https://doi.org/10.5194/egusphere-2026-1744
Preprint. Discussion started: 14 July 2026

From research to reality: Academic methane measurement systems tested at the TADI controlled release facility

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https://doi.org/10.5194/egusphere-2026-1744
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Abstract. Accurate methane emission quantification is critical for climate mitigation efforts in the oil and gas industry. This study evaluates the performance of five academic methane measurement systems through single-blind controlled release testing at the TotalEnergies Anomaly Detection Initiatives (TADI) facility in France during June and September 2024. Vehicle-based teams from Technical University of Denmark, Heidelberg University, and a collaborative team from Utrecht University/LSCE/Cyprus Institute/Royal Holloway deployed mobile *in situ* measurement systems, while aircraft-based solutions from Empa/UZH and FAAM BAe-146 utilized hyperspectral imaging and airborne *in situ* measurements, respectively. Vehicle-based systems demonstrated strong detection capabilities with true positive rates of 93-100% and minimum detection thresholds below 1 kg CH_4 h^{-1}. Quantification accuracy varied significantly, with slopes ranging from 0.38 to 1.04 when comparing estimated versus true emission rates. Aircraft systems showed more variable performance due to operational constraints and limited data availability. Post-unblinding analysis revealed critical insights into systematic errors, including background concentration calculation issues and wind measurement limitations. Low wind conditions (<2 m s^{-1}) particularly challenged quantification accuracy across all platforms. These findings highlight the importance of robust validation procedures and high-quality meteorological data for reliable methane emission quantification in real-world applications.

1 Introduction

Methane emissions represent a significant environmental challenge in the oil and gas (O&G) industry, primarily due to the sector's substantial contribution to global greenhouse gas emissions. The energy sector contributes approximately 35% of global anthropogenic methane emissions (IEA, 2022), meaning accurate detection and quantification of these emissions are essential for developing effective mitigation strategies. The majority of these emissions originate from the upstream segment of the industry, which encompasses both onshore and offshore oil and gas production (EPA, 2024). Methane is a highly potent greenhouse gas, with a global warming impact 28-80 times larger than that of carbon dioxide (IPCC, 2023). Additionally, methane emissions from O&G operations result in economic losses, with broader costs rising when accounting for the associated environmental and human impacts. Efforts to reduce methane emissions in the sector are gaining momentum, driven by international initiatives and national commitments to curb greenhouse gas emissions. Addressing methane emissions effectively is critical for mitigating the climate crisis and enhancing the overall sustainability of the O&G sector.

Recent developments in regulation and reporting, such as the Oil and Gas Methane Partnership 2.0 (OGMP 2.0), are driving the need for rigorous industry standards in methane inventories. The European Union's (EU) methane policy adopted in 2024 introduced new requirements for monitoring, reporting, and verifying the emissions of domestically produced and imported fuels, making accurately quantifying methane emissions a critical challenge for the O&G industry.

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Recent advances in detection and measurement technologies have resulted in measurement-informed inventories and studies becoming more commonplace. Methane measurement sensors can broadly be categorized into three types: *in situ* sensors measuring local methane concentrations, active scanning systems, and remote imaging systems. Sensors are deployed on a variety of different platforms, ranging from fixed, ground-level sensors situated around a production site to global satellite constellations. Recent advancements in remote sensing technologies have improved the ability to monitor methane emissions, providing wide area coverage, while a variety of ground-based and mobile platforms have been employed to measure methane emissions at industrial sites.

Controlled release testing is a crucial methodology used to evaluate the performance of methane emission measurement technologies (Ars et al., 2017; Chen et al., 2024; El Abbadi et al., 2023; Morales et al., 2022; Sherwin et al., 2021; Wietzel et al., 2025; Yver Kwok et al., 2015). These tests typically involve intentional releases of methane in a controlled environment to study detection and quantification capabilities under specific conditions. In single-blind testing, participants are informed about some aspects of the release (e.g. timing or location) but are unaware of the actual emissions rates, which allows researchers to assess the detection accuracy while minimizing bias. Differing levels of relevant information are kept from participants to eliminate potential expectations influencing their assessments, depending on the experimental constraints. Recent advancements in controlled release testing methodologies include the development of standardized protocols aimed at improving the consistency and comparability of results across different technologies (Bell and Zimmerle, 2020; METEC and TADI, 2025).

Ongoing research and collaboration among academic institutions and industry experts are vital for the advancement of methane emission measurement technologies. Over four weeks in June and September 2024, five academic teams participated in a methane controlled release experiment at the TotalEnergies Anomaly Detection Initiatives (TADI) research site in Pau, France. They joined with several commercial operators of methane measurement technologies. The academic and commercial teams are evaluated in separate papers for two reasons: (1) the academic teams were all aircraft or vehicle-based technologies, with no crossover into the commercial satellite, drone, and fixed sensor technology groups; and (2) the academic researchers are authors of this paper. There was no difference in the evaluation of the participants (i.e., the single-blind was maintained throughout the initial analysis), but the collaborative nature of academic teams allows for a more detailed analysis of measurements when compared to proprietary methods and algorithms. Vehicle-based academic teams consisted of researchers from the Technical University of Denmark (DTU), Heidelberg University (UHEI), and a combined team from Utrecht University, the French Laboratory for Climate and Environmental Sciences, the Cyprus Institute, and Royal Holloway University of London (UU/LSCE/CYI/RHUL). Aircraft-based solutions included technologies from the FAAM Airborne Laboratory and the Swiss Federal Laboratories for Materials Science and Technology

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(Empa) in collaboration with the University of Zurich (UZH).The analysis team consisted of researchers from Stanford University and TotalEnergies.

This paper presents a comprehensive evaluation of the detection and quantification performance of academic methane measurement technologies tested during the TADI controlled release experiments. Through rigorous single-blind testing protocols, we assess the capabilities and limitations of various vehicle-based and aircraft-based measurement platforms across different emission rates and environmental conditions. Our analysis employs detection limit curves and parity plot comparisons to provide quantitative insights into measurement accuracy and precision, contributing valuable empirical data to the growing body of knowledge on methane emission measurement technologies. The findings from this study will inform the development of more effective methane monitoring strategies and support evidence-based decision-making for emission reduction initiatives in the oil and gas industry.

2 Experimental methods

The controlled release experiments were conducted over four weeks in June and September 2024 at the TADI research facility in southwestern France. The study employed a single-blind testing protocol where academic teams were informed of release timing but remained unaware of the actual emission rates, release locations, and whether emissions were occurring during each measurement period. This section describes the experimental setup, data collection procedures, and systems used by each team to provide estimates of methane emission rates. A comprehensive description of the experimental design, site layout, release procedures and true release rates, and environmental monitoring can be found in the Supplementary Information (SI). The results presented in this study were collected at the same time as the data contained in McManemin et al., which presents the parallel evaluation of commercial methane measurement technologies conducted during the same campaign.

2.1 Experimental setup

Each testing day followed a structured schedule with approximately eight 45-minute measurement periods, separated by 15-minute intervals to allow for atmospheric dispersion and return to background methane concentrations. The controlled releases encompassed a range of emission rates from zero (for false positive testing) to over 300 kg CH_4 h^{-1}, designed to evaluate detection limits and quantification accuracy across different scales relevant to industrial operations. Methane was released from a dedicated platform at the TADI site using calibrated flow control systems with known uncertainties.

Controlled release parameters, including flowrates, locations, timing, and associated uncertainties, were recorded on-site by TADI engineers. Environmental conditions were monitored through daily meteorological observations and continuous high-resolution wind measurements using a ZX 300 Wind Lidar system positioned at the test site. However, the high-

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resolution wind data were not made available to participants until after the unblinding of true emission rates.

The academic teams deployed various measurement platforms, including vehicle-based mobile systems and aircraft-based technologies, each operating according to their standard protocols and methodologies. Teams were required to provide their own ancillary measurements (such as wind data) as needed for their quantification algorithms, reflecting real-world operational conditions.

2.2 Data submission and filtering procedures

Following each testing week, participants submitted their emission rate estimates and associated metadata. True release rates were unblinded only after all participants for each respective week had completed their submissions, with TADI wind lidar data provided simultaneously to enable post-analysis comparisons and method refinement.

After submission, the data filtering process categorized submitted estimates into three types: non-zero estimates (teams reporting measurable emission rates), zero estimates (teams reporting 0 kg h^{-1}) and N/A estimates (release for which teams provided no quantification). Three quality control (QC) frameworks were implemented: Strict QC (most restrictive), Stanford QC (team-specific criteria, used as default), and Participant QC (exactly as submitted by teams). The Stanford QC process utilized additional contextual information submitted with estimates to distinguish between genuine zero detections (e.g. “no plume visible”) and measurement failures due to external factors (e.g. adverse weather conditions). Detailed descriptions of the data filtering and categorization methods can be found in SI Sect. S4. After categorization, each submitted estimate was further classified into a true positive, false positive, true negative, or false negative estimate, depending on the true release rate (see SI Sect. S5.1).

