SENSIRION
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Nubo Sphere

Test Method for Periodic Screening

Application for Approval as Periodic Screening Alternative Technology

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Alternative Test Method – Detection of Methane Emissions using Laser-Based Photoacoustic Methane Point Sensor Technology for Periodic Screening using Sensirion Connected Solutions Nubo Sphere

Minimum Detection Threshold: ≤3 Kg/h with 90% Probability of Detection

1 Scope and Application

1.1 Analytes

Analyte	CAS No.
Methane (CH_4)	74-82-8

1.2 Scope

This method is an alternative test method for periodic screening to detect fugitive emissions from fugitive emissions components affected facilities and to determine compliance through the inspection and monitoring of covers and closed vent systems in lieu of the procedures set forth in the regulations presented in Table 1, including optical gas imaging (OGI) and EPA Method 21.

1.2.1 The methodologies in this alternative test method are specifically designed to be applied using the Nubo Sphere laser-based photoacoustic methane sensing technology. Sensirion Connected Solutions (SCS) is the sole provider of this technology.

1.2.2 The method sensitivity is 3 Kg/h with a 90% probability of detection.

1.2.3 This method applies to single wellhead well sites, multi-wellhead sites, well sites with major production equipment and processing equipment, centralized production facilities, and compressor stations.

1.2.4 This method characterizes emissions at a facility-level spatial resolution, meaning the technology has the ability to identify methane emissions within the boundary of a well site, centralized production facility, or compressor station.

1.2.5 This method applies to all sites within the US, provided that operation within the operating conditions specified in section 5 and the document *SCS Nubo Sphere Alt tech 3 Kgh - Operating Conditions* is achievable.

Table 1: Sections of 40 CFR Part 60 Containing Applicable Regulations

OOOOa (NSPS)	OOOOb (NSPS)	OOOOc (EG)
40 CFR §60.5397a	§60.5397b	§60.5397c
§60.5416b(a)(1)(ii), (a)(2)(ii) and (iii), (c)(1)(ii) through (iv), (c)(2)(iv), and (d)(1)(ii) through (iv)	§60.5416b(a)(1)(ii) and (iii), (2)(ii) through (iv), and (3)(iii) and (iv)	§60.5416c(a)(1)(ii) and (iii), (2)(ii) through (iv), and (3)(iii) and (iv)

1.3 Data Quality Objectives

Adherence to the requirements of this method will enhance the quality of the data obtained from air pollutant sampling methods

2 Summary of the Method

2.1 Methane concentration data measured by a point-sensor network are combined with wind data and an inversion plume dispersion model to detect, localize and quantify methane emissions on oil and gas sites.

2.2 The sensor nodes of the point-sensor network and the anemometer(s) are positioned at the fence line around the site and at selected positions on the site.

2.3 Local methane concentrations are measured using a laser-based photoacoustic methane sensor using a laser source emitting infrared radiation with a wavelength specific to a methane absorption line.

2.4 Methane emissions rates are determined using a human-supervised inversion algorithm.

2.5 Methane emission data, atmospheric conditions and system health information are continuously recorded and provided to operators via wireless communication and a cloud-based interface.

2.6 Quarterly periodic screening is conducted and all active emissions on the site with an average emission rate above 3 Kg/h are reported to the operator.

2.7 Initial sensor placement including positioning and determination of the number of sensors is performed using SCS's siting procedure contained in Appendix A – Siting Procedure.

3 Definitions of Method

- **Photoacoustic methane sensor**: methane sensor used in the Nubo Sphere monitoring system based.
- **Nubo Sphere monitor:** sensor node hardware including the photoacoustic methane sensor.
- **Sensor cartridge**: removable slot for sensor cartridges to enable easy maintenance. The sensor cartridge contains the photoacoustic methane sensor.
- **Device health**: system status of the Nubo Sphere monitor including battery charging status, sensor status, connectivity.
- **System health**: system status of the Nubo Sphere methane monitoring system to ensure valid methane measurements. It includes the status of the Nubo Sphere monitors, the connectivity, and data transfer and processing.
- **Siting**: procedure to determine the number of Nubo Sphere monitors on a site as well as their positioning to ensure coverage of all emission sources on the site.

4 Interferences

4.1 Interference from trace gases

The laser-based photoacoustic measurement principle reduces the interference of other trace gases to very low levels, such that interference from trace gases can be neglected in most practical settings. A detailed interference summary is provided in *CBI - SCS Nubo Sphere Alt Tech 3 Kgh - Sensor Performance*.

