METHANE EMISSIONS FROM INDUSTRIAL ACTIVITIES USING DRONES

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Summary

Innovative drone-based methods have been developed to map and quantify methane leakages from various industrial activities, such as refineries, Liquified Natural Gas (LNG) terminals, landfills, and water treatment facilities. These methods use a high-speed, high-sensitivity laser sensor and were validated through controlled gas releases. They were also compared to a ground-based infrared absorption-based technique. This initiative is supported by the Swedish Governmental Agency for Innovation Systems (Vinnova) and aligns with UN Sustainable Development Goals 9, 11, and 13. The goal is to reduce methane emissions significantly, aiding Sweden in achieving net-zero greenhouse gas emissions by 2045. Accurate measurements enable effective, targeted, and trackable measures to minimize emissions, resulting in a rapid positive climate impact. The project has led to the development of two distinct drone-based methods: the wall approach and the tracer approach. The wall approach measures gas concentrations across the entire cross-section of the plume, whereas the tracer approach measures the ratio of leaking gas to source gas. Depending on the source's size, one approach may be preferred over the other, with the tracer method being more suitable for point sources and the wall approach for larger sources. The custom-designed drone in this project, provided and operated by Gerdes Solution. is equipped with a high-sensitivity laser sensor and has a flight duration of about 12 minutes while carrying a 3 kg payload. This limitation presents a challenge when conducting wall measurements, which require approximately 25 minutes of flight time for the studied sources. Due to the drone's limited flight time, it necessitates landing and battery replacement, which complicates the process and limits the number of repeat measurements. In future endeavors, employing a drone with a longer flight duration would be advantageous. In total, the study detected about 220 kg/h of methane emissions and 3 kg/h of nitrous oxide emissions, equivalent to an emission rate of about 7 tons/h of carbon dioxide. The emissions were dominated by the water treatment plant and landfills, with relatively little coming from the refinery and LNG plant. However, the wall measurements in thus study serve as demonstrations of how the technique can be used and do not provide a comprehensive picture of the actual emissions from the individual sites; this would require more statistical data in terms of repeat measurements and measurement days. It is shown that drone measurements using the new high sensitivity laser is a valuable tool for mapping methane concentrations from various types of industrial sources, which are challenging to investigate today due to diffuse emissions, large dimensions, and complex geometries. The validation studies show that both the wall approach and controlled tracer releases can be used to quantify emissions, achieving an accuracy of up to 10 % for a simple, single, source. However, in the real measurement situation, the wall approach may be difficult to execute due to practical challenges like flying restrictions and the need for spatially dense data that can be interpolated to a homogenous grid and repeated measurements. In several cases, when the drone had to fly relatively close to the plumes, downwind of large buildings in complex and turbulent wind fields, the wall approach yielded large variability in the resulting flux. It is hence evident that the wall approach requires a thorough understanding of the measurement situation, and that repeated measurements are needed, at different distances from the source and in varying wind directions. The tracer approach was therefore preferred choice for obtaining emission rates in this study, although it is challenging to carry out representative tracer releases for larger sources and for cases when the measurements are performed near to the source, and in this case the wall approach is preferred. It was also shown that the drone-based tracer approach is advantageous to the ground based since it is then easier to capture the full plume.

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1 Aim and background

Methane is a significant contributor to global warming, and for Sweden to achieve zero net emissions of greenhouse gases by 2045, methane emissions must be drastically reduced. However, measuring methane emissions is challenging because they often occur diffusely and are difficult to detect. Sources of methane emissions include tanks, leaking sealing flanges, pipelines, water treatment ponds, digesters, soil processes, sludge piles, leaking gas wells, landfills, and more recently, natural gas-powered vessels (LNG) that may experience potential leakages during bunkering or while in operation.

In this project (2021-04561), which is funded by Vinnova (Swedish Governmental Agency for Innovation Systems), a drone-based method has been developed and tested for mapping and quantifying methane leakages from various industrial activities. The method was validated by controlled gas releases and compared to an infrared absorption-based technique (MeFTIR, Mobile extractive Fourier Transform InfraRed). Using drones is advantageous because they can access gas plumes wherever they may be and fly in towards leakage points facilitates identification of sources of methane. The aim of the project was to develop a reliable and efficient drone-based method for mapping and quantifying methane emissions, which can complement other advanced ground-based optical techniques. The drone-based method, along with complementary optical techniques, was tested with stakeholders at an LNG storage terminal, an oil harbor, a water treatment facility, a refinery, and several landfills operated by two waste handling companies. In addition, a controlled source release experiment was conducted in which four gases were released and then estimated using the drone-based method. In the project, we also attempted to measure methane emissions from LNG ships and fueling in the Gothenburg harbor. However, during the project period, there were very few opportunities to do this. Instead, we conducted a leak survey at another LNG gas terminal in Eastern Sweden. These measurements can help drive abatement actions from stakeholders. Note that the measurements serve as demonstrations of how the technique can be used and do not necessarily provide a comprehensive picture of the actual emissions from the individual sites; this would require more statistical data in terms of repeat measurements and measurement days. Methane has a global warming potential that is 28 times greater than CO_2 over a 100-year timespan and about 80 times over 20 years. Its relatively short atmospheric lifespan of 9±2 years makes it a good target for immediate climate change mitigation.

2 Instrumentation

The initial phase of the project involved adapting a sensor package to a drone platform and implementing radio communication. The drone, SkyEye, was provided by Gerdes Solutions (see cover picture) and they assisted in mounting the laser spectrometer and carried out the all flying. Two separate measurement devices were used on the drone throughout the campaign: a new laser spectrometer and a multi-sensor box. The laser spectrometer, shown in Figure 1, measures both methane and ethane in the infrared wavelength range (2.5 - 4.5 µm), with high sensitivity (~1 ppb) at a 1-second time resolution. This instrument also provides additional data, such as temperature, humidity, Global Positioning System (GPS) coordinates, etc. The system weighs approximately 2.5 kg and has an approximate dimension of 15 x 15 x 10 cm.

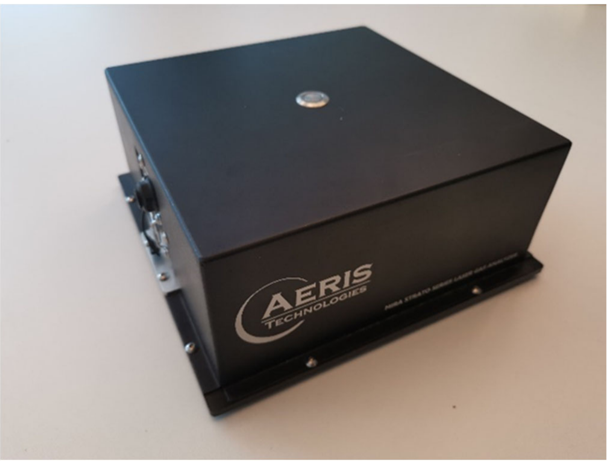

Figure 1. The laser spectrometer used measures methane and ethane with 1 ppb sensitivity at 1 s time resolution. The data are transmitted to the ground via radio modem and shown in real-time on a computer.

The second instrument used is a multi-gas sensor, which measures CO_2 and Volatile Organic Compounds (VOCs). CO_2 is measured with NDIR technique (Non-dispersive Infrared), while VOC is detected with PID (Photo-ionization detection). The instrument also includes an ultrasonic, lightweight wind sensor, which is installed on a 15 cm pole on the drone to reach above the propeller draft. The multi-gas sensor also provides GPS coordinates, temperature, pressure, and humidity. The data transmission between these instruments and the ground station is done using a 2.4 GHz LoRa radio. The data is received on the ground and visualized in real-time using custom software developed at Chalmers.

In addition to the measurements by the drone-based system, complementary and comparative measurements were performed from a measurement van with a mobile infrared absorption system from FluxSense denoted MeFTIR, shown in Figure 2. This instrument is designed to measure concentrations of VOCs and other gases in the extracted air using internal IR-light (Vecchi et al., 2023). In this project, it was used to measure methane, ethane, and tracers (N_2O, acetylene). The system consists of an infrared spectrometer and a multi-pass optical reflection cell mounted in a temperature-controlled enclosure. The instrument provides ground-level concentrations of a range of specific gases. When used together with controlled trace gas releases (Galle et al., 2001), the emission rate (g/s) can be retrieved (see methodology section below).

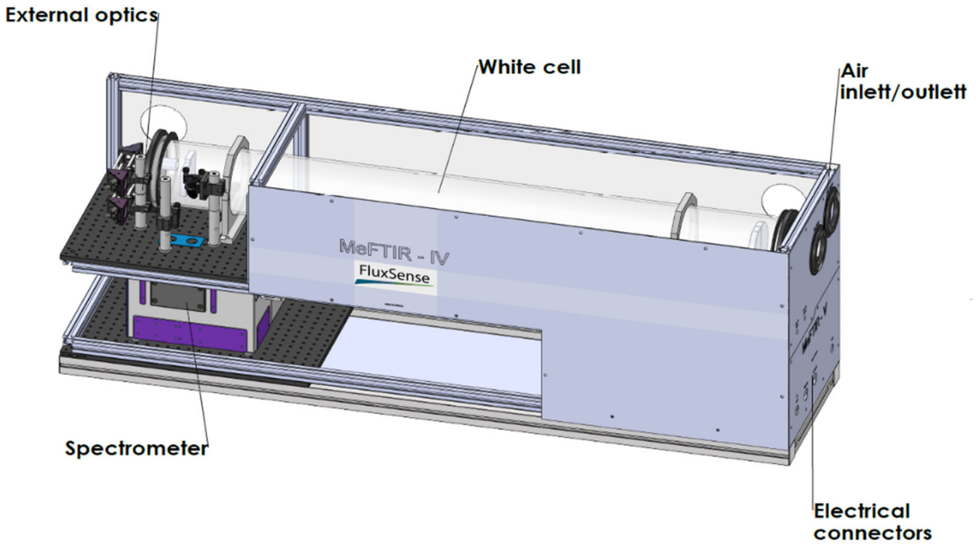

Figure 2. Overview of the MeFTIR (Mobile Extractive FTIR). This system measures for example, acetylene, CH_4, ethane, N_2O and many other VOCs. This system is operated from mobile laboratory (measurements van). The measurements are combined with controlled tracer releases of for instance N_2O or acetylene at the source to estimate the emission of the source.

3 Measurement methodology

The different campaigns included several types of measurement methodologies:

- Wind Profiling
  The wind sensor mounted on the drone was calibrated against a *Windsonic* sensor that was mounted on a 15 m mast and used as the reference wind. During the calibration, the drone hovered at mast height, 5-10 m away from the mast to avoid the propellers affecting the reference readings. The measurements were taken at different heights for a period of 10 to 12 minutes to obtain a vertical wind profile. This was conducted up to the maximum allowed drone flight height.

- Wall Measurement method
  The wall measurement method was used to investigate emissions from identified point or smaller area sources. This technique involves measuring the gas concentration across the entire cross-section of the plume, perpendicular to the wind direction, and multiplying it with the wind speed. It requires a persistent horizontal wind during the measurements. The drone measurements were conducted along a predetermined route downwind of the source at different altitudes and orthogonal to the wind direction, and attempts were made to get out of the plume on either side. The transects performed form a virtual wall downwind of the source. However, obstacles and loss of reception can limit this approach in some places, making it difficult to get out of the plume. The gas flux from the source is calculated by multiplying the integrated concentration across the wall with the orthogonal wind speed. However, the measured data cannot be used directly as it is necessary to interpolate the data over the full cross-section of the plume due to uneven distribution and gaps between different measurement heights. In this study, trapezoidal integration (using Matlab) was employed to interpolate the measured data on an even grid. In this process, the direction of the wall is first defined as the average direction of the point space measured by the sensor, using a least squares calculation.

- Tracer approach
  In the tracer approach, also known as the tracer correlation method (TC) or tracer dispersion method (TDM) (Galle et al. 2001), the emission rate of a certain source can be obtained by releasing a trace gas, also called tracer, in the vicinity of the source and then measuring the ratio of the leaking source gas to the trace gas downwind of the plume. In this project ethane was used as a tracer and it was released at the source and then measured by the laser system on the drone together with leaking methane and by MeFTIR on the ground. The latter measurements were also performed using N_2O as alternative tracer. The tracer was generally released from several gas cylinders simultaneously to minimize the cooling effects when releasing pressurized gas and to mitigate phase transition effects from liquid to gas phase inside the cylinders. The release rate of the tracer was obtained by weighing the gas cylinders with a high-precision scale and ensuring a steady flow with a flow meter or mass flow controller. Wind information from a 3-m mobile mast was used to support the leak detection. The Tracer method is standardized by CEN since 2021 and Chalmers and FluxSense has carried out measurements using this method at numerous landfills, industrial plants and gas wells. In the method it is crucial to locate the trace gas release in vicinity of the emissions. This is done by first mapping the concentrations across the emission site, identifying the dominant source at each site. A trace gas is then released near the

identified source and subsequent measurements are performed from a drone or from a measurement van on the ground to obtain the methane emissions. Multiple measurements (at least 4) are required and they should ideally be carried out on, ideally on separate days, distances and wind directions. The latter was outside the scope of this project.

4 Campaigns

4.1 Validation trial

A controlled gas release was conducted at a rural test site in November 2022. Four gases were released from the same point at constant rates: 2.15 kg/h for methane, 1.83 kg/h for ethane, 2.18 kg/h for N_2O, and 1.86 kg/h for acetylene. A precision scale was used to weigh the mass release.

Figure 3 depicts an example of a measurement using MeFTIR. The height of the curves represents the concentration of methane (yellow) and N_2O (turquoise) at ground level above the background concentration. From this, a methane emission rate of 2.4 kg/h was obtained, compared to the release rate of 2.1 kg/h. Figure 4 presents examples of wall measurements at the same site with the drone-based laser sensor, showing an emission rate of 2.17 kg/h, compared to the controlled source release rate of 2.15 kg/h. In total, four wall measurements were conducted, with graphs of these, including ethane, available in Appendix A.

The overall results from the controlled release experiment are shown in Table 1. It presents the results from the four different variants used to estimate the average methane emission rate during a specific release period: a) drone-based laser spectrometer and ethane tracer, b) Ground-based laser spectrometer and ethane tracer, c) Ground-based MeFTIR and ethane tracer, d) Ground-based MeFTIR and N_2O tracer, and e) drone-based laser (wall estimate). The measurement errors range from 2-12 %.

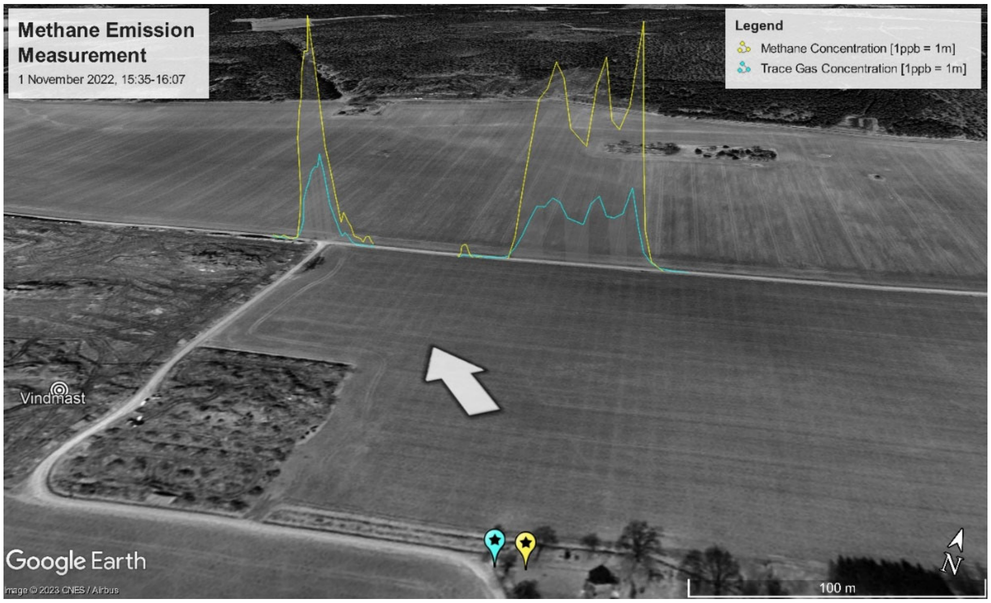

Figure 3. Example of a methane emission measurement at a rural test site near Gothenburg, November 1, 2022, carried out at 16:00. The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The yellow curve corresponds to the methane concentration with maximum concentration 89 µg/m³. The turquoise curve corresponds to the tracer concentration (here N_2O concentration). White arrow indicates wind direction. The turquoise marker shows the position of the tracer release. Map: Google Earth™ © 2022.

