MEMO^2 : Methane goes Mobile- Measurements and Modelling

Estimating local methane sources from drone-based laser spectrometer measurements by mass-balance method

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Outline

Motivation of the study

- CH_4 is primarily emitted from diffusive sources such as landfills or wetlands and from leaks during oil- and gas-production
- Measurements from drones offer an attractive means to sample the plumes in 3D of individual sources to quantify its emissions

Main challenges:

A need for a lightweight but precise CH_4 measurements that can be mounted on a drone system → World's lightest laser-spectrometer developed by Empa

Commercial drone (Matrice 600, DJI) has a vertical accuracy of ±0.50m which is not sufficient in performing the mass balance quantification method → Implement an RTK-GPS system which has a precision of 2.0 mm

Limited flight-time, limited sampling of turbulent plumes → Design the best measurement strategy for sampling atmospheric trace gases, particularly CH_4

Lightweight and precise QCLAS developed by EMPA and an accurate RTK-GPS system mounted on the drone system

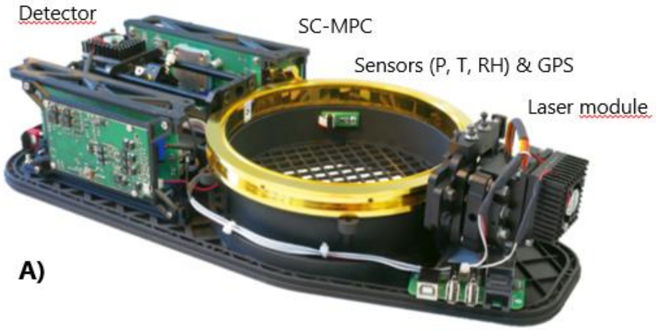
QCLAS-Drone system

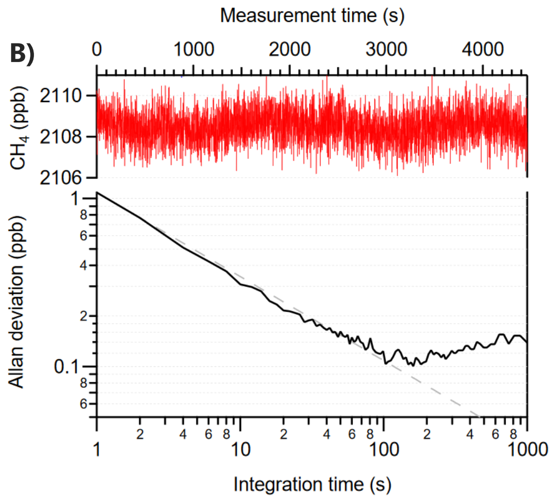
A: Picture of the optical system. The central components are the segmented circular multi-pass cell [1] and the collimated quantum cascade laser source packaged in TO-3. Further peripherals are the environmental sensors.

B: Allan-deviation plot showing the precision of the instrument under lab conditions [2].

C: The instrument, covered by a white polymer cover, is mounted on the drone-system (Matrice 600, DJI) used for field measurements.

Table: Overview of the relevant specifications of the QCLAS system [2].





Parameter	
Weight incl. battery	2.2 kg
Power consumption	15 W
Precision (CH_4)	1.1 ppb @ 1 s
Sampling rate	1-10 Hz

[1] Graf *et al.*, Optics Letters, 43, 2018
[2] Tuzson *et al.*, AMTD, 2020 https://doi.org/10.5194/amt-2020-102

Measurement procedure

I. Determine dominant wind direction

II. Fly the drone to a starting position downwind of the source where CH_4 is not detected by the QCLAS sensor

III. Start the mass balance method by flying the drone at approximately 1m/s following a straight transect perpendicular to the dominant wind direction.

