Ministry of Environment of Denmark
Environmental Protection Agency

The Plane Project

Mapping and quantification of GHGs from diffuse emission sources using drone technology and vertical measuring walls

MUDP Report

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Contents

LIST OF ABBREVIATIONS and SPECIFIC TEMINOLOGY

DFM	Drone Flux Measurement Method
TDM	Tracer gas Dispersion Method
GHG	Greenhouse Gas
WWTP	WasteWater Treatment Plant
Flight path	Path identified by the drone; it defines the inspected area
Wall	Name used to identify the inspected area
Transect(s)	For DFM: a single near horizontal segment of which the flight path is made of For TDM: a single downwind transversal plume data collection
Observation point	Point in the three-dimensional space where wind and gas concentrations data are collected
Gas Flux	Quantity of gas passing through the inspected area; expressed in kg_{gas} / h
Flux Density	Quantity of gas passing through the inspected area; expressed in kg_{gas} / m^2 / h
Gross gas concentrations	Collected gas concentrations composed of atmospheric background gas and the potential gas emitted by the source
Net gas concentrations	Gas concentrations caused by the site of interest fugitive emissions; they are estimated by subtracting the gas background concentrations from the gross ones
Apparent wind	Wind direction and speed measured by the moving drone and expressed in a drone-based reference system
Relative wind	Wind direction and speed measured by the moving drone and expressed in a ground-based reference system
Drone velocity	Drone speed in relation to the ground
Absolute wind	Real wind direction and speed expressed in a ground-based reference system; calculate by vector addition of the relative wind and drone velocity
True horizontal wind	Horizontal components of the absolute wind

Planprojektet - Sammenfatning og konklusioner

På en lang række områder er udledninger af klimagasser til luften præget af diffuse emissioner, som traditionelt har været besværlige og dyre at måle, ligesom resultaterne har været behæftet med stor usikkerhed. Dels fordi emissionerne i sagens natur driver med vinden, dels fordi mange kilder er spredt over store arealer og/eller er svært tilgængelige, og endelig fordi hidtidige måleteknologier og -koncepter har været utilstrækkelige. Det gælder f.eks. måling af metanudledningen fra biogasanlæg, olie/gasproduktion og spildevandsanlæg. Særlig svært er det at kvantificere udledningerne, så man får et præcist billede af omfanget af udslippet fra en given diffus kilde. Uden kvantitative målinger kan man ikke definere grænseværdier for totaludledningen eller vurderer effekten af reduktionstiltag, hvilket er særlig vigtigt i den grønne omstilling.

Projektet ”The Plane Project” har haft til formål at udvikle en ny og omkostningseffektiv metode og et operationelt koncept for måling af klimagasser fra diffuse kilder ved brug af droner og innovative sensorer til opstilling af vertikale målemure (planes). Med bevilling fra MUDP-puljen er det lykkedes at udvikle både teknologi, metode og koncept til et stadie, hvor måleydelsen er klar til markedsintroduktion.

Teknologien tager udgangspunkt i en kortlægning af udledningerne nedvinds fra en kilde, f.eks. et biogas- eller offshoreanlæg. Snifferdronen gennemflyver et adaptivt flyvemønster og afdækker et tværsnit af udledningen ved at opstille en lodret flade af datapunkter (en målemur), der omkranser hele udledningen. I fladen måles både gaskoncentrationer, vind- og arealparameter, hvorefter specialdesignet software-analyseværktøj udviklet af Explicit kan foretage en præcis kvantificeringsberegning af den faktiske udledning fra kilden inklusive hensyntagen til eventuelle baggrundskoncentrationer.

Metoden, kaldet DFM (Drone Flux Measurement), er udviklet i projektet af Explicit ApS. Herudover har DTU Miljø som projektpartner bidraget med ekspertviden samt hjælp til felttest og validering, herunder kontrolleret udledningstest med kendte gasser og målinger mod den dynamiske sporgasmetode (TDM), udviklet af DTU Miljø. Sidstnævnte anvendes i dag til kvantificeringsmålinger. FORCE Technology har som underleverandør ligeledes bidraget med komparative tests med TDM samt laboratorietest og usikkerhedsberegninger på DFM-metoden.

I projektet har der været fokus på måling af metan. I alt er der målt metanudledning på 11 biogasanlæg, to renseanlæg, to svinefarme, et nedlagt affaldsdeponi og én offshore olie- og gasindvindingsplatform. I alt er der i projektet foretaget 28 målekampagner med til sammen 128 målemure.

En afgørende del af projektets succes af været at demonstrere implementering og performance af de valgte sensorer, både gas- og vindsensorer. Her beviste laboratorietest tidligt i projektet sensorernes egnethed til droneapplikationen.

Der er i projektet blevet foretaget en lang række komparative tests, både ved måling af kontrollerede gasudledninger og samtidige komparative målinger mellem de to kvantificeringsmetoder: DFM og TDM. I forbindelse med målingerne af de kontrollerede gasudledninger udviste DFM-metoden forskelle på mellem 2 og 19 % i forhold til referencemålingerne. Ved de repræsentative komparative målinger med TDM-metoden, viste DFM-metoden afvigelser ned til mellem 3 og 9%; hvilket må siges at være meget tilfredsstillende.

På baggrund af et væsentligt datasæt af samtidige komparative målinger mellem metoderne, har FORCE Technology fastsat en udvidet usikkerhed (expanded uncertainty) på DFM-metoden på ca. 21 %.

DFM-metoden er allerede introduceret til markedet og ventes fremover at kunne yde et vigtigt bidrag til en bedre forståelse og håndhævelse af de faktiske, diffuse udledninger.

1. Summary

The Drone Flux Measurement (DFM) method has shown to produce accurate, quick and cost-efficient CH_4 quantification measurements on a wide range of sources.

The main findings of the project can be summarized as follow:

- The selected methane- and wind sensors proved to be suitable for drone application
- Controlled CH_4 release tests showed differences between the measured and calculated releases of 2 to 19%, even at low emission rates
- The representative simultaneous comparative tests between the DFM and TDM method showed differences down to between 3 and 9%.
- The method uncertainty, calculated using the comparative tests, was calculated to appx. 21% expanded uncertainty on a single measurement wall.

In total, the DFM method was tested on 11 biogas plants, 2 wastewater treatment plants and 2 pig farms, as well as on one landfill and one offshore oil platform. Some of the facilities have been measured twice, leading to a total number of 24 measuring campaigns.

2. Introduction

In October 2020 the Danish government launched the Global Climate Action Strategy *'A Green and Sustainable World'*. One of the goals of this long-term strategy plan is a 70% reduction in the GHGs emissions by 2030 and climate neutrality by 2050.

One year after, at the COP26 summit, nearly 90 countries have stated their jointly effort to slash emissions of the potent greenhouse gas methane 30% by 2030 from 2020 levels.

Sensing the importance of monitoring GHGs emissions, the Plane Project was born to develop a new cost-effective method to measure GHGs diffuse emissions such as methane (and other gases, e.g. ammonia) emissions from biogas plants, oil/gas production, agriculture, landfills and wastewater plants etc.

The method itself has been developed by Explicit ApS and it involves the use of drones equipped with high-performance wind and gas sensors. The idea is to use the sniffer drone to, through an adaptive flight pattern, simultaneously collect wind and gas concentration data around the emissions source and to use these data to quantify the amount of gas emitted by the source. A detailed description of the method and technologies used is given in Section 4.

The main purpose of the Plane Project is to create an ultimate prototype of Explicits' measuring method, called the Drone Flux Measurement method (DFM). For doing that, Explicit ApS has collaborated with DTU Environment and FORCE Technology. DTU has provided expert knowledge, help with field tests and method validation; FORCE Technology has run laboratory tests as well as comparative tests using the dynamic tracer gas dispersion method.

Most of the tests were focused on methane emissions and their quantification from biogas- and wastewater plants; however, the method was also tested at pig farms (also using an ammonia sensor), a landfill and an oil rig, for a total of 24 campaigns and 128 measurement walls.

3. Project objective

The Plane Project final objective was to create the prototype of Explicits' new Drone Flux Measurement method (DFM) for quantifying GHGs emissions from diffusive sources, and to define the applicability of such method as well as its limitations and prospects.

The goal was achieved through four main work packages. The first step was to verify the sensors' quality and usability. The gas sensors were tested in laboratory under controlled conditions to determine linearity, response times, uncertainty budget and potential dependencies on temperature, humidity, pressure etc. Wind sensors were tested to study the impact of the drone's air displacement and of the sensors' orientation on the data collected. The wind sensors were also verified at laboratory conditions in wind tunnels. Once the sensors had been individually tested, the method design and operational concept as well as the data infrastructure was defined.

The second step was to validate the drone system by performing open landscape-controlled release tests and comparative tests at actual facilities, in which the sniffer drone results were compared against the tracer gas dispersion method (TDM) ones.

The third step was a demonstration of the final operation procedure at a biogas facility. At the demonstration, the dynamic tracer gas method was also implemented to present the final quantification report from both methods.

The fourth and final step was completing the prototype and finalise the measuring concept.

4. Method and technology

4.1 Method

The new DFM method to quantify fugitive gas emissions involves the use of a drone equipped with high-performance sensors. The drone flies downwind from the site of interest, approximately in the crosswind direction. The flight defines a vertical surface - also called flux wall – where data regarding gas concentration, wind- speed and direction, position and altitude are collected throughout the flight. Since wind and gas data are correlated in time and space, it is possible to calculate the gas flux across the inspected area and create a consistent representation of the flux density. FIGURE 1 provide an illustration of the DFM method performed at a biogas plant.

The technologies used in this method, the operational procedure and the flux calculation are described in detail in the following sub-chapters.

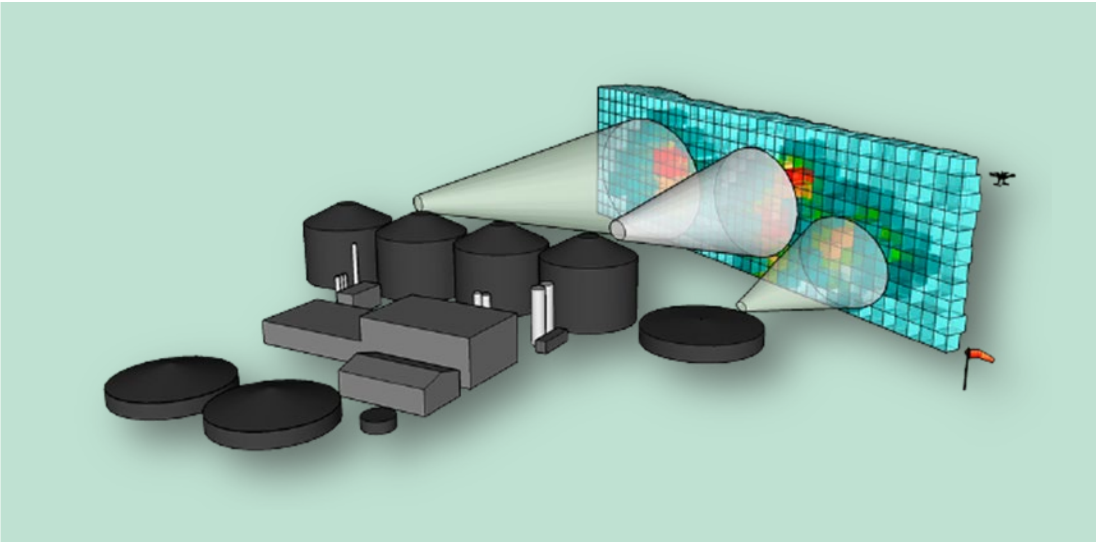

FIGURE 1. General illustration of the DFM method at a biogas facility where the cones represent gas emission plumes and the colours represent the magnitude of the estimated gas flux (red=high, light blue=low).

