SENSIRION
connected solutions

Nubo Sphere

Description of the Measurement Technology

Application for Approval as Periodic Screening Alternative Technology

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1 Scientific Theory

Nubo Sphere is a point-sensor network emission detection system. The sensor nodes use laser-based photoacoustic methane sensors to measure local methane concentration with high sensitivity, low cross-sensitivity and high stability. The local methane concentrations are combined with atmospheric conditions (wind speed, wind direction, temperature and humidity) to detect emissions, determine the start and end of an emission and localize the emission. The emission rate is calculated using an inverse dispersion model based on the emission location, the methane concentration and the atmospheric data. The localization and quantification steps are performed under human supervision to ensure high quality and consistent emission estimates.

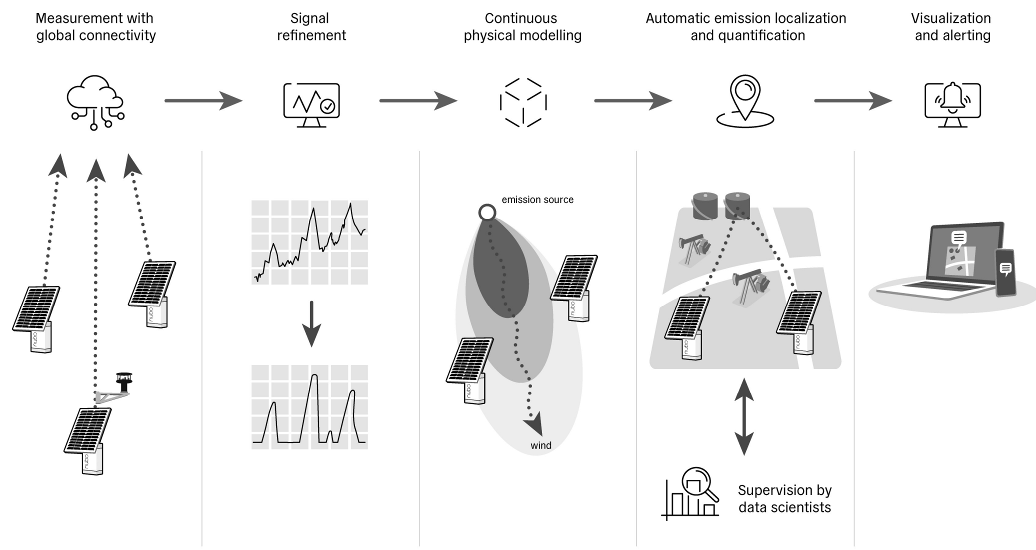

Figure 1: Schematic overview of the Nubo Sphere as a point-sensor network emission detection system.

1.1 Photoacoustic methane sensing

Photoacoustic detection exploits the characteristic property of CH4 molecules to strongly absorb infra-red (IR) light with wavelengths in the mid-infrared range. When shining light of this wavelength through a gas sample, the CH4 concentration can thus be calculated from the proportion of light that is absorbed. The infra-red light is produced by a laser with a wavelength tuned to the methane absorption band. When pulsing the infra-red emitter, CH4 molecules absorb infra-red light periodically. This causes additional molecular vibration resulting in a pressure wave inside the measurement chamber. The higher the CH4 concentration, the more light is absorbed, resulting in a greater amplitude of the acoustic wave. A microphone inside the gas chamber measures the amplitude of the acoustic wave, from which the CH4 concentration can then be calculated[1].

[1] Popa et al, Towards Integrated Mid-Infrared Gas Sensors, Sensors (Basel). 2019 May; 19(9): 2076.

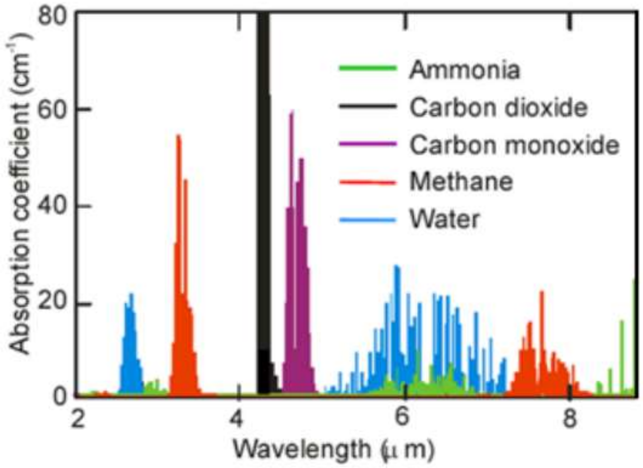

Figure 2: Absorption spectra of common trace gases (HITRAN2016 molecular spectroscopic database)