Table 1. Release counts by participant through the filtering process.

Participant	Measured Releases	QC Passing Estimates			Main Filtering Reason
		Zero	*Non-Zero*	*Total*	
DTU	40	3	37	40	N/A
UHEI	34	0	19	19	Wind conditions
UU/LSCE/CYI/RHUL	37	1	33	34	Wind conditions
Empa/UZH	16	6	9	15	Cloud shadow
FAAM	4	0	1	1	N/A

Measured releases is the number of releases that the participants measured during the testing periods. QC passing estimates is the number of measured estimates that passed the Stanford QC method, divided into zero and non-zero estimates by participant (i.e. the classification of the release rate submitted by the participant, which could be different than the true release rate).

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2.3 Technology descriptions

The following sections describe the sensor technology, systems, and measurement procedures of the participating academic teams. Table 2 contains a summary of the participating team name, solution name, technology and sensor types, and testing week. More details on measurement and quantification methodologies can be found in SI Sect. S2.

Table 2. Participant and deployed solution, technology type, and week(s) of controlled release testing.

Participant	Solution Name	Technology Type	Sensor Type	Quantification Method	Testing Week
DTU	N/A	Vehicle	*In situ*	Tracer gas correlation	1
UHEI	N/A	Vehicle	*In situ*	Gaussian plume model / OTM33a	2
UU/LSCE/CYI/RHUL	N/A	Vehicle	*In situ*	Gaussian plume model	4
Empa/UZH	AVIRIS-4	Aircraft	*Passive imaging*	Integrated mass enhancement	4
FAAM	N/A	Aircraft	*In situ*	ADMS6 atmospheric dispersion model	3

2.2.1 Technical University of Denmark (DTU)

The DTU team deployed a mobile ground-based system using a 2017 van equipped with a Picarro cavity ring-down spectrometer (model G2203) that measures methane and acetylene concentrations *in situ*. This gas analyzer has a specification of CH_4 precision of 3 ppb (1σ, 2 seconds). The team employed a tracer gas dispersion method for emission quantification, which combines the controlled release of acetylene as a tracer gas with downwind measurements of both methane and acetylene concentrations to reconstruct plume dispersion characteristics.

The methodology involves releasing acetylene at a known, constant rate from the suspected emission source while conducting at least 10 cross-plume measurements of atmospheric methane and acetylene concentrations using the mobile platform. Air is sampled at approximately 2 m height as the vehicle traverses downwind transects. The approach assumes that methane and acetylene undergo identical dispersion and transport processes, allowing methane emission rates to be inferred from the ratio of observed methane to acetylene concentrations and the known acetylene release rate. This tracer gas dispersion method is described in detail in earlier publications and has been shown in previous controlled release studies to achieve quantification errors very likely less than 20% for fugitive emissions from area sources (Delre et al., 2018; Fredenslund et al., 2023, 2019; Kissas et al., 2022; Mønster et al., 2014). Additional details on this methodology can be found in Mønster et al. (2014) and Fredenslund et al. (2019).

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For the TADI experiments, acetylene was released via tubing into the center of the ATEX zone from a gas cylinder positioned near the test site (i.e., only the tubing and the tracer gas release point were within the gas release platform as required by TADI safety practices), and the acetylene releases occurred for the entirety of the methane release periods. Due to the central position of the acetylene gas cylinder, the maximum distance to the edge of the platform was 32m, and methane releases typically occurred within a 10m radius of the cylinder. The measurements at TADI deviated from typical operational practices in two key ways. First, the emission zone could not be surveyed beforehand to determine precise emission locations, and emission location within the platform varied and was blinded to participants, which prevented optimal tracer gas placement at or near the actual sources. Second, real-time adjustment of tracer placement based on methane-acetylene correlation during measurement – a standard practice to optimize method performance – was not possible due to the controlled experimental constraints.

2.2.2 Heidelberg University (UHEI)

The Heidelberg University team deployed a mobile ground-based measurement system using a 2019 Volkswagen van equipped with a CH_4 and CO_2 optical feedback-cavity enhanced absorption spectrometer from LICOR (LI-7810) for *in situ* concentration measurements, with a specification of 1σ precision of 0.25 ppb at 2 ppm with 5 second averaging. During the five-day release campaign, a standard gas cylinder was measured regularly for stabilization control of the instrument. The system incorporated dual meteorological monitoring capabilities, consisting of a fixed 3D anemometer and a mobile weather station mounted on the vehicle roof, near the intake line. These instruments provided local atmospheric wind data necessary for emission quantification algorithms. To apply the Gaussian plume dispersion method, the UHEI team conducted mobile transects around the gas release platform as shown in Fig. 1. The typical driving pattern involved driving the roads around the platform that were located approximately 50m to the northeast, 65m northwest, 80m southwest, and 90m southeast. The minimum, maximum, and mean measurement distances were 64m, 211m, and 105m, respectively. The emission plume was crossed at least 10 times during these transects. When wind conditions permitted, measurements were carried out at two different distances from the TADI platform to enhance the spatial resolution and robustness of the emission estimates. Furthermore, stationary measurements were conducted during three controlled release experiments, during which methane concentrations were recorded directly downwind, aligned with the prevailing wind direction.

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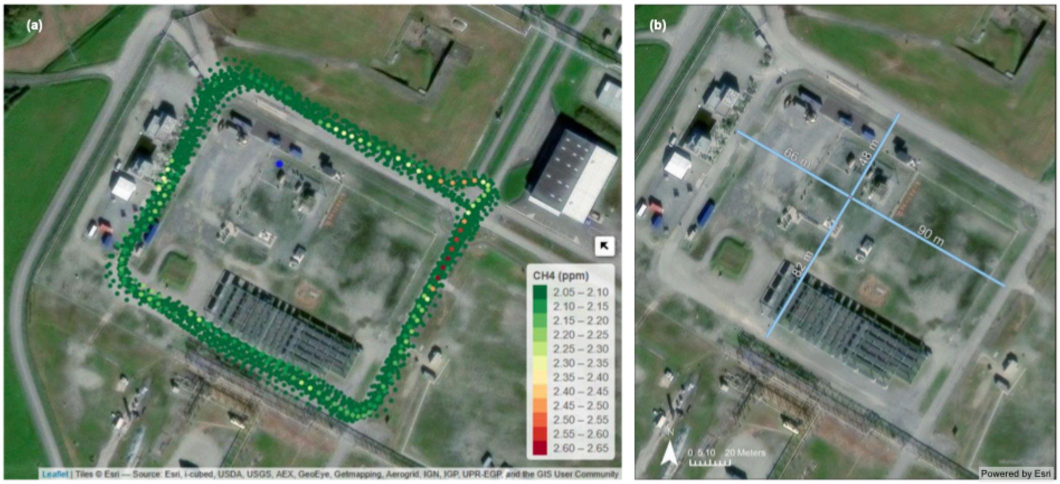

Figure 1. (a) Example path driven around the TADI platform and measured CH_4 concentration by the UHEI team. The map was created using leaflet for R (©Esri). (b) Distances in meters from center of gas release platform to surrounding roads.

Methane emission rates were calculated using one of the following methods: 1) the Other Test Method 33a (OTM33a) protocol (Korbeń et al., 2022; Morales et al., 2022) or 2) a Gaussian plume modeling approach (Korbeń et al., 2022; Wietzel et al., 2025) . The OTM33a method provides a standardized framework for quantifying emissions from point sources through stationary measurements, while the Gaussian plume method is based on measured CH_4 concentrations collected during transects through the emission plume. Only two estimates were submitted using OTM33a, limiting the intercomparison of these methods. Both models account for atmospheric dispersion characteristics based on the collected meteorological data. Since plume behavior is influenced by wind speed, which is a critical parameter in determining CH_4 emission rates using Gaussian plume modelling (Wilson et al., 1976) measurements taken at wind speeds below 2 m s^{-1} were reported but flagged as such during the participants' quality control process. A detailed description of the measurement setup and methodology employed for emission detection and quantification surveys by the Heidelberg team can be found in Korbeń et al., 2022 and Wietzel et al., 2025.