4.2 Equipment

4.2.1 Drone

The drone system used to perform the measurements consists of several components. The drone is equipped with a programmable flight computer for controlling the vehicle's flight; a positioning system for measuring the position of the drone itself, a gas sensor for determining the gas concentration, two wind sensors for determining the relative wind speed and relative wind direction and a data interface for collecting the data during the flight.

The drone currently used by Explicit is a DJI MATRICE 300 RTK with dimensions 810 x 670 x 430 mm (unfolded and with propellers excluded) and a payload capacity of 2.7 kg. Due to the sensors needed for the data collection, the maximum flight time pr. wall is around 30 minutes with wind resistance up to 15 m/s. Any type of unmanned aerial vehicle can be used if the wind

Explicit's drone equipped with a methane gas sensor and two wind sensors.

and gas sensors can be installed in a configuration that prevents the impact of the drone´s air displacement on the collected data.

4.2.2 Wind sensor

The wind sensor used on the drone is the TriSonica Mini sensor from Anemoment. It's the world´s smallest and lightest 3D ultrasonic anemometer. The sensor collects information regarding the wind speed along all the three directions of the air flow, together with temperature, humidity, pressure and compass data.
TABLE 1 shows selected sensor specification.

TABLE 1. Wind sensors specifications regarding wind speed and direction.

	WIND SPEED	WIND DIRECTION
Range	0 – 50 m/s	Horizontal plane: 0 - 360° Vertical planes: ± 30°
Resolution	0.1 m/s	1.0°
Accuracy	(0 - 10 m/s): ± 0.1 m/s (11 - 30 m/s): ± 1% (31 - 50 m/s): ± 2%	± 1.0°

FIGURE 2. Wind sensor.

4.2.3 Methane sensor

The gas sensor used by Explicit for collecting methane concentrations is the Laser Gas Detection (LDG) Compact-A produced by Axetris. The laser is based on Tunable Diode Laser Spectrometry (TDLS) and has a sampling rate of 2 Hz. The onboard digital signal processing unit compensates drift phenomena and provide reliable and stable measurements. TABLE 2 shows some of the sensor specifications.

TABLE 2. Methane sensor specifications.

	METHANE CONCENTRATIONS
Range	0 – 100 ppm
Resolution	0.01 ppm
Accurancy	± 2 % FS (Full Scale)

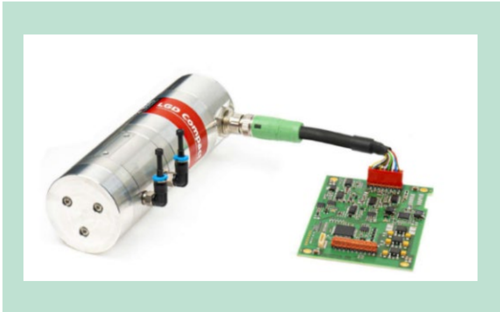

FIGURE 3. Methane sensor.

4.2.4 Ammonia sensor

Like the methane sensor, also the ammonia sensor is a Laser Gas Detection (LDG) Compact-A sensor produced by Axetris, with a sampling rate of 0.7 Hz. The sensor specifications are presented in TABLE 3 (valid at the reference conditions: operating temperature 45°C, pressure 1013 hPa and humidity 20% rH).

TABLE 3. Ammonia sensor specifications.

	AMMONIA CONCENTRATIONS
Range	0 – 100 ppm
Resolution	0.01 ppm
Accurancy	± 2 % FS (Full Scale)
T_{90} time	≤ 1.8 s at 2 L/min

FIGURE 4. Ammonia sensor.

4.3 Operational concept

4.3.1 Site inspection

The first step of any measurement campaign is the site inspection. This can be done either on site or online by looking at the latest available maps of the site and surroundings. The site survey is essential to identify the feasible flight paths, avoiding possible obstacles like vegetation (i.e. high trees), topography or other buildings in the surroundings.

The pilot must be able to perform a flight path that covers the entire site downwind projection to be sure that all fugitive gas emissions from the inspected site are measured. Thus, in this step, the pilot investigates if there are any wind directions that could prevent this.
Moreover, at this stage, the presence of potential external emission sources is checked, to avoid to falsely include these in the total measurements.

4.3.2 Flight path

The measurements take place if the weather conditions are favourable (e.g. no heavy rain or snow) and if the wind is substantially coming from a direction that allows the pilot to perform a flight path that covers the entire plant downwind projection.

The data should preferably be collected throughout a near vertical plane downwind from the source of interest, approximately perpendicular to the mean wind. The drone flies on an open path, which can be divided into near-horizontal transects, flown in alternating flight directions, and small vertical flights when changing transect. An example of the most common flight path is shown on FIGURE 5.

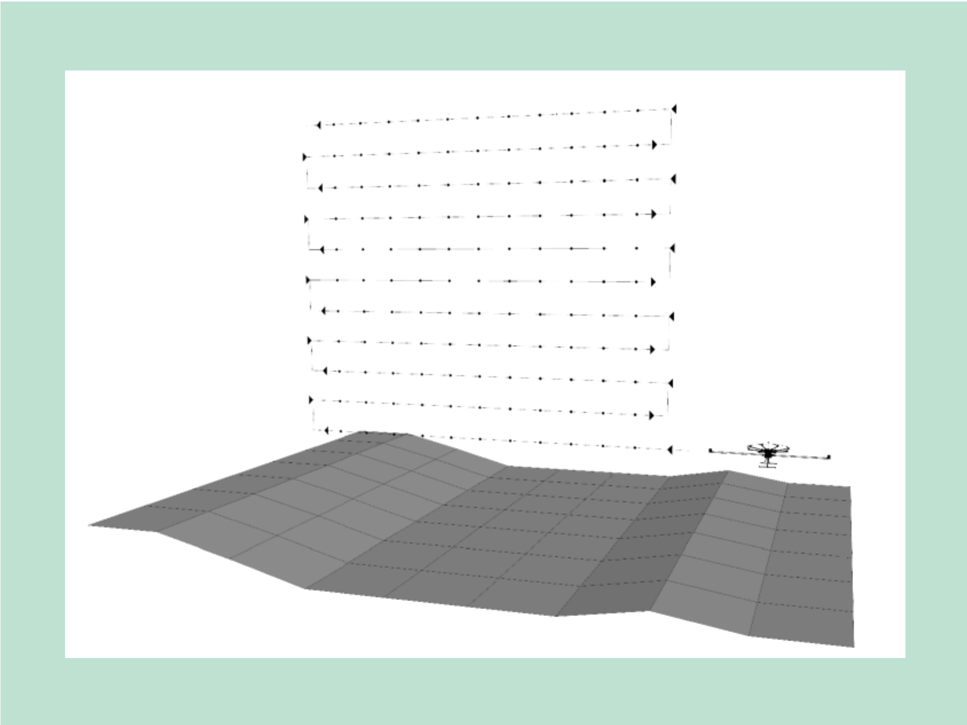

FIGURE 5. Example of a flight path.

The determination of the flight path – that can either be straight, curved or segmented - is based on information regarding the mean wind direction and the topography of the site. The pilot chooses the shape of the flight path by defining at least two points in the longitudinal direction through which the drone has to navigate to: these points are known as "waypoints". Moreover, the pilot defines an "anchor point" positioned at the suspected gas emission; in case of no evidence, the anchor point is set in the middle of site of interest.

The maximum height of the flight is set depending on the plant size and vertical dispersion of the emitted gas plume and usually it is in the order of dozens of meters. Often the start minimum height is as close to the terrain as the drone obstacle sensors will allow.

The area of the wall is determined using GPS coordinates at each observation point, typically thousands of points, and in this way the uncertainty of the overall area is effectively eliminated.

Usually the pilot perform at least three walls, depending on the dynamics of the emission. After each flight, the pilot observes the magnitude of the collected gas concentrations throughout the wall. In case there are high gas concentration close to the edges of the inspected area, the wall dimension, orientation and position of the following flight are adapted so that the highest concentrations are included and well positioned inside the inspected area. Also the distance between transects can be adjusted, e.g. to optimise the pattern where you have high gas concentration gradients.

4.3.3 Data collection

During the flight, the sensors collect the following data at a frequency of 2 Hz (using the CH_4 sensor):

- Time;
- Geographical coordinates and altitude (GPS);
- Elevation above the ground;
- Gross gas concentration, composed of atmospheric background gas and the potential gas emitted by the source;
- Temperature and air pressure;
- The three spatial apparent wind components (U, V, W);
- The drone's orientation and speed U_G in relation to the ground;
- Additional control parameters for wind sensors' operation;

Each point in which these datasets are collected is called an observation point. Note that the perfect symmetric data grid like the one shown in FIGURE 5 is a rare case. Most of the time the data grid is heterogeneous: each observation point is not perfectly aligned with the surrounding observation points and the distance between each transects is not constant.

FIGURE 6 is an example of how the CH_4 concentrations collected in a vertical open plane are visualised.

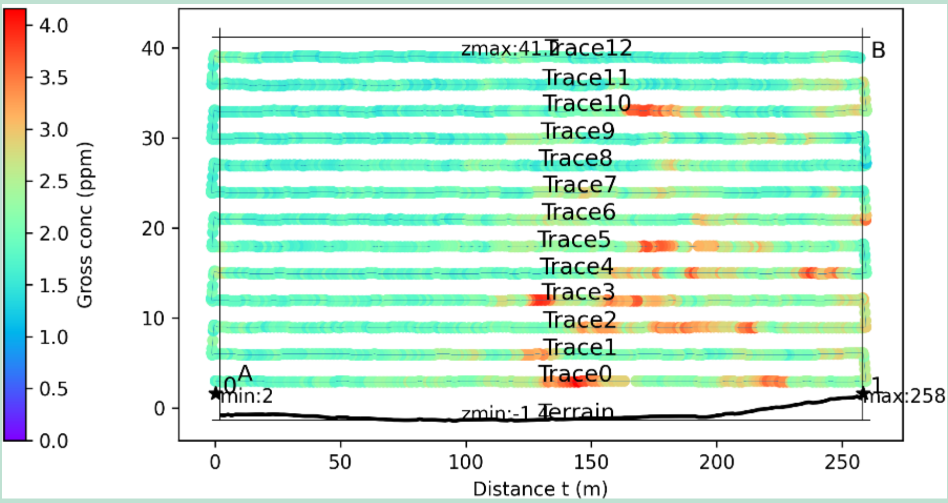

FIGURE 6. Visualisation of the collected gross CH_4 concentrations.

4.4 Data processing

Once the drone has completed a flight, the collected datasets are uploaded to the cloud. Wind and gross gas concentration data are then analysed to obtain real wind data and gas background concentrations, which are later used in the flux calculation.

4.4.1 Real wind

The wind sensor measures the relative wind $\vec{U} = (U, V, W)$ in a coordinate system that depends on the drone´s orientation and velocity. To evaluate the absolute wind with respect to the ground, the relative wind $\vec{U}$ is expressed in the ground base coordinate system (E, N, Z) to get $\overrightarrow{U_{Rel}} = (UR_E, UR_N, UR_Z)$. Finally, as Eq. 1 and 2 show, the absolute wind ($\overrightarrow{W_{Abs}}$) in the terrestrial coordinate system is calculated by vector addition of the relative wind ($\overrightarrow{U_{Rel}}$) and the drone´s speed in relation to the ground $\overrightarrow{U_G} = (UG_E, UG_N, UG_Z)$.

$$\overrightarrow{W_{Abs}} = \overrightarrow{U_{Rel}} + \overrightarrow{U_G} \quad (1)$$

$$(W_E, W_N, W_Z) = (UR_E, UR_N, UR_Z) + (UG_E, UG_N, UG_Z) \quad (2)$$

The true horizontal wind direction and the wind speed data are calculated for each observation point and used in the flux calculations.