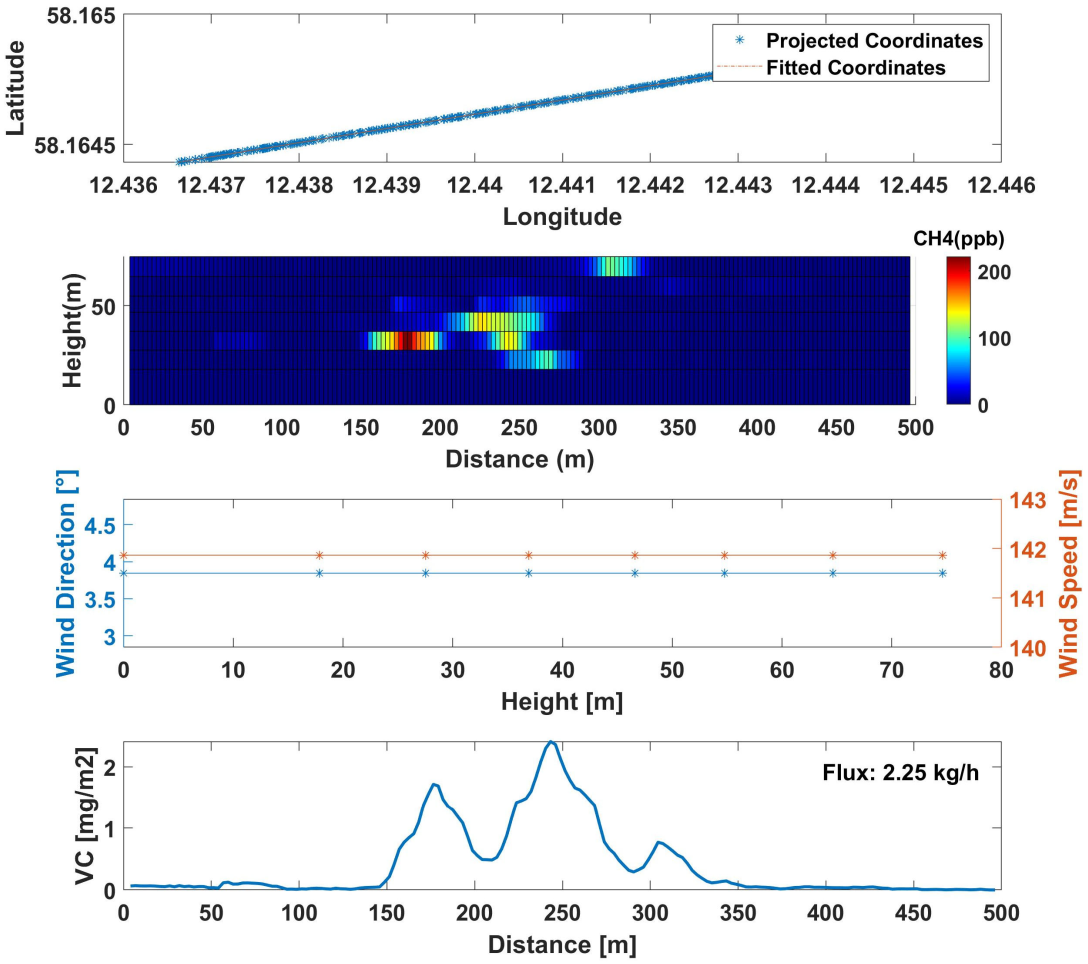

Figure 4. Results from the experiment with controlled gas release of methane at a rural site on November 1, 2022, at 16:02. Wall-measurements showed a CH_4 emission rate of 2.25 kg/h, which can be compared to the controlled gas release rate of 2.15 kg/h. The upper graph displays the geographic coordinates of the wall direction, the second graph shows the interpolated CH_4 mixing ratio, the third graph displays the height profiles of wind speed and direction, and the fourth graph shows the integrated vertical column (mg/m^2) of methane as a function of distance.

Table 1. Emission measurement validation of drone-based laser sensor (wall and tracer measurements) and ground-based MeFTIR and tracer (N_2O or ethane) for controlled gas release (2.15 kg/h CH_4) at a Rural test site on November 1, 2022. No. corresponds to numbers of measurements.

Description	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)	**Error**
Drone-based laser, ethane tracer	1517-1621	24	2.4	0.1	12%
Ground-based laser, ethane tracer	1655-1721	7	2.2	0.2	2%
MeFTIR, ethane tracer	1412-1622	25	2.1	0.2	-2%
MeFTIR, N_2O tracer	1412-1609	23	2.4	0.2	12%
Drone-based laser, wall appraoch	1517 - 1618	4	1.98	0.36	-8%

4.2 Landfills, operator A

4.2.1 Results at Landfill A1

An example of measurements of diffuse emissions from the entire Landfill A1 is shown in Figure 5. At this site drone-based laser measurements with ethane as tracer and ground-based MeFTIR with N_2O as the tracer were performed as shown in Table 2. In addition, one wall measurement was carried out. It can be noted that there is about a factor of two difference between the two methods in Table 2, in contrast to the results in the controlled gas release experiment. This difference could be due to uplift of leaking methane gas from the ground, indicating that part of the emission may not be captured on the ground by MeFTIR. However, these differences need to be analyzed further.

Table 2. Emission estimation of the entire A1 Landfill on Oct 13, 2022. Measurements by drone-based laser, tracer and wall approach, and ground-based MeFTIR with tracer release. No. corresponds to numbers of measurements.

Description	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)
Drone-based laser, tracer	1104 -1128	5	47.6	29.8
Drone-based laser, wall approach	1405-1435	1	17.6	
Ground-based MeFTIR. tracer	1502 -1601	8	20.6	4.4

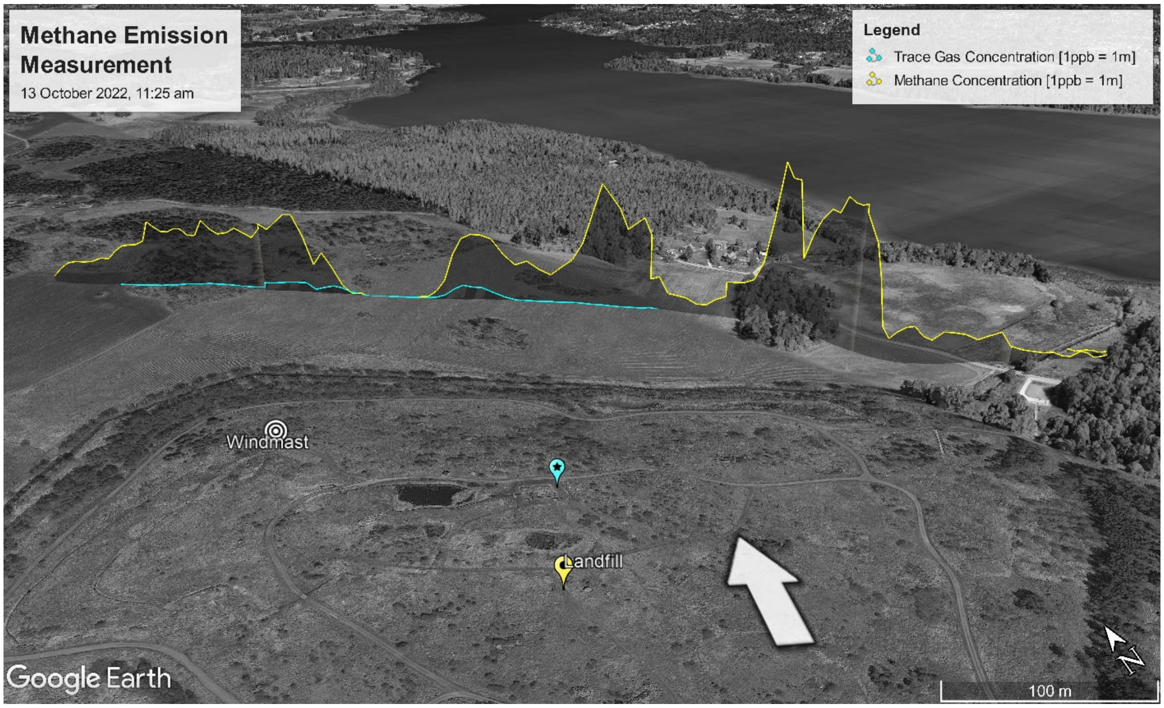

Figure 5. Example of a total methane measurement at Landfill A1 on 13 October 2022 carried out at 11:25am. The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration for this measurement was 92 µg/m^3. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

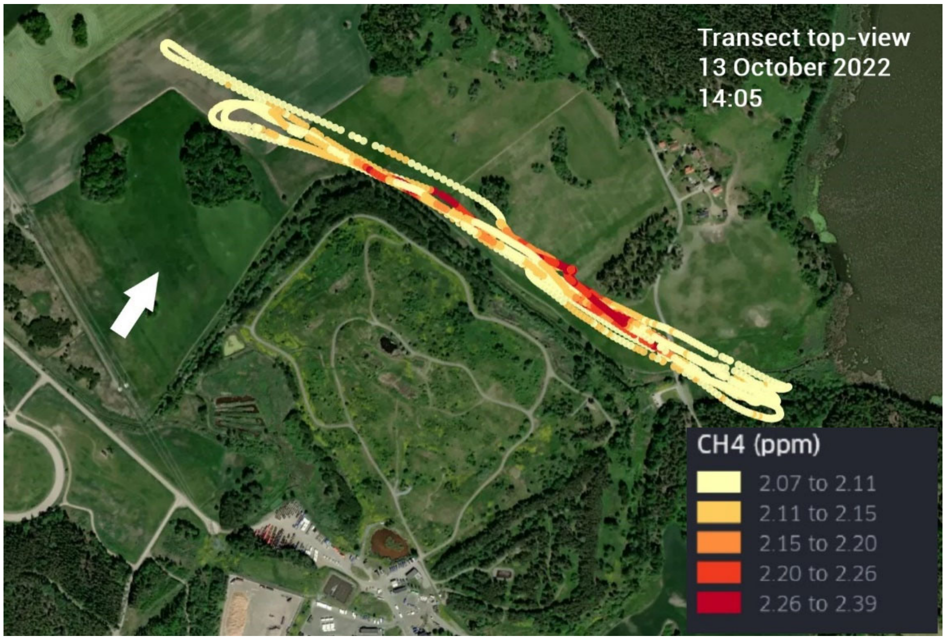

Figure 6. Visualization of the performed measurement transects while carrying out drone-based laser measurements using the wall approach at Landfill A1 on October 12, 14:05. Graphic from: www.kepler.gl© with underlying Map from Mapbox©.

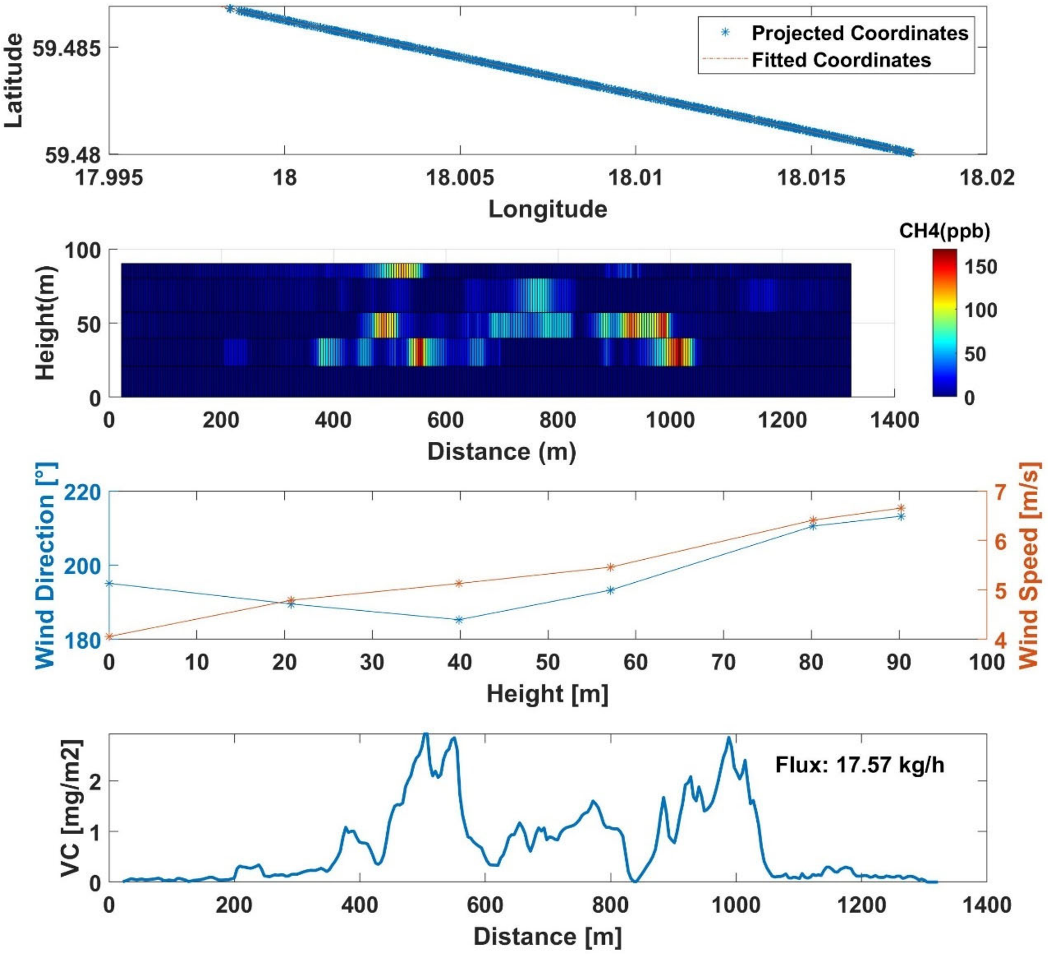

Figure 7. Drone-based laser measurements using the wall approach at Landfill A1 on October 12, 14:05. The estimated emission rate from the full site corresponds to 17.6 kg/h in this measurement. See Figure 4 for an explanation of the principles of the individual graphs.

4.2.2 Results at Landfill A2

An example of a ground-based methane measurement at Landfill A2 is shown in Figure 8 using the laser instrument for measuring methane and ethane from a measurement van and utilizing ethane as tracer. The emission results are shown in Table 3. Wall measurements were not carried out at this site due to snowy weather and only the emissions from the sludge heaps were measured.