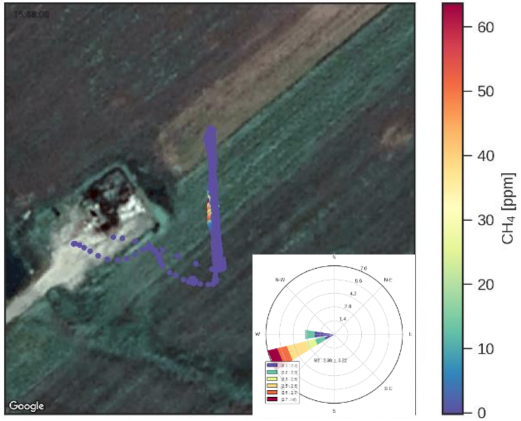
IV. Continue flying the drone until the QCLAS sensor pass through elevations of CH_4 molar fractions above background.

V. Once the QCLAS sensor no longer measures CH_4 molar fraction elevations, continue flying the transect to properly sample background values of CH_4.

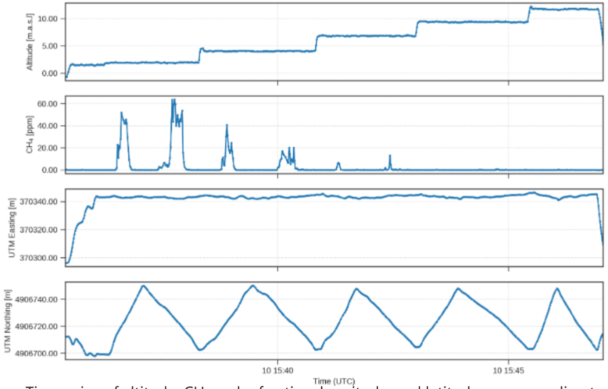
VI. Depending on the design of the flight, either fly the drone to the next vertical layer for sampling or traverse the same transect, going back to the starting position, before moving on to the next vertical level.

Accurate RTK-GPS receiver mounted on top of the drone

3D sonic anmemoter measuring wind conditions at a sampling frequency of 20.0 Hz



Mass balance quantification method applied during a campaign in Romania. Drone flight is designed to fly almost perpendicular to the dominant wind directions



Timeseries of altitude, CH_4 molar fraction, longitude, and latitude corresponding to the measurement in the figure above

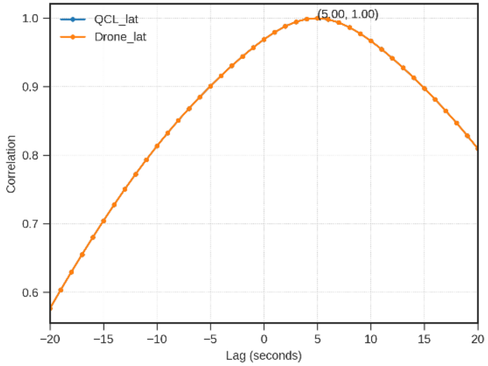
Quantification of methane emission

Treatment of obtained CH_4 measurement data

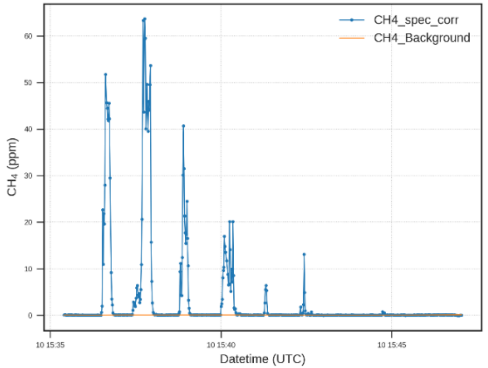
I. The clocks between measured CH_4 molar fraction and positional coordinates from the RTK-GPS system were synchronized by performing a cross correlation between the longitude and latitude from the QCLAS sensor and the RTK-GPS system