2.2.3 The Cyprus Institute, Royal Holloway University of London, Utrecht University, and the Laboratory for Climate and Environmental Sciences (UU/LSCE/CYI/RHUL)

The collaborative team from Utrecht University, the French Laboratory for Climate and Environmental Sciences, the Cyprus Institute, and Royal Holloway University of London

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deployed a shared mobile measurement system during Week 4 of the campaign. The instrumentation comprised three complementary methane concentration analyzers: an ABB LGR-ICOS™ UAV-Microportable Analyzer, GLA133-GGA Model sampling air at a rate of 10 Hz (accuracy: +/- 1%, instrument CH_4 precision: 0.9 ppb (1 s) / 0.3 ppb (10 s)), an Aeris MIRA Ultra methane analyzer (1 ppb CH_4 precision (1σ, 1 second)), and a Picarro G2311-f analyzer (CH_4 precision (1σ, 10 Hz) ≤ 3 ppb) , all mounted in a single vehicle equipped with an Airmar150WX WeatherStation® and GPS system for real-time positioning and local meteorological data collection. To supplement the mobile wind measurements, the team installed a stationary LI-550 Trisonica Mini 3D Wind Anemometer (10Hz) near the release area to provide additional wind field characterization. The dual anemometer configuration was designed to capture both local wind conditions at the measurement vehicle and representative conditions near the emission source area.

The detection methodology involved repeated driving patterns around the release area while monitoring real-time methane concentration displays to identify plume crossings. Team members rotated between roles including driver, co-pilot, and control room operations, with four personnel on-site covering all operational functions. An example of driven path can be seen in Figure 3c.

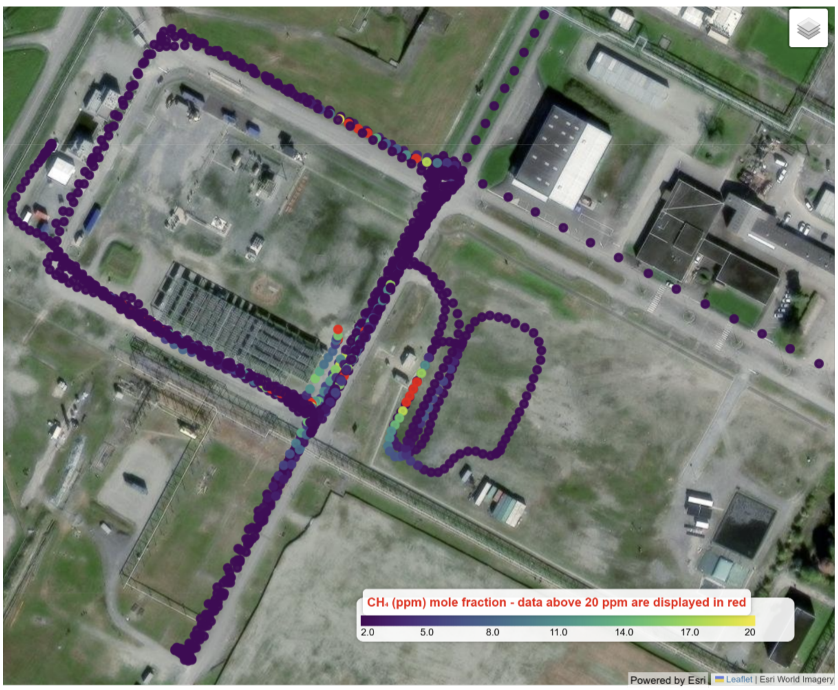

Figure 2. Example path driven around the TADI platform by the UU/ LSCE/CYI/RHUL team. The underlying satellite view layer is based on Esri World Imagery©, methane concentration

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collected by the AERIS MIRA analyzer are displayed using a colormap that scales linearly with the concentration up to 20 ppm; for clarity, data points above 20 ppm are shown in red. Refer to Fig. 1b for distances from the center of the gas release platform to the surrounding roads.

Upon detecting concentration enhancements, the team used visual screening of the online sensor displays to verify plume encounters and guide subsequent survey patterns. For quantification, methane concentration data from all three analyzers were integrated with GPS positioning and wind measurements to estimate the emission source location. Atmospheric dispersion coefficients were determined using different methodologies: LSCE-CYI used the stability class estimate provided by the TriSonica® station, RHUL a traditional determination process based on the cloud coverage and the wind speed at the time of measurements. Finally, UU estimated the horizontal dispersion coefficient (σ_y) as the standard deviation of a gaussian function fitted on the peaks of methane enhancement above the background. Then, the stability class that yields the closest estimate of the σ_y value based on the downwind distance from the estimated source position and it is used to estimate the vertical dispersion coefficient (σ_z). This method is adapted from the methodology used in Maazallahi et al., 2020. The estimated location and atmospheric stability classification were then incorporated into a Gaussian plume dispersion model to calculate emission rates based on the observed concentration field.

For all members of the UU/LSCE/CYI/RHUL team, the modelling approach required assumptions about the release point height, as this parameter was not known in the single-blind experimental design.

Originally, the participating institutions (CYI/LSCE, RHUL, and UU) planned to provide separate quantification and detection results despite sharing the common vehicle platform and meteorological instrumentation. However, following the campaign's conclusion, the collaborative team decided to submit unified emission rate estimates for each release (e.g. an average of the independent results), reflecting the integrated nature of their measurement approach and data analysis. The unified estimates were provided by averaging results that were converging towards similar values (within uncertainty estimate); when the estimates from two members for were converging and the estimate from the third member was not converging towards the same value, this third estimate was not included in the averaging process and was submitted to the analysis team as additional information. Only the unified results are presented in this paper to keep the evaluation process consistent across all participants, including the commercial teams.

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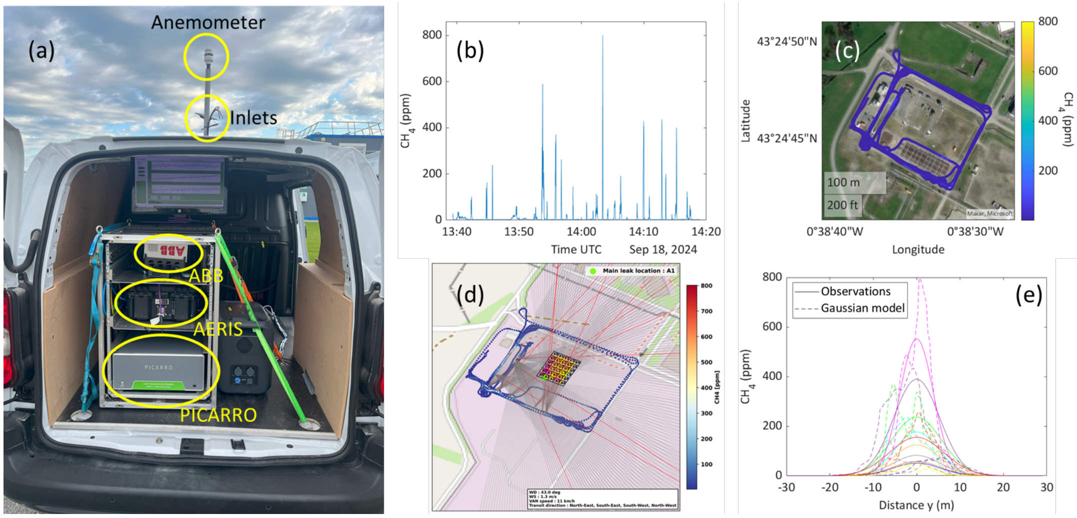

Figure 3. (a) Vehicle setup, (b) CH_4 time series of a 45-minute release, (c) Live mapping/visualization of CH4 mole fractions (Sources: Maxar, Microsoft | Powered by Esri), (d) Identification of potential source location using triangulation of wind direction during each plume transect, (e) Observed and modelled CH4 mole fractions of identified useful peaks.

2.2.4 Swiss Federal Laboratories for Materials Science and Technology (Empa) and University of Zurich (UZH)

The Empa/UZH team deployed an aircraft-based hyperspectral imaging system using the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS-4), developed by NASA Jet Propulsion Laboratory and operated by the University of Zurich. The instrument was mounted aboard a Cessna 208B Grand Caravan EX. AVIRIS-4 captures hyperspectral data across 287 spectral bands spanning wavelengths from 375 to 2500 nm, with most observations collected during this campaign at altitudes of 3300 and 4200 feet AGL (Hueni et al., 2025). Wind data for emission quantification were sourced from the ERA5 reanalysis product.