4.2 Interference from temperature and water vapor

The temperature and humidity dependencies of the photoacoustic methane sensors are compensated as part of the pre-processing step based following the procedure described in the datasheet of the sensor (see document *CBI - SCS Photoacoustic Methane Sensor_Datasheet_v01*). The resulting compensated methane concentration values show minimal interference from temperature and humidity.

5 Limitations

5.1 Wind speed and direction

The method requires wind speeds in the range of 0.5m/s – 10 m/s to transport methane to the sensors without too much dilution. The wind direction must be such that methane is transported to at least one of the Nubo Sphere monitors for some period the methane emission is ongoing.

5.2 Sensor placement

Sensors should be placed such that all potential emission sources are within the typical operating range of 5 to 125m of at least one monitor. In addition, the monitors must be placed in such a way that all potential emission sources are covered given the prevailing wind direction and variation of wind direction on the site. This is ensured during the siting procedure before the installation (see *Appendix A – Siting Procedure*).

5.3 Temperature

Temperatures must be within the operating window of -20°C to +50 °C (-4°F to +122°F).

5.4 Humidity

Absolute humidity must be within the operating window of 0.7g/m3 to 50g/m3.

5.5 Solar radiation.

The location of the Nubo Sphere monitor must ensure that sufficient solar radiation reaches the sensor to ensure regular charging of the battery. This aspect is considered as part of the siting procedure.

5.6 System health

System health is continuously monitored and requires the recording and transmission of valid methane readings and sensor operation within the specified operating window at the time of the periodic screening (e.g., wind speed, temperature).

5.7 LTE connectivity.

All Nubo Sphere monitors must have LTE or 2G cellular connectivity.

6 Safety

6.1 Disclaimer.

This method may involve hazardous materials, operations, and equipment. This alternative test method may not address all the safety problems associated with its use. It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to performing this alternative test method.

6.2 Hazardous Pollutants.

Methane, leaks of which may be determined by this method, and other compounds commonly found in the crude oil and natural gas sector may be irritating or corrosive to tissues or may be toxic. Nearly all are fire hazards. Compounds in emissions should be determined through familiarity with the source. Appropriate precautions can be found in reference documents, such as reference No. 4 in Section 16.0 of EPA Method 21.

6.3 Other considerations.

All personnel performing installation or field maintenance must complete appropriate training, follow standard safety procedures, and obtain safety certificates as required for the site where the sensor network will be installed. Nubo Sphere monitors are not positioned within hazardous areas or where they would interfere with regular operations of the site. Ensure all monitors are mounted on poles that are properly secured against falling.

7 Equipment and Supplies

7.1 Nubo Sphere monitor package

Each Nubo Sphere monitor package shall include the following equipment:
1 sensor node that includes a preinstalled Nubo Sphere laser-based photoacoustic methane sensing cartridge
1 solar panel with mount and cable
2 pole mounts
4 band ties for the pole mounts

7.2 Photoacoustic methane sensor

The sensor nodes shall be capable of measuring methane concentrations with a detection limit of <1ppm (3 sigma), an accuracy of <10%+0.5ppm of measured value (3 sigma), a response time of <10s, a measurement frequency of >1 Hz, a low cross-sensitivity to interfering gases including Hydrogen, and Carbon Monoxide. Accuracy specifications must be checked during manufacturing for every sensor.

7.3 User Manual

The instructions in the *Nubo Sphere User Manual* must be followed during the installation.

7.4 Mounting poles

Mounting poles with a height of approximately 2 to 3m (6.5 to 10ft) must be installed at positions determined in the siting procedure. The poles must be secured against tipping-over and rotation.

7.5 Device Position

The devices must be installed on a mounting pole at least 1.5m (5ft) above the ground with the sensor cartridge facing toward the ground. Each sensor node should be placed approximately 5 to 70m (16 to 328ft) downwind of potential emission sources.

7.6 Hazardous Zones

No elements of the system must be placed within hazardous zones.

7.7 Solar Panel Orientation

Solar panels should face the orientation of the sun at noon.

7.8 Wind Meter Package

Each Nubo Sphere wind meter package shall include the following equipment:
1 wind meter, including cable
1 wind meter mounting adapter
1 pole mount
2 band ties for the pole mount

7.9 Wind Meter Orientation

The wind meter must be oriented such that the red mark on the wind meter is pointed toward another sensor node at least 20m (66ft) away and in direct line of sight with an accuracy ±10deg.