II. Background CH_4 were removed using the *Robust Extraction Baseline Signal (Ruckstuhl, 2012)*

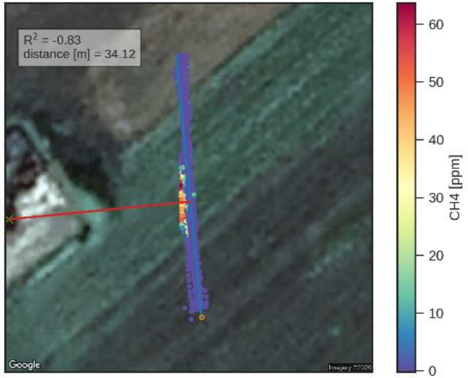
III. Take-off and landing of the drone is removed from the data and the remaining measurement points are projected into a single cross-sectional area



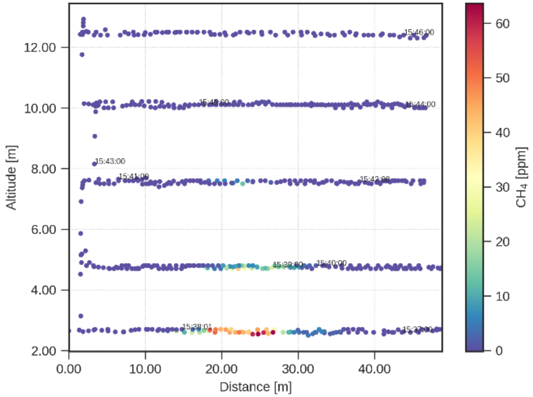
Cross correlation between the longitude of the QCLAS and the GPS-RTK system



Timeseries of CH_4 elevations after removing background values using REBS



Measurement points projected into a single plane. Orange circle at the bottom signifies where the 0.00m distance is located



CH_4 elevations projected in one cross-sectional area.

Quantification of methane emissions

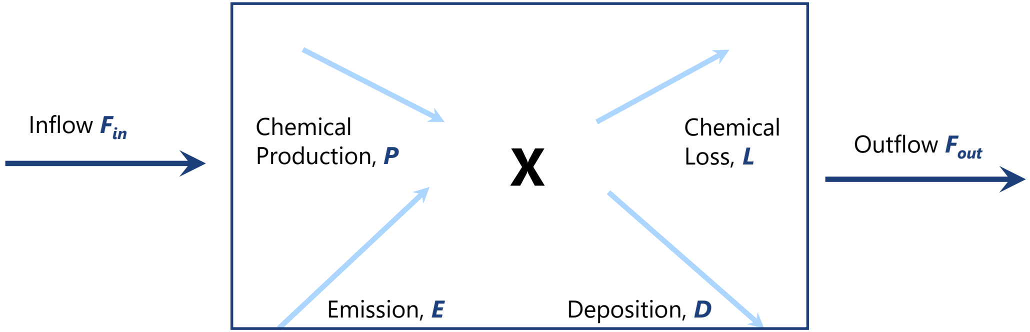
Mass balance method

- An application of the *conservation of mass* in physical systems where everything that goes into the system must also go out.

- Utilizing this principle, the amount of mass flowing in a system can theoretically be estimated.

Atmospheric "box"

spatial distribution of **X** within box is not resolved



$$\frac{dm}{dt} = \sum \text{sources} - \sum \text{sinks} = F_{\text{in}} + E + P - F_{\text{out}} - L - D$$

- Assuming no inflow, no deposition and no chemical production and chemical loss, the mass flowing into the system per unit time is

$$\frac{dm}{dt} = \sum \text{sources} - \sum \text{sinks} = E - F_{\text{out}}$$

- In stationary conditions, $\frac{dm}{dt} = E = F_{out} = 0$

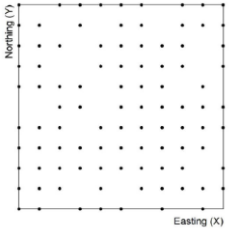
Quantification of methane emissions

Geostatistical Interpolation (Kriging)

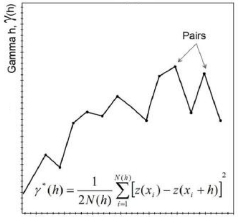
Procedure to analyze the spatial variability of a sparsely sampled surface.