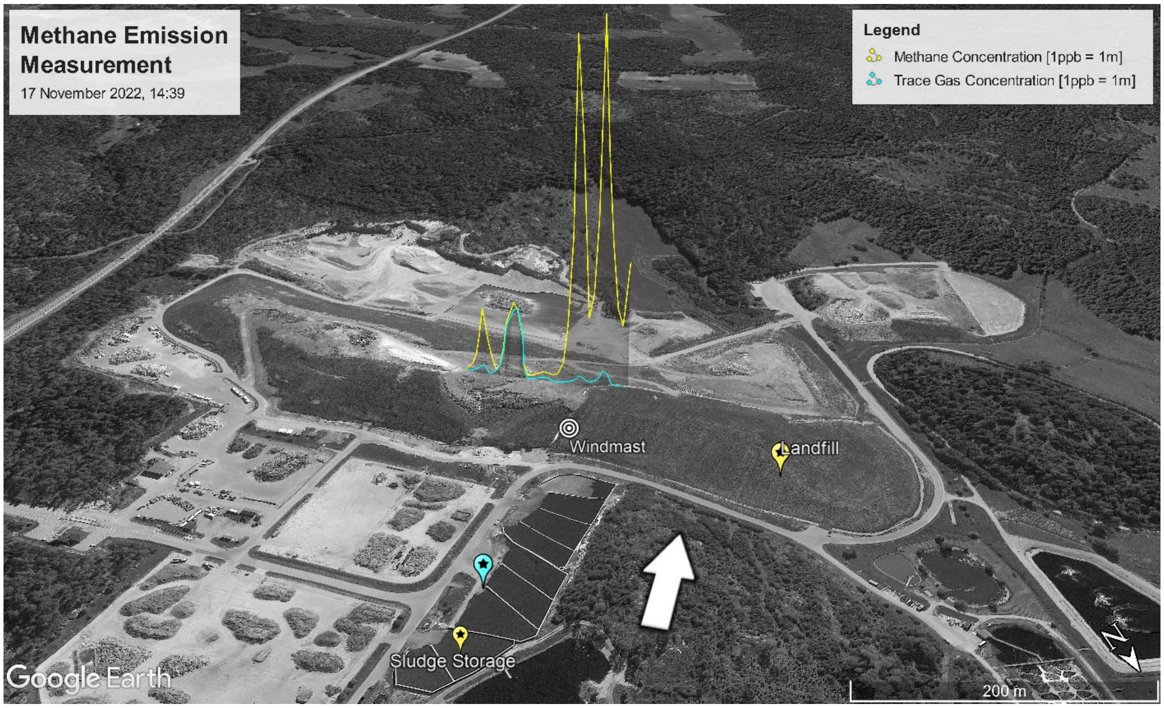

Figure 8. Example of a total methane measurement at Landfill A2, on November 17, 2022, carried out at 14:39. The height of the curves correspond to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration at this measurement was 354 µg/m³. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

Table 3. Emission measurements at site A2 using the tracer approach and measurements from drone and ground. No. corresponds to numbers of measurements.

Description	**Date** (yyyymm)	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)
Drone-based laser, tracer	20221117	1435 -1451	6	9.4	4.6

4.3 Landfills, operator B

4.3.1 Results at Landfill B1

The provided text discusses methane measurements conducted over two days at Landfill site B1 using drone-based and ground-based techniques. The drone-based measurements involved wind profiling and wall measurements downwind of the landfill, with the plume ending at around 75 meters height above ground. Occasionally, there were difficulties in getting out of the plume due to forest cover and hills limiting flight distance at lower heights, and loss of radio contact with the drone. Figure 9 illustrates a methane leak search at the northern landfill of site B1 on October 12, 2022. A ground-based laser sensor was attached to a motorbike that was driven around the landfill to detect methane leaks. Colored spheres represent methane measurement points, with each color indicating the absolute concentration in parts per million (ppm) above the background level. Three methane sources were identified: the northern part of the landfill, sludge heaps in the southeast part, and a neighboring horse manure storage site to the east that was not part of the landfill. Table 4 presents the ground-based laser sensor results for site B1, which include data for the full site, sludge heaps, horse manure storage, and the northern landfill. The emission data for the northern landfill was determined by calculating the difference between the measurements from all sites during easterly wind conditions on November 16 and the combined emissions of the horse manure and sludge heaps.

Figure 10 presents the laser-based drone measurements, which utilized the wall approach, and were conducted during southwesterly winds, downwind of the northern landfill, sludge heap, and horse manure storage on October 12. The emission rate was measured at 28.8 kg/h, as noted in Table 4. A similar measurement was conducted downwind of the landfill but upwind of the horse manure storage and the sludge heap, revealing an emission rate of 11.5 kg/h. This value is lower than the 24 kg/h, which is the corresponding value obtained using the ground-based tracer approach about one month later. The differences in the northern landfill emissions between the two methods are likely due to the fact that these are single wall measurements which are associated with relatively large uncertainties.

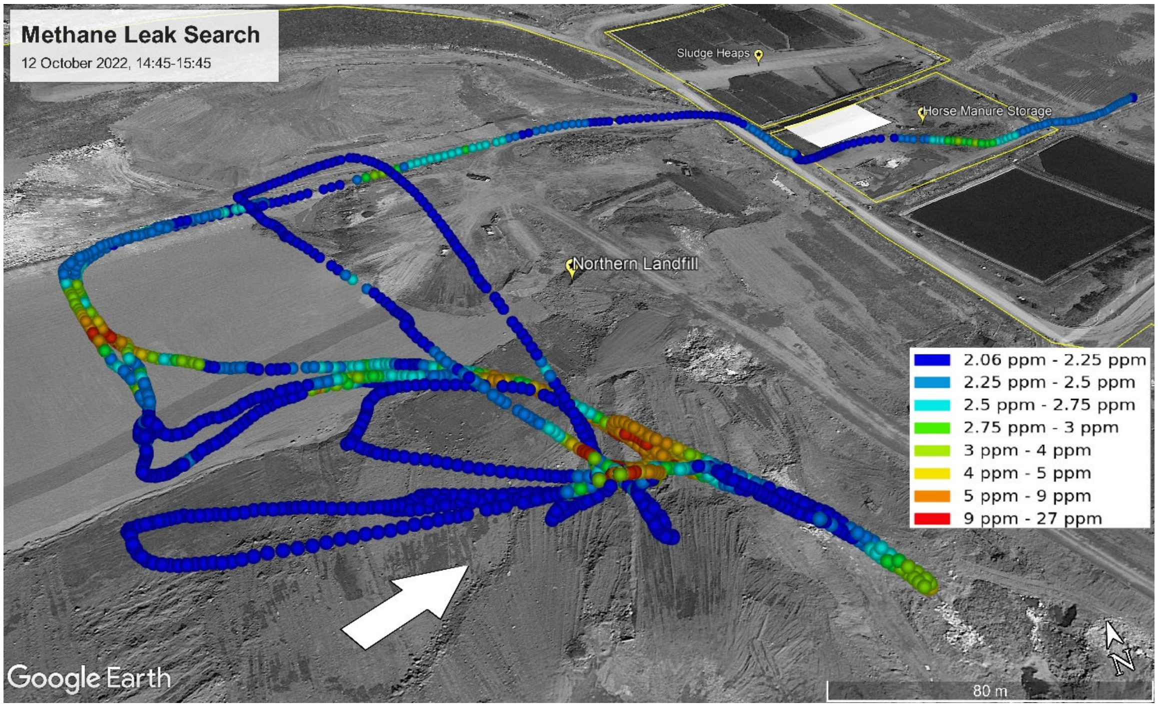

Figure 9. Leak search of methane at the northern landfill at site B1 carried out on October 12 2022 between 14:45 - 15:45, carried out from the ground using a moped. The coloured spheres indicate methane measurement points, and each colour indicates absolute concentration in ppm above background level. Map: Google Earth™ © 2022.

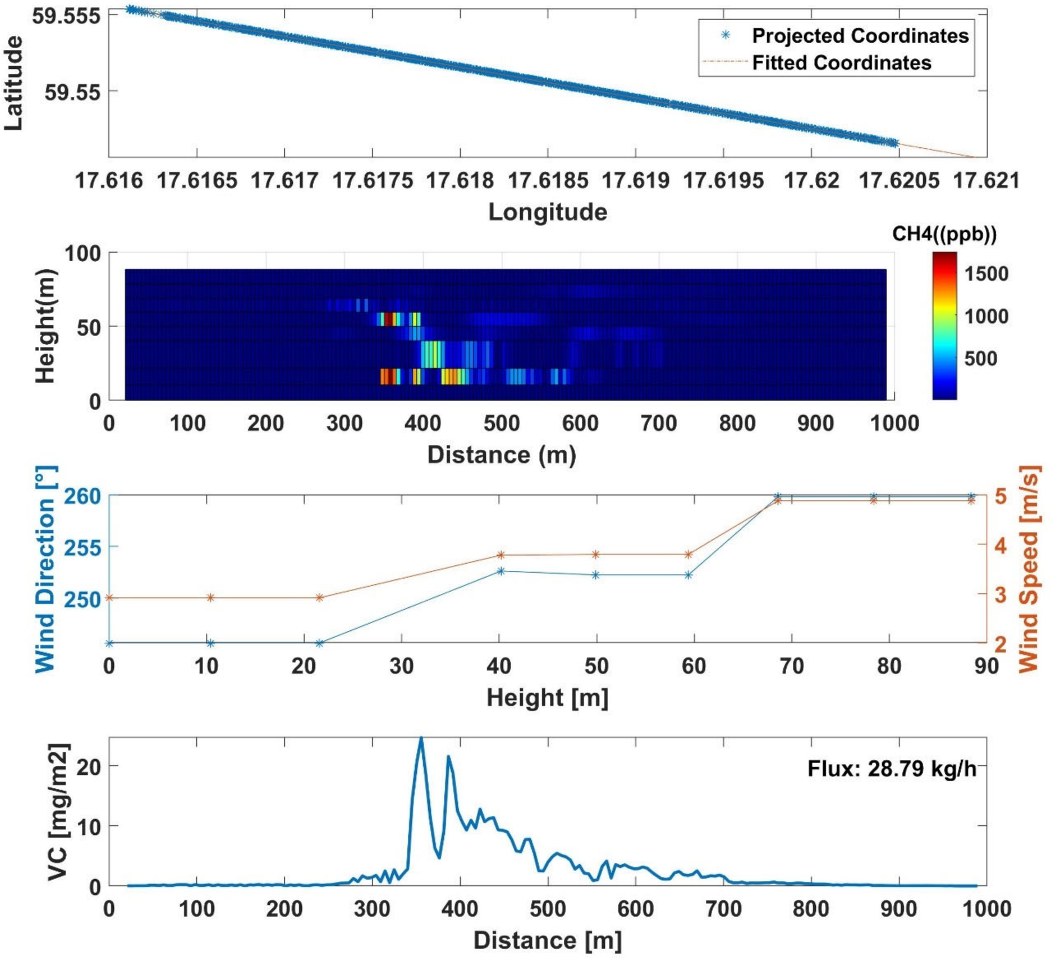

Figure 10. Drone-based laser measurements using the wall approach at site B1 on October 12, 16:15-16:30. The emission rate from the full sites corresponded to 28.8 kg/h. See Figure 4 for an explanation of the principles of the individual graphs.

Table 4. Ground-based laser sensor measurements of methane at site B1 using drone-based wall approach and ground-based tracer approach on November 16, 2022. No. corresponds to numbers of measurements.

Measured object	**Date** (yyyymm)	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)
All sites, drone based laser and wall approach	20221012	1615 - 1630		28.8	
Northern Landfill , drone based laser and wall approach	20221012	1053-1127		11.5	
All sites, ground-based laser and tracer	20221116	2157 - 2228	6	34.4	6.6
Sludge heaps, ground-based laser and tracer	20221116	1958 -2027	5	4.2	5.3

Horse Manure Storage, ground-based laser and tracer	20221116	2023 -2033	4	10.5	6.2
Northern Landfill, calculated	*20221116*			*34.4-4.2-10.5= 19.8*	*10.5*

All site= *Northern Landfill, Sludge Heaps and the upwind Horse Manure Storage*

Full site= *Northern Landfill and Sludge Heaps*

4.3.2 Results at Landfill B2

At Landfill B2 on November 18, both drone-based measurements using a laser sensor and ground-based measurements using MeFTIR were conducted using the tracer approach. These measurements were carried out along the road south of the site (about 200 m from the landfill), with the drone flying at a constant altitude of 40 m. A decent correlation between methane and the tracer, ethane, was observed as shown in Figure 11. The measured emissions from both drone and ground-based measurements are presented in Table 5, showing reasonable agreement (18 % difference) between the two techniques. At this site only one drone-based wall approach was carried out, with a result that was approx. half of the other techniques. This discrepancy is likely a manifestation of the need to perform multiple wall measurements when conducting such experiments, like the SOF method which requires at least 3 transects for a reasonable uncertainty range (Mellqvist et al., 2010).

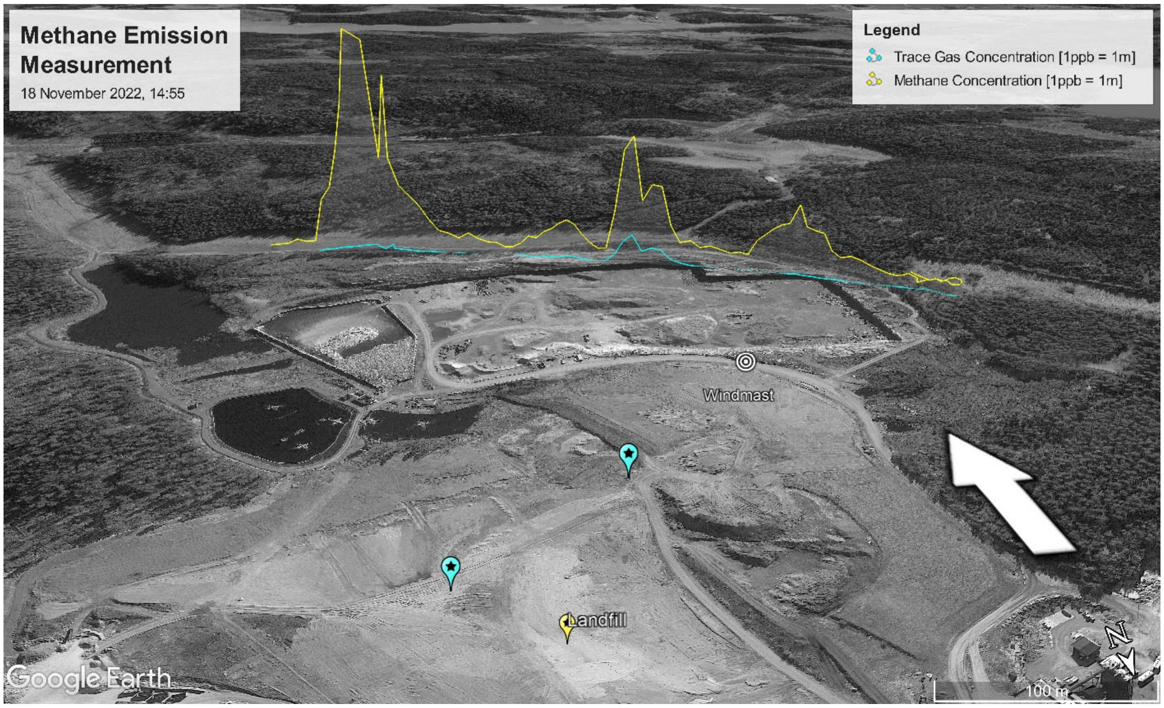

Figure 11. Example of a total methane measurement at Landfill B2 on, November 18, 2022 (14:55), carried out using the drone-based laser sensor using the tracer approach. The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration at this measurement was 131 µg/m^3. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

Table 5. Methane emissions from entire Landfill B2 on November 18, 2022, obtained using ground-based MeFTIR and drone-based laser sensor (wall and tracer approach). No. corresponds to numbers of measurements.