1.2 Plume Dispersion

The transport of methane in the atmosphere is described by an advection-diffusion partial differential equation.

$$\frac{\partial c}{\partial t} + \nabla \cdot (c\mathbf{u}) - \nabla \cdot (\mathbf{K}\nabla c) = s,$$

With c the methane concentration, u the wind field vector, K the diffusion coefficient and s the source term.

A widely employed solution of this equation is the Gaussian plume model. It is based on several simplifying assumptions including

- Emission from a point source
- Steady-state conditions
- No blockage or topography

Based on these simplifying assumptions, the methane plume can be described by a Gaussian plume shape.

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

With $c_{CH4}(x, y, z, Q)$ is the averaged methane concentration, $\sigma_{y,z}$characterizing the plume width, H_0 the source height, u the wind speed, and Q the emission rate.

Using the measured methane concentrations and the wind conditions, an inverse calculation of the plume model is performed to determine the emission rate at the source[2].

[2] Jia et al., https://doi.org/10.26434/chemrxiv-2023-hc95q-v2

2 Physical Instrumentation

The Nubo Sphere instrumentation consists of the Nubo Sphere monitor with the laser spectroscopy sensor cartridge, an external solar panel and an ultrasonic anemometer. All parts of the system are mounted on suitable poles that are preinstalled on the oil and gas site by the operator. Data from the Nubo Sphere system is transmitted via LTE to the cloud, where data processing and storage is performed.

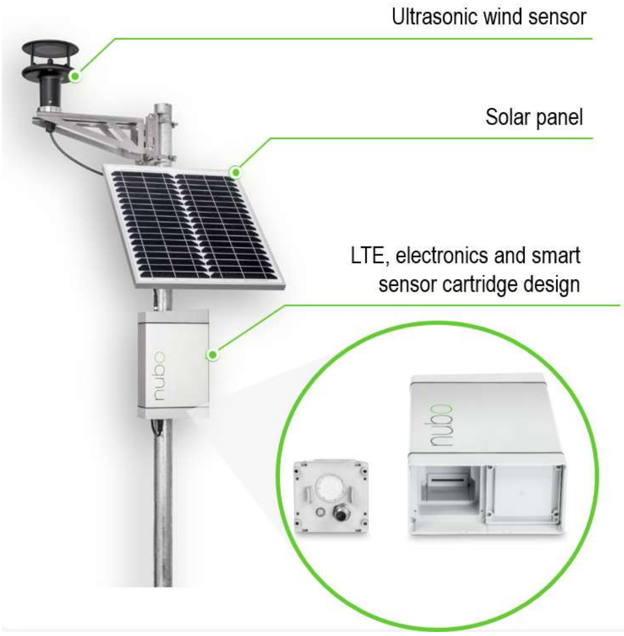

Figure 3 - Picture of the Nubo Sphere monitor with a close-up view of the sensor cartridge.

2.1 Nubo Sphere monitor

The Nubo monitor is a robust IoT sensor node with an internal rechargeable battery, a microprocessor, a power management unit, and a modem with a SIM card for LTE connectivity. Each monitor has two slots for sensor cartridges to enable easy exchange of sensor cartridges for future upgrades, maintenance, and adding additional measurement parameters. The monitor is IP 64 rated, dust and snow proof, and designed to operate at temperatures between -20°C and +50 °C. It is equipped with easy mounting adapters to enable fast and safe installation. The Nubo Sphere monitor is connected to an external solar panel that regularly charges the internal battery. The battery capacity is chosen such that the Nubo Sphere monitor can be operated for at least 6 days without solar irradiation. The battery charging status is constantly monitored as part of Nubo Sphere's device health monitoring.

2.2 Nubo Sphere Sensor Cartridge

The Nubo Sphere Methane Cartridge contains a laser-based photoacoustic methane sensor. Further sensor cartridges providing additional sensing parameters beyond methane are available as extensions to the Nubo Sphere monitoring system.

Figure 4 – Photoacoustic methane sensor cartridge.