Two major steps involve:

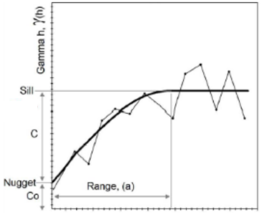
a. Semivariogram analysis
b. Kriging estimation and mapping



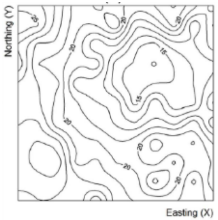
Plot of measurement data



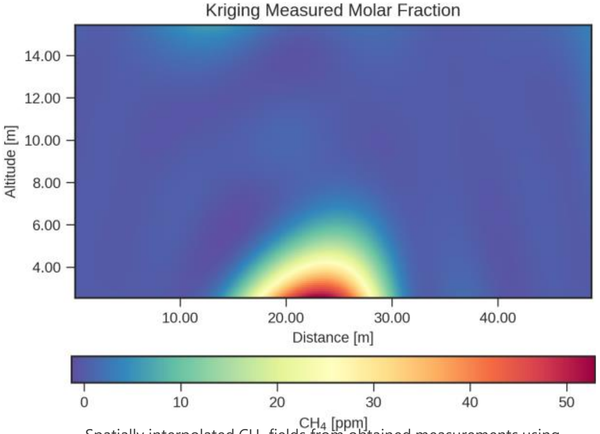
Experimental semivariogram



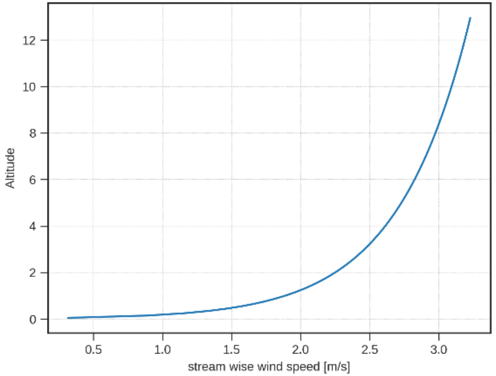
Theoretical semivariogram



Spatially filled kriged values



Spatially interpolated CH_4 fields from obtained measurements using Ordinary Kriging



Generated logarithmic wind profile assuming a neutral stability condition of the atmosphere

- A logarithmic wind profile is generated using the semi-empirical relationship describing the vertical distribution of horizontal wind speeds. The average friction velocity is computed by averaging the meteorology parameters gathered during the duration of the measurement flight

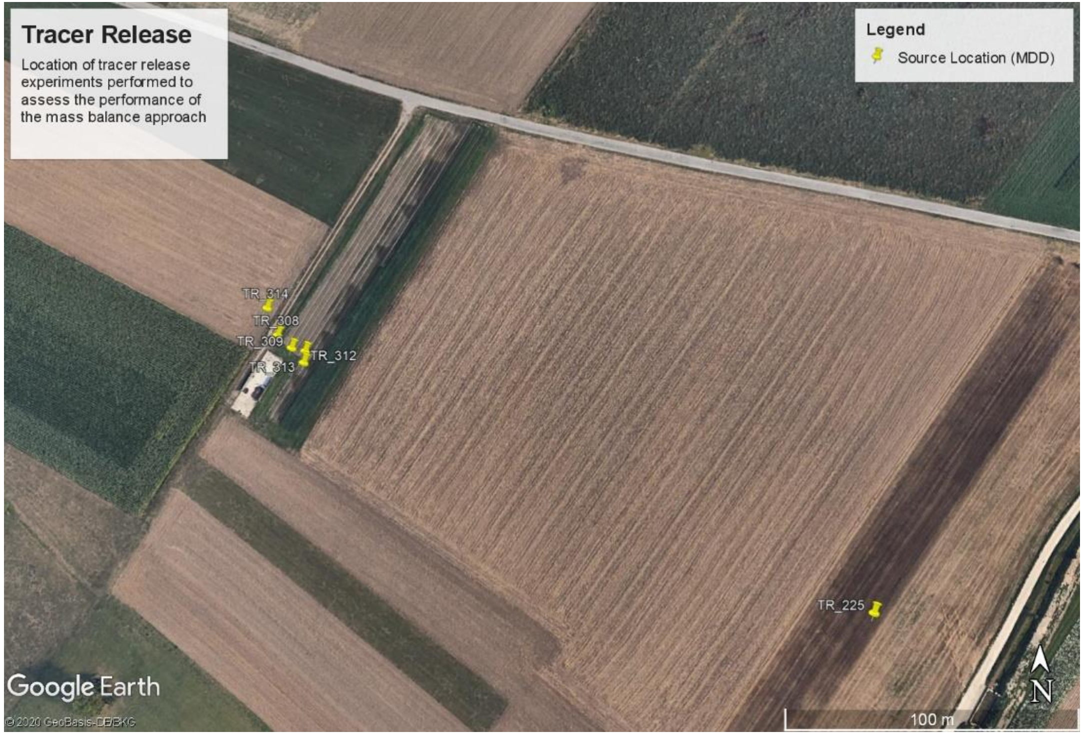
$$\frac{dm}{dt} = Q = \sum C_{i,j} A_{i,j} U_j$$