Description	**Time** (hhmm-hhmm)	**No.**	**CH4** (kg/h)	**95% CI** (kg/h)
Drone-based laser, tracer	1421 -1500	16	21.3	8.3
Ground-based MeFIR, tracer	1452 -1515	6	17.5	2.5
Drone-based laser, wall method	1200 -1230	1	8.4	

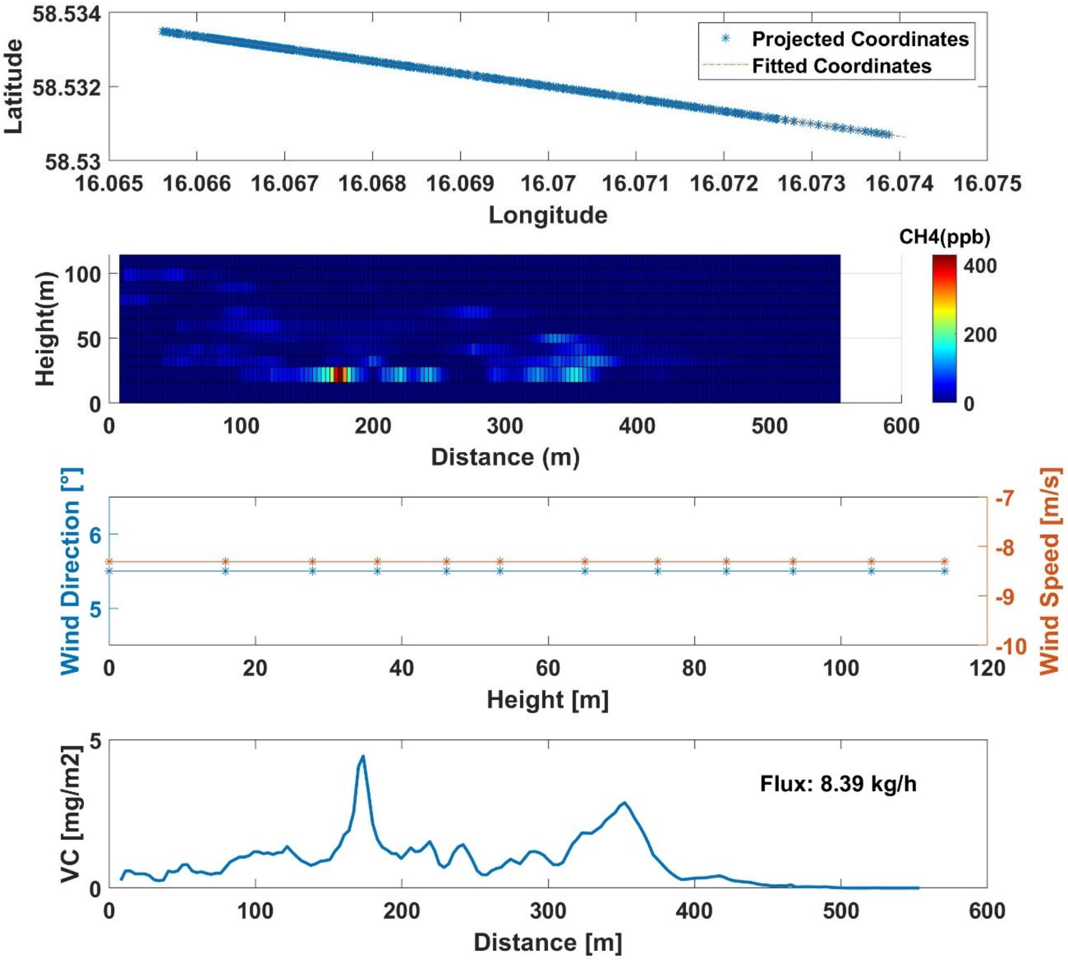

Figure 12. Drone-based laser measurements using the wall approach at site B2 on November 18, 12:00-12:30. The emission rate from the full sites corresponded to 8.4 kg/h. See Figure 4 for an explanation of the principles of the individual graphs.

4.4 Liquified Natural Gas terminal

On October 14, 2022, drone-based measurements using the tracer approach were conducted at an Liquified Natural Gas (LNG) terminal. Methane concentrations were mapped downwind at 40 m altitude using drone-based measurements and at 2 m altitude from a measurement van as shown in Figure 13. The wind was light (2-4 m/s) and south-south westerly. Figure 14 demonstrates an example of the drone-based laser measurements while performing controlled tracer releases of ethane. Twenty such measurements resulted in an average emission of around 4 kg/h while MeFTIR measurements conducted three weeks earlier reported an average emission of around 26 kg/h, Table 6. The difference in measurements between the first and second occasion is directly related to the maintenance of two valves. These valves were identified by the operators as having diffuse leakage and were subsequently repaired before the second set of measurements were taken. Emission measurements using the wall method was also carried out from the drone on October 14 as shown in Figure 15 and Table 6. As seen in the table both the tracer and wall measurement approach resulted in low emissions between 1-5-4 kg/h. On October 14, MeFTIR measurements were also conducted at a nearby LNG truck loading, Table 7, reporting an average emission of 0.36 kg/hr. However, this site could not be covered with drone measurements due to flying restrictions over/near gas pipelines in the facility.

Table 6. Total emission of methane at the LNG terminal obtained by drone -based laser (wall and tracer approach) and MeFTIR, on September 21 and October 14. No. corresponds to numbers of measurements.

Measured object	**Date** (yyyymm)	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)
Ground-based MeFTIR, tracer	20220921	1748 -1855	11	25.5	8.8
Drone-based laser sensor, tracer	20221014	1513 -1616	20	3.9	0.3
Drone-based laser, wall method	20221014	1200-1615	2	1.47	NA

Table 7. MeFTIR Results at LNG truck loading on October 14, 2022. No. corresponds to numbers of measurements.

Measured object	**Date** (yyyymm)	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)
Ground-based MeFTIR, tracer	20221014	1230 -1317	14	0.36	0.20

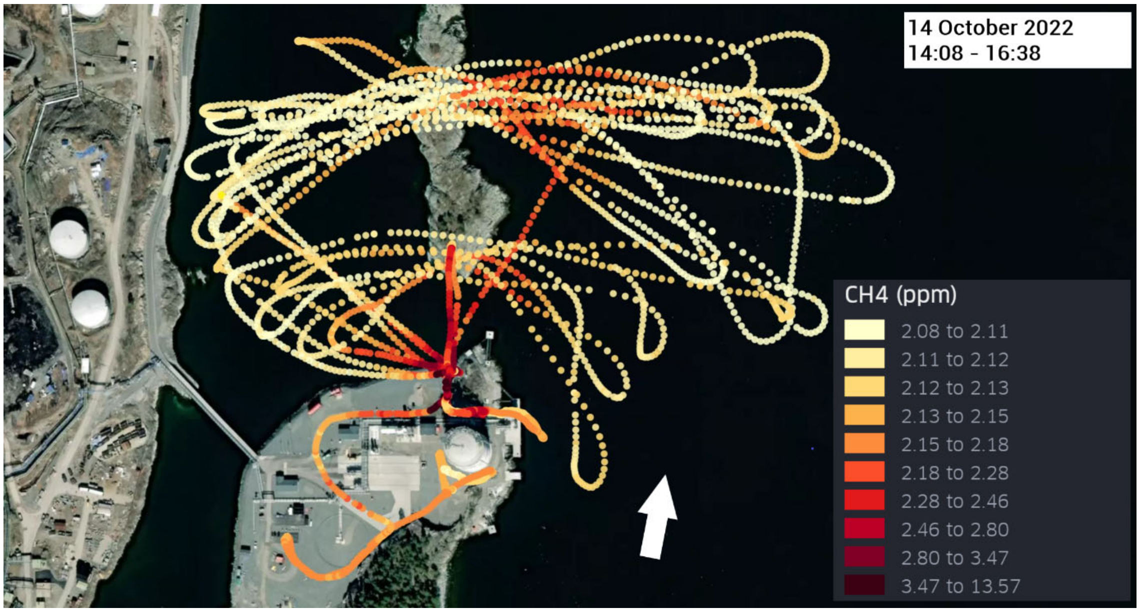

Figure 13. Measured methane concentrations at an LNG terminal on October 14, 2022, between 14:08-16:38. The scale is logarithmic and shows the concentration in ppm from laser sensor according to the colour scale in the Figure. The wind was light (2-4 m/s) and SSW (190°) during the measurements. Note that the offshore measurements were made by drone at 40 m altitude and the land-based measurements by car (2 m altitude). Graphic from: www.kepler.gl© with underlying Map from Mapbox©.

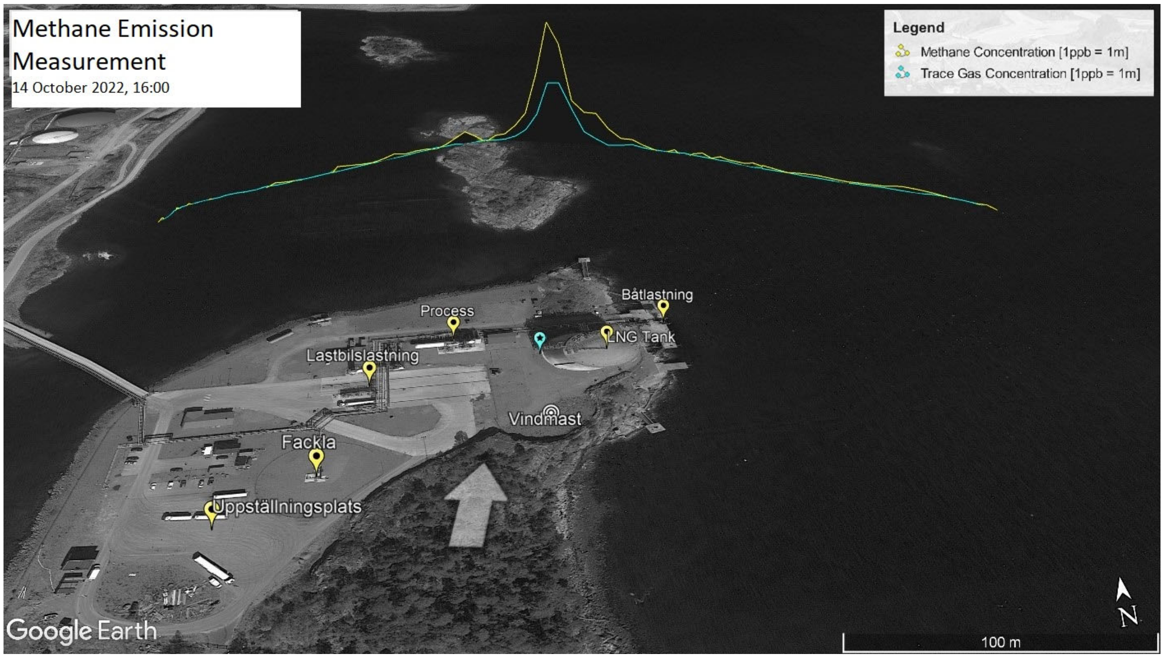

Figure 14. Example of a total methane measurement at an LNG-terminal on October 14, 2022, carried out at 16:00. The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration at this measurement was 301 µg/m^3. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

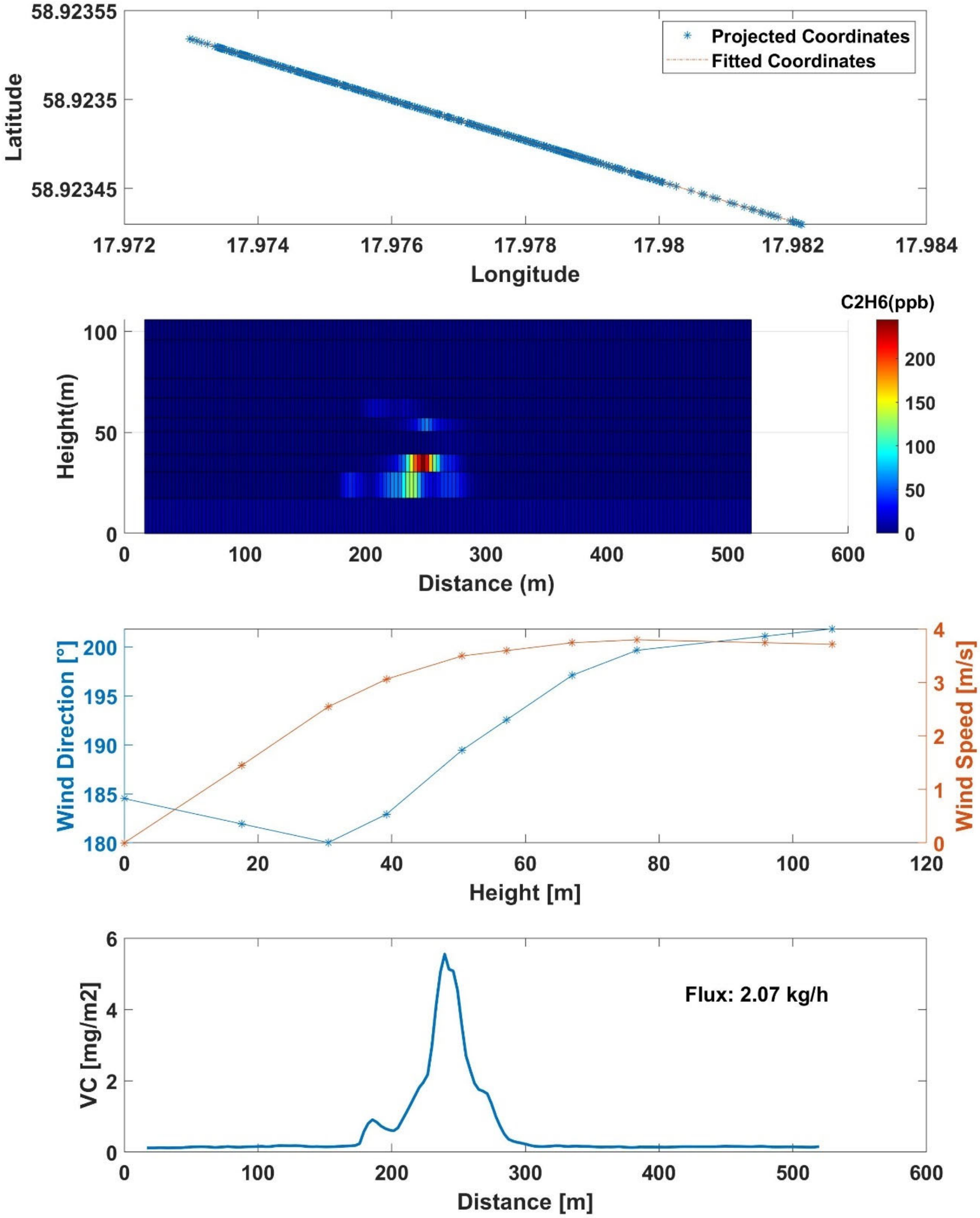

Figure 15. Drone-based laser measurements using the wall approach at site B2 on October 14, 2022, at 12:00-12:30. The emission rate from this site corresponded to 2.0 kg/h. Another measurement 4 h later showed 0.66 kg/h See Figure 4 for an explanation of the individual graphs.

4.5 Waste Water Treatment plant

An emission study was conducted at a wastewater treatment (WWT) plant from October 17 to 21, 2022. The plant typically has two operational anaerobic digesters that produce bio-methane. However, during the study, the second tank was under reconstruction and not in operation. The remaining sludge from the anaerobic digesters is stored in sludge piles for about three weeks before being moved to an external intermediate Landfill area, where methane emissions are expected to be relatively low.

