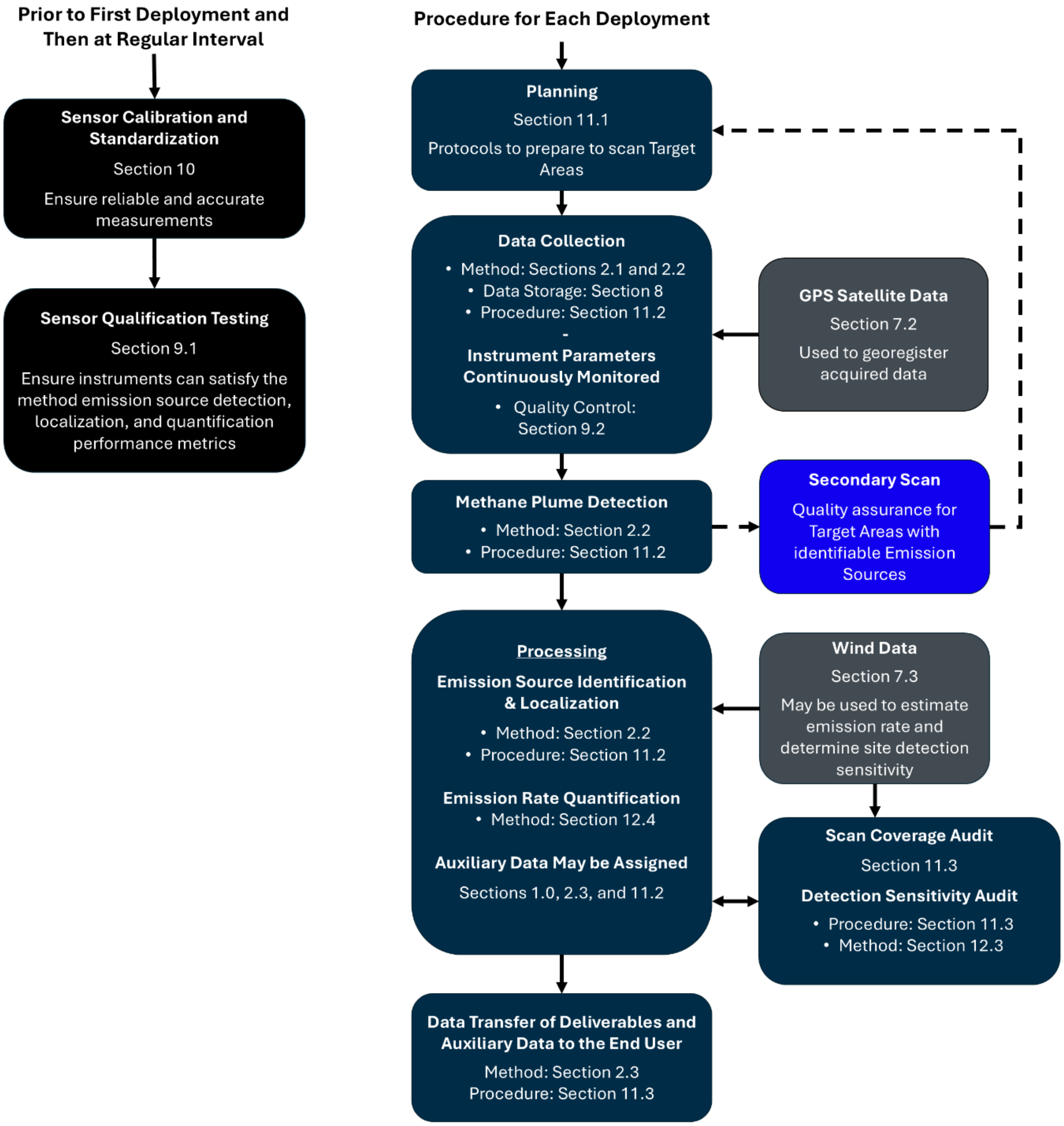

Figure 9. Subject method flow chart.