The emission quantification methodology employed a mass-balance approach to the retrieved high-resolution images of methane enhancements. Following radiometric and spectral calibration, methane enhancements were retrieved using a matched filter algorithm applied to two spectral windows with independent albedo corrections for each window. The matched filter technique uses unit absorption spectra calculated from simulated atmospheric conditions to detect methane enhancements above background levels (Kuhlmann et al., 2025; Meier et al., 2026). Plume detection involved applying enhancement thresholds to identify emission sources from high-resolution methane imagery, with background concentrations estimated using spatial low-pass filtering assuming smooth background fields. The emissions were determined using the integrated mass enhancement (IME) method implemented in Python library for data-driven

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emission quantification (ddeq;). For each controlled release, final emission estimates were computed as weighted averages of all overpasses during that release period, with uncertainties determined using median values to account for systematic errors in wind speed estimation and pixel sizing. 7-8 overpasses were generally performed per release (see Figure 2 in

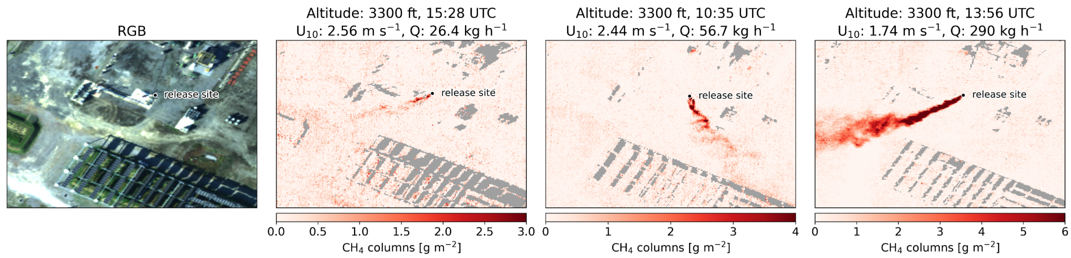

Figure 4. Examples of true color images and CH_4 concentration maps acquired by the AVIRIS-4 imaging spectrometer at 0.4 m spatial resolution. The images show emission plumes associated with reported emission rates (Q) for three distinct release events (from Meier et al. 2026).

2.2.5 FAAM Airborne Laboratory

The FAAM team deployed the instrumented UK's BAe-146-301 Atmospheric Research Aircraft equipped with comprehensive *in situ* atmospheric measurement capabilities. The primary methane measurements were conducted using a customized Los Gatos Research Fast Greenhouse Gas Analyzer (model 907-011-000-000) based on laser absorption off-axis integrated cavity output spectroscopy, providing 10 Hz measurements of CH_4 along with other greenhouse gases (O'Shea et al., 2013; Shaw et al., 2022). The payload also measures additional trace gases to provide chemical fingerprinting for plume identification and source discrimination. The aircraft positioning is provided by a GPS-aided inertial navigation system, and a full description of the meteorological measurements' capability (e.g. temperature, humidity, winds) is provided in Price, 2022.

Due to airspace restrictions within the prohibited area around the TADI site and low-level flying constraints (i.e. aircraft were required to fly at least 500 feet above ground level (AGL)), FAAM adapted their typical crosswind transect methodology and instead conducted repeated 2 nautical mile (3.7 km) radius orbital surveys around the TADI site. This orbital approach was designed based on Gauss's theorem cylinder methodology to maximize plume interceptions during the controlled release periods, though it was acknowledge that this methodology is more suited for spatial scales of approximately 1 km (Conley et al., 2017). Plume detection involved manual identification of methane enhancements during each orbit, with chemical tracers (NO_x, CO_2, SO_2, and aerosols) used to distinguish controlled release plumes from combustion sources and background emissions, as shown in Fig. 3. The team developed a novel quantification approach using the ADMS6 atmospheric dispersion model, which simulates methane dispersion fields

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optimized for aircraft- measured meteorological conditions. The methodology assumes a single point source and scales an initial emission rate based on the ratio of observed to modeled integrated CH_4 enhancements along the flight track.

The quantification approach faced several challenges unique to the TADI experimental conditions, including low wind speeds (below FAAM's typical 5 m s^{-1} operational threshold), unstable boundary layer conditions, and the presence of multiple plume sources in the complex industrial environment. Additionally, the limited altitude sampling range (150 m AGL due to safety restrictions) prevented full vertical integration of enhancements, required the use of "instantaneous" emission rates for each plume interception rather than traditional surface-integrated assessments.

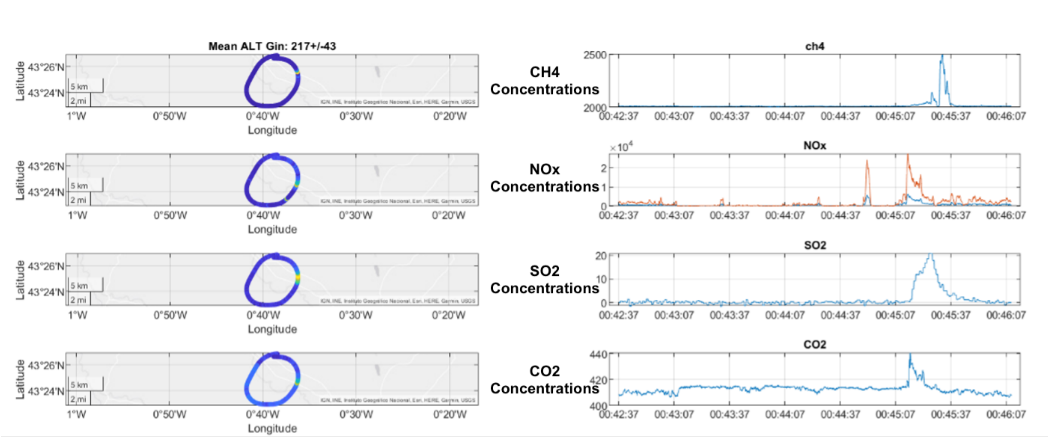

Figure 5. Mole fractions of CH_4 (ppb), NO_x (NO in blue, NO_2 in red, ppt), SO_2 (ppb), and CO_2 (ppm) during one FAAM orbit flown anti-clockwise around TADI as shown on left-hand side heat map. The time base is the number of seconds elapsed since start of release.

3 Results

The performance evaluation of academic methane measurement technologies is presented through detection accuracy, quantification precision, and environmental factor analysis. Results vary considerably across different measurement platforms and methodological approaches, reflecting the diverse capabilities and operational constraints of each system. The weather and wind conditions under which each team also varied substantially, potentially contributing to performance (see Tables S11-S13).

3.1 Detection analysis

Detection performance across the five academic teams demonstrated generally strong capabilities for identifying methane emissions, with true positive emission rates ranging from 60% to 100% (Table 3). The vehicle-based teams (DTU, UHEI, UU/LSCE/CYI/RHUL) achieved true positive

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rates between 93% and 95%, with DTU and UU/LSCE/CYI/RHUL each recording one false negative of 0.01 kg h^{-1} and 0.02 kg h^{-1}, respectively, and UHEI achieving perfect detection of all measured releases. False positive rates remained low across all ground-based systems, with only UHEI and UU/LSCE/CYI/RHUl reporting single false positive detections. The aircraft-based systems showed more variable performance. FAAM achieved 100% detection accuracy but measured only one release that passed quality control criteria, limiting statistical assessment of their detection capabilities. Empa/UZH recorded a 60% true positive rate with six false negatives out of 15 releases, representing the highest false negative rate among all participants.

Table 3. Summary of true positive (TP), false positive (FP), true negative (TN), and false negative (FN) releases by participant.

Solution	TP	FP	TN	FN	TP (%)	FP (%)	TN (%)	FN (%)	Max Release Detected [kg h^{-1}]	Min Release Detected [kg h^{-1}]
DTU	37	0	2	1	93	0	5	2	126.0	0.66
UHEI	18	1	0	0	95	5	0	0	136.6	0.01
UU/LSCE/CYI/RHUL	32	1	0	1	94	3	0	3	290.0	0.19
Empa/UZH	9	-	-	6	60	-	-	40	290.0	5.5
FAAM	1	-	-	0	100	-	-	0	210.0	210.0

The percentages are calculated by dividing by the total number of non-zero releases included in the analysis. The table also includes the minimum and maximum release flowrates detected by each team (i.e. the participant reported in a quantification estimate for that release). A dash (-) indicates that that no releases were able to be categorized as FP / TN due to that solution not measuring any zero releases or no zero releases passed the Stanford QC process.

Minimum detection thresholds varied significantly between measurement approaches. The ground-based systems all demonstrated very low minimum detection capabilities at rates below 1 kg h^{-1}. The downwind distance of the vehicle deployment (Fig. 1b) should be considered while utilizing these numbers, as minimum detection limit is dependent on measurement distance. The scope of the experimental set-up did not allow for determination of the detection limit of aircraft solutions. Among aircraft systems, Empa/UZH's minimum detected was 5.5 kg h^{-1}, while FAAM's single measurement was at 210 kg h^{-1}. Figure 6 illustrates the distribution of estimate categorizations across different emission rate ranges, showing how detection performance varies with release magnitude. Figure 7 presents probability of detection curves for releases below 30 kg h^{-1}, demonstrating the detection thresholds and reliability of each ground-based system through logistic regression analysis.