Various techniques were employed during the study, including drone-based laser sensors and ground-based MeFTIR to record methane and tracer concentrations at different heights and locations within the facility. The study encompassed leak detection, drone-based and ground-based emissions, and wind profiling. The investigated areas included the basins (inlet and outlet), anaerobic digesters, sludge pile, and an external Landfill area. A specific study focused on N_2O emissions from the nitrifying trickling filters at the water treatment plant, estimating an emission rate of 3 kg/h.

Due to the complexity of the wind field and the necessity to fly close to isolate the source, the wall-based approach produced variable emissions (10-190 kg/h). Therefore, the tracer approach was used to obtain more accurate results.

Notable findings include:

- High methane concentrations at the primary clarifiers, with an emission rate of around 20 kg/h, as shown in Figure 16 and Figure 17.
- The largest source of methane emissions at the WWT plant was the sludge piles, with emissions of around 50 kg/h, measured by both drone-based laser and ground-based MeFTIR, as seen in Figure 18, Table 8 and Table 9.
- The second bio-chamber's reconstruction affected the WWT plant's optimal operation, possibly influencing the emission levels.
- Ground-based MeFTIR measured N_2O emissions from the nitrifying trickling filters at 3 kg/h.
- Drone-based measurements detected a small leakage of 0.3 kg/h from the anaerobic digesters.
- The total methane emission measurement of the WWT plant on October 20, 2022, was around 70 kg/h, Figure 19, consistent with more detailed measurements.
- The team also studied an external sludge storage location where sludge is moved after about three weeks of weathering at the main facility. High methane concentrations were detected, as shown in Figure 21. The tracer-based approach resulted in uncertain values ranging between 35 to 75 kg/h due to proximity to the source. The wall-based approach for one full measurement resulted in 37 kg/h, see Figure 22.

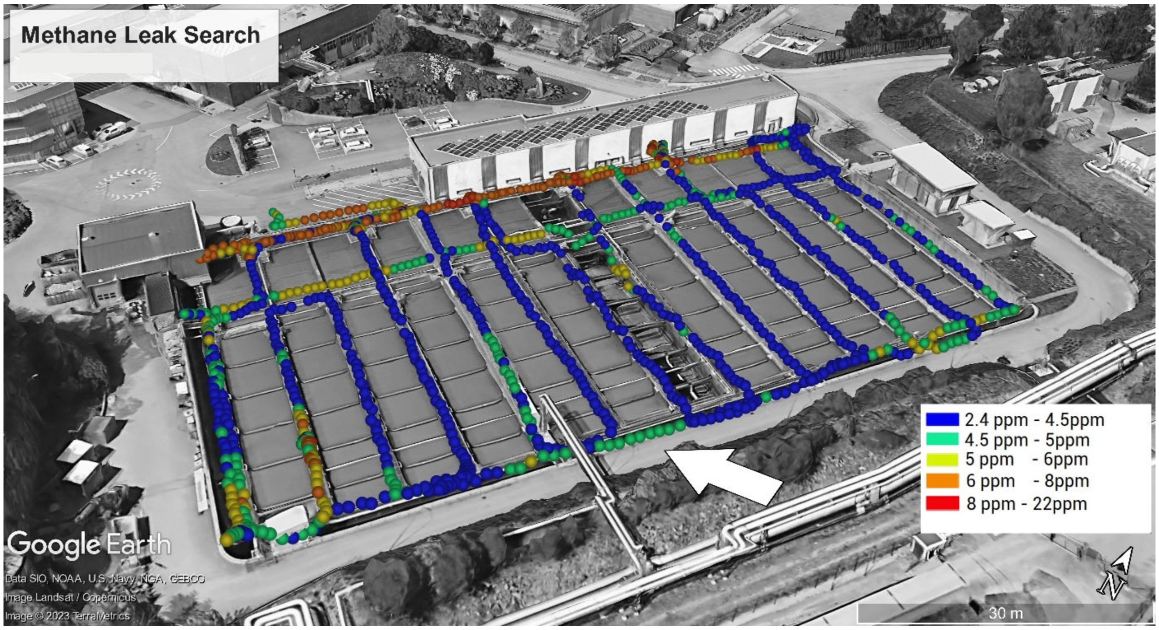

Figure 16. Leak detection of methane at the inlet basin of the WWT plant obtained by person-held laser sensor measurements out on 18 November 18, 2022, at 11. The coloured spheres indicate methane measurement points, and each colour indicates absolute concentration in ppm above background level. Map: Google Earth™ © 2022.

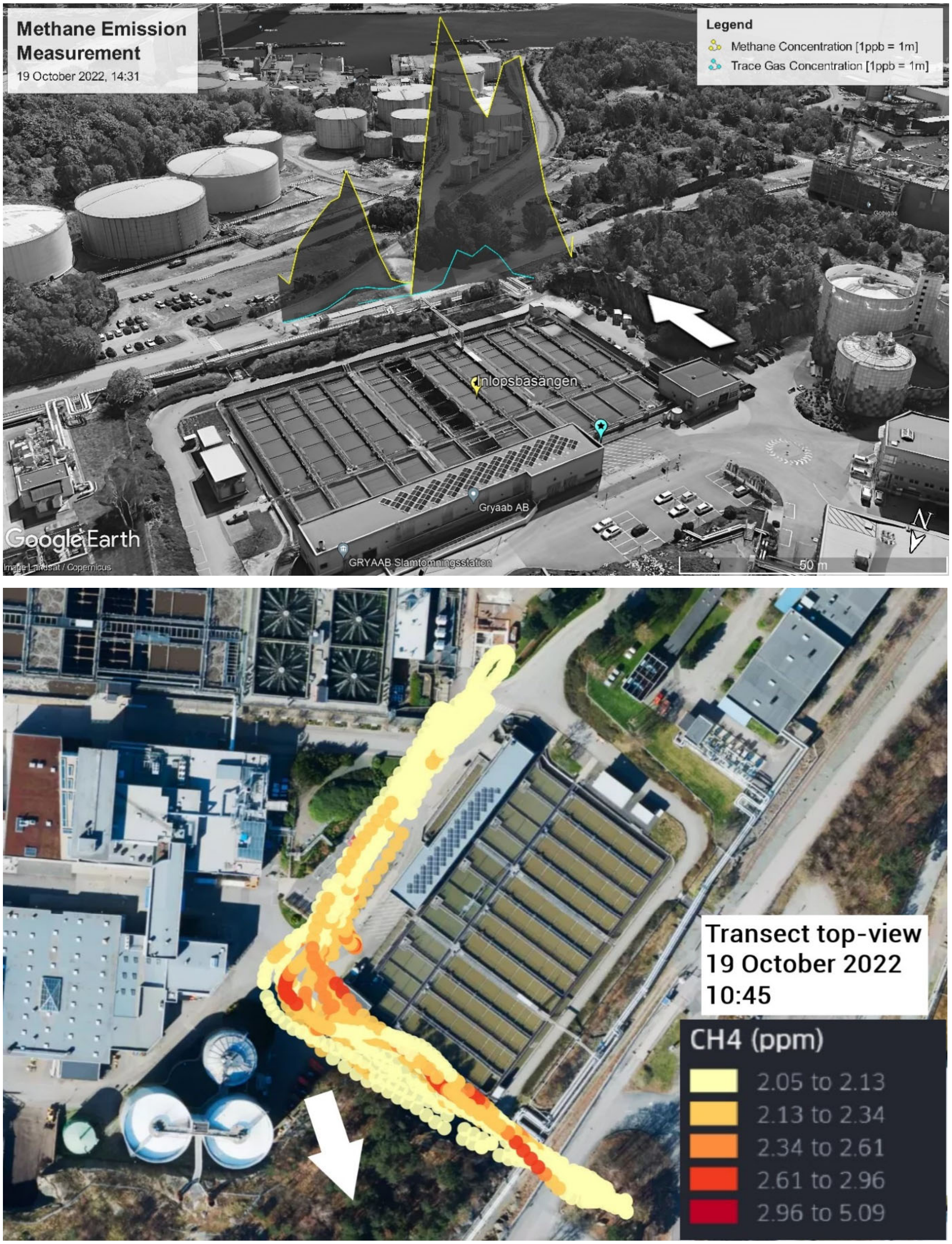

Figure 17. Example of a drone-based methane measurement at the primary clarifiers of the WWT plant on October 19, 2022, carried out at 14:31. In the upper graph The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration at this measurement was 301 µg/m^3. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022. The lower graph visualizes the flight path of the drone as seen from above. Graphic from: www.kepler.gl© with underlying Map from Mapbox©.

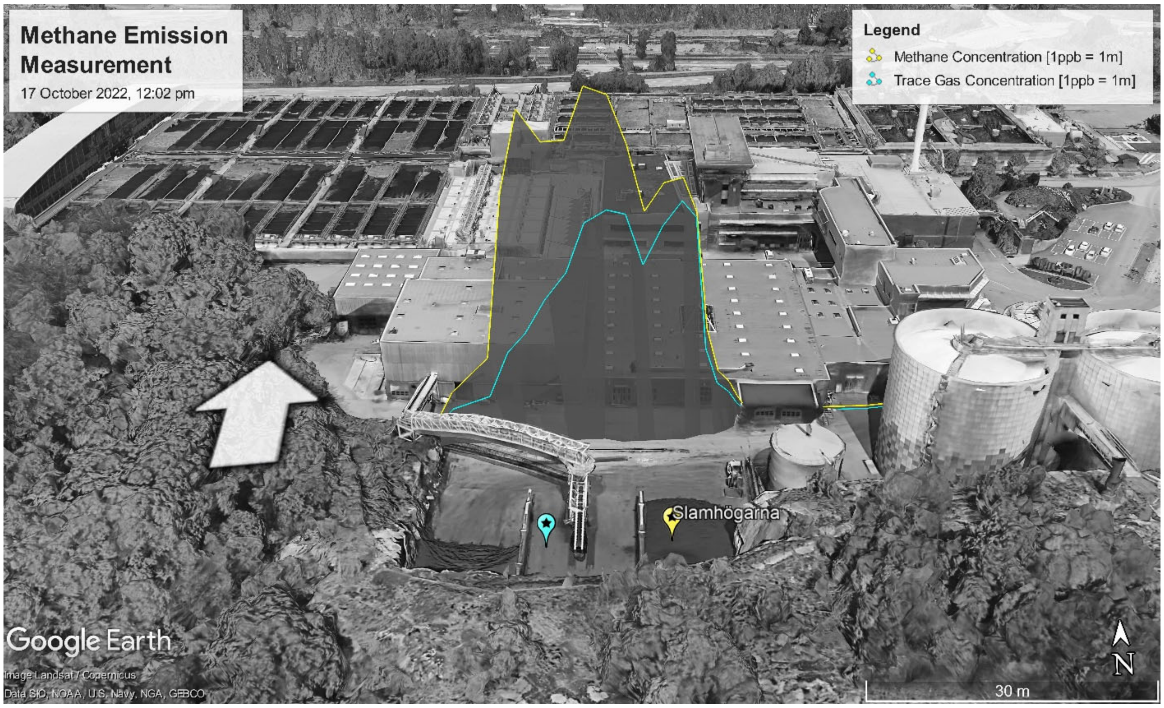

Figure 18. Example of a drone-based methane measurement using the tracer approach of the sludge piles (Slamhögar) at the WWT plant. This measurement was performed on October 17, 2022, at 12:02. The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration at this measurement was 1390 µg/m^3. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

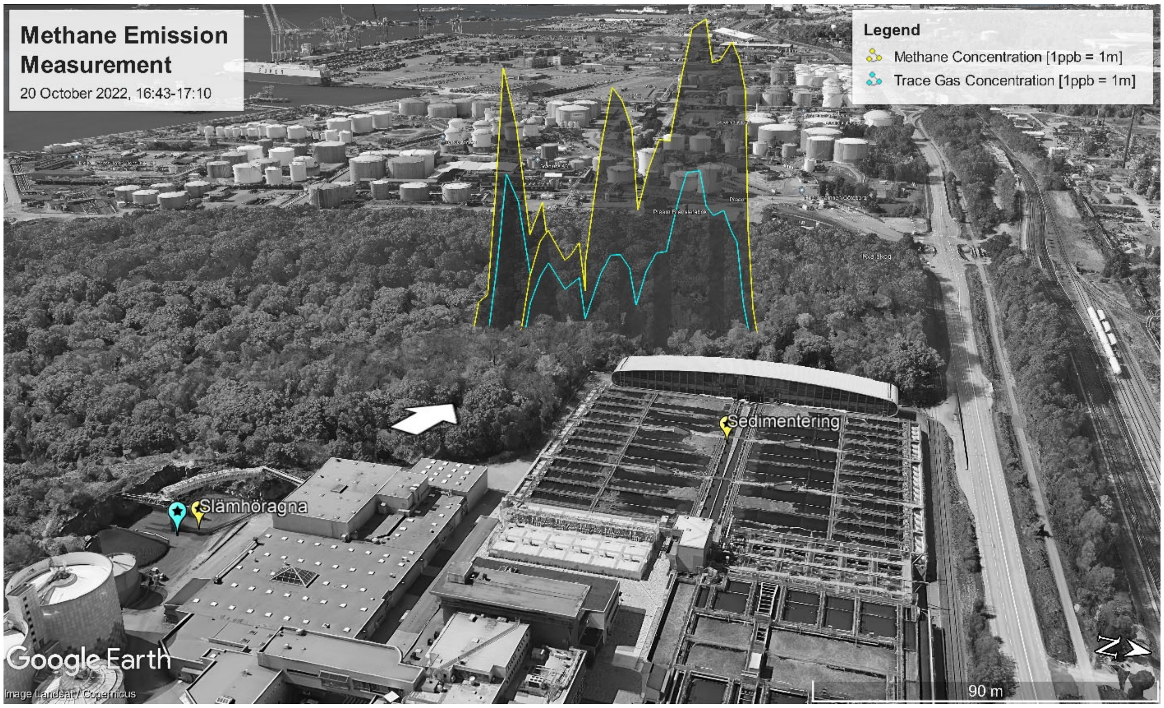

Figure 19. Example of a total methane emission measurement at the WWT plant on October 20, 2022. The height of the curves corresponds to the concentration of the measured gas at ground level (above background concentration). The highest measured methane concentration at this measurement was 584 µg/m^3. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

Table 8. Methane emissions at the WWT plant obtained using drone-based laser sensor measurements. No. corresponds to numbers of measurements.

Description	Date (yyyymmdd)	Time (hhmm-hhmm)	No.	CH_4 (kg/h)	95% CI (kg/h)
Sludge Piles, tracer	20221017	1157-1204	5	48.6	15.3
Sludge Piles, tracer	20221020	1636-1713	11	58.4	13.0
Primary clarifiers, tracer	20221019	1347-1434	7	19.3	11.3
Bio Gas Tanks, tracer	20221021	1509-1518	8	0.56	0.26
Entire Facility*, tracer	20221020	1638-1725	14	70.5	13.2
External waste storage, wall approach	20221021	1243-1315	1	37	

** Measurement across the entire site on the western side. The tracer was placed at the sludge piles.*

Table 9. Methane emissions at the WWT plant obtained using ground-based MeFTIR from a measurement van and controlled tracer releases. No. corresponds to numbers of measurements.

Description	Date (yyyymmdd)	Time (hhmm-hhmm)	No.	CH_4 (kg/h)	95% CI (kg/h)
Sludge Piles	20221017	1113 -1435	3	60.3	0
Sludge Piles	20221020	1109 -1720	8	43.4	11.7

Table 10. N_2O emissions obtained using by ground-based MeFTIR in measurement van at the WWT plant. No. corresponds to numbers of measurements.