7.10 Wind Meter

The wind meter must be able to measure wind direction in at least two dimensions as well as wind speed in the range of 0 m/s to >15 m/s.

8 Reagents and Standards

No reagents or standards are required for this test method. In particular, the photoacoustic methane sensor does not need to be calibrated in the field.

9 Sample Collection, Preservation and Storage

9.1 Data Collection and Storage

The Nubo Sphere monitor continuously measures and records data including methane concentration, ambient humidity, ambient temperature, ambient atmospheric pressure, wind speed, and wind direction as well as the device location and a sensor data quality parameter. Measured data is transmitted every 15 minutes via a cellular LTE connection to the SCS cloud infrastructure and ingested into the IoT Hub and stored. It is then continuously processed using automated pipelines to increase data quality in a process called pre-processing. These pipelines are monitored, and all logs are stored and analyzed. SCS then creates 3 different data products based on pre-processed data.

9.2 Periodic Screening Data Collection Procedure

The procedures for collection, processing, and delivery of data for the subject alternative test method include the following steps (see visualization in **Error! Reference source not found.**):

- All Nubo Sphere data is continuously recorded and stored in the SCS cloud infrastructure (see section 12.2).
- The target dates and times of the periodic screening are determined in the monitoring plan of operator.
- To perform a periodic screening at the pre-determined date, the data for the 12h time window prior to the reporting time is evaluated.
- The quality control checks described in section 12.4 are performed to determine if a valid periodic screening can be performed.
- In case all quality control checks are valid, all ongoing emissions at the reporting time are determined and emission with an emission rate ≥ 3 Kg/h are reported according to the procedure described in section 12.3.
- In case the quality control checks are not valid because of environmental conditions outside the operating window or an insufficient site coverage, an alternative 12h time window for reporting is chosen. The nearest 12h period with valid operating conditions and site coverage is chosen as alternative time window.

10 Quality Control

10.1 Siting Quality Control

10.1.1 The number and positions of all Nubo Sphere monitors must be determined according to the siting procedure.

10.1.2 The siting procedure needs to ensure that all potential emission sources are covered by at least one monitor based on their distance from the monitors

10.1.3 The siting procedure needs to ensure that all potential emission sources are covered for >80% of the year based on the typical variation of the wind direction over a period of 12 hours.

10.2 Device Health and System Health

10.2.1 Device and system health checks are performed on a continuous basis by SCS.
10.2.2 Any failure on a system level triggers an alert and investigation by remote specialists
10.2.3 Device Health checks include:
- Solar panel connection
- battery charge status and capacity
- availability of anemometer data
- sensor cartridge status
- methane sensor signal
- firmware version
- atmospheric humidity and temperature
- cellular connectivity
- device location

10.2.4 System Health Check includes
- Availability of all measured data in the SCS cloud
- Status of all data processing pipelines
- Status of all APIs
- Status of web interface

10.3 Methane concentration data quality check

10.3.1 Quality control of concentration and emission data is performed automatically on a continuous basis.
10.3.2 Methane concentration data is only used if the photoacoustic sensor quality indicator shows valid results.
10.3.3 Valid emission rates are only calculated if the methane concentration exceeds a minimum threshold of 2.6 ppm for a certain period to ensure a sufficient signal-to-noise ratio.
10.3.4 Methane concentration data points are only used to report an emission and calculate an emission rate if the standards above are met.

10.4 Operating window

10.4.1 The environmental conditions must be within the specified operating window (see document *SCS Nubo Sphere Alt tech 3 Kgh - Operating Conditions*) the period of 12 hours prior to the periodic screening.
10.4.2 Valid emission rates are only calculated if the system is operated within its operating window, specifically if wind speeds are within the range of 0.5m/s to 10 m/s, absolute humidity is within the range of 0.7 g/m3 to 50 g/m3, and temperatures are within the range of -20°C to +50°C.