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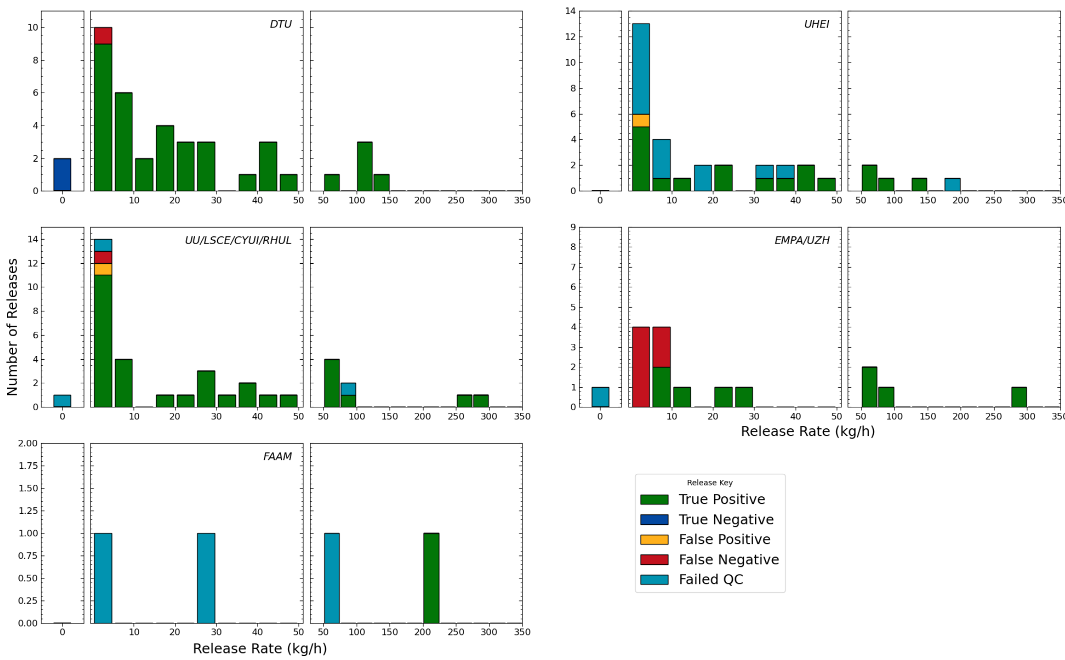

Figure 6. Distribution of estimate categorizations for each participant, with colors representing different result classifications: true positive, true negative, false positive, false negative, and failed QC (releases during which measurements were taken but failed to pass the Stanford QC process). The y-axis is the number of releases, and the x-axis corresponds to the binned methane release flowrate. Note the different y-axis scales per row.

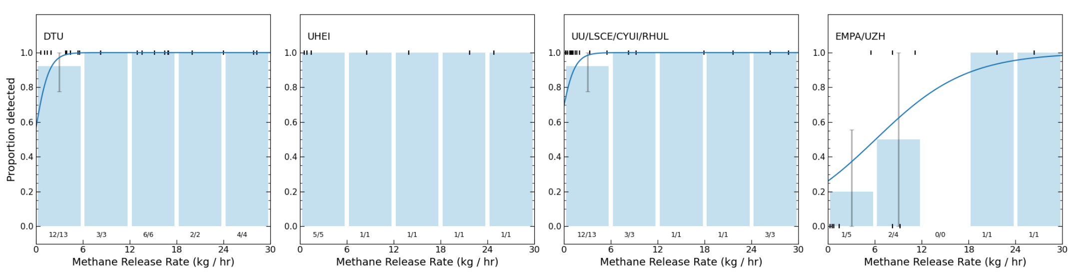

Figure 7. Detection capabilities below 30 kg CH_4 h^{-1} for quantified releases. Each release is marked by a vertical line at y = 0 if not detected and y = 1 if detected, ordered along the x-axis by release volume. Blue bars indicate the proportion of detected releases within each bin, with error bars representing 95% confidence intervals based on a binomial distribution. The darker blue line is the best fit of a logistic regression model on the probability data. FAAM is excluded

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due to not measuring any releases below 30 kg CH_4 h^{-1}. UHEI detected all non-zero releases. The x-axis bins are based on the true release rate.

3.2 Quantification analysis

Quantification accuracy exhibited substantial variation across measurement platforms and emission rate ranges (Table 4). The average performance of teams are evaluated using the slope and R^2 values associated with the linear regression (non-zero intercept) between the true and estimated emission rates. DTU achieved the most accurate overall performance with a slope of 1.04 ($R^2 = 0.89$) across all measurements, indicating minimal systematic bias. Performance varied further for releases below 100 kg h^{-1}, with a slope of 1.18 ($R^2 = 0.92$). UHEI demonstrated good linear correlation ($R^2 = 0.89$) with a slope of 0.87, representing moderate underestimation, and achieved near-perfect quantification for smaller releases (slope = 1.03, $R^2 = 0.87$ for < 100 kg h^{-1}). The collaborative UU/LSCE/CYI/RHUL team showed strong correlation ($R^2 = 0.85$) but significant underestimation (slope = 0.38), with performance degrading for smaller releases (slope = 0.32, $R^2 = 0.34$). Empa/UZH exhibited moderate correlation ($R^2 = 0.74$) with considerable underestimation (slope = 0.33), though performance improved for releases below 100 kg h^{-1} (slope = 0.77). FAAM's single quantified measurement limits statistical assessment but the true value fell within the estimated uncertainty ranges.

Table 4. Key metrics for quantification performance across all participants.

Solution	Qualified nonzero measurements	Slope (R^2) for all measurements[a]	Slope (R^2) for measurements with true release rate < 100 kg h^{-1}	Participant estimate bounds encompassing the metered value (%)[b]	Participant estimates within +/- 50% of the true value (%)[c]	Total emissions quantified by each participant (%)[d]
DTU	37	1.04 (0.89)	1.18 (0.92)	43	95	110 [93, 126]
UHEI	18	0.87 (0.89)	1.03 (0.87)	28	78	89 [71, 106]
UU/LSCE/CYI/RHUL	32	0.38 (0.85)	0.32 (0.34)	28	28	40 [18, 63]
Empa/UZH	9	0.33 (0.74)	0.77 (0.68)	44	56	61 [39, 82]
FAAM	1	N/A	N/A	100	100	144 [39, 249]

[a] Slope and R^2 are associated with the linear equation of best using ordinal least squares.
[b] The percent of measurements that included the true release rate within the upper and lower bounds of each estimate provided by each participant. Participants reported their own minimum and maximum values associated with an emission quantification which are used for this analysis. See SI Table S23 for more information on participant confidence level and sources of uncertainty; uncertainty bounds may not be consistent between participants.
[c] The percent of estimates that fell within +/- 50% of the true release rate.
[d] The percent of true CH_4 emissions quantified by each participant (the total emissions quantified by this solution compared to the total amount of methane emitted during these releases) with upper and lower uncertainty ranges reported by participants.

Practical accuracy metrics reveal additional performance insights, although they are limited by the number of data points available for analysis by the aircraft teams. DTU achieved the highest

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proportion of estimates within +/-50% of the true values, followed by UHEI and Empa/UZH. The UU/LSCE/CYI/RHUL team achieved only 28% of estimates within this accuracy threshold. When considering participant-reported uncertainty bounds, DTU (43%) and Empa/UZH (43%) showed the best calibration of uncertainty estimates. Total emission quantification, representing the cumulative accuracy across all measurements, ranged from 40% (UU/LSCE/CYI/RHUL) to 144% (FAAM). Three of the participating teams (DTU, UHEI, and FAAM) contained 100% of all true methane emissions within their cumulative estimate uncertainty intervals. Figure 8 presents parity plots comparing estimated versus true emission rates for all participants, illustrating the range of quantification performance and systematic biases across different measurement approaches.