FIGURE 7 shows the wind data versus altitude collected by the sniffer drone during a flight. On the graphs, each dot represents the wind data value collected in an observation point while the star represents the average value for the transect; blue and red are used to colour marking the alternating direction of the flight. This example highlights how wind direction and particularly wind velocity can vary among observation points and transects.

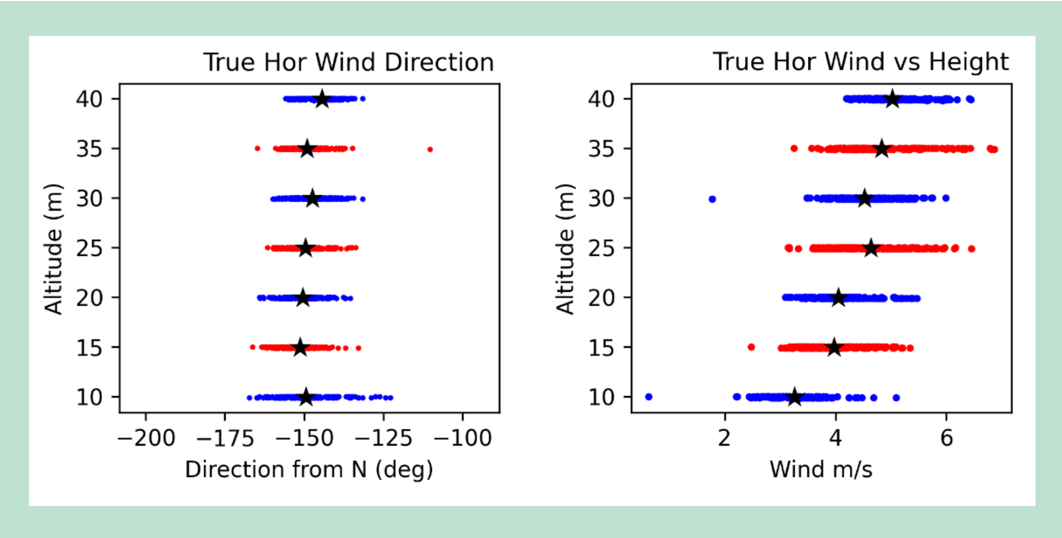

FIGURE 7. True horizontal wind direction and speed estimated in each observation point.

Unlike other methods, the DFM method does not heavily rely on mean approaches or similar approximations to estimate the wind speed when calculating the gas flux. In the DFM method any micro meteorological wind variation is taken into account, decreasing the uncertainty in the quantification and localisation of the sources.

4.4.2 Background gas concentration

A statistical method is used to evaluate the gas background concentration for each transect to define a background gas concentration profile (FIGURE 8). The profile is used in the gas flux calculation: for each transect, the gas background concentration is subtracted to the measured gas gross concentration to estimate the concentration component that is related to the site of interest´s emission. Unlike other methods, which use a mean background gas concentration, the DFM method takes into account even the small variations in the background concentrations, leading to a more precise evaluation of the gas emissions.

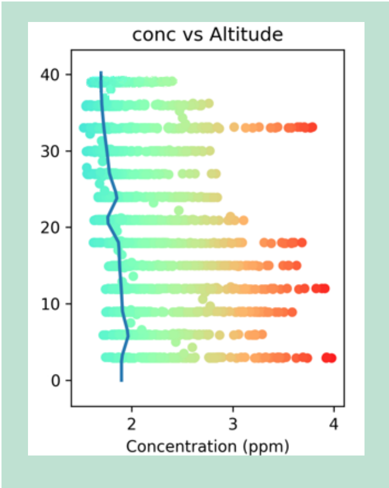

FIGURE 8. Background CH_4 concentration profile.

4.5 Flux calculation

The mass flux of a generic gas compound through a generic area is evaluated as

$$\boldsymbol{Flux} = \boldsymbol{U_n} \cdot \boldsymbol{A} \cdot \boldsymbol{C} \qquad (3)$$

where U_n is the wind velocity component normal to the surface in m/s, A is the area of the surface in m^2 and C is the concentration of the gas in the air in $kg_{gas}/m^3{}_{air}$. Using this method to calculate the net gas flux through the inspected area, Eq. 3 is expanded to:

$$\boldsymbol{Flux} = \boldsymbol{const} \cdot \boldsymbol{U_n} \cdot \boldsymbol{A} \cdot (\boldsymbol{C} - \boldsymbol{C_{bkg}}) \qquad (4)$$

where $const$ includes pressure and air temperature corrections as well as other constants needed for units conversion and C_{bkg} is the atmospheric gas background concentration.

Two main methods are used to evaluate the total net flux; the trace method for numerical integration of the gas flux through the wall and the contouring method to produce a flux density map, mainly for visualization purposes.

4.5.1 Trace method

In the trace method, the flux is first calculated through each single transect. In each observation point P(i) an area element is laid, which extends halfway from the previous and halfway to the next measuring point, as well as halfway up to the overlying transect and halfway down to the underlying transect. For the first transect the area elements will extend all the way to the terrain, and for the last transect they will extend upwards with a distance halfway to the transect below. By using Eq. 4, the gas flux through a single area element is calculated by multiplying the net gas concentration by the area of the surface element and the normal projection of the absolute wind into the surface element. The flux through a single transect is then calculated by adding all contributions:

$$\boldsymbol{Flux} = \boldsymbol{const} \cdot \sum \boldsymbol{U_n} \cdot \boldsymbol{A} \cdot \left(\boldsymbol{C} - \boldsymbol{C_{bkg}}\right) \qquad (5)$$

FIGURE 9 shows that the flux is first calculated per each transect, and the total net gas flux trough the wall is calculated by adding up each trace contribution.

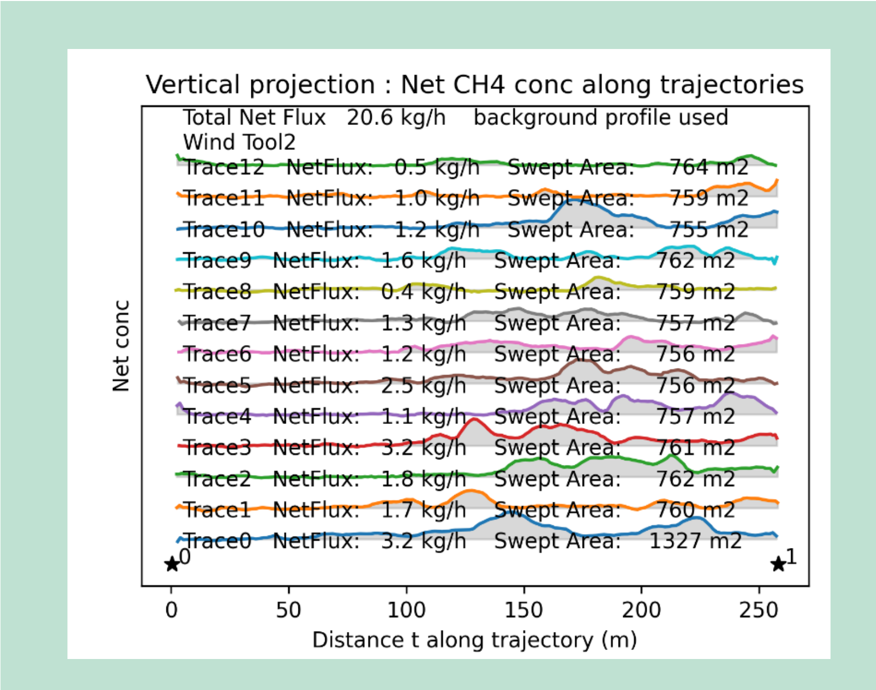

FIGURE 9. Net CH_4 flux along transects.

4.5.2 Contouring method

For the contouring method, a lattice surface is individuated based on the drone flying path. On this surface, a regular grid of lattice points is built. The flux density at the generic lattice points are calculated by performing a weighted interpolation of the flux densities from all observation points (Eq. 6).

$$\boldsymbol{Flux} = \boldsymbol{const} \cdot \sum \boldsymbol{weight} \cdot \boldsymbol{U_n} \cdot (\boldsymbol{C} - \boldsymbol{C_{bkg}}) \qquad (6)$$

FIGURE 10 shows the representation of the flux density across the inspection area obtained using the contouring method.

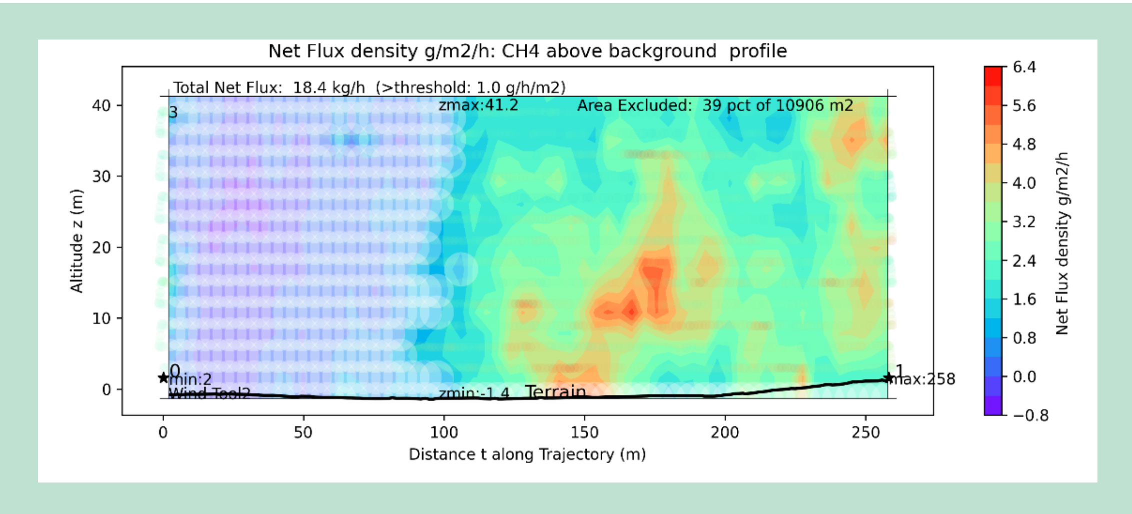

FIGURE 10. Example of a density flux map.

The flux density results are projected onto a vertical crosswind plane (mean wind) and shown on the plant map (FIGURE 11). These visualisations can then be used to estimate the location of the potential emission source.