Q = Emission flux [g/s]
$C_{i,j}$ = Concentration at every grid cell [g/m^3]
$A_{i,j}$ = Area of each grid cell [m^2]
$U_{i,j}$ = wind speed at every vertical level [m/s]

Controlled release experiments in Dübendorf, Switzerland

Several controlled release experiments were conducted in Dübendorf, Switzerland over a span of 9 days. In total, 35 measurement flights were performed in which 19 are suitable for quantification.

Release points were chosen arbitrarily, but was made sure that the vicinity of the source is free from any obstacles. Controlled releases were approximately 1.5m above ground coming from a point source in a form of a natural gas bottle which is 92.2% methane. Moreover, meteorology conditions were measured using 3D and 2.5D anemometers, whenever available, which is placed right next to the point source.



Quantification of methane emissions

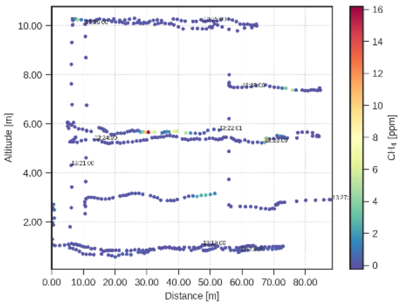
Measurements using different flight patterns

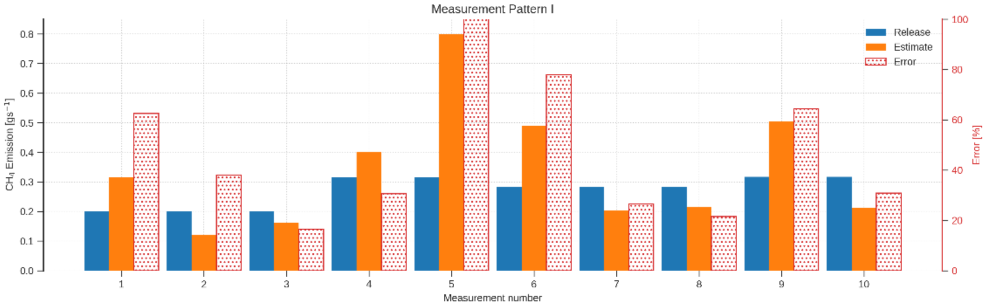
To test whether different flight patterns affect the performance of the quantification technique, two flight patterns were designed during the whole campaign.

Measurement Pattern I

The Drone-QCLAS system samples the specified vertical layer twice. From an initial starting height above ground, the drone samples the CH_4 plume and returns along the same transect before moving on to the next vertical layer.