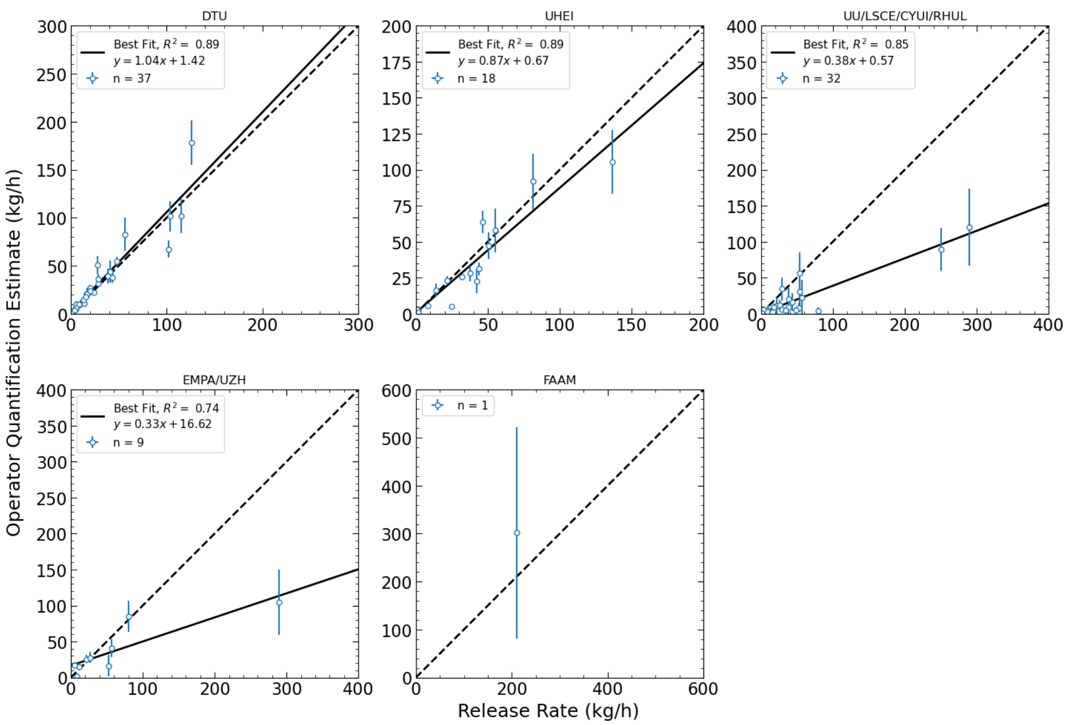

Figure 8. Quantification accuracy of the participants. Metered release rate is on the x-axis. There is a small uncertainty associated with the true release flowrates, not shown in this figure. Participant reported quantification estimates are on the y-axis. The dashed line represents the x = y parity line. The solid line indicates an ordinary least squares (OLS) linear regression performed on the participant data with non-zero y-intercept (i.e., intercept not forced through origin)

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3.3 Wind analysis

Environmental conditions, particularly wind characteristics, could have had significant influence on measurement performance. Figure 9 demonstrates the combined quantification performance of all teams except FAAM binned by wind conditions, possibly highlighting a systematic relationship between atmospheric parameters and measurement accuracy. When looking at the joint results of all teams, quantification performance improved with increasing wind speeds, with the best agreement between estimated and true emission rates occurring at wind speeds above 2 m s^{-1}. Low wind speed conditions (below 1 m s^{-1}) are correlated with increased scatter and underestimation. Wind speed coefficient of variation, indicating temporal variability of wind speed during measurements, also influence performance, with more stable wind conditions generally producing more accurate quantification results. Wind direction variability, measured through coefficient of variation, showed a similar relationship with quantification accuracy. Periods with stable wind direction (low CoV) are associated with better measurement performance compared to highly variable wind conditions.

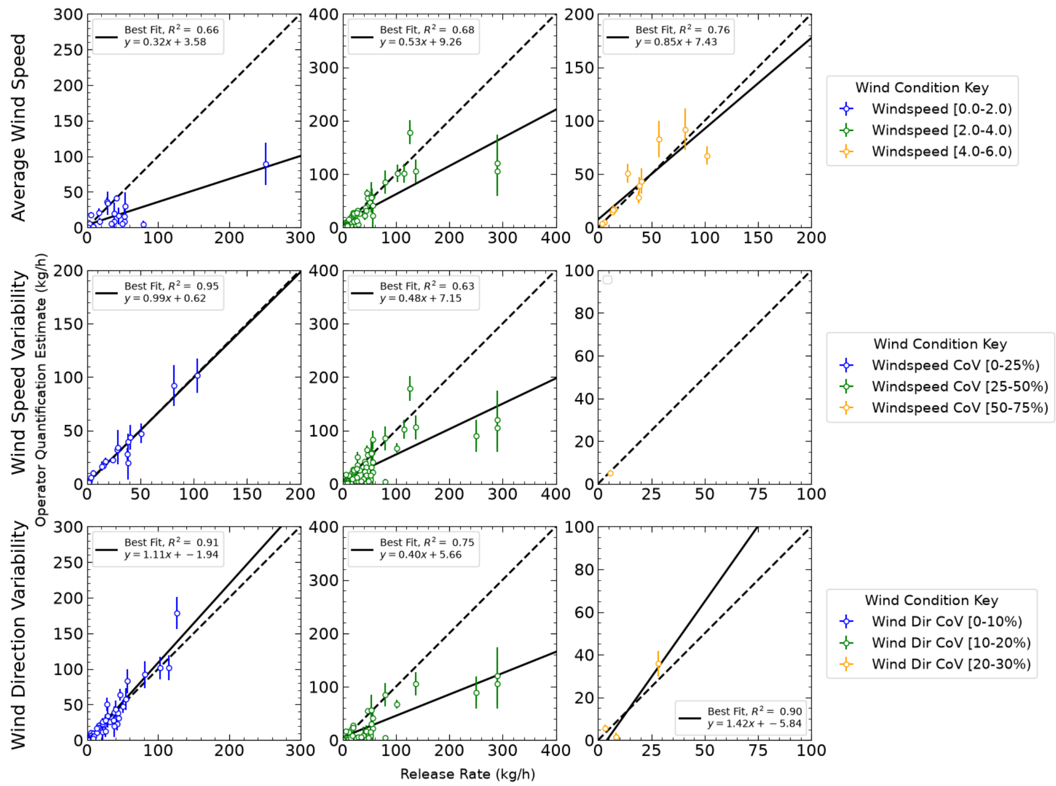

Figure 9. Parity plot for combined data of all solutions, binned into different wind conditions during the release. The first row bins the releases by average wind speed, the second row bins the

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releases by wind speed CoV, and the third row bins the releases by wind direction CoV. FAAM's single measurement is excluded from this analysis.

It is important to note that the wind conditions varied widely across the four weeks of testing (SI Sect. 3.2-3). Parity plots broken into each wind condition bucket for each participant can be found in SI Sect, 7.The challenge of low average wind speeds (< 2 m s^{-1}) are generally assumed for participants using local atmospheric dispersion modeling (Wilson et al., 1976) and previous experiments have highlighted the expected relationship between wind conditions and quantification ability (Liu et al., 2024; Morales et al., 2022), but more controlled release testing is needed to further quantify the relationship between wind conditions and the error of specific systems.

4 Discussion

4.1 Detection and quantification performance

Vehicle-based systems demonstrated strong detection performance with false positive rates remaining low and true positive rates exceeding 80%, successfully detecting releases below 0.7 kg h^{-1} and achieving 90% probability of detection at below 5 kg h^{-1}. Quantification abilities showed more variability. Overall, DTU showed impressive quantification ability, with a slope of the regression line of 1.04 for their tracer gas dispersion method (a slope of 1 is ideal). UHEI also quantified quite well, especially smaller emissions, resulting in a slope of 1.03 for releases under 100 kg h^{-1}. The UU/LSCE/CYI/RHUL team demonstrated a tendency to underestimate in their quantification analysis (on average around -60%); however, their measurement week (Week 4) presented the most challenging measuring conditions (e.g., low wind speeds). Overall, although the vehicle teams used different methods and quantification performance varied between operators, vehicle methane detection and quantification ability shows significant improvement from older studies utilizing a single-blind independent controlled release format (Ravikumar et al., 2019) while reproducing quantification results for vehicle-based methods in a more recent study (Liu et al., 2024). Direct comparison with these studies are difficult due to the differences in experimental methods (e.g., distribution of release rates), analysis methods (e.g., quality processing prior to result submissions), and environmental conditions. However, while no participant in Ravikumar et al. used a tracer correlation method, the tracer method in Liu et al. also performed quite well, as demonstrated in this study.

Aircraft-based performance was more difficult to assess due to limited measurements, with the Empa/UZH AVIRIS-4 system demonstrating detection capabilities on par with other recent controlled release testing of aircraft based systems (El Abbadi et al., 2023; Sherwin et al., 2021). Both aircraft operators filtered substantial portions of potential measurements due to clouds and precipitation, highlighting the operational challenges of deploying remote sensing technologies in European weather conditions; the fact that the test conditions were more challenging than desert weather reflects a performance achieved closer to a conservative version of reality.

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Although remote sensing campaigns are generally carried out in summer periods with more favorable weather and illumination, conditions posed a problem to remote sensing participants in all four weeks across June and September (McManemin et al., 2026); this also may cause estimates to be biased toward summer and fair weather conditions. Additionally, the operational constraints of the site restricted low flight level surveying, resulting in measurements conducted while deviating from typical protocol (i.e. offshore oil and gas measurements as described in Campos et al., 2024 and Foulds et al., 2022). This suggests opportunities for technological innovation compared to more established remote sensing programs in other regions.