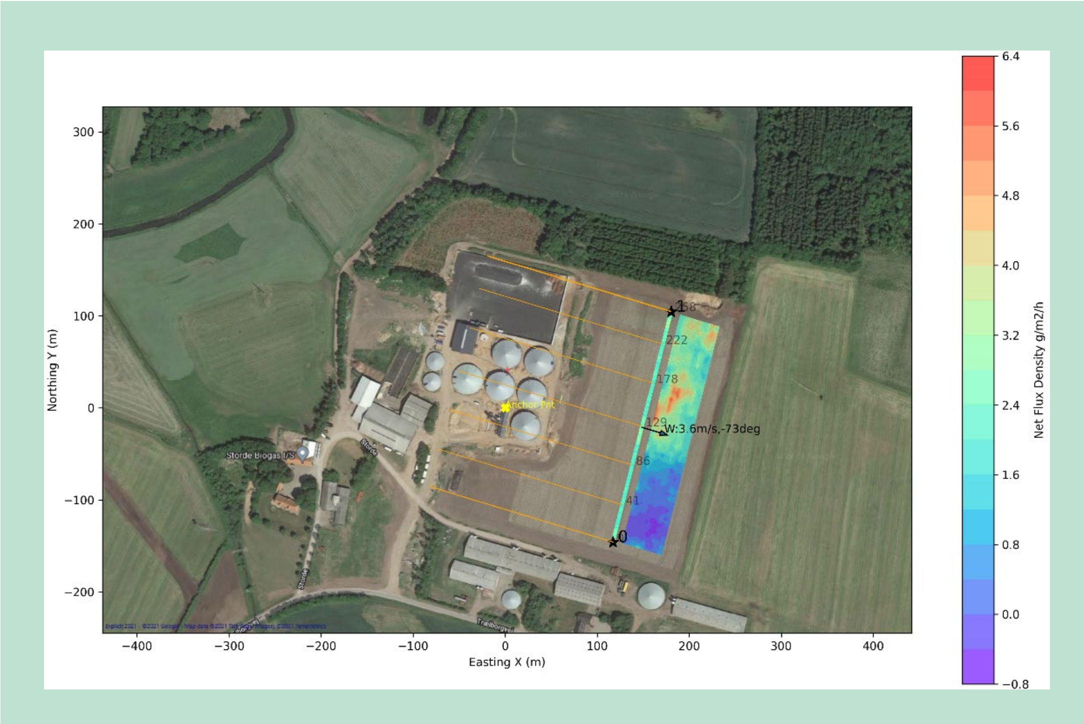

FIGURE 11. Map used to approximately localise the sources.

5. Tracer Gas Dispersion Method

The tracer gas dispersion method (TDM) is a widely method in Denmark to quantify CH_4 emissions/leaks from landfills, biogas plants and other sources of emission. The method is based on a controlled and continuous release of a tracer gas (e.g. acetylene) close to the site of interest. The CH_4 and tracer gas concentrations are measured using a high-precision gas analyser in a vehicle that's travelling across the downwind plume at a distance securing fully mixing of CH_4 and tracer (often ~2 km). By cross plume integration, the methane to tracer gas ratio is obtained. Emission rates are then calculated using the Eq. 6

$$E_{CH4} = Q_{tracer} \frac{\int_{plume_{start}}^{plume_{end}} (c_{CH4} - c_{CH4,bkg})\, dx}{\int_{plume_{start}}^{plume_{end}} (c_{tracer} - c_{tracer,bkg})\, dx} \frac{MW_{CH4}}{MW_{tracer}} \quad (6)$$

where E_{CH4} is the CH_4 emission rate in kg/h; Q_{tracer} is the release rate of the tracer gas in kg/h; C_{CH4} and C_{tracer} are the measured downwind concentrations in ppb; $C_{CH4,bkg}$ and $C_{tracer,bkg}$ are the measured background concentrations in ppb, MW is molar weight of the gas. According to the TDM procedure, the final CH_4 emission must be the average of at least 10 transects. Further information regarding the method and the equipment, and assessment of measurement accuracy can be found in Mønster et al. (2014) and Fredenslund et al. (2019).

In this project, the TDM is used as a reference method to "validate" the DFM method. Controlled release tests and several on-site campaigns have been conducted using both methods simultaneously and the results compared to determine the DFM method's validity.

6. Lab results and verification

6.1 Ammonia sensor

The Axetris LGD Compact NH_3 sensor was validated in lab by FORCE Technology to examine its ability to measure relevant NH_3-concentration levels at fast response times, as these are necessary parameters to measure ammonia flux using the DFM method.

Initial tests exposed the sensor to NH_3 concentrations of 0.1, 0.2, 0.5, 1.0, 3.0 and 5.0 ppm for 2 minutes each. Concentrations were produced on a HOVACAL and stored in inert bags for minimal surface interactivity. An initial test at ambient conditions at 20°C without NH_3 exposure showed an offset of -0.7 ppm and a noise signal of $\pm$ 0.15 ppm.

The results of the test (FIGURE 12), shows that the sensor is unable to detect the lowest concentrations (0.1 and 0.2 ppm) and is in general struggling to measure concentrations below 1.0 ppm, but at higher concentrations the sensor shows better linearity.

A ”memory” effect of NH_3 is observed (dashed line in FIGURE 12), which may be caused by the retention of NH_3 in the sensor and slow release, a typical behaviour of NH_3 in unheated systems. The reaction time T_{90} (the time at which 90% of the maximum signal is reached) at 3.0 ppm and 5.0 ppm has been estimated approximately equal to 40 seconds.

To further investigate the NH_3 sensor’s reaction time, the sensor was exposed to a 5.0 ppm environment for 10, 5, 2 and 1 s. This pulse concentration test demonstrated that an exposure of 10 s gives approximately 75% of max signal, 5 s gives approximately 65% while 2 s and 1 s give a signal below 50%.

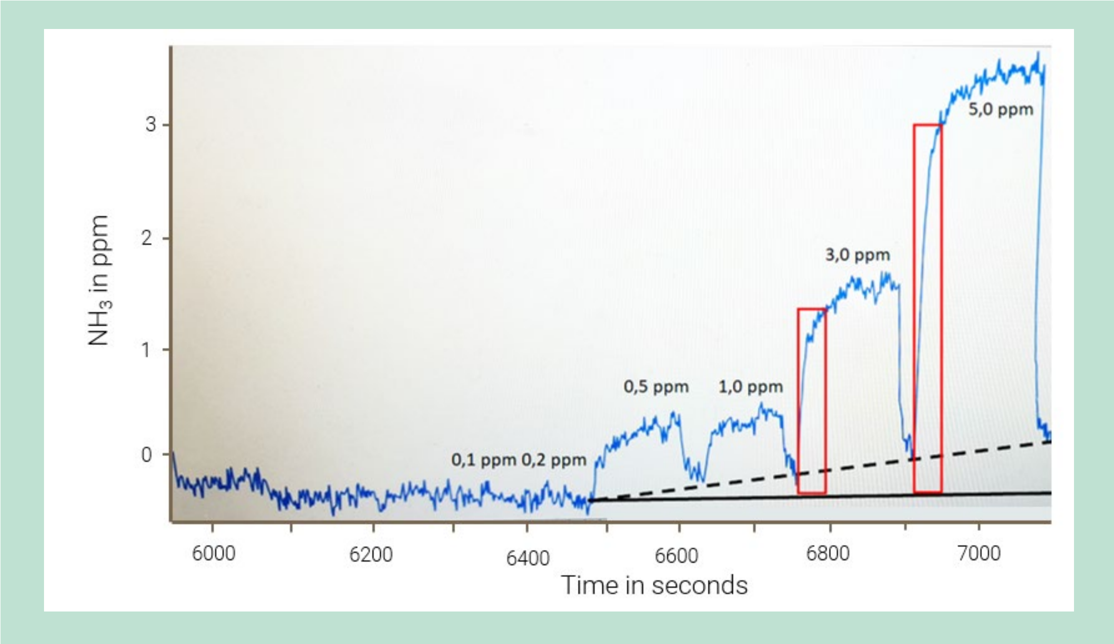

FIGURE 12. Ammonia sensor test results.

The laboratory tests showed that the LGD Compact-A NH_3 was unusable for the DFM method, mainly due to the slow signal response at standard atmospheric conditions (20°C).

6.2 Methane sensor

A thorough test on the Axetris LGD Compact CH_4 sensor was performed in lab by FORCE Technology. The test plan included tests regarding linearity, response time, gas cross interference, humidity, precision, reproducibility and noise levels.

Two test setups were used, one with a standalone sensor and one with a sensor integrated on the drone for validating the final application performance. The main test results are shown on FIGURE 13, FIGURE 14, FIGURE 15 and FIGURE 16.

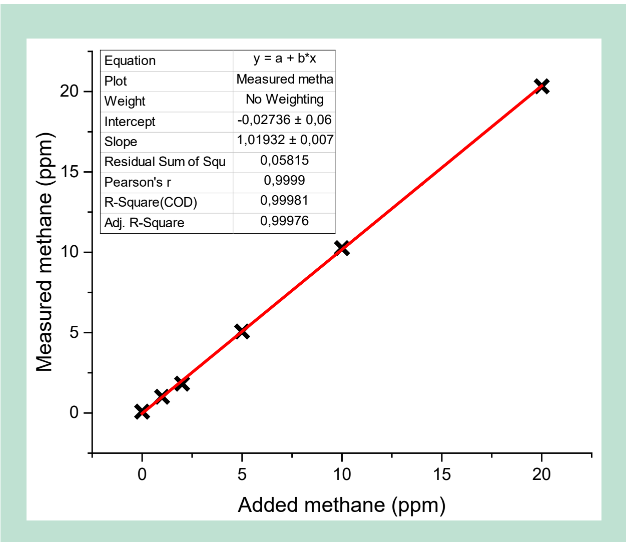

FIGURE 13. Linearity of the CH_4 sensor – sensor alone.

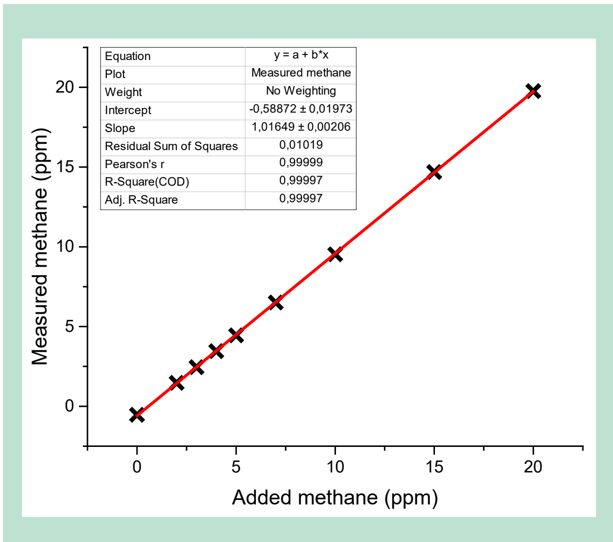

FIGURE 14. Linearity of the CH_4 sensor – sensor integrated on the drone.

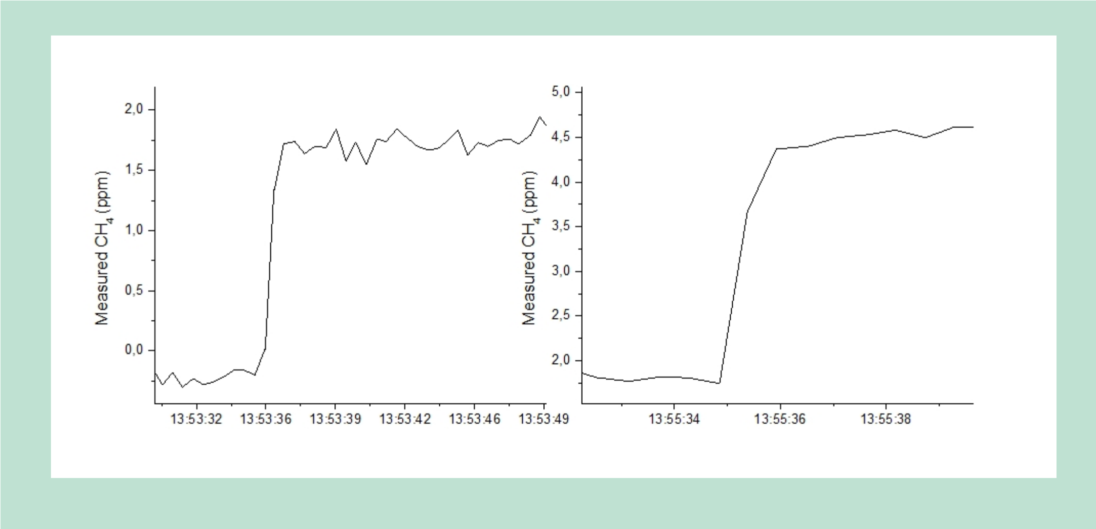

FIGURE 15. Response time of the CH_4 sensor at 2 and 4 ppm.