Chosen vertical layers [m.a.g.l] in consecutive order are:
2.5, 7.5, 12.5, 5.0, 10,

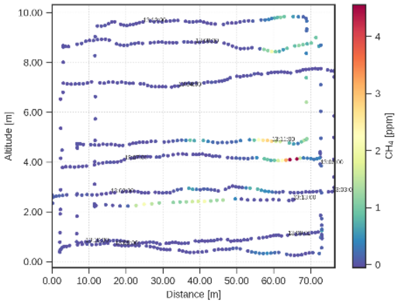


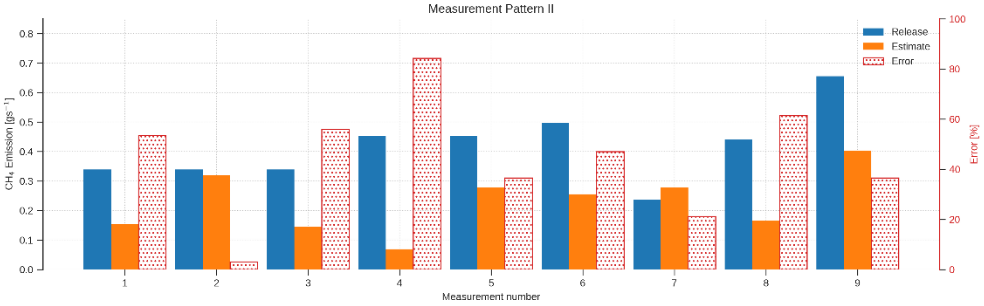


Measurement Pattern II

The system samples the specified vertical layer once. From an initial starting height above ground, the drone samples the CH_4 plume only once in a specific vertical layer and moves on to the next layer right after. This pattern results to a higher sampling density of the cross-section of the plume.

Chosen vertical layers [m.a.g.l] in consecutive order are:
4.0, 9.0, 2.0, 6.0, 11.0, 3.0, 7.0, 12.0 ,5.0





Deviations of estimated emissions from known releases were computed using the simple error formula to be able to compare how each measurement performs

$$\delta = \frac{|v_a - v_e|}{v_e} \cdot 100\%$$

δ_a = Error
v_a = actual value
v_e = estimated value

Quantification of methane emissions

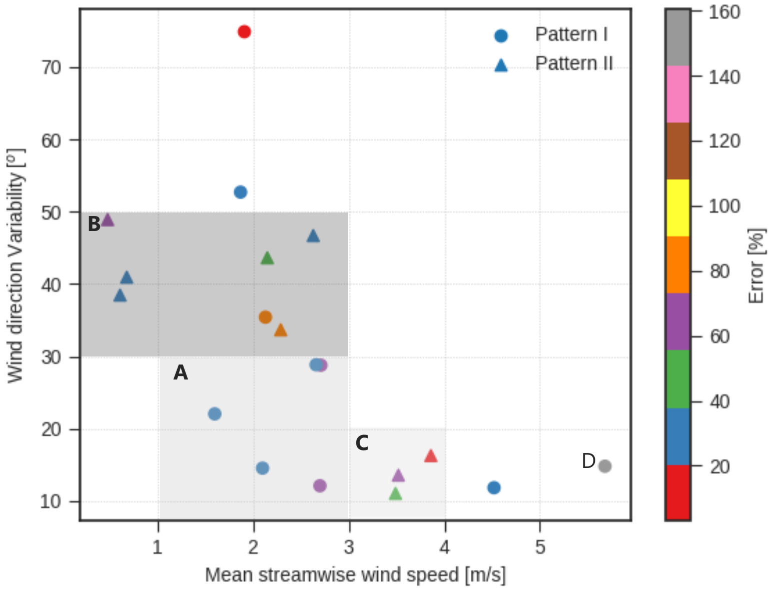
Emission estimate compared with wind direction and wind speed

A) Emission quantification using flight pattern I gives an error estimate of 20-60% from real emissions when mean streamwise wind speeds are between 1-3 m/s and wind variability ranges from 0-30 degrees

B) The same error range (20 to 60%) was observed at mean streamwise windspeeds of 0-3 m/s and wind direction variability of 30-50 degrees when emissions were quantified using flight pattern II