Excluding FAAM's single measurement, none of the participants contained the true value within their submitted estimate ranges more than 44% of the time (Table 4, Column 5). Even for teams with regression slopes close to unity (e.g., DTU and UHEI), the ability to quantify individual measurements within uncertainty ranges could be improved. This suggests that further work to better estimate the uncertainties associated with individual quantification estimates could be pursued as a result of this experiment. Three of the five teams (DTU, UHEI, and FAAM) quantified the total amount of methane released within their uncertainty ranges (Table 4, Column 7), which suggests the ability of these technologies to quantify emissions overall, although individual measurement ability may vary. Quantification error by order of magnitude of release is shown in Fig. 10.

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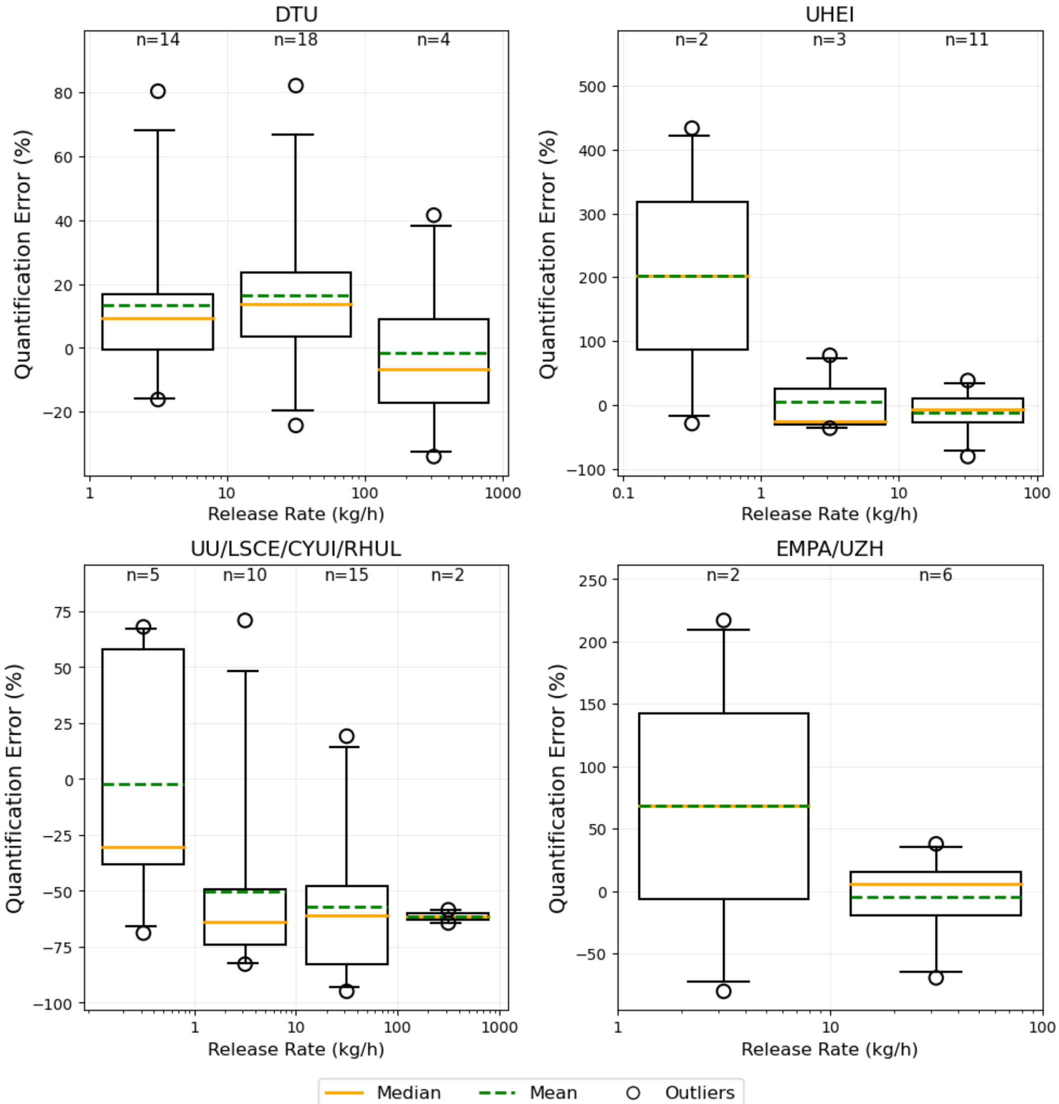

545 **Figure 10.** Quantification accuracy within each order of magnitude. The mean (dashed line), median (solid line), inner quartiles (box), and 95% confidence are shown for quantification error of release estimates for each order of magnitude (e.g. for DTU, the bins are between 1 and 10, 10 and 100, and 100 and 1000 kg h^{-1} from left to right), with number of samples (n). Only segments with more than one measurement (n>1) are shown. FAAM is excluded due to their single estimate. Layout adapted from Bell et al., (2022).

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4.2 Post unblinding analyses and sources of systemic error

Following the unblinding of true release rates and provision of high-resolution wind data from the TADI site, several academic teams conducted detailed analyses of their methodologies to identify sources of systematic error and opportunities for improvement. These post-campaign evaluations provide valuable insights into the challenges of real-world methane quantification and highlight areas where measurement protocols can be refined.

4.2.3 Background concentration calculation issues

The UHEI team identified a programming error in their background concentration calculation that affected quantification accuracy for smaller releases. The methane background concentration baseline was not updated from previous analyses, resulting in an additional 10 ppb being subtracted from calculated methane background concentrations, effectively lowering the baseline and artificially inflating measured concentration enhancements. This systemic bias particularly impacted release below 2 kg h^{-1}, affecting approximately 35% of their total measurements.

UHEI estimated that the error manifested as a 10-30% overestimation of emission rates for controlled releases between 0.5 and 2.0 kg h^{-1}, with larger relative impacts on smaller releases where the 10-ppb offset represented a more significant fraction of the total enhancement signal. Upon correction of the background calculation methodology, the team states their quantification accuracy for low-emission scenarios improved, demonstrating the critical importance of background characterization in mobile measurement applications and for small-volume releases. Figure 10 shows the quantification error by order of magnitude of true release rate, supporting the conclusion that quantification accuracy improved for higher releases when defined by percent error. This finding underscores the sensitivity of *in situ* measurement systems to low concentration enhancements and highlights the value of controlled release testing in identifying basic algorithmic issues that might not be apparent in routine field operations.

4.2.2 Wind measurement and low wind speed challenges

The collaborative UU/LSCE/CYI/RHUL team deployed three complementary methane sensors, each with distinct accuracy, resolution, and response characteristics. Post-unblinding analysis of these sensors revealed systematic underestimation of emission rates, particularly under the low wind speed conditions (< 2 m s^{-1}) prevalent during their week of testing in the TADI campaign. The team hypothesized that weak wind scenarios caused emissions to elevate above vehicle sampling height prior to detection, resulting in incomplete plume captures and highly variable enhancement signals that differed by more than an order of magnitude across individual releases. In addition to the challenging wind conditions, wind speed measurements showed systematic differences between the two anemometers deployed by the team and TADI's own wind Lidar sensor. These discrepancies, combined with the challenges of partial plume sampling in slack

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wind conditions, highlight the need for refined analytical approaches specifically adapted to low wind speed environments in mobile methane quantification applications.

An alternative solution is to only conduct measurements when average wind speeds are above a certain threshold (e.g. 2 m s^{-1}), supported by the analysis in this study. The UHEI team typically avoid mobile measurements when wind speeds are below 2 m s^{-1} due to increased plume meandering under calm conditions. However, due to the limited controlled releases available for each team to measure, measurements were conducted under all weather conditions. UHEI applied quality control criteria and filtered results to include only measurements taken at wind speeds above 2 m s^{-1} (when averaged across the periods in which UHEI was actively measuring) and under low wind direction variability, resulting in only 19 of 34 participated releases included in the blind analysis.

The Empa/UZH team utilized the AVIRIS-4 airborne imaging spectrometer with the IME method for methane quantification, which requires accurate effective wind speed estimates as a critical input parameter. Initially, the team employed 10-meter wind data from the ERA5 reanalysis product (approximately 25 km spatial resolution) for emission calculations. However, post-unblinding comparison with the TADI wind Lidar measurements revealed poor correlation between the reanalysis and ground-truth wind data, indicating significant limitations in the meteorological product's representation of local wind conditions. Substituting the lidar-measured wind speeds at 10 meters AGL as the effective wind speed input resulted in substantial improvement in AVIRIS-4 emission estimate accuracy (Meier et al., 2026). This finding demonstrates the critical importance of high-quality, site-specific wind measurements for atmospheric-based emission quantification methods. The results indicate that standard meteorological reanalysis products, despite their widespread availability and use, may not be able to capture the specific wind conditions during an aircraft overpass taking only a few seconds, especially during the low and varying wind conditions characteristic of the September campaign period. In particular, the agreement between ERA5 and ground-based wind measurements is particularly weak for the time and length scales of the observed plumes in this study (<20s and < 30m). A more thorough discussion of the Empa/UZH results can be found in Meier et al.