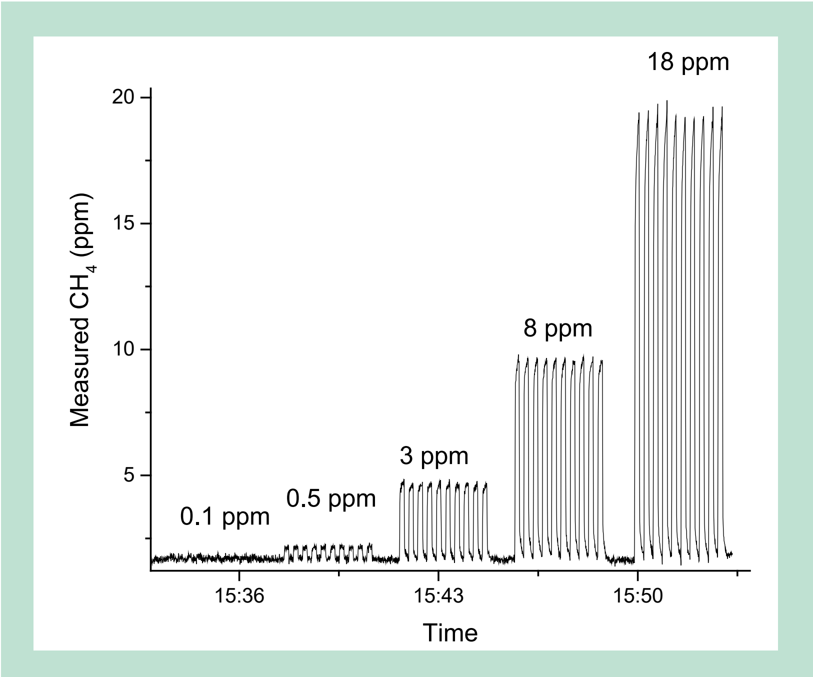

FIGURE 16. Reproducibility of fast pulses of CH_4 at 0.1, 0.5, 3, 8, and 18 ppm.

The calibration and linearity tests in both setups showed very good linearity with a small offset. The test for interference with humidity and other gases showed no interference.

The response time of the sensor was down to 1 s at low concentrations (<5 ppm), but increased slightly at higher concentrations, however still with a very good reproducibility on ten repeating pulses.

The overall conclusion from the laboratory tests was that the LGD Compact-A CH4 was indeed usable for the DFM method.

6.3 TriSonica Mini wind sensor

The TriSonica Mini was tested both in wind tunnels and in different field tests to determine the sensor performances when mounted and flown on the drone.

Smoke test

During flight, the drone displaces air around itself to create lift and movement. This may impact the data collected by the wind sensor, leading to a compromised measured wind speed and wind direction signal. A test with smoke grenades was performed to study this impact.

The drone was kept at a stationary position above ground, at 5 – 8 m/s wind speed and the smoke was used to trace the wind turbulence (FIGURE 17). This study provided feedback on where to position the wind sensors to avoid the drone generated turbulence.

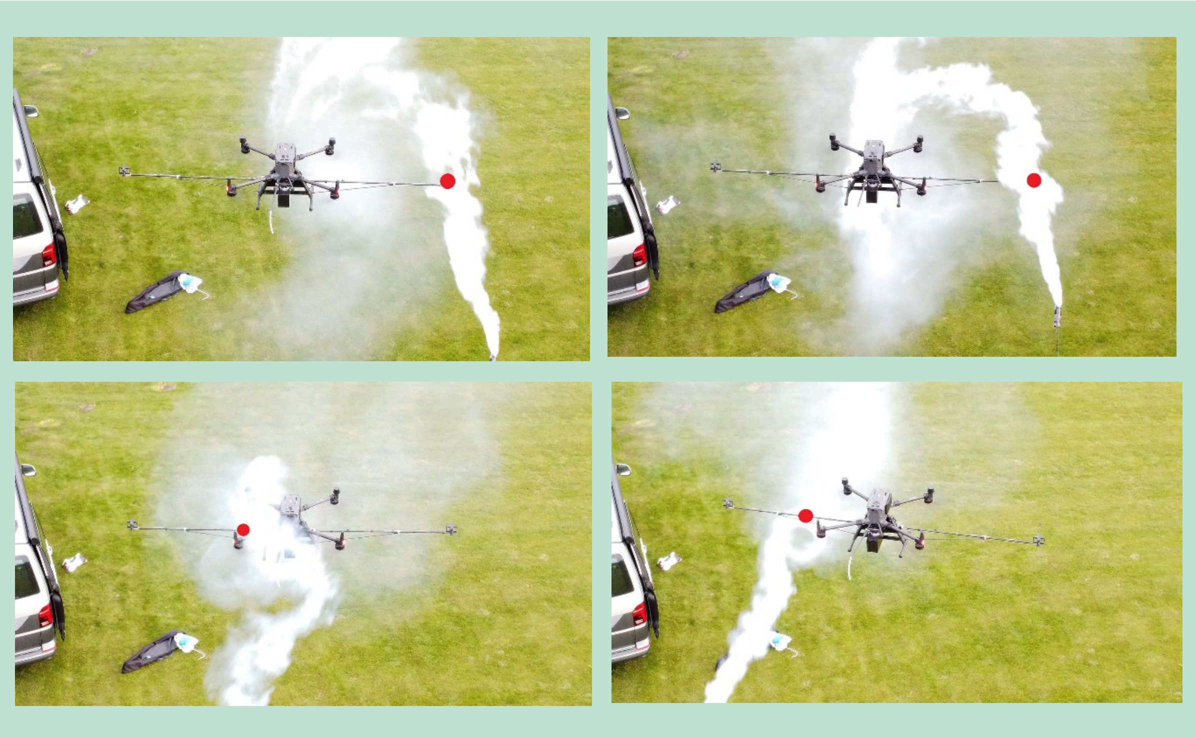

FIGURE 17. Outcome of the wind sensor smoke test. The red dot identifies the virtual position of the wind sensor.

Mast tests

To further verify the drone generated turbulence on the wind sensors and to help optimize the positioning of the sensors on the drone, several mast tests were conducted in “open-air”.

For the initial tests, two wind sensors were positioned on two different 12 m long masts, at a 10 m distance downwind from each other. This test was performed to verify if the two sensors were collecting similar wind measurements, at a delay matching the downwind speed. In the following tests, the downwind mast and wind sensor was substituted with the drone mounted with two wind sensors (FIGURE 18). Different orientations of the drone were tested, and the measurements compared with the mast measurements.

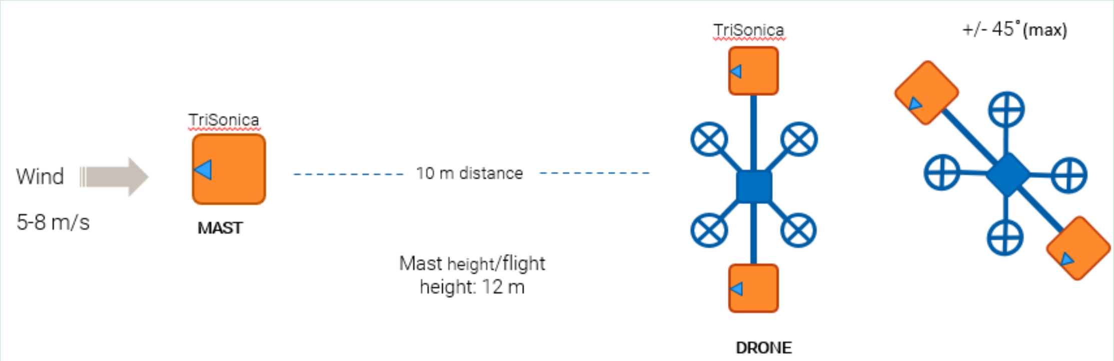

FIGURE 18. Example of a mast test set-up.

Wind tunnel tests

Several configurations have been tested to study the measured wind components at different sensor orientations, resulting in more than 1000 wind tunnel tests performed with different wind speeds, sensor pitch and/or sensor yaw and with different sensors (TABLE 4).

TABLE 4. Parameters ranges.

Type	Anemometers	Wind speed [m/s]	Tilt/pitch [°]	Wind direction/yaw [°]	N. of measurements [-]
A - slow	EX001	2, 5, 10, 16	-20, 0, 20	0:5:360	876
		4, 12	-25:2.5:25	0, 45	84
		2:1:16	-20, 0, 20	0, 45	90
		4, 12	0	-45:2.5:90	112
B - fast	EX002 EX003 EX004 EX005	5, 12	-20, 0, 20	345:5:15 30:5:60 315:15:90 0:45:360	138

This example from the tests (FIGURE 19) shows the measured wind components (U, V vectors) at different wind speeds and sensor orientations.

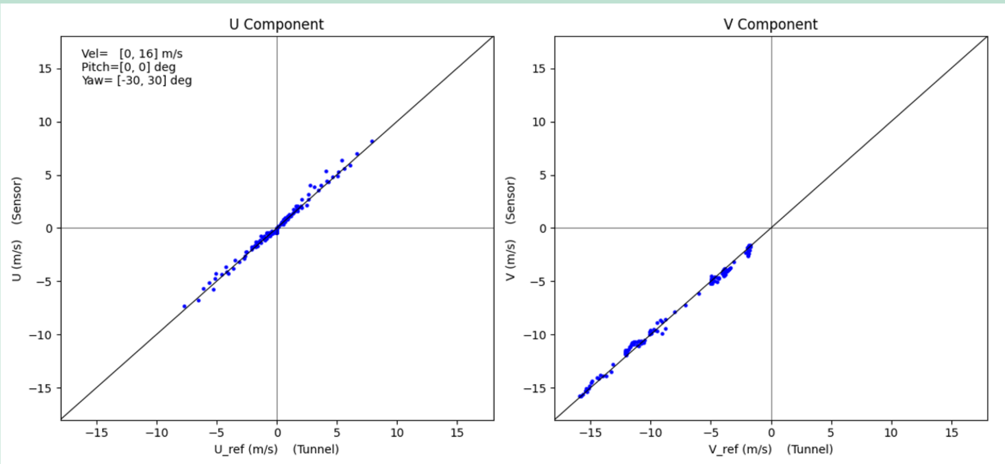

FIGURE 19. Example of a result obtained in the wind tunnel test.

A second detailed wind tunnel test, also focused on pitch and yaw orientation, was used for calibration purposes. FIGURE 20 shows the results of the test, where V_ref is wind velocity inside the tunnel (which was kept constant at 10 m/s), and the colours represent the difference between the drone-measured wind velocity and V_ref as a function of the drone´s pitch and yaw. FIGURE 21 is a zoom of the red frame in FIGURE 20, showing the measurements at the representative pitch and yaw values used by the DFM method.