10.5 Site coverage

10.5.1 At the time of periodic screening, each potential emission sources on a site must be covered by at least one monitor for >20min in the 12 hours prior to the periodic screening based on the location of monitors, the location of potential emission sources and the variation of the wind direction (see document *CBI - SCS Nubo Sphere Alt Tech 3 Kgh - Description of Measurement Technology*)

11 Calibration and Standardization

11.1 Photoacoustic Methane Sensor

The laser-based sensor is factory calibrated (see document *CBI - SCS Nubo Sphere Alt Tech 3 Kgh - Sensor Performance*). No field calibration or bump testing are required due to the inherent stability of the laser-spectroscopy sensing principle in combination with drift compensation algorithms (see document *CBI - SCS Nubo Sphere Alt Tech 3 Kgh - Validation Data for Detection Threshold*).

11.2 Anemometer

The anemometer is calibrated by the manufacturer and does not require any field calibration.

12 Analytical Procedures

12.1 Siting Procedure

- Collect site information from operator including site coordinates, satellite picture, potential emission sources, hazardous zones
- Generate wind rose based on publicly available historic wind data to determine the predominant wind directions and speeds.
- Determine number and placement of Nubo Sphere monitors and anemometer according to the procedure described in section 18.2.2.
- The siting proposal is then sent to the customer for review. Once the siting is accepted by the customer, the installation of the Nubo Sphere monitors is performed.

12.2 Data Collection Procedure

- Nubo Sphere is continuously monitoring methane concentration data, meteorological data, device position and device health indicators.
- Methane concentration data is recorded with a sampling frequency of 1 Hz. In addition, a sensor-specific data quality indicator is collected.
- Meteorological data: atmospheric temperature, humidity, and pressure are recorded with a sampling frequency of 60s. Wind speed and wind direction data is recorded with a sampling interval of 5s.
- Device location and device health indicators are recorded.
- All collected data is transmitted every 15 minutes via a cellular LTE connection to the SCS cloud infrastructure and ingested into the IoT Hub and stored.

12.3 Data Processing Procedure

12.3.1 Pre-processing

- Raw data output from the methane sensor is pre-processed to generate compensated and valid methane concentration values.
- Four pre-processing steps are performed.
  - data averaging for noise reduction
  - temperature and humidity compensation

- long-term drift compensation
- data quality check

12.3.2 Emission event detection

The event detector identifies emission events. It continuously monitors the methane concentration values for every Nubo Sphere monitor on a site and triggers an event if the concentration values exceed a threshold.

12.3.3 Emission detection and localization

The emission detection and localization step are performed with supervision by human specialists at SCS. The output of this step are emission events with a start time, a stop time in case the emission is over, and an emission location.
The SCS specialists use the time trace of methane concentrations as well as wind direction and speed visualized on a map of the site including potential leaks sources. The location of the emission source is determined via a triangulation procedure by the human specialist. An internal software tool is used to support this process.

12.3.4 Emission quantification

In this process step, the emission rate for each identified emission source is calculated and updated in regular intervals. The calculation uses the time traces of methane concentration from all sensors on the site, as well as the wind speed and wind direction. In addition, it uses the position of each Nubo Sphere monitor and the position of the emission source. The output of the calculation is the emission rate for every emission source on the site.

12.3.5 Emission reporting

For reporting the results of the periodic screening, all ongoing emission at the time of reporting are identified. The average emission rate for all identified emissions over the 12h time window is calculated. The average emission rate is compared to the detection threshold of 3 Kg/h. All emissions with emission rate above the threshold are reported as part of the periodic screening reporting.

12.4 Data Quality Assurance Procedure

12.4.1 Data quality assurance is performed by the quality control procedures defined in section 10 Quality Control.

12.4.2 Specifically, at the time of reporting, valid emissions are reported only after performing the following quality checks.
- system health quality check
- operating window quality check
- site coverage quality check
- methane concentration data quality check

12.4.3 All these checks are performed automatically on a continuous basis and evaluated specifically for the time of the periodic screening.

12.4.4 Supervision by human specialists
The source location of each emission event as well as its start and stop time must be verified by a human specialist. The specialists use the time trace of methane

concentrations as well as wind direction and speed visualized on a map of the site including potential leaks sources. The location of the emission source is determined via a triangulation procedure by the human specialist. An internal software tool is used to support this process.

The human specialists are trained according to an SCS internal training program including theoretical and practical training sessions. In addition, every specialist must perform supervised emission verification tasks on real field data. The training program is typically 2-4 weeks in duration. The effectiveness of the training must be checked with a standardized test including the verification of real emission events. All specialists must participate in an ongoing training program that involves the regular review of their emission verification based on real emission events.