The tracer gas correlation method used by DTU should theoretically work better in low wind speeds when the tracer gas is emitted near the methane release point (i.e., the use of the tracer ratio inherently reduces assumptions about wind speed and direction). The week in which DTU measured (Week 1) offered relatively strong wind speeds, with only 3 releases with wind speeds below 2 m s^{-1}. This supports the conclusion that to gain a full understanding of each approach, releases should be conducted across a wide variety of environmental conditions and wind speeds, as the experiment did not offer the ability to rigourously evaluate DTU's method under low wind speed conditions.

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Overall, for this specific experiment, not enough data points were collected to rigorously test the impact of wind conditions on measurement accuracy. Although the analysis of combined results supports the literature in establishing the importance of stable wind conditions in quantification, each technology evaluated in this campaign needs to undergo further testing to determine specific operational limits. Due to the experimental setup, participants undertook measurements in conditions that may differ from operational practice, and performance could change under different conditions, highlighting the need for more controlled release testing. Because the measurement systems are not equivalent, results at different wind speeds cannot be directly compared across all participants, which supports further research in this area. Additional single-blind controlled release tests that require participants to submit quantification estimates for all releases measured (different from what was implemented in this study due to quality control processes) and facilitate conccurent measurement by technology group would offer the ability to further investigate this important facet of methane emission quantification. This would require an extra layer of collaboration with the participants that was unavailable in this study.

5 Conclusion

This study presents the first comprehensive evaluation of academic methane measurement technologies in Europe through single-blind controlled release testing at the TADI facility in France, providing critical insights into the capabilities and limitations of diverse measurement platforms for oil and gas emission quantification.

The results demonstrate that vehicle-based systems achieved strong detection performance, with true positive rates exceeding 93% and minimum detection thresholds below 1 kg CH_4 h^{-1}. These ground-based platforms successfully identified emissions across a wide range of release rates, from sub-kilogram to over 300 kg h^{-1} releases. However, quantification accuracy varied significantly between methodologies, with slopes ranging from 0.38 to 1.04 when comparing estimated versus true emission rates. The DTU tracer gas dispersion method demonstrated the most accurate overall quantification, and UHEI also achieved strong performance, particularly for emissions below 100 kg h^{-1}. The collaborative UU/LSCE/CYI/RHUL team demonstrated a systematic underestimation of the results. However, it is important to note that each vehicle team conducted measurements in different weeks, which offered varying environmental conditions as described in this paper. The results for each participant do not encapsulate the same distribution of wind conditions which makes direct comparison more difficult. The substantial performance variability observed between academic teams using similar measurement principles highlights the cruciality of methodology refinement and quality control protocols, particularly as it applies to wind conditions.

Aircraft-based systems faced greater operational challenges, with limited data availability due to weather constraints and airspace restrictions. The first blinded test of the AVIRIS-4 hyperspectral imaging system used by the Empa/UZH team achieved 60% detection accuracy with a minimum

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detection threshold of 5.5 kg h^{-1}, while FAAM's orbital measurement approach was restricted to a single qualifying measurement. These results highlight the trade-offs between spatial coverage capabilities and operational constraints inherent in airborne measurement platforms.

Post-unblinding analysis revealed critical insights into systematic error sources that significantly impact measurement accuracy. Background concentration calculation errors affected small-release quantification for the UHEI team, while wind measurement limitations and low wind speed conditions (< 2 m s^{-1}) challenged all platforms. The substitution of high-resolution wind lidar data for ERA5 reanalysis substantially improved aircraft-based quantification accuracy, emphasizing the crucial role of meteorological data quality in emission estimation algorithms.

Environmental conditions emerged as a dominant factor influencing measurement performance across all technologies. Low wind speeds and high temporal variability in wind direction degraded quantification accuracy, with optimal performance occurring at wind speeds above 2 m s^{-1}. These findings underscore the importance of meteorological considerations in both measurement planning and algorithm development for real-world applications. However, more research is needed to fully understand the limits of each technology within environmental constraints, and the relationship between wind conditions and quantification ability is still not fully understood. For instance, a full evaluation and comparison of all data collected by the vehicle participants of this study could help improve understanding of the impact of wind conditions and allow a direct comparison of the different methods (i.e., Gaussian plume model vs. tracer gas correlation). In addition, comparison of the simultaneous measurements deployed by the UU/LSCE/RHUL team would allow differences between methane sensors housed on the same platform to be evaluated.

This research contributes essential empirical data to the growing body of knowledge on methane emission measurement technologies, particularly for European operational conditions. The results inform evidence-based selection of measurement approaches for different industrial applications and emission scenarios. The identified systematic error sources and environmental sensitivities provide clear targets for technological improvement and protocol development. Future research should focus on addressing the identified limitations, particularly related to the challenges of conducting measurements in low wind speeds (e.g., developing robust measurement conditions or quantification approaches that minimize assumptions about atmospheric transport at low wind speeds) and improving the integration of high-quality meteorological data into quantification methodologies. Extended controlled release campaigns under diverse environmental conditions would further validate these findings and support the development of more reliable measurement standards for the oil and gas industry, including in offshore environments where significant O&G assets are deployed. While controlled release testing is instrumental in evaluating the sensitivity and accuracy of methane measurement technologies, it is crucial to note that results obtained in controlled environments may not always translate directly to real-world conditions. This discrepancy highlights the need for additional

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challenge releases that replicate operational scenarios, thereby providing a more comprehensive understanding of how technologies perform in diverse environmental contexts.

The findings from this study directly support the advancement of methane monitoring capabilities essential for achieving greenhouse gas reduction targets and enhancing the environmental sustainability of oil and gas operations. As measurement-informed emission inventories become increasingly important for regulatory compliance and corporate responsibility initiatives, the insights from this controlled evaluation provide a foundation for implementing more effective methane detection and quantification strategies across the industry.

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Code and data availability

All data and code used in this study are available at https://doi.org/10.5281/zenodo.18381031 (McManemin et al., 2026). The repository includes scripts for data preprocessing, analysis, and figure generation, as well as documentation to reproduce the results presented in the manuscript. Additional details or support can be provided upon request.

Author contribution

Conceptualization: AM, CJ, VB, AB, JF

Project administration: AM, CJ, VB, JF

Data collection and processing: AM, CJ, VB, SM, MV, AH, GK, SB, PL, MB, JW, MS, CS, AF, RPag, PQ, RPap, JF, PB

Software: AM

Formal analysis: AM, CJ, AB

Writing - original draft: AM

Writing - review & editing: AM, CJ, VB, SB, DB, PB, JF, AF, AH, GK, SM, RPag, RPap, JP, PQ, TR, CS, MS, MV, JW, AB

Supervision - DB, GK, AB

Competing interests

At least one of the (co-)authors is a member of the editorial board of Atmospheric Measurement Techniques.

Acknowledgements

We acknowledge all of those who supported participation in this test and provided logistical and coordination support. Thank you to the TADI team (Jordi Jourde, Yvan Faucher), and participants who are not authors of this paper: Aeromon (Matti Irjala, Sina Hamedani Raja), Airtask Ltd (Barney Black), GSMA (Florian Parent), Flylogix (Charles Tavner), SeekOps (Brendan Smith, Michael Gully-Santiago), UHEI (Julian Grossmann, Till Gonser), Empa/UZH (Dominic Berger), GHGSat (Marianne Girard), Sensirion (Susanne Pianezzi), SLB (Manasi Doshi, Tetsushi Yamada, Gokhan Erol), and SENSIA (Jorge Mataix Clau, Gonzalo Guerrero Torija). Their collective contributions were instrumental in the successful completion of this study.

https://doi.org/10.5194/egusphere-2026-1744
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Airborne data was obtained by the FAAM Airborne Laboratory BAe-146-301 Atmospheric Research Aircraft, operated by Airtask Ltd, managed by the National Centre for Atmospheric Science, leased through University of Leeds, and owned by UK Research and Innovation and the Natural Environment Research Council (project NE/T014849/1).

AI tools such as ChatGPT, Claude, and Cursor were used to assist in light editing of this manuscript and code generation.

Financial support

This research was funded by United Nations Environmental Programme International Methane Emissions Observatory (agreement no. CCD24-CMB6608/RC/MSS).

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