Development of a small unmanned aircraft system to derive CO_2 emissions of anthropogenic point sources

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Atmospheric Measurement Techniques

Introduction and outline

Introduction

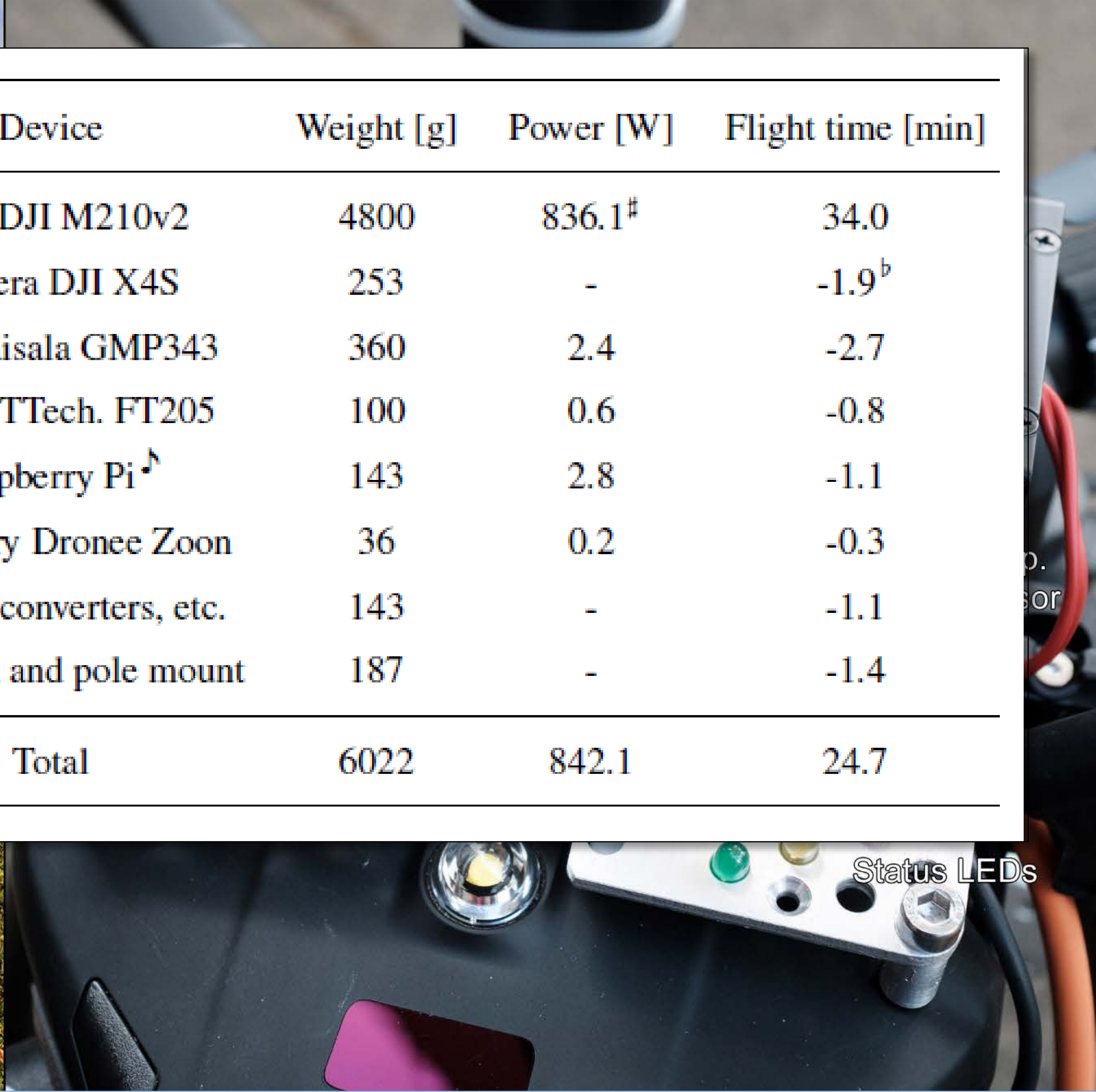
- CO_2 emissions are the primary cause of man-made climate change.
- Large parts of the human CO_2 emissions come from point sources such as power plants.
- On a global level, a monitoring by means of satellites is envisaged (e.g., CO2M).
- Regionally, this is going to be complemented and validated with airborne measurements.
- UAV (unmanned aerial vehicle) based measurements can provide a cost-effective way to contribute to these activities.
- **For this purpose, a sUAS (small unmanned aircraft system) has been developed to quantify the CO_2 emissions of a nearby point source from its downwind mass flux without the need for any ancillary data.**