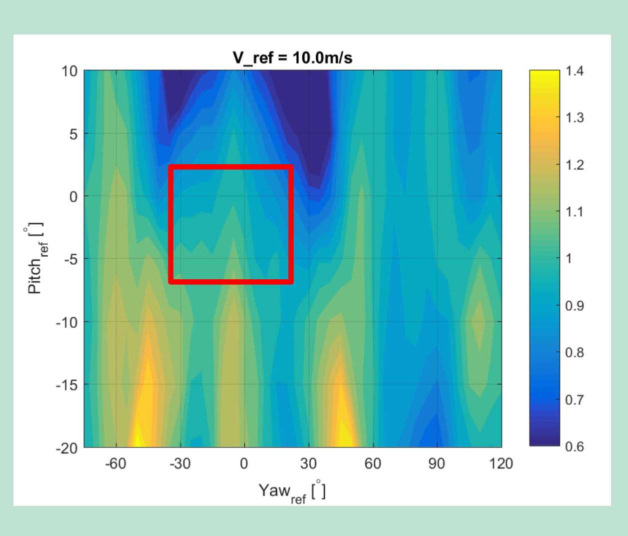

FIGURE 20. Difference between measured and reference wind while varying drone’s pitch and yaw.

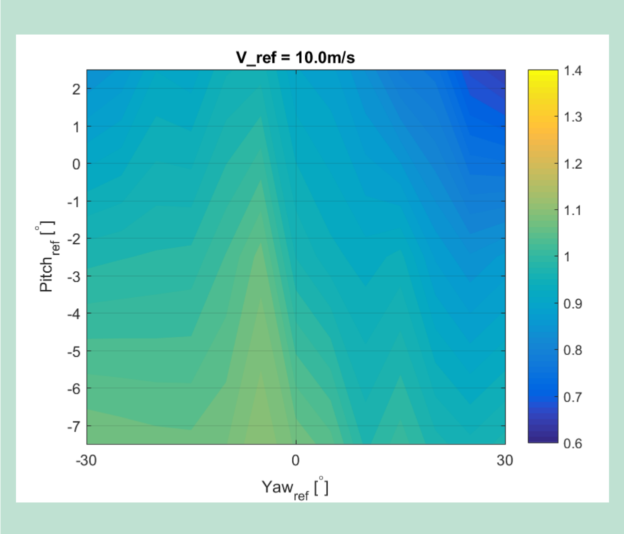

FIGURE 21. Zoom of FIGURE 20.

When the sensor is used and calibrated correctly (sensor pitch in the range [-7°, 2°] and sensor yaw in the range [-30°, 30°)], the sensor provides wind velocities that differ from the references of around 10%. These wind sensor tests results prove that the sensor is well suited for the DFM method.

Field tests


EXPLICIT
emissions data
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7. Field Results

7.1 Controlled CH_4 release tests

Several controlled CH_4 release tests were performed, with the help of DTU Environment.

For these tests, three CH_4 gas cylinders, equipped with flow meters, were used to simulate real emission sources. In the first experiment, two gas cylinders were positioned close to each other to simulate a single bigger source whereas, and in the second set-up, they were positioned 20 meters apart, to act as two weaker emissions sources. In the last test, to simulate stack emissions, the last gas cylinder was connected, through a tube, to another drone flying at 50m altitude to simulate emissions at height.

For comparative reasons, during these open field tests, the data was collected using both the DFM and TDM methods.

The results from the comparative release tests are shown in TABLE 5 and graphically visualized in FIGURE 22 – where "ground source" represent the average results of the single and double source release measurements. On the graph, the small white numbers in the coloured bars represent the number of walls and transects performed using the DFM and TDM methods respectively. The DFM results' error bars represent the standard deviation of the estimated CH_4 fluxes, whereas the error on TDM results was provided by DTU Environment.

TABLE 4. Difference (%) from the controlled CH_4 release (controlled release rate – measured emission rate)/(controlled release rate).

	DFM	TDM
Single source	+4 %	-5 %
Double source	-16 %	-8 %
Ground source	-2 %	-7 %
Release at 50 m	-19 %	-8 %

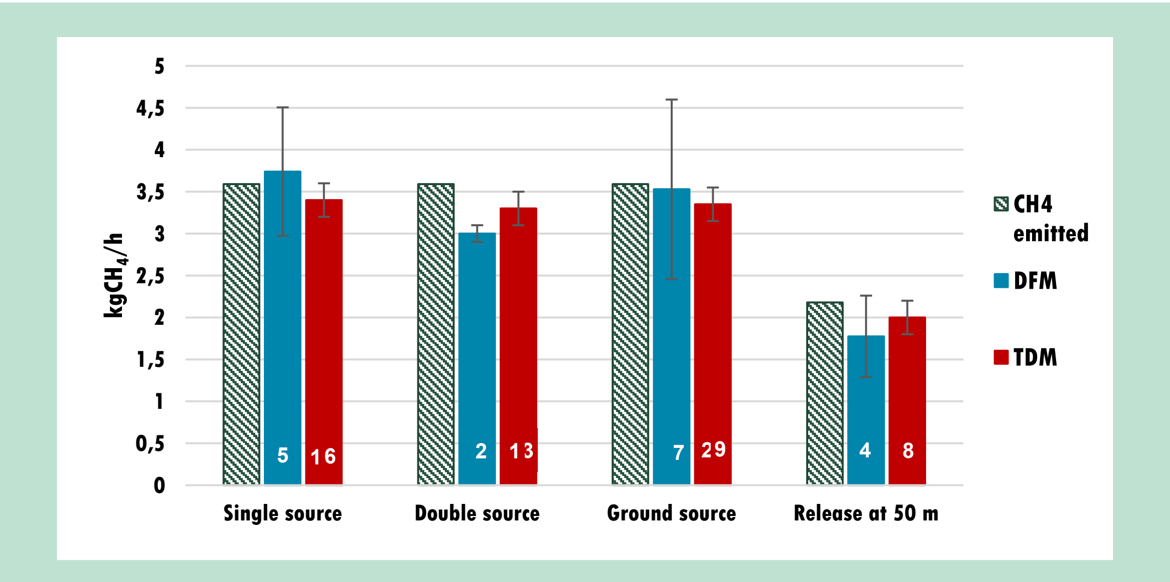

FIGURE 22. Graphical visualization of the controlled release test results.

On the single and double source experiment, the overall CH_4 emitted by the gas cylinders was 3.59 kg/h. By looking at the results, it can be observed that the DFM method seems to slightly underestimate the CH_4 emissions in the “double source” set up (-16% difference). However, this might be caused by the low single source emission rate, which was around 1.8 kg/h (even if the total emission amount was kept constant at 3.59 kg/h).

The same explanation could explain the underestimation of the CH_4 flux in the high release test (-19% difference), during which only 2.18 kg CH_4/h were released at the point source.

7.2 Tests on real sources

During 2021, several comparative campaigns were conducted, using both the DFM and TDM methods, to measure CH_4 emissions from different facilities. TABLE 6 summarizes all the measuring campaigns conducted for The Plane Project. Considering that some facilities have been measured twice, the DFM method performed a total of 24 campaigns and 128 successful walls.

TABLE 5. Tests conducted on real sources.

	DFM	TDM
Biogas plants	11	9
Wastewater treatment plants	4	3
Landfills	1	0
Agricultural production	1	1
Offshore	1	0

7.3 Comparative tests

Although many facilities have been measured using both the DFM and TDM methods, only few facilities were monitored simultaneously with both methods. For this reason, only 6 of all the measuring campaigns can be used as direct comparative tests (TABLE 7).

TABLE 6. Summary of the comparative test results. The difference (%) is given by (TDM emission rate – DFM emission rate)/(TDM emission rate).

Plant ID	Type	DFM			TDM			Difference	
		no. of walls	flux [kg/h]	std [kg/h]	no. of transects	flux [kg/h]	std [kg/h]	Data collection	flux
A	Biogas Plant	2	20.0	4.7	14	20.2	2.0	simultaneous	1 %
B	Biogas Plant	6	14.7	4.0	33	15.2	3.4	simultaneous	3 %
C	WWTP	7	4.4	0.7	10	6.5	2.1	1.30 h	33 %
D	Biogas Plant	2	23.4	3.7	14	15.2	1.9	simultaneous	-54 %
E	Biogas Plant	4	3.9	1.4	13	7.3	1.5	20 min	47 %
F	Biogas Plant	13	26.8	5.6	77	24.51	6.5	simultaneous	-9 %

For plant A and plant D, the simultaneous measuring campaigns lasted only 30 minutes, during which the DFM method only performed 2 walls. On plant D, a stack emission at height at appx. 6 kg CH_4/h was measured only by the DFM method, explaining the difference.

Plant C and plant E were measured on the same day, but the data collection did not happen simultaneously, hence not taking plant dynamics into account.

Measurements from the plant B and plant F were both simultaneous and with large comparative datasets (7 walls and 33 transects performed at plant B; 13 walls and 77 transects performed at plant F). Both comparative tests results are therefore analyzed in detail in the following sections.

7.3.1 Plant B comparative test result

The CH_4 emission rates from the DFM walls and TDM transects are plotted as a function of time in FIGURE 23.

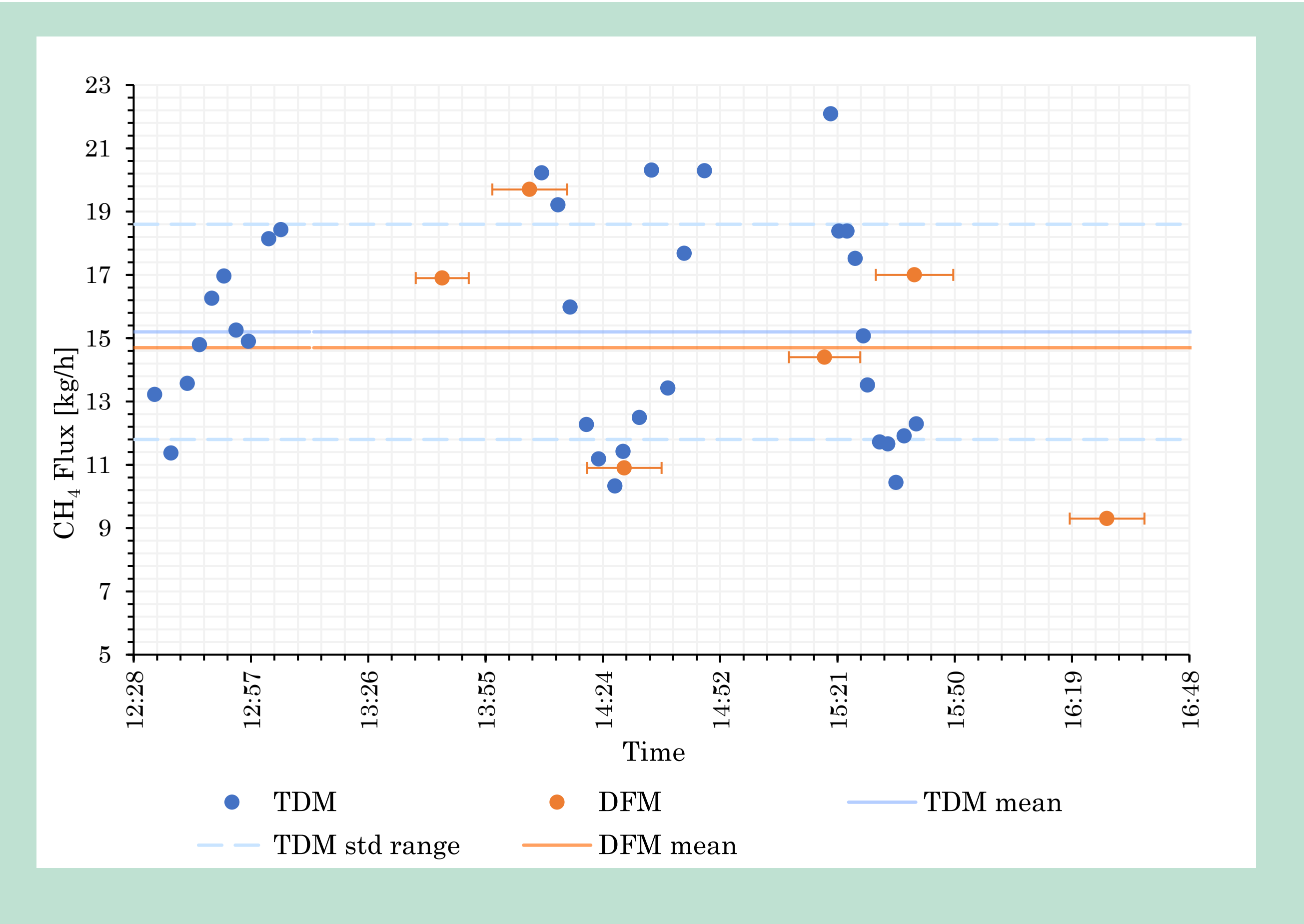

FIGURE 23. Comparison among single CH_4 emission results obtained using TDM and DFM method – Plant B.