12.5 Reporting Procedure

The results of every periodic screening are provided to the operator in the form of a periodic screening report. The report is created automatically within maximum 24h after the periodic screening. The report is sent via email and available for download via the Nubo Sphere web application. The periodic screening report contains the following information for every site.

12.5.1 Site information

- Site information: name, location, type
- Time of the periodic screening
- System health status at time of the periodic screening
- Operating window conditions: temperature, wind speed
- Site coverage quality check result

12.5.2 Reported emissions – reporting information

- Emission identifier

12.5.3 Reported emissions - additional information

- Emission start time
- Estimated emission rate: average
- Estimated emission localization

13 Data Analysis and Calculations

13.1 Forward model

The expected local methane concentration values for a given emission rate and wind direction are calculated by

$$c_{CH4}(x, y, z, Q) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H_0)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H_0)^2}{2\sigma_z^2}\right)\right]$$

With c_{CH4} the local methane concentration (in ppm), Q the emission rate in m^3/s, u the wind speed, H_0 the emission source height (in m), and σ_y and σ_z parameters characterizing the spread of the plume. The coordinate system is chosen such that the x-axis is aligned with the wind direction and the emission source is located at the origin. Both σ_y and σ_z depend on the downwind distance x.

13.2 Inverse Model

The calculated methane concentration values at the position of the Nubo Sphere monitors are compared with the measured values for all wind direction bins. The best estimate emission rate is determined by a maximum likelihood estimator.

13.3 Detection Threshold Calculation

SCS determines the 90% probability detection threshold for all reported detections as follows.

- For each release experiment, SCS determines the sum of all emission rates to determine the total emission rate for the experiment
- For each experiment, SCS determines if emissions are reported (True detection) or if emissions are missed (False detection)
- SCS clusters the reports in bins of 300 g/h and calculate the fraction of True detections
- SCS creates 1000 data sets by randomly sampling (bootstrapping) from the data points.
- For each of the 1000 data sets, we perform a logistic regression to determine the probability of detection curve. The following equation is used

  $$y(r) = \frac{1}{1 + e^{-(b_0 + b_1 \cdot r)}}$$

  where r is the emission rate in kg/h, b_0 and b_1 are fitting parameters, and y is the probability of detection curve.
- SCS determines the best fit probability of detection curve by taking the mean of the fit parameters b_0 and b_1 of the 1000 probability of detection curves.
- SCS uses the best fit probability of detection curve to calculate the detection threshold at 90% probability.

14 Method Performance

14.1 Detection Threshold

Third-party controlled release testing in a field-like setting has demonstrated a detection threshold of <3 Kg/h at a 90% probability of detection (see document *CBI - SCS Nubo Sphere Alt Tech 3 Kgh - Validation Data for Detection Threshold*). The corresponding data set is shown in Figure 2. These results are confirmed by field tests on operated oil and gas sites (see document *CBI - SCS Nubo Sphere Alt Tech 3 Kgh - Validation Data - Field Data Case Studies)*.

15 Pollution Prevention

Pollution prevention is not relevant, as no physical samples are collected under this method.

16 Waste Management

No waste is produced during operation of the Nubo Sphere emission monitoring system. The Nubo Sphere monitoring hardware has a lifetime of >5 years. The sensor cartridge system allows for sensor replacement without replacing the Nubo monitor itself, thereby reducing the amount of electronic waste.

17 Tables, Diagram, Flowcharts and Validation Data

17.1 Data processing flow chart

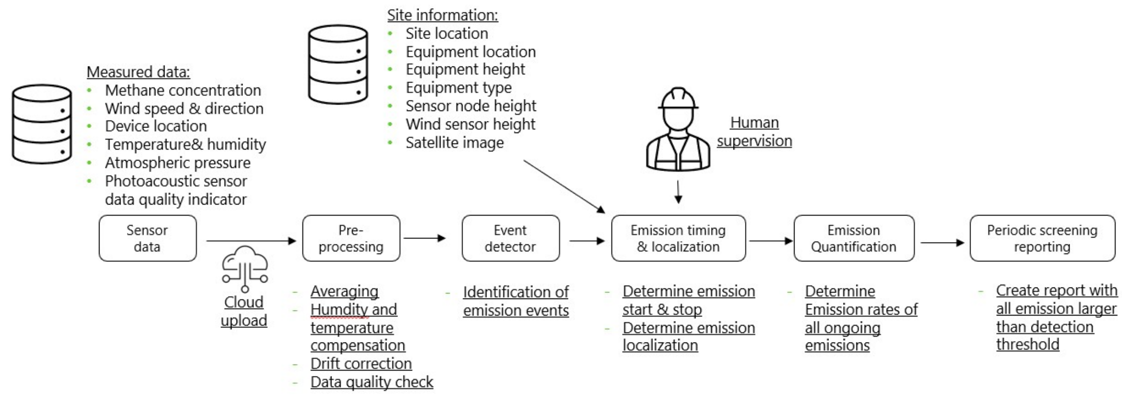

Figure 1 - Schematic overview of the data processing workflow.