2.3 Anemometer

An ultrasonic anemometer provides accurate wind speed and wind direction data. The anemometer is mounted above the Nubo Sphere monitor at the same pole and connected via a cable to the monitor. Typically, one ultrasonic anemometer per site is used.

3 Types of Measurement

The Nubo Sphere monitoring system is a stationary in-situ measurement method. The Nubo Sphere monitors are placed on and around an oil and gas site. Methane from an emission source is transported to the sensors by wind and other atmospheric transport processes. Local methane concentrations are measured by the Nubo Sphere monitors. The emission rate at the source is calculated from these measurements in combination with local wind data.

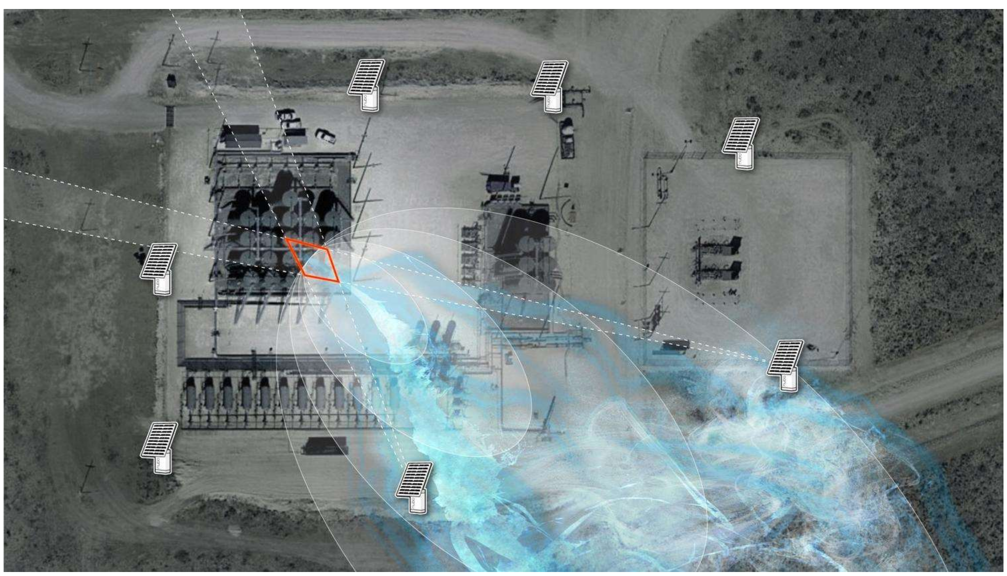

Figure 5 – Visualization of the Nubo Sphere measurement concept. Nubo Sphere monitors (symbols) are placed around an oil&gas site. Methane from an emission source is transported by wind to the Nubo Sphere monitors (light blue). The emission source is located by a triangulation procedure (red).

4 Limitations of the Technology

4.1 Wind speed

The measurement principle relies on wind transport of methane from the emission source to the sensor nodes. At very low wind speeds, diffusion becomes the dominant mode of atmospheric transport and therefore, the direction of methane transport is less correlated to the wind direction. This increases the error of localization and quantification of the emission. Based on controlled release testing and field data, we define a lower limit for the wind speed of 0.5 m/s to provide valid measurements[3].

At high wind speeds, the methane plume is quickly diluted and the local concentration at the sensor node might decrease below the detection limit of the methane sensor. Based on controlled release testing and field data, we define an upper limit for the wind speed of 10 m/s to provide valid measurements.

In summary, valid measurements are produced for wind speeds in the range of 0.5-10 m/s. The wind speed range is included as part of the operating window in the periodic screening test method[3].

4.2 Wind direction and emission duration

The Nubo Sphere sensor nodes are positioned according to our siting guidelines. The siting is based on the site coverage concept ensuring that all emission sources are within the covered angle and distance of at least one Nubo Sphere monitor.

There is a possibility that the wind direction transports the methane plume in a direction where no sensors are placed. Such conditions can occur at higher wind speeds or in situations where wind comes from an unusual direction. As a result, the methane plume is not detected by a sensor of the sensor network.

Mitigation: We use the site coverage concept described in section **Error! Reference source not found.** to ensure that the periodic screening reporting is performed at a time at which all potential emission sources on a site are covered. We also use the same concept and historical wind data as part of our initial siting procedure.

4.3 Methane plume rise

At high emission rates and low wind conditions methane will rise due to the different density of methane compared to air (buoyancy). This effect can be amplified by thermal convection in situations with high solar irradiation. The rising methane plume will result in lower methane concentration values at the Nubo Sphere sensors placed at a height of typically 1.5m.