Description	Date (yyyymmdd)	Time (hhmm-hhmm)	No.	N_2O (kg/h)	95% CI (kg/h)
Nitrifying trickling filters	20221020	1515 - 1550	10	2.8	0.4

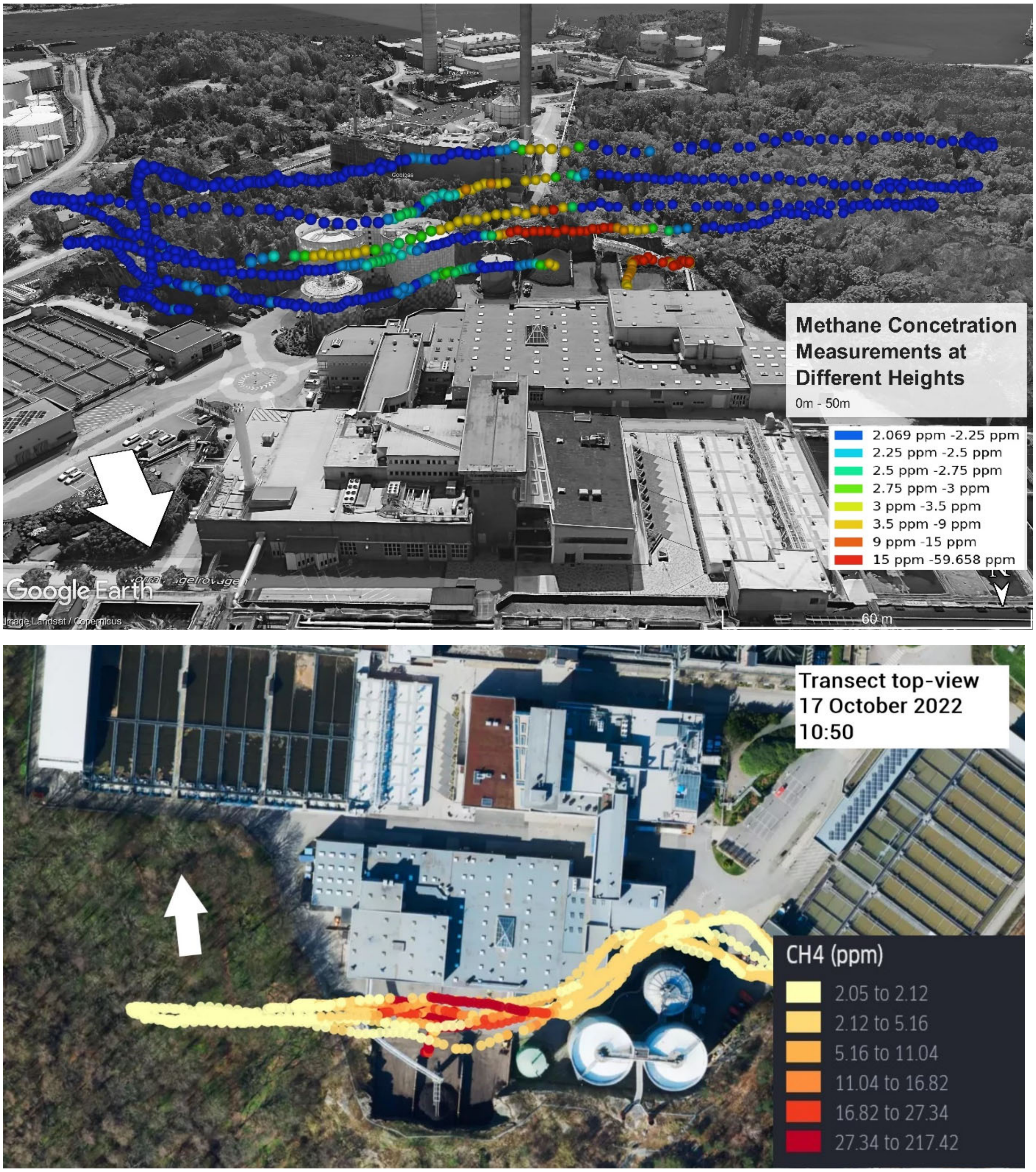

Figure 20. A typical example of a "wall transect" downwind of the sludge piles at the WWT plant on October 17, 2022. These transects were carried out at various heights, from 0m to 50m. The spheres indicate methane measurement points, and each colour indicates absolute concentration in ppm above background level. White arrow indicates wind direction. Map: Google Earth™ © 2022.. The lower graph visualizes the flight path of the drone as seen from above. Graphic from: www.kepler.gl© with underlying Map from Mapbox©.

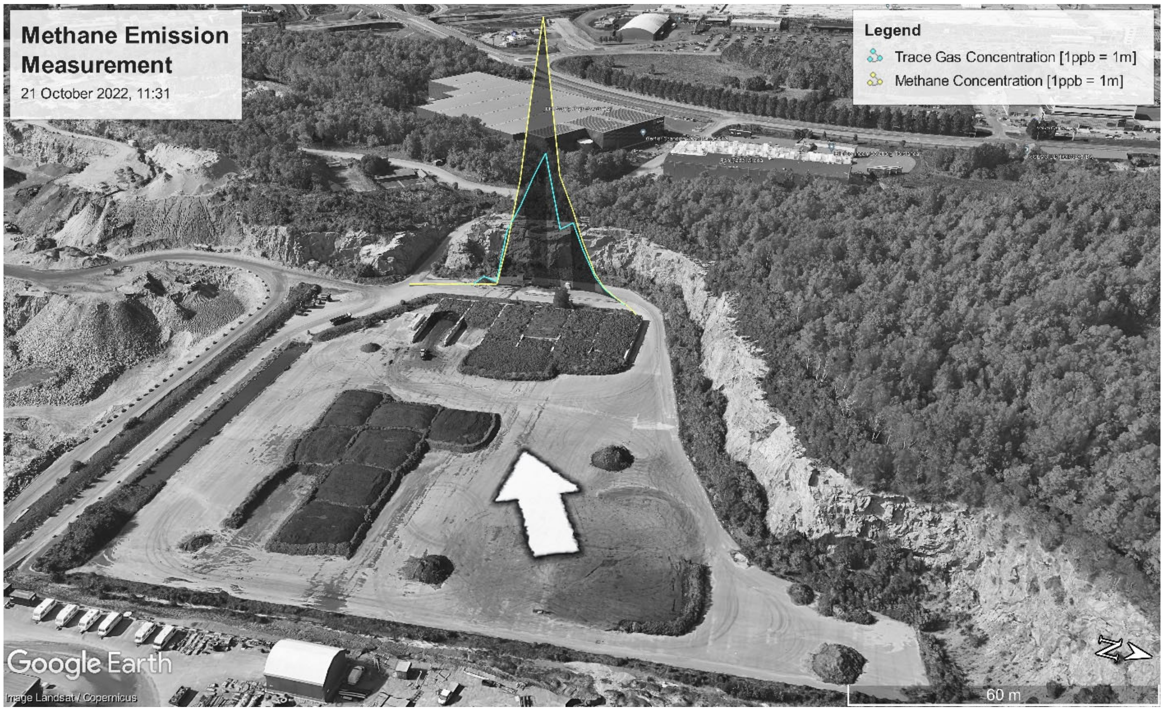

Figure 21. Example of a drone-based laser sensors measurements of methane and tracer concentrations at the external sludge storage location on October 21, 2022, carried out at 12:10. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

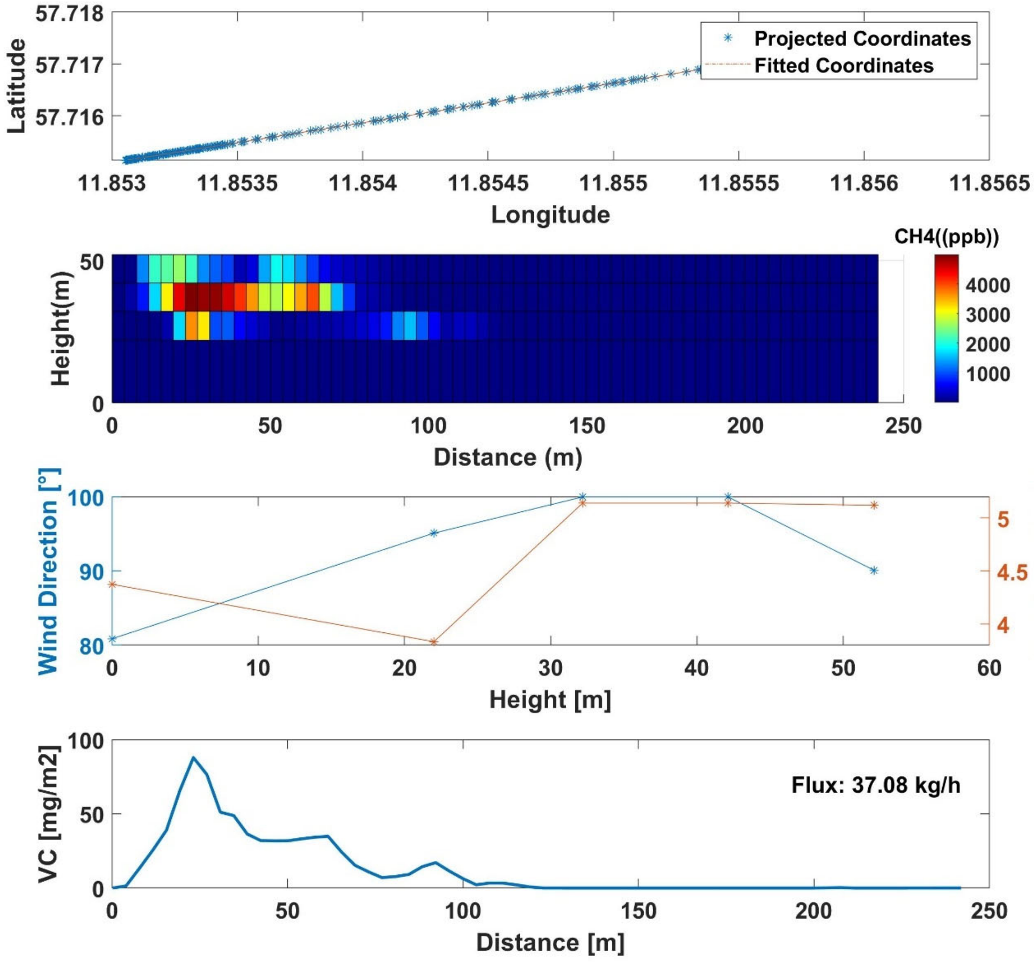

Figure 22. Drone-based laser measurements using the wall approach at the external sludge storage location on October 21,2022 carried out at 12:06. The emission rate from this site corresponded to 37 kg/h. See Figure 4 for a general description of the individual graphs.

4.6 Refinery

During a three-day span in 2022, from November 21 to 23, both drone- and ground-based measurements were undertaken at a crude oil refinery to assess the emission of methane, ethane, CO_2, and heavier VOCs. The measurements were conducted under southeasterly winds and they were taken along three paths both downwind and upwind of the crude oil tank park and upwind of the refinery wastewater treatment (WWT) plant, as illustrated in Figure 23.

Figure 24 shows the drone-based laser measurements of methane from the Wastewater Treatment (WWT) using the tracer approach, and the corresponding emission rates are presented in Table 11. The drone-based tracer approach detected methane emissions of about 6 kg/h, which is twice the amount detected by the ground-based MeFTIR at 3 kg/h. This discrepancy suggests that MeFTIR might not capture some emissions when measuring from the ground, demonstrating an advantage of the drone-based tracer approach. However, the MeFTIR measurements were carried out somewhat close to the water treatment facility, due to available roads, and this may induce measurement errors. Ideally, measurements should have been taken from another wind direction as well, and a leak search should have been done inside the water treatment facility to plan the tracer measurements better. However, these additional measures were outside the scope of this study

A typical wall measurement approach using a drone is shown in Figure 25. We conducted concentration measurements of CH_4 and other species directly downwind of the process area and the main process flare. These measurements were performed across the plume at various heights, ranging from 10 m to 120 m. The collected data were interpolated to an even grid and multiplied with wind profile data, as displayed in Figures 26 and 27. The resulting emissions were about 5 kg/h for methane and 2 kg/h for ethane, with a strong correlation between these species, as shown in Table 12. During the same measurement, heavier VOCs, using Photo Ionization Detection and CO_2 were also measured and these results are presented in Figure 28 and Figure 29. The correlation between methane and heavier VOCs, but not CO_2, suggests diffuse emissions from the process area rather than from the flare. It should be highlighted that these emission values carry substantial uncertainties, as they are based solely on a single full wall transect. To achieve a reliable value, multiple repetitions (more than 3) are necessary. However, drone-based measurements downwind from the WWT, including the process area and flare, indicated similar values as shown in Table 12, suggesting relatively minor methane emissions from the process area and flare. Methane and ethane measurements were also conducted in the crude oil tank park, with possible inflow from the background, which corresponds to the process area, flare, and WWT, as shown in Figure 30 and Figure 31. As shown in Table 12, the emission values were approximately 10 kg/h and 5 kg/h for methane and ethane, respectively. As this was only a single wall measurement, it carries relatively high uncertainties.

The measurements reveal that the emission sources of methane and ethane are relatively minor at the studied locations, despite relatively large measurement uncertainties, demonstrating the efficacy of drone-based measurements. Future studies would benefit from a significantly higher number of measurements to provide more reliable statistics.

Table 11. Drone-based laser sensors measurements, tracer approach, at the refinery WWT and ground-based MeFTIR. No. corresponds to numbers of measurements.

Description	**Date** (yyyymmdd)	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**95% CI** (kg/h)
Drone based laser, tracer	20221123	1043-1126	23	6.3	3.9
MeFTIR, tracer	20221123	1050-1147	13	2.6	0.5

Table 12. Drone-based laser sensors measurements, wall approach, at the crude oil tank park, refinery WWT and process area. No. corresponds to numbers of measurements.

Description	**Date** (yyyymmdd)	**Time** (hhmm-hhmm)	**No.**	**CH_4** (kg/h)	**C_2H_6** (kg/h)
Crude tank park*	20221122	1010-1040	1	9.9	4.8
Water treatment**	10221122	1115-1145	1	3	3
Process area &flare	20221122	1323-1353	1	4.6	1.6

* background inflow from process area, flare and WWT. ** background inflow from process and flare.