17.2 Detection threshold validation data

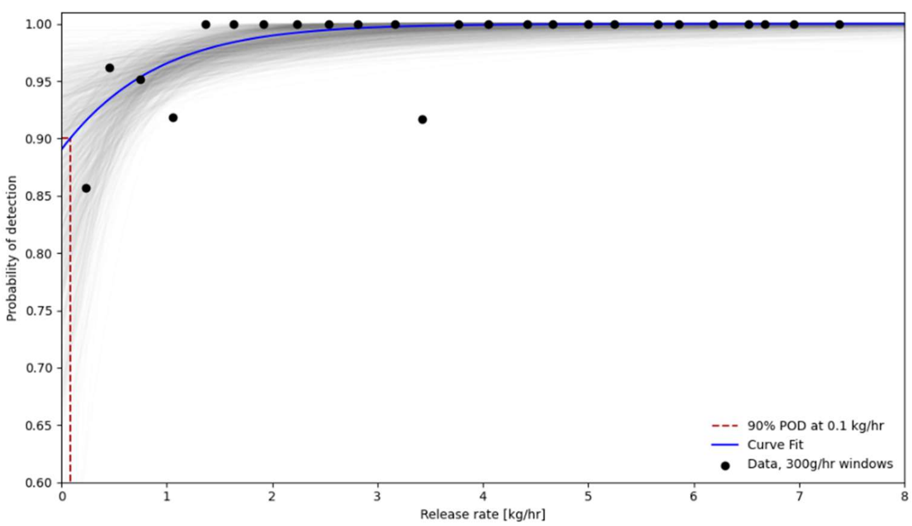

Figure 2 – Detection threshold validation data. We show the reported emissions (black dots), the best fit probability of detection curve based on a logistic regression (blue line) and alternative fitted curves based on random sampling of the data set (grey lines). Black circles datapoints are the ratio between True positives and False negatives clustered in bins of 300 g/h emission rate. Based on the best fit logistic regression, we extract a 90% POD at 0.1 Kg/h (red dashed line).

17.3 Periodic Screening Data Collection and Reporting Procedure

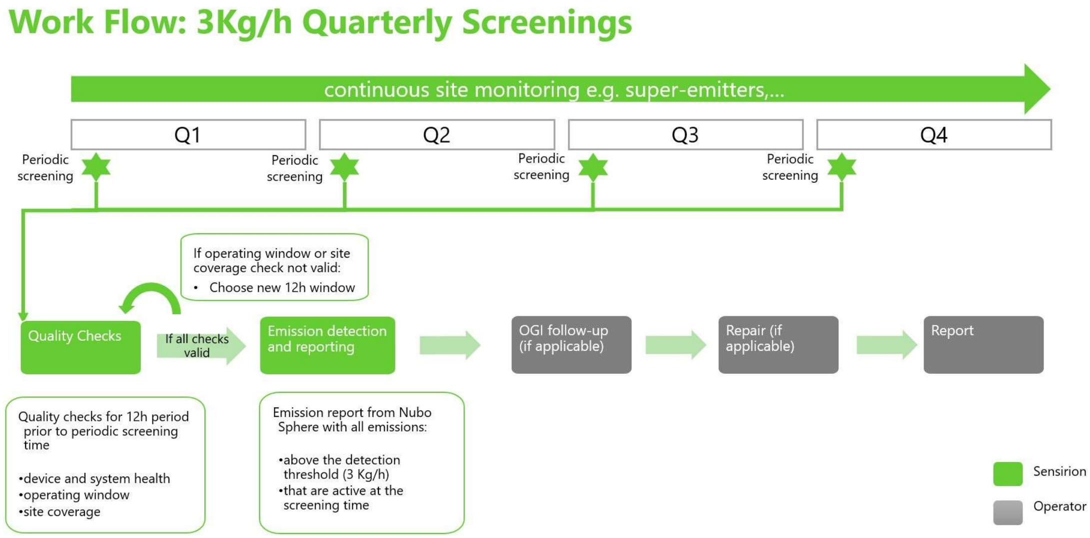

Figure 3 – Schematic overview of the periodic screening data collection and reporting procedure