In FIGURE 23 the variability that characterize dynamic CH_4 emissions from biogas plants is shown. Results from the two methods seem to follow the same trend with only a small average deviation at 3%.

The biogas map together with a density flux result from a DFM wall at plant B is shown on FIGURE 24. The map shows a wall with four waypoints encompassing the total emission from the plant. At each section of the transects the wind sensors are alignment by rotating (yawing) the drone in the horizontal plane, to optimize the relative wind measurements.

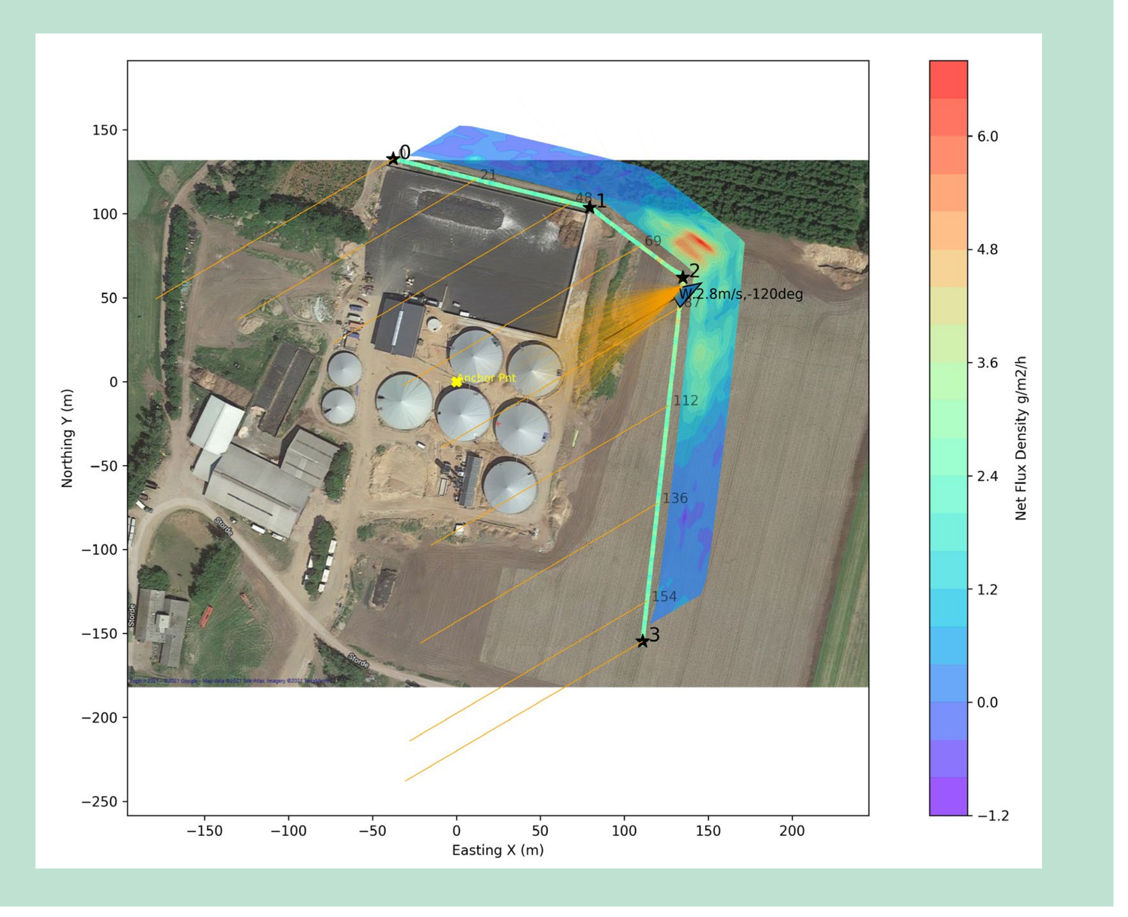

FIGURE 24. Visualization of a single wall result for Plant B.

7.3.2 Plant F comparative test result

FIGURE 25 shows how CH_4 emissions highly fluctuate over time, but even with these dynamics, the methods produce measurements with an average that only differ appx. 9%.

The biogas map together with a density flux result from a DFM wall at plant F is shown on FIGURE 26.

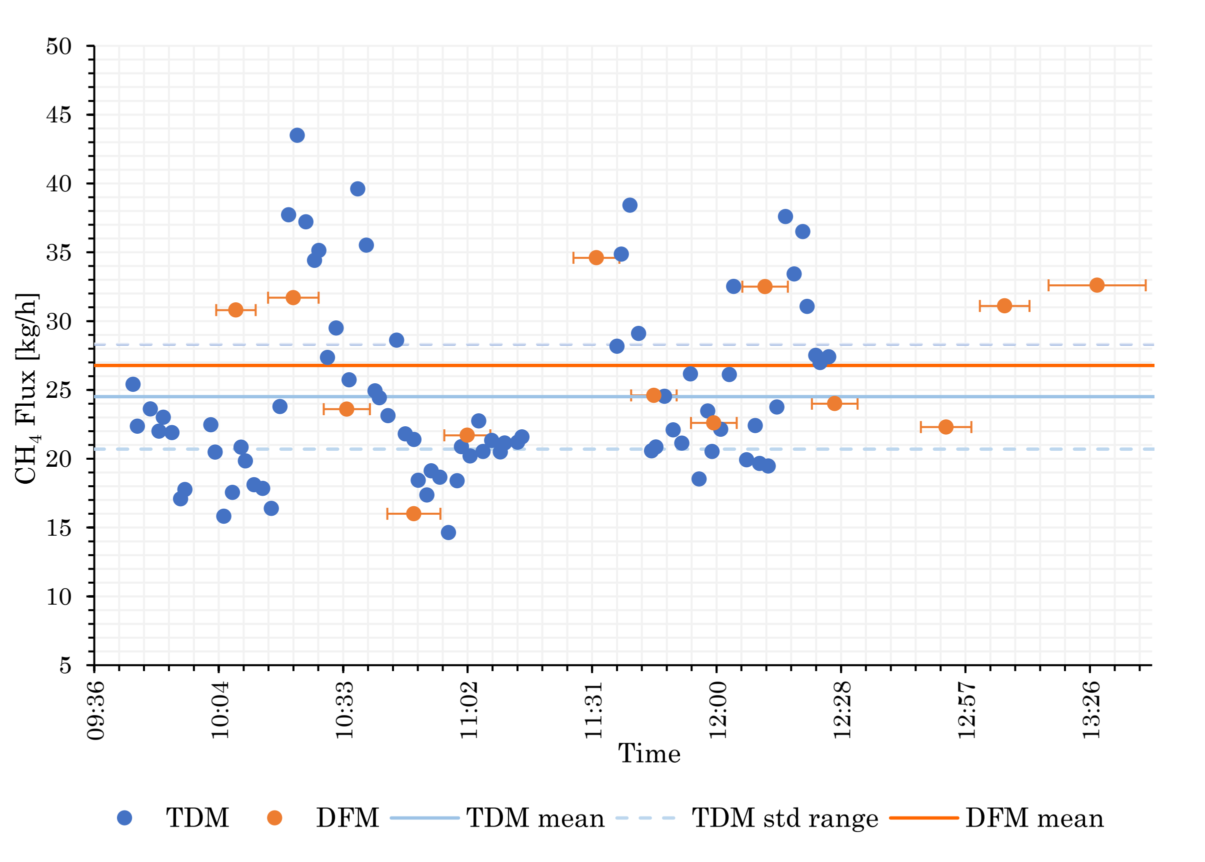

FIGURE 25. Comparison among single CH4 emission results obtained using TDM and DFM method – Plant F.

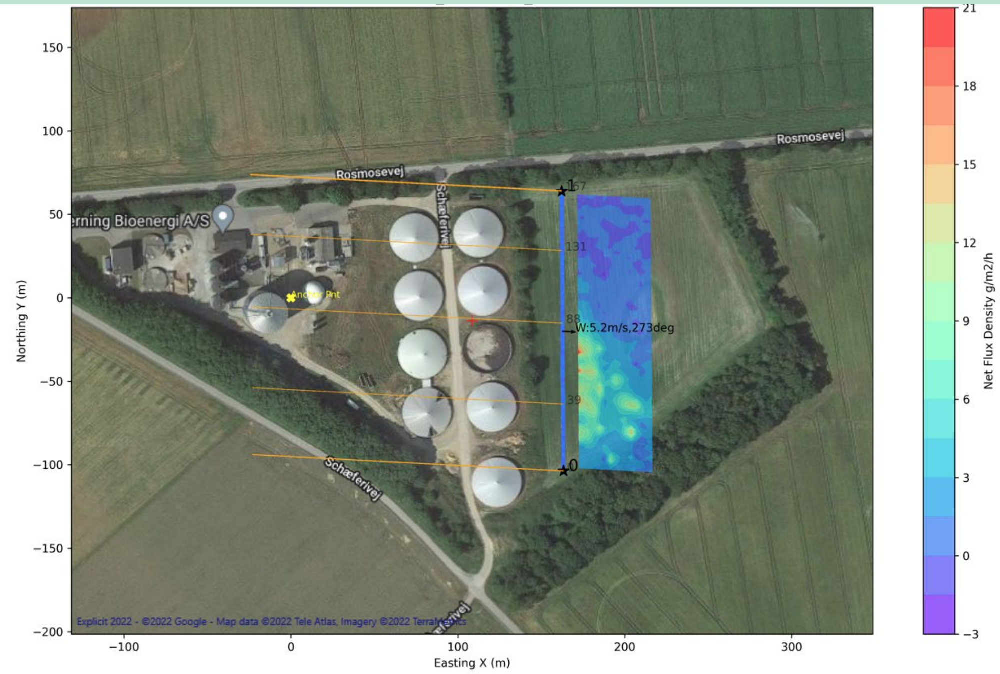

FIGURE 26. Visualization of a single wall result for Plant F.

8. Demonstration of prototype

The purpose of the demonstration of the prototype was to show the stakeholder group the final DFM method prototype and the project outcome. A total of 4 measurement walls was successfully performed at a biogas plant on Funen. Visualizations and results of the demonstration measurements are shown in FIGURE 27 to FIGURE 30.