Mitigation: The high sensitivity of the laser-spectroscopy sensor enables the detection of small methane concentrations present at the edge of the methane plume. Therefore, even in conditions with significant plume rise, the emission can be detected, but typically with reduced quantification accuracy[4].

[3] *SCS Nubo Sphere Alt Tech 2 Kgh - Test Method*

[4] *Chen at al, Comparing Continuous Methane Monitoring Technologies for High-Volume Emissions: A Single-Blind Controlled Release Study, ACS EST Air*

4.4 Temperature Range

The Nubo Sphere monitor and sensor cartridge are designed to measure in the temperature range of -20°C to +50°C. Operation at temperatures below -20°C or above +50°C is possible and will not result in permanent damage to the sensor, but no valid measurements will be reported outside of this temperature range. The operating temperature range is included as part of the operating window in the periodic screening test method[5].

4.5 Power Supply

The Nubo Sphere monitor is powered by a solar panel in combination with an internal rechargeable battery to enable autonomous operation. The battery can ensure power supply of the Nubo monitor for >6 days without solar irradiation. The Nubo Sphere will lose its power supply in the rare case of a period of more the 6 days without solar irradiation. Based on solar power simulations and field testing close to the US-Canadian border, we conclude that time periods of more than 6 days without solar irradiation are extremely rare. Even in the case of a loss of power supply, the Nubo will automatically restart operation as soon as solar irradiation is charging the battery.

5 Conversion of Results to Mass Emission Rates

[CBI]

6 Description of models and calculations

[CBI]

7 Data Collection and Generation

7.1 Data collection, maintenance and storage

Data in the Nubo Sphere solution is created in three different ways:

- **Site information**. To perform emissions monitoring at an oil and gas site, the Nubo Sphere solution requires specific information about the site. This information is provided by the customer and user of the Nubo Sphere application as part of the siting procedure. It consists of coordinates of the site, coordinates of the equipment present at the site, the type and height of those equipment and the installation height of the sensor.
- **Measurement data**. Nubo Sphere is continuously measuring 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.
- **System health data**. Internal parameters including battery charge status and system power, LTE connectivity, solar radiation, availability of anemometer data, availability of

[5] *SCS Nubo Sphere Alt Tech 2 Kgh - Test Method*

sensor data, quality of sensor raw data, internal quality parameters are continuously recorded.

- **Emission data.** This consists of emission event start and end times, emission rate timeseries, and emission location.

The measurement data and the system health data is stored on the Nubo Sphere device and then sent in batches to the cloud (Azure IoT Hub) every 15 minutes via LTE Cat. M1 or using 2G as a fallback option. The Nubo Sphere solution uses the MQTT protocol to transmit data from the device to the cloud, while data encryption is ensured by using TLS 1.2 protocol and symmetric key authentication between the device and the cloud. The Nubo Sphere devices require at least TLS 1.2 (SSL 3.3) to operate and use Mbed TLS 2.16.11 (since Dec. 17th, 2021). To secure the network connection, the following cipher suite is typically used: TLS-ECDHE-RSA-WITH-AES-256-GCM-SHA384.

Data is maintained both on the device and in the cloud as follows:

- Sensirion performs firmware tests and release procedures regularly to make sure data is not corrupted.
- Device, site and system health are monitored continuously to ensure data availability and quality (see section 8).
- Sensirion protects all information assets according to its Information Classification Policy, ensuring that data is only shared with the authorized personnel.

Data can be stored in two different ways depending on the type:

- Meta-data is stored in Azure Cosmos DB database. It is a fully managed database service by the provider, which ensures data encryption and security updates.
- Measured data is stored in Azure Blob Storage. It is a fully managed service by the provider, which ensures data encryption and security updates.
- Sensirion's backup strategy involves routinely creating secure copies of critical data to ensure its availability and integrity. This includes daily incremental backups for dynamic data and weekly full backups for static data. Backups are stored on encrypted off-site and on-site storage systems. Regular testing and verification of backup effectiveness are conducted to ensure data recovery and business continuity in case of data loss or system failure.