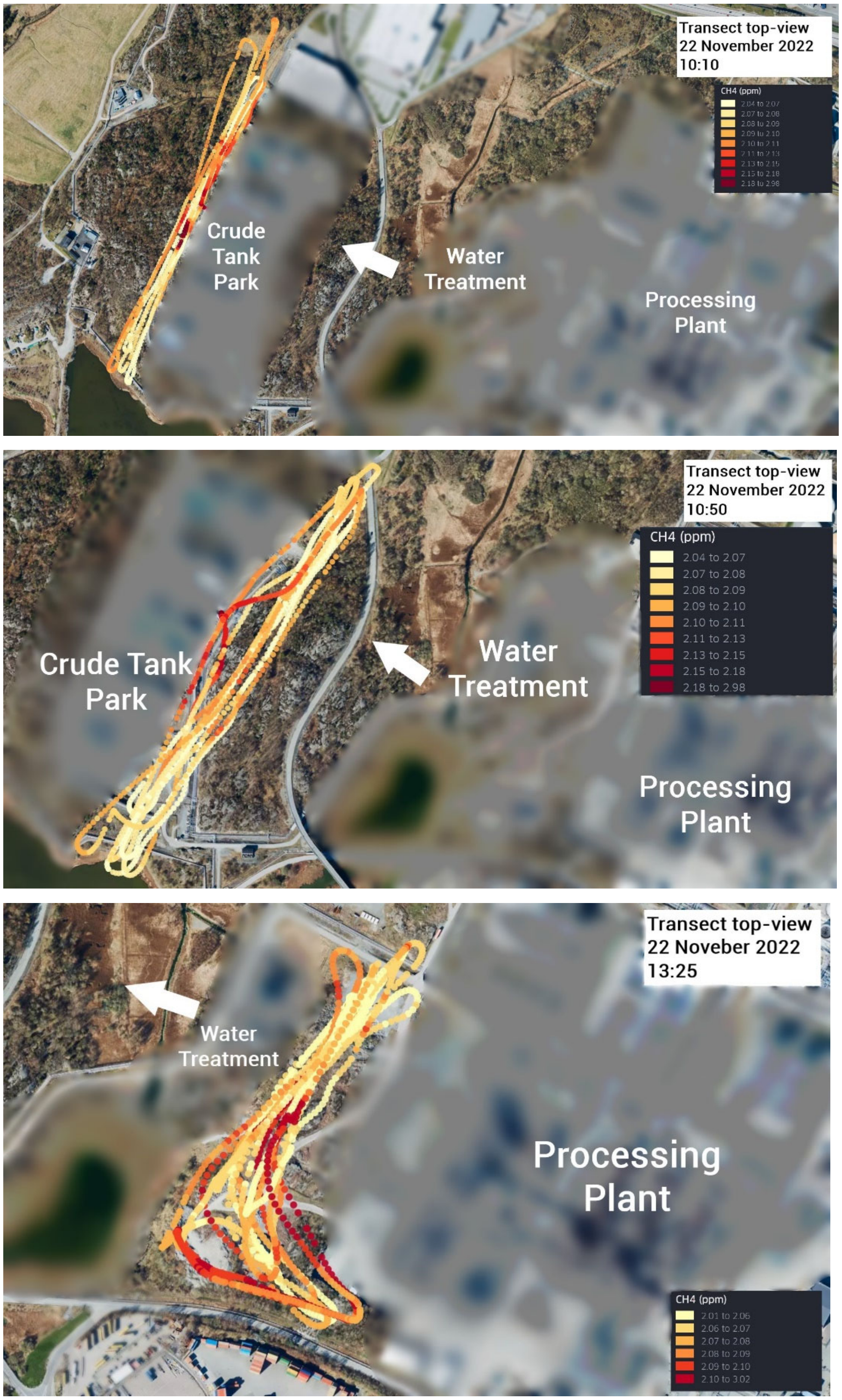

Figure 23. Visualization of the measurement transect applied by the drone in the refinery. Note that the wind was ESE (70^{o}). Graphic from: www.kepler.gl© with underlying Map from Mapbox©.

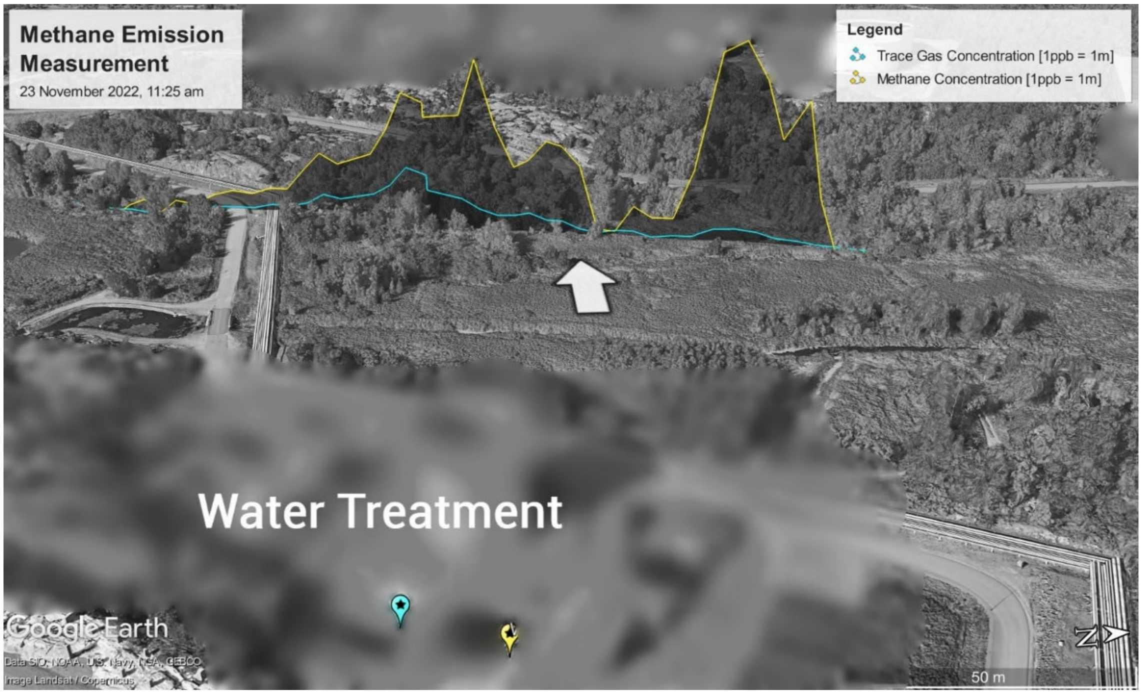

Figure 24. Example of drone-based laser measurements of the methane emission at the refinery WWT, using the tracer approach. The measurements were conducted on November 23, 2022, at 11am. The highest measured methane concentration at this measurement was 35 µg/m^3. The location of the tracer release is indicated with the light blue bubble. See Figure 3 for a general description of the graph structure. Map: Google Earth™ © 2022.

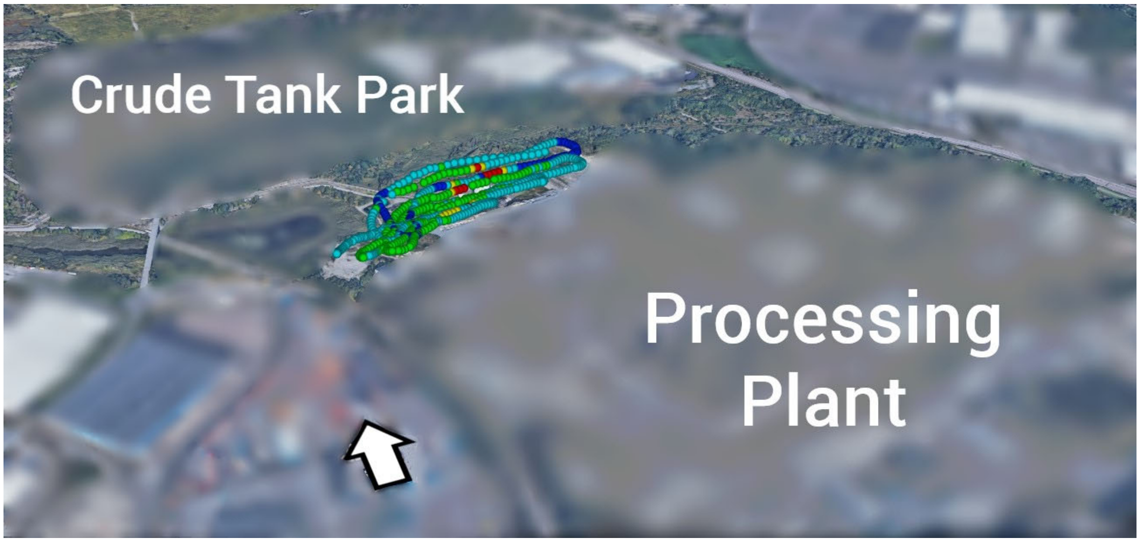

Figure 25. A typical example of the wall measurements approach using the drone. Here is shown the transects while measuring CH_4 downwind of the processing plant of a refinery on November 22, 2022. Measurements were carried out at various heights, from 10 m to 120m. The spheres indicate methane measurement points, and each colour indicates absolute concentration in ppm above background level. Blue colour corresponds to values below 2.05 ppm while red corresponds to values above 2.125 ppm. Map: Google Earth™ © 2022.

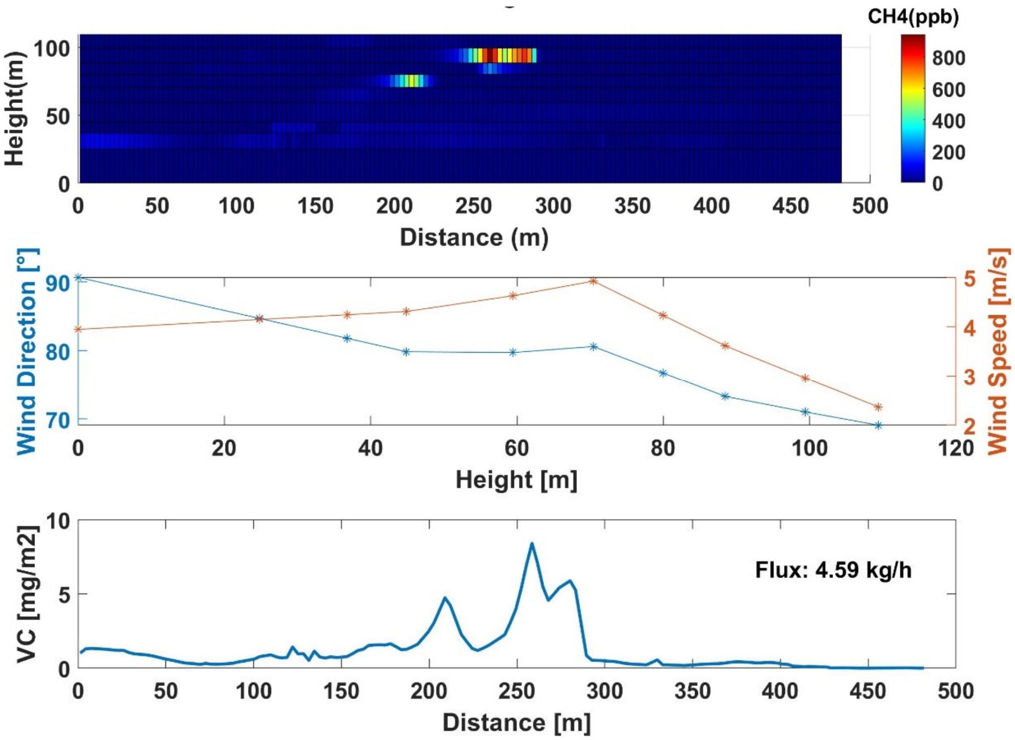

Figure 26. Drone-based laser measurements of the methane emissions downwind the process area and flare in a refinery, obtained using the wall approach on November 22, 13:23, 2022. See Figure 4 for a general description of the individual graphs.

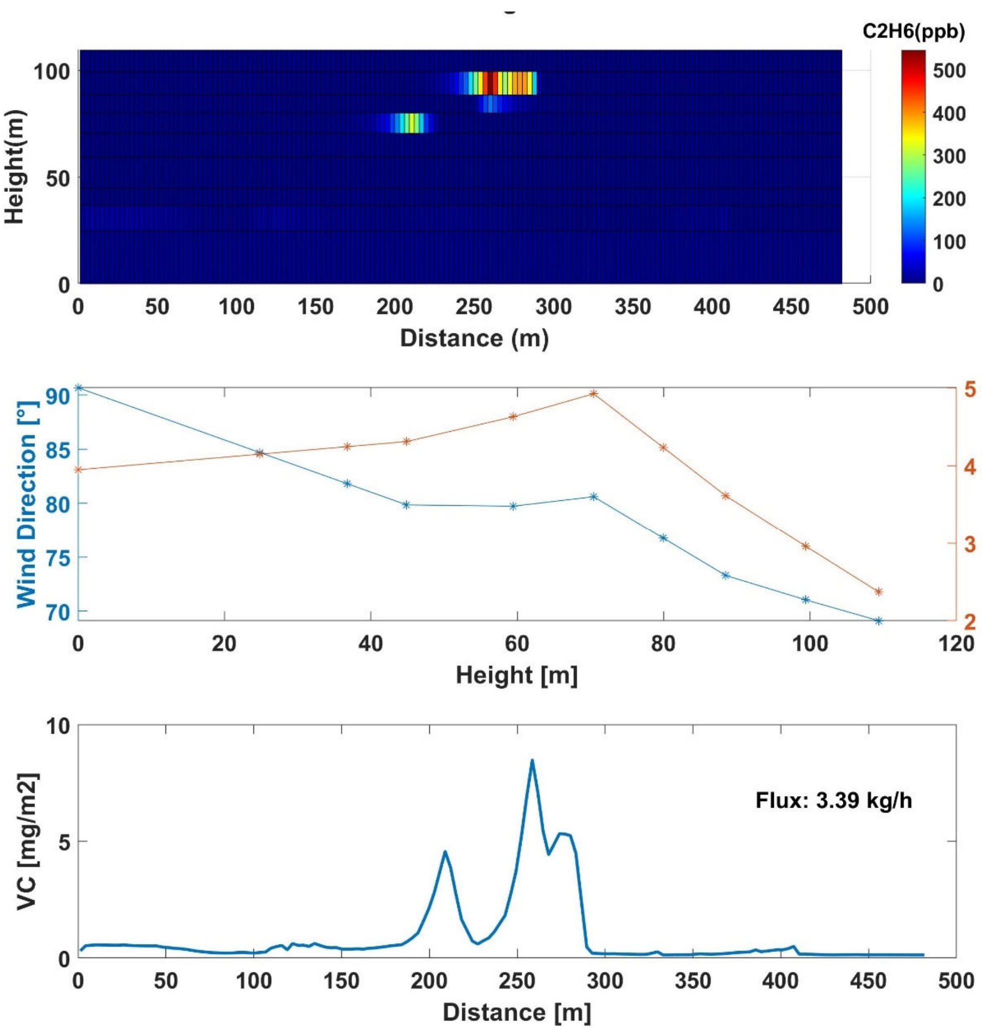

Figure 27. Ethane emission data corresponding to same measurements as in Figure 26. See Figure 4 for a general description of the individual graphs.