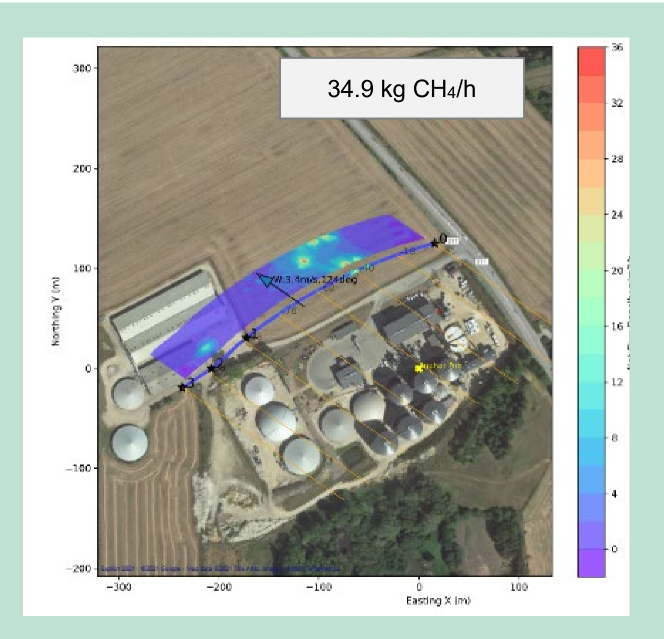

FIGURE 27. Wall 1 flux density.

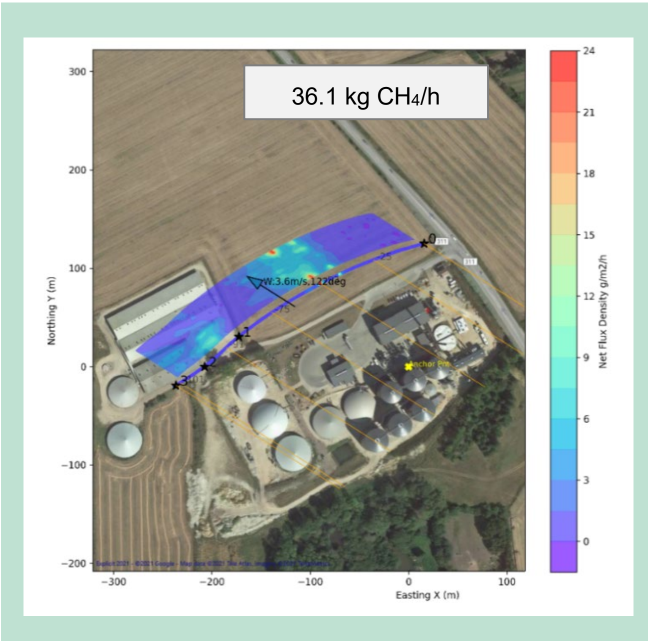

FIGURE 28. Wall 2 flux density.

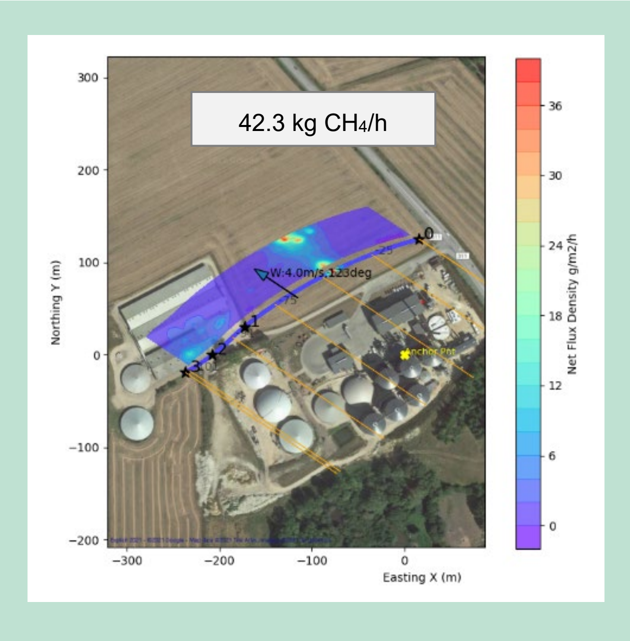

FIGURE 29. Wall 3 flux density.

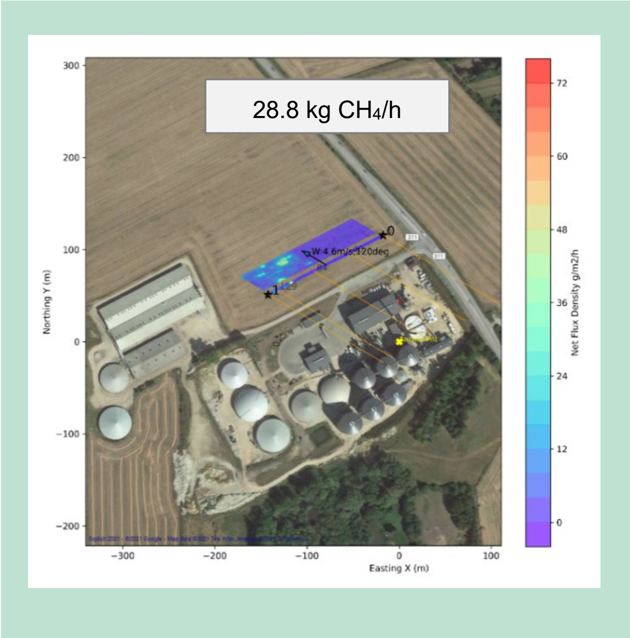

FIGURE 30. Wall 4 flux density – only part of plant.

Comparative valid TDM results were not obtained at this campaign, due to interference from a nearby pig farm (located North West of the plant).

9. Uncertainty

FORCE Technology has evaluated the uncertainty of the DFM method. This chapter contains their assessment.

The uncertainty was determined by performing parallel measurement series in which both the method of interest (DFM) and a reference method (TDM) were used simultaneously (direct approach), in accordance with DS/EN ISO 20988. With this approach, the sum of all the uncertainty contributions of the tested method was determined.

The prerequisite for the direct approach is that the method to be tested and the reference method, in a number of measurements, find the same average value, within a certain uncertainty. This was the case for the tests performed at Plant F which results are presented in TABLE 8. The two measurements series, parallel in time, were performed at Plant F implementing the DFM method by Explicit and the reference TDM method by FORCE Technology.

TABLE 7. Plant F CH_4 emissions results estimated with the DFM and TDM methods.

DFM - Tested method		TDM - Reference method		y(j) – yR(j)
Start time	kg/h	Start time	kg/h	kg/h
10:04	30.8	10:04	32.2	-1.4
10:16	31.7	10:16	30.4	1.3
10:29	23.6	10:29	22.2	1.4
10:44	16.0	10:44	19.8	-3.8
10:57	21.7	10:57	21.1	0.6
11:27	34.6	11:27	25.9	8.7
11:40	24.6	11:40	24.2	0.4
11:54	22.6	11:54	25.2	-2.6
12:06	32.5	12:06	29.9	2.6

The measurement interval found by the tested method (DFM) was 16.0 kg/h to 34.6 kg/h.

To calculate the DFM uncertainty, knowledge regarding the TDM uncertainty is required, but currently the TDM uncertainty is not known with sufficient validity to satisfy ISO standards as assessed by FORCE. In this case, the standard states that, if the uncertainty of the reference method is not known, it should be set to zero to be the most conservative. As zero uncertainty is not a realistic scenario, as a good estimate, FORCE has assumed that the two methods have equal uncertainty. This however is not in accordance with the ISO 20988, but produces a more representative uncertainty.

The uncertainty on the difference between the two methods results is theoretically calculated in Eq. 7:

$$u_{difference}{}^2 = u_{DFM}{}^2 + u_{TDM}{}^2 = 3.5^2 \quad (7)$$

Assuming equal uncertainty Eq. 8 follows:

$$u_{difference}{}^2 = 2 * u_{DFM}{}^2 = 3.5^2 \rightarrow u_{DFM} = \sqrt{\frac{3.5^2}{2}} = 2.5 \quad (8)$$

With 9 degrees of freedom, the Students t-factor (coverage factor) is 2.262. The expanded uncertainty for measurements in the interval 16.0 kg/h to 34.6 kg/h is consequently 5.6 kg/h, corresponding to 21% of the average value (26.5 kg/h). This is shown in TABLE 9.

TABLE 8. Calculation of uncertainty on Plant F results

Number of measurements	N	9	
Bias	bias	0.81	kg/h
Estimated uncertainty reference method, $u_{ref-est}$	$u(y_R)$	3.5	kg/h
Uncertainty on results, u_{method}	u(y)	3.5	kg/h
Uncertainty on difference	$u(e_y)$	2.5	kg/h
Degrees of freedom		9	
Coverage factor (Students t)		2.262	
Expanded uncertainty		5.6	kg/h

The uncertainty on a single measurement of appx. 21%, in a representative measurement interval, is considered a successful result, proving the DFM method reliability and its suitability for monitoring emissions from biogas plants.

10. Conclusion

All the goals that were set out in the Plane Project have been met, the final DFM method prototype completed and demonstrated.

The DFM system was validated through blind CH_4 release tests and simultaneous comparative measurements with the TDM method at different sites, with results of less than 9% overall difference. The comparative tests prove that the DFM method is as valid as the TDM and has some advantages particularly on the emission estimation of high sources.

The methane- and wind sensors tested in laboratory proved to be very suited for the method, however the selected ammonia sensor exhibited a slow signal response time unsuitable for the DFM method, thus giving erroneous measurements when tested on agriculture sites.

The DFM method has proved to be suitable for monitoring CH_4 emissions from many different sites (e.g. biogas plants, WWTP etc.). Moreover, the tests performed on a landfill and on an offshore oil rig showed that the DFM method also can be used for measuring these emissions.

The estimation of the uncertainty shows good performance of the DFM method, with 21% uncertainty on a single measurement in the test performed. The uncertainty will be further validated in industrial controlled release tests.

In conclusion, the DFM method allows accurate, quick and cost-efficient quantification measurements on a wide range of sources, enabling an easier monitoring of the national and international reduction targets.

11. References

Fredenslund, A. M., Rees-White, T. C., Beaven, R. P., Delre, A., Finlayson, A., Helmore, J., Allen, G. Scheutz, C. (2019). Validation and error assessment of the mobile tracer gas dispersion method for measurement of fugitive emissions from area sources. Waste Management, 83, 68–78. https://doi.org/10.1016/j.wasman.2018.10.036

Mønster, J. G., Samuelsson, J., Kjeldsen, P., Rella, C. W., Scheutz, C. (2014). Quantifying methane emission from fugitive sources by combining tracer release and downwind measurements - A sensitivity analysis based on multiple field surveys. Waste Management, 34 (8), 1416–1428. https://doi.org/10.1016/j.wasman.2014.03.025

The Plane Project - Mapping and quantification of GHGs from diffuse emission sources using drone technology and vertical measuring walls

The Drone Flux Measurement (DFM) method has shown to produce accurate, quick and cost-efficient CH_4 quantification measurements on a wide range of sources.
The main findings of the project can be summarized as follow:

- The selected methane- and wind sensors proved to be suitable for drone application
- Controlled CH_4 release tests showed differences between the measured and calculated releases of 2 to 19 %, even at low emission rates
- The representative simultaneous comparative tests between the DFM and TDM (Tracer gas Dispersion Method) method showed differences down to between 3 and 9 %.
- The method uncertainty, calculated using the comparative tests, was calculated to appx. 21 % expanded uncertainty on a single measurement wall.

In total, the DFM method was tested on 11 biogas plants, 2 wastewater treatment plants and 2 pig farms, as well as on one landfill and one offshore oil platform. Some of the facilities have been measured twice, leading to a total number of 24 measuring campaigns.

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