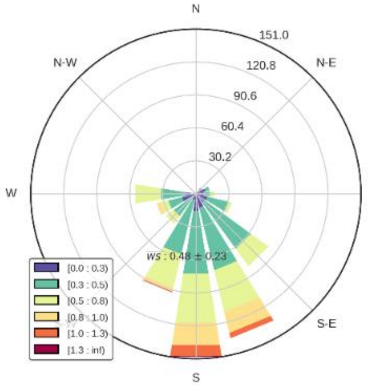
C) Best emission estimates were obtained using flight pattern II at higher wind speeds of 3-4 m/s and lower wind direction variability ranging from 0-20 degrees

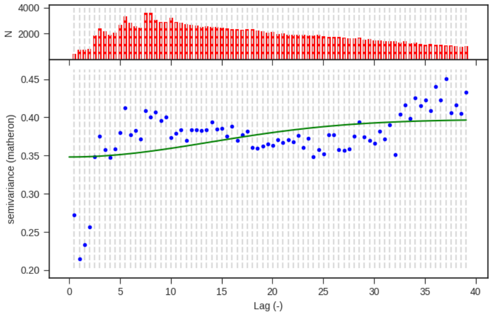
D) The unusually high 160% error obtained at wind speed of around 6 m/s can be attributed to the magnification of CH_4 elevations at higher altitudes as generated wind speed profile increases in magnitude logarithmically with altitude.



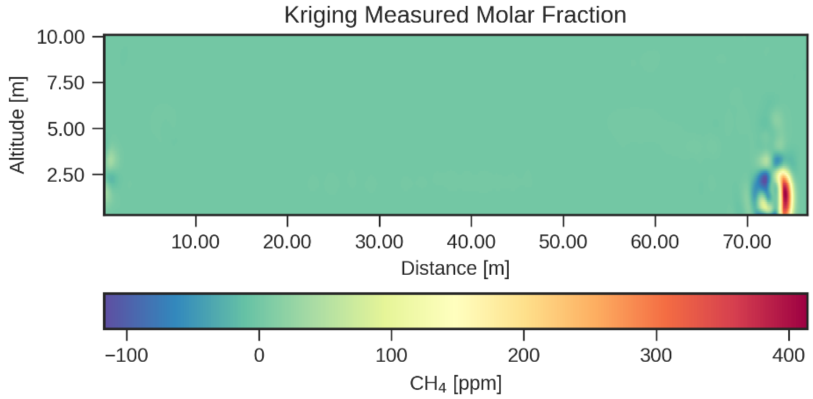
Issues with stationary ordinary Kriging

Ordinary kriging assumes stationary spatial distribution of a variable in a geophysical field surface. Since plume position and its intensity vary together with wind speed and direction. An application of a single wind profile may lead to an overestimation or underestimation to the quantification depending on whether winds speeds are higher or lower than average.





Ordinary kriging highly depends on a stationary spatial semivariogram model to interpolate data in a surface field. Since atmospheric trace gases are not stationary, correlation lengths , used in generating semivariograms, between two measurement points of the same spatial distance are not the same which causes the Kriging estimation to fail.



Summary

- Controlled release experiments were performed to characterize the performance of a drone-based mass balance approach in quantifying methane emissions.
- A flight pattern which samples each vertical level once- mapping the vertical profile as dense as possible- results to better quantification estimates.
- Steady wind speeds of 3-5 m/s with low variability (0-20 degrees) results to estimates close to real emissions
- Applying a single wind profile in the quantification technique may lead to overestimation or underestimation of point sources if winds are not in right conditions
- Ordinary Kriging assumes spatial stationarity among all measurement points which largely affects how the geophysical field is being interpolated.

Outlook

- A spatiotemporal moving window Kriging is currently being explored to account for the temporal variability of CH_4 elevations due to changing wind conditions.

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Acknowledgements

This work was supported by the ITN project Methane goes Mobile – Measurements and Modelling (MEMO2; https://h2020-memo2.eu/).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 722479.