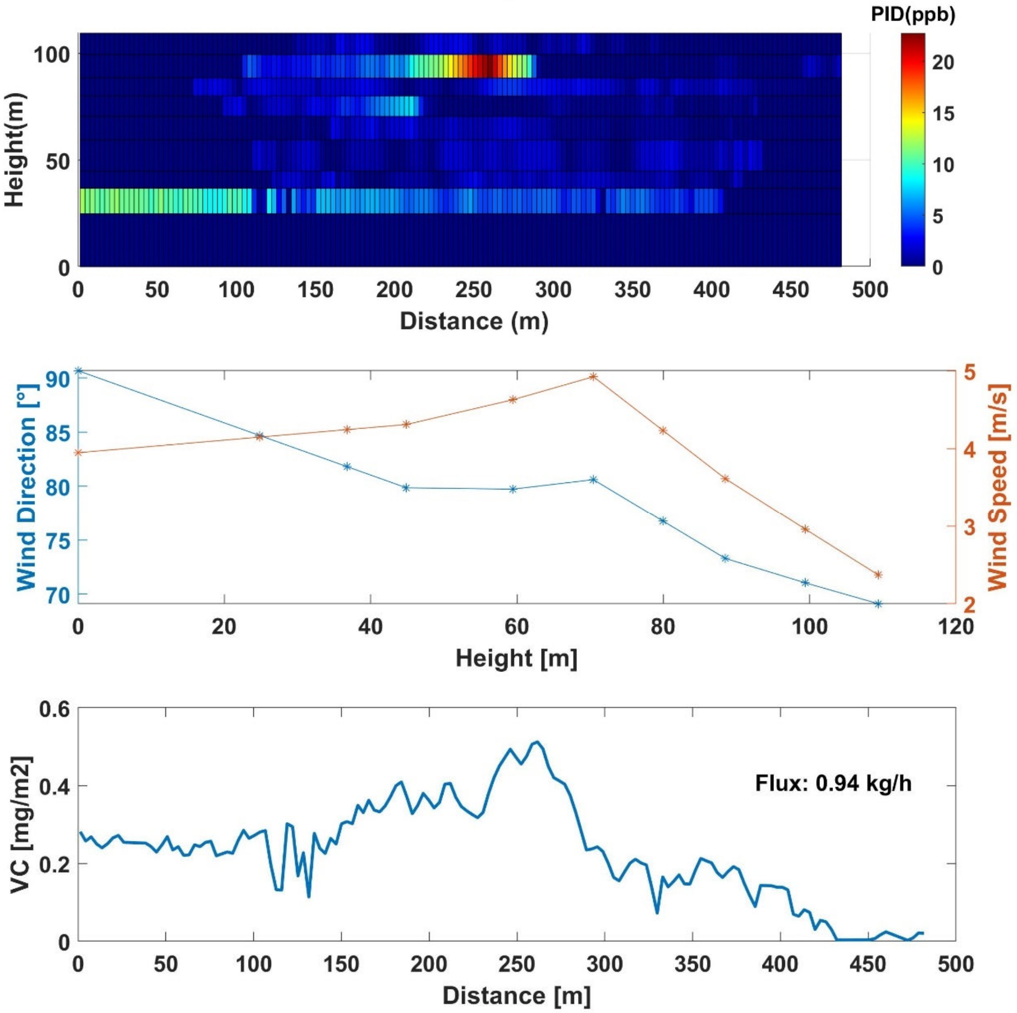

Figure 28. PID (Photo Ionization Detector) emission data given in isobutylene equivalents corresponding to the same measurements as in Figure 26. See Figure 4 for a general description of the individual graphs.

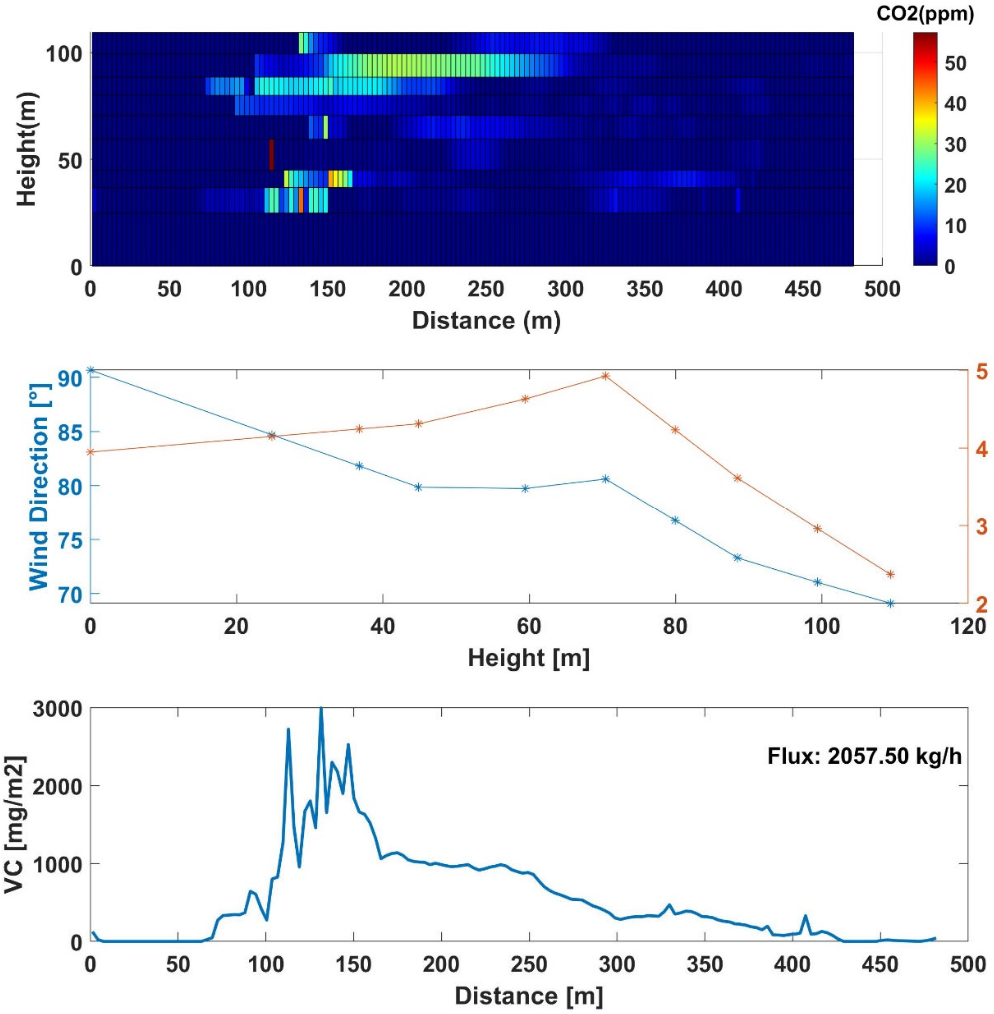

Figure 29. CO_2 emission data corresponding to same measurements as in Figure 26. See Figure 4 for a general description of the individual graphs.

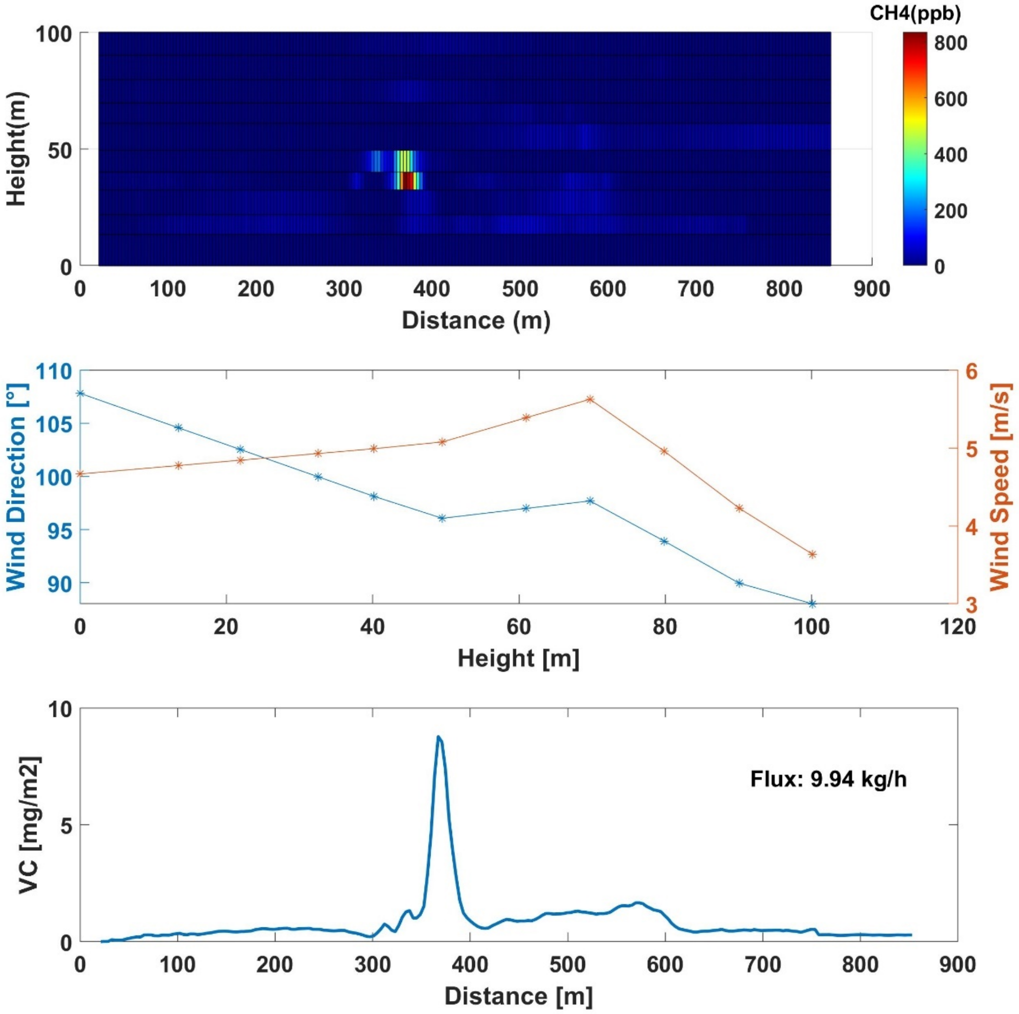

Figure 30. A Drone-based laser measurements of the methane emissions downwind the crude oil tank park in a refinery using the wall approach on November 22, 10:23, 2022. There was potential background inflow from process area, flare and WWT. See Figure 4 for a general description of the individual graphs.

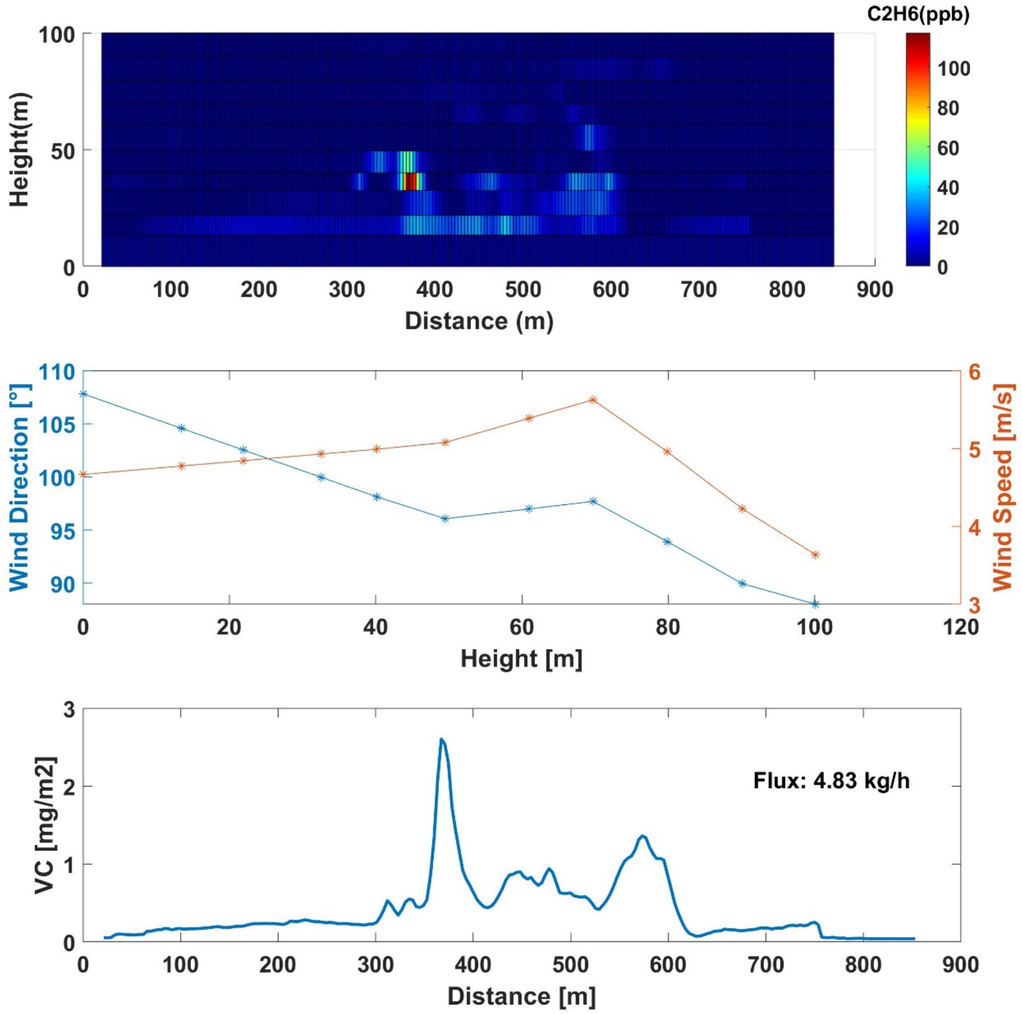

Figure 31. Ethane emission data corresponding to same measurements as in Figure 30. See Figure 4 for a general description of the individual graphs.

5 Conclusion

It has been demonstrated that drone measurements of methane using the new sensitive laser are a valuable tool for mapping methane concentrations from various types of industrial sources. These sources are challenging to investigate today due to diffuse emissions originating from multiple points, as well as large dimensions and complex geometries of the industries. It has also been shown that it is possible to quantify emissions from these complex sources using either a wall approach, which involves measuring a cross-section of the plume downwind, or by controlled tracer releases, where known amounts of trace gases are released and measured alongside the target gases.

Validation studies reveal that an accuracy of up to 10% is achievable for a simple source using either approach. However, in real measurement situations, it is found that the wall measurement approach is difficult to execute due to practical challenges, such as covering the full plume from the sources due to flying restrictions and making spatially dense and repeatable measurements. In several cases, the drone had to fly relatively close to the plumes, resulting in the wall approach yielding large apparent measurement errors. These errors were partly due to building geometries causing turbulent wind fields. It is hence evident that the wall approach requires a thorough understanding of the measurement situation, and multiple measurements need to be performed to reduce variability, ideally carried out at different distances from the source and in varying wind directions. In practice, the tracer approach was the preferred choice for obtaining emission rates in this study. However, for larger, spatially extensive sources, executing representative tracer releases is challenging. The tracer approach relies on releasing known amounts of a trace gas alongside the target gas. The ratio of the tracer to the target gas is then used to calculate the emission rate of the target gas. If the source area is too large, it becomes challenging to distribute the trace gas evenly and to ensure the drone captures a representative sample of both the tracer and target gases. This can lead to underestimations or overestimations of the target gas emissions.

Therefore, while the tracer approach is often preferred for its relative simplicity and accuracy, it may not be the best method for all types of sources. Differences by a factor of 2 between the drone-based tracer approach measurements and the ground-based ones were observed on some occasions. This could be caused by uplift of the source plume, causing the ground-based technique to miss some of it. However, this needs to be further investigated.

In total, the study detected methane emissions of about 220 kg/h from seven industrial facilities and 3 kg/h of N_2O. The emissions were dominated by landfills and the water treatment plant. The combined emissions are equivalent to about 7 tons/h of CO_2 equivalents in terms of their contribution to climate change, corresponding to the equivalent of 22,000 personal cars driven 15,000 km per year. If part of these emissions could be mitigated, it could make a significant contribution to reducing greenhouse gas emissions.

6 References

Galle, B., Samuelsson, J., Svensson, B. H., & Borjesson, G. (2001). Measurements of methane emissions from landfills using a time correlation tracer method based on FTIR absorption spectroscopy. Environmental Science & Technology, 35(1), 21-25. https://doi.org/10.1021/es0011008

Mellqvist, J., et al. (2010). Measurements of industrial emissions of alkenes in Texas using the solar occultation flux method. Journal of Geophysical Research, 115. https://doi.org/10.1029/2008JD011682

Vechi, N. T., Mellqvist, J., Samuelsson, J., Offerle, B., & Scheutz, C. (2023). Ammonia and methane emissions from dairy concentrated animal feeding operations in California, using mobile optical remote sensing. Atmospheric Environment, 293. https://doi.org/10.1016/j.atmosenv.2022.119448