Outline

- Hardware setup and instrumentation
- CO_2 sensor characterization
- Anemometer calibration
- In-fight validation using ICOS measurements
- Demonstration flights downwind of an industrial facility

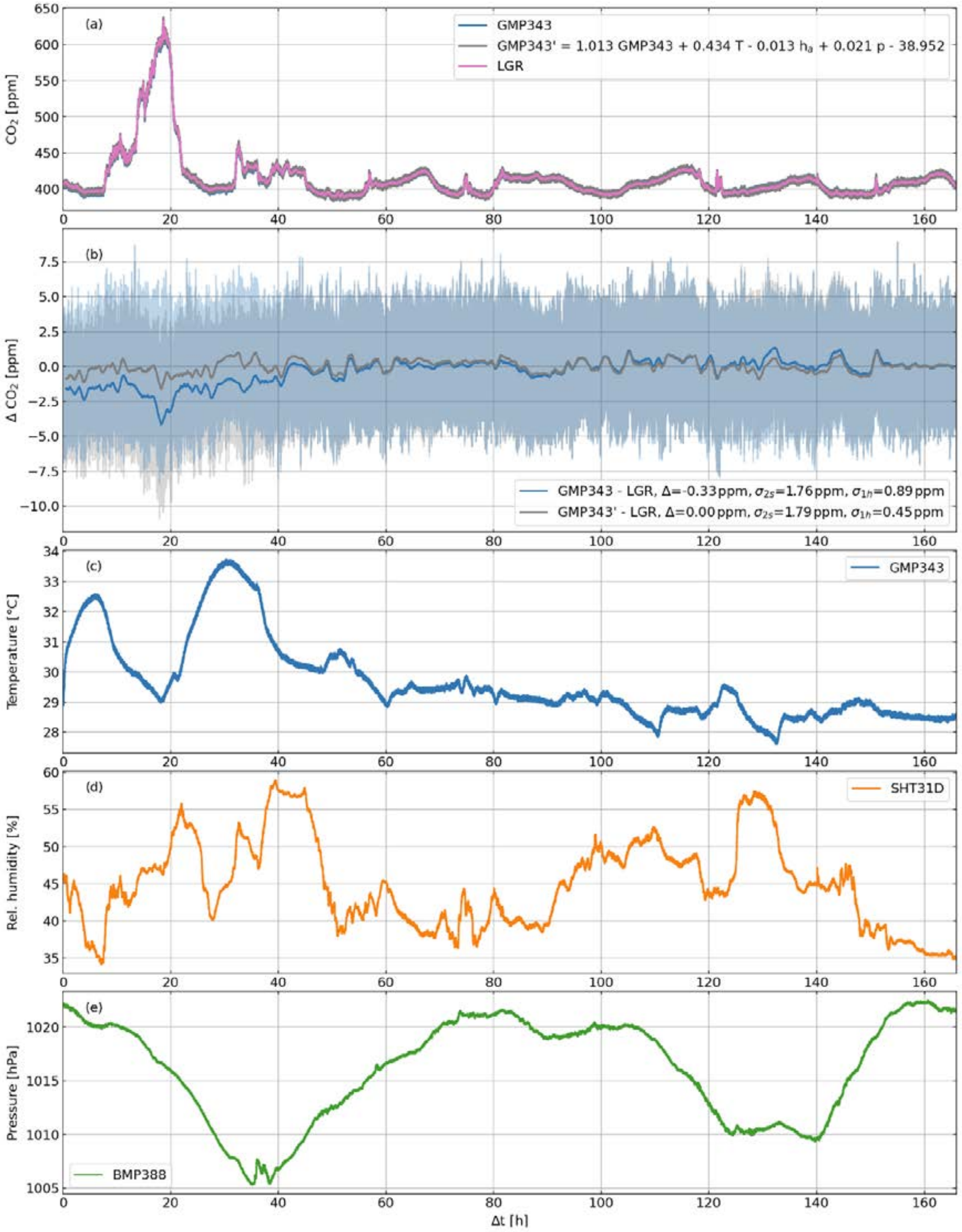
UAV and instrumentation

Device	Weight [g]	Power [W]	Flight time [min]
UAV DJI M210v2	4800	836.1♯	34.0
Camera DJI X4S	253	-	-1.9♭
CO_2 Vaisala GMP343	360	2.4	-2.7
Wind FTTech. FT205	100	0.6	-0.8
Raspberry Pi ♪	143	2.8	-1.1
Telemetry Dronee Zoon	36	0.2	-0.3
Wiring, converters, etc.	143	-	-1.1
Plattform and pole mount	187	-	-1.4
Total	6022	842.1	24.7



- Usage of off the shelf components. UAV: DJI Matrice 210v2. CO2: Vaisala GMP343. Wind: FT Technologies FT205. Pressure: Bosch BMP388. Temperature and humidity: Sensirion SHT31-DIS.
- Total weight: 4.8kg UAV + 1.2kg Payload (including camera)
- Maximum flight time: 24.7min.

Characterization of the CO2 Instrument



- We compared measurements of the Vaisala GMP343 CO2 sensor with those of a highly accurate (±0.3ppm) ABB LGR-ICOS ultra-portable greenhouse gas analyzers
- The comparison period was about one week
- Ambient pressure, temperature, and humidity varied larger than expected for the measurement flights
- The single sounding precision is about 1.8ppm (1σ)
- Drifts are in the order of 0.9ppm (1σ)
- A linear correction using temperature, pressure, absolute humidity, and the measured CO2 concentration can reduce drifts to 0.4ppm
- The linear correction mainly corrects for an underestimation of the CO2 variability of 1.3%

Calibration of the anemometer

- Mounting the anemometer aboard an UAV makes a **calibration necessary**
- Straight foreword approach: wind tunnel
  - Hovering in place not easy
  - Large wind tunnel not easily available
- **Our approach: use head wind for calibration**

Calibration of the anemometer

Without ambient wind (w=0)

Calibration function: u’ = A m’

u’ = calibrated measurement
m’ = raw anemometer measurement
A = calibration coefficient

-v

v

Calibration

u’ = -v = A m’

A = -v/m

Calibration of the anemometer

With ambient wind ($w \neq 0$)

Calibration function: $u' = A\ m'$

u' = calibrated measurement
m' = raw anemometer measurement
A = calibration coefficient

-v **w**

v **w**

Calibration

$w - v = A\ m'$

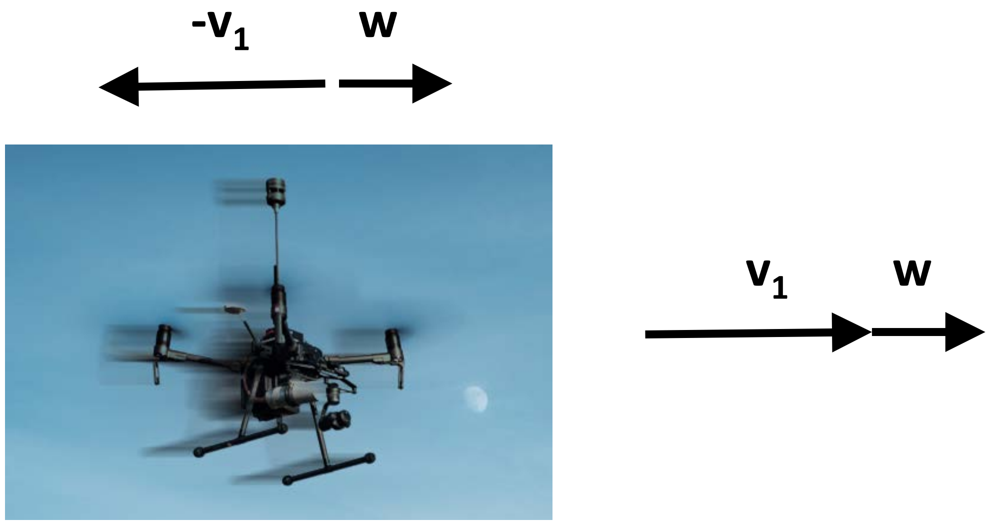
UNDERDETERMINED

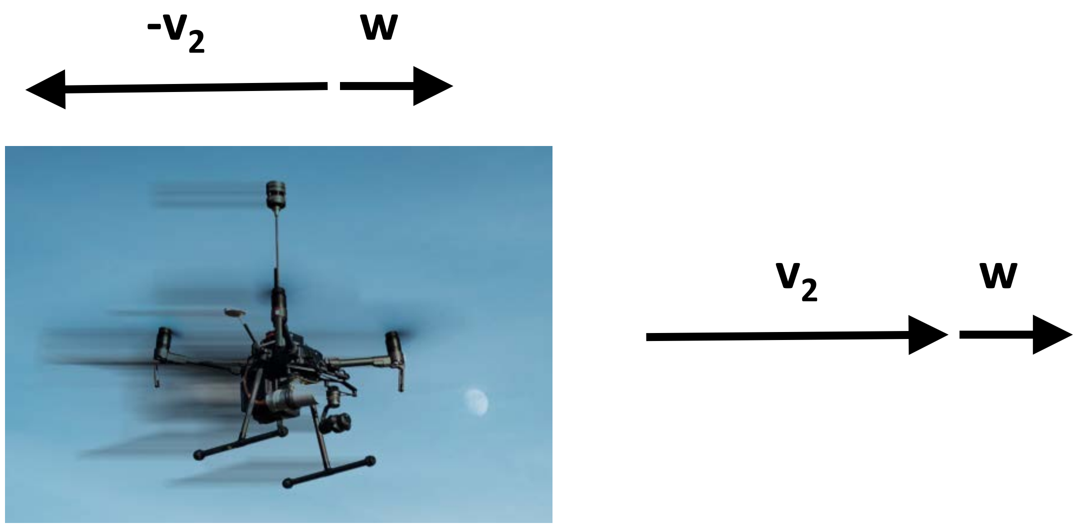
With ambient wind ($w \neq 0$)

Calibration function: $u' = A\,m'$

u' = calibrated measurement
m' = raw anemometer measurement
A = calibration coefficient

Calibration of the anemometer





Calibration

$$w - v_1 = A\,m_1'$$

$$w - v_2 = A\,m_2'$$

$$\mathbf{A = (v_2 - v_1)/(m_1' - m_2')}$$

Calibration of the anemometer

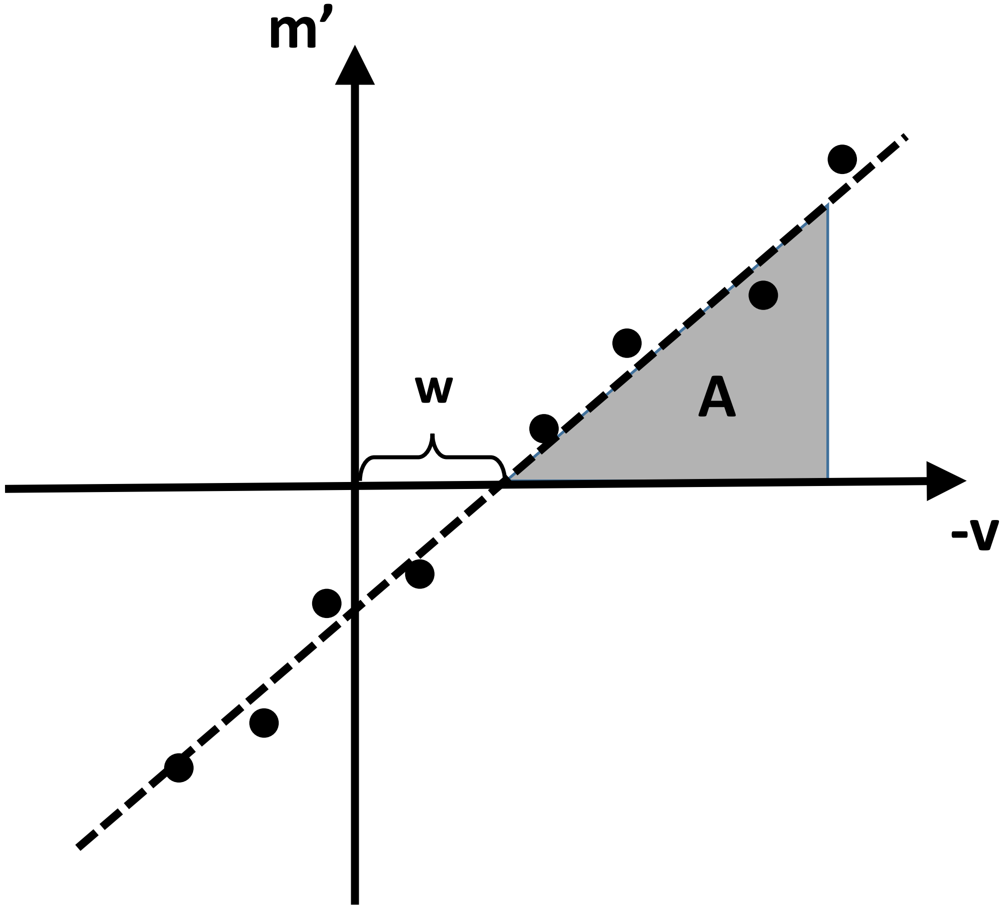
With ambient wind (w≠0)

Calibration function: u’ = A m’

u’ = calibrated measurement
m’ = raw anemometer measurement
A = calibration coefficient

Various velocities, forward+backward

Calibration



Calibration of the anemometer

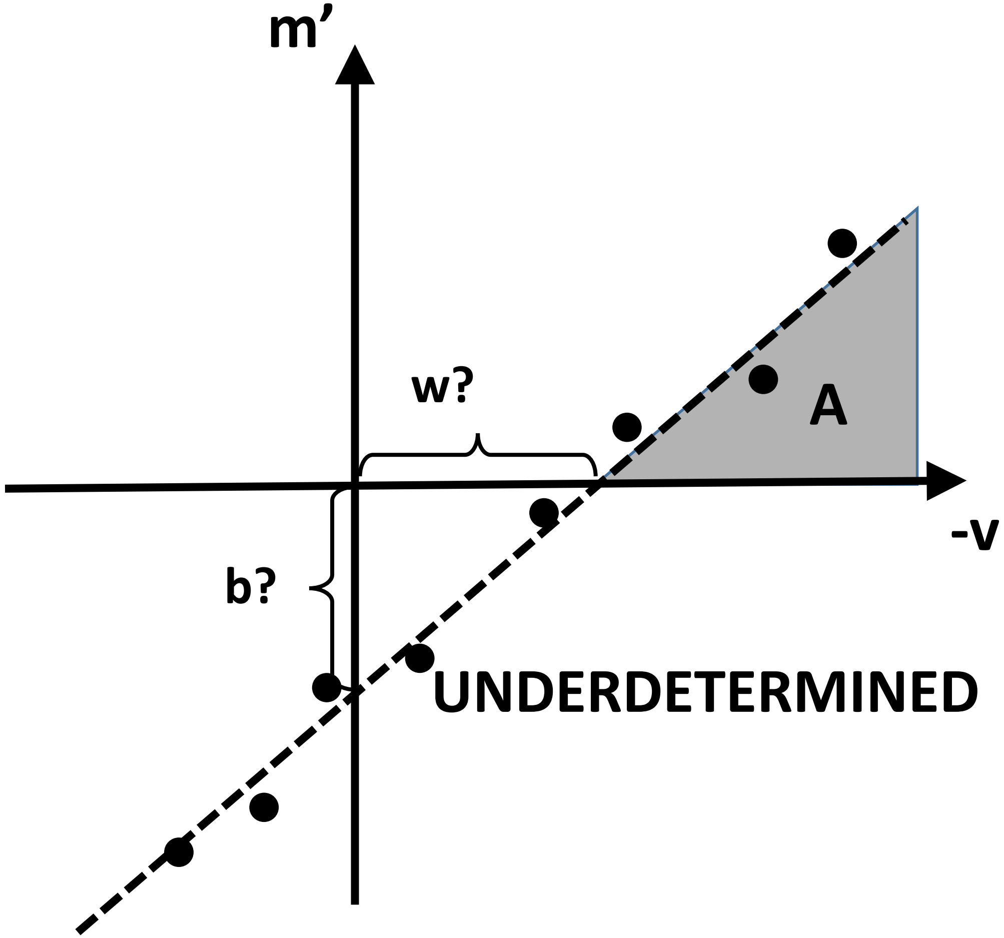
With ambient wind (w≠0)

Calibration function: u’ = A m’ + b

u’ = calibrated measurement
m’ = raw anemometer measurement
A = calibration coefficient
b = constant bias

Various velocities, forward+backward

Calibration