7.2 Information security and cryptography policy

- Sensirion's cryptography policy only allows the highest degree of security protocols – such as TLS 1.2 and 1.3, and cipher suites that match the key length requirements – to ensure data transmission and storage is not compromised.
- Sensirion Connected Solutions has implemented an information security management system (ISMS) which is certified according to the ISO 27001 standard. It covers the development, delivery, maintenance, and support of SCS's methane emission monitoring IoT platform and service. The objective is to establish and maintain confidentiality, integrity, and availability throughout the platform's lifecycle,
- Sensirion Connected Solutions has implemented a quality management system that is certified according to the ISO9001 standard.

7.3 Secure Development Policy

Sensirion has a *Secure Development Policy* in place, which ensures proper maintenance of software versions and corresponding logs.

Security of Sensirion's development environments is ensured by having all testing software in private networks protected from the internet. Tools are in place to automatically check and get notified about possible updates on code dependencies and library versions, so software does not run on outdated packages. Only open-source third party libraries and those whose licenses can be managed online can be used, to minimize software dependencies. SCS does not allow the use of proprietary software.

All code changes are going through a security testing process, which includes code reviews, peer-review approval, and automated pipelines with unit, end-to-end, and integration tests. All documentation of changes is available on Change Management Platforms (Azure DevOps and GitHub).

Architecture structure is created and managed via infrastructure-as-code, so every infrastructure change history will be stored in a code versioning system and must be approved by the developer team. All disruptive software errors are logged into a 3rd party service, being sure not to store any sensitive information. In this way we can keep track of any code bug, leading to a more effective incident resolution.

After the development process, SCS releases the software to the testing environment, where acceptance testing is performed. User and business requirements are evaluated, and new features can be requested during this testing. The software is released to the production environment after all tests are completed and user and business requirements are fulfilled. Documentation about the software and acceptance tests outcomes is automatically created and updated with every software release.

7.4 Description of end-user data streams

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.

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

Reported emissions – reporting information

- Emission identifier
- Emission start time

Reported emissions - additional information

- Estimated average emission rate
- Estimated emission localization

In addition to the periodic screening reporting, Nubo Sphere provides the following data streams to operators. These data streams are listed here for completeness but are not part of the periodic screening test method.

- Sensor API: it provides access to pre-processed data, which consists of 20 seconds averages of methane concentration measurements (in ppm) and wind data measurements (direction and speed).
- Emission data API. All emission data including emission rate, emission start and stop time, and emission localization is available via SCS's Alerting API.
- Nubo Sphere web application. Real-time emission data, alert logs, site information, device health information, and alert feedback from customers are provided via a web application interface.

8 Device, Site and System Health

Device, site and system health serve as aggregated indicators reflecting the overall status of the Nubo Sphere emission monitoring system, applicable to individual Nubo Sphere monitors, specific sites and the overall solution, respectively. All parameters contributing to device, site and system health are continuously monitored, updated, and logged. Certain parameters are verified automatically, while more complex parameters necessitate manual inspection due to their requirement for in-depth knowledge.

8.1 Device & Site Health

The following parameters are monitored to determine the device health status:

Parameter	Information
Solar panel connection	Yes / No
Charging status	Yes / No
Battery capacity	Battery voltage > threshold
Availability of anemometer data	Yes / No (if applicable)
Sensor cartridge status	OK / NOT OK
Methane sensor signal	Yes / No (Within sensor specifications)
Firmware version	Use case dependent
Humidity and temperature of the Nubo	Alert if humidity and temperature values from inside and outside the Nubo Sphere monitor differ
Cellular connectivity	Yes / No (Signal strength in dBm according to available radio technology)
GPS position of the device	Alert when GPS position changes

For the site health status, we perform a site coverage quality check as part of the periodic screening, as explained in section 9.2. For that, all Nubo Sphere monitors that are used for the screening need to have good device health, and at least one anemometer in the site needs to be working and reporting data.

The device and site health status are continuously monitored and logged. If a device or site with a problem is identified, a remote investigation by a specialist is triggered to identify the root cause. If necessary, a follow-up on-site visit, or a replacement of a device is triggered.

8.2 System Health

The following parameters are monitored to determine the system health status.

Parameter	**Information**
Availability of all measured data in the SCS Cloud	Yes / No
Status of data processing pipelines	Yes / No
Status of APIs	Yes / No
Status of web interface	Yes / No

The system health status is continuously monitored and logged. If a problem is identified, a remote investigation by a specialist is triggered to identify the root cause.

9 Siting Procedure Validation

[CBI]