18 Appendix A – Siting Procedure

The goal of the siting procedure is to effectively monitor the site for emissions by maximizing the probability of detecting these emissions, while complying with regulatory requirements and keeping costs as low as possible. Based on the location of potential emission sources, historical wind data and other site-specific information, an SCS technical expert creates a siting proposal using an internal software tool (Siting Wizard). This is reviewed by the site operator and the installation is performed after final release of the proposed siting.

18.1 Requirements for installation

- LTE or 2G cellular coverage by a provider
- devices need to be installed outdoors
- Unrestricted view to sky to get GNSS data,
- Direct line of sight to sun for solar panel (front side, daytime)
- No installation in hazardous zones
- Required information for siting
  - Location: coordinates of the site
  - Emission sources: location, height and type of equipment (tank, wellhead, separator, etc.)
  - Hazardous zones
  - Other special areas that do not allow for an installation of sensor nodes

18.2 Siting Process steps

18.2.1 Wind Data

We generate a wind rose based on publicly available historic wind data to determine the predominant wind directions and speeds.

18.2.2 Nubo Sphere Monitor Placement

We determine the number of Nubo Sphere monitor and the optimal placement of those sensors based on 4 factors:

- **Spatial coverage**: all potential emission sources must be within the operating range of 5m to 125m of at least one Nubo Sphere monitor.
- **Wind direction coverage**: We use historic wind data to calculate the typical direction and variation of the wind direction over time. Using this data, we position the Nubo Sphere monitors such, that methane plumes from all potential emission sources are transported to at least one of the monitors with >90% probability within each 12h period over 1 year.
- **Excluded areas**: no placement of sensors within hazardous zone or other areas excluded by the operator
- **Other considerations**:
    - Existing infrastructure for mounting: the monitors can be mounted in already existing infrastructure such as light poles or fences, which facilitates installation for the customer
    - Additional sensors: additional sensors can be used to improve localization accuracy and quantification accuracy depending on customer requirements

18.2.3 Anemometer placement:

After choosing the optimal monitor placement, the anemometer is typically installed upwind of the prevailing wind direction, or on a sensor with obstacle clearance when the wind is blowing from the predominant direction.

18.2.4 Siting Proposal and installation

The siting proposal is then sent to the customer for review. Once the siting is accepted by the customer, the installation process can start.

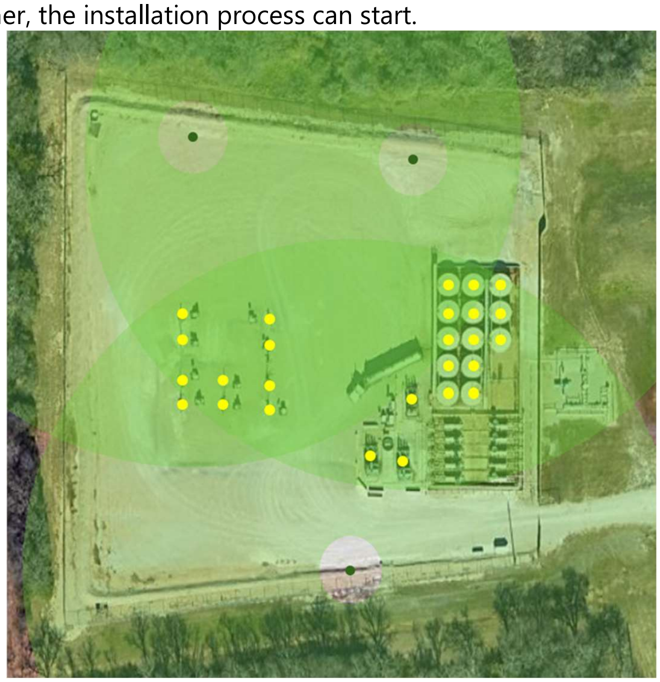

Figure 4 Visualization of the Nubo monitor operational range. Green dots indicate locations of Nubo devices, yellow dots indicate potential emission sources. The shaded green circles show the operating range of each Nubo monitor covering all potential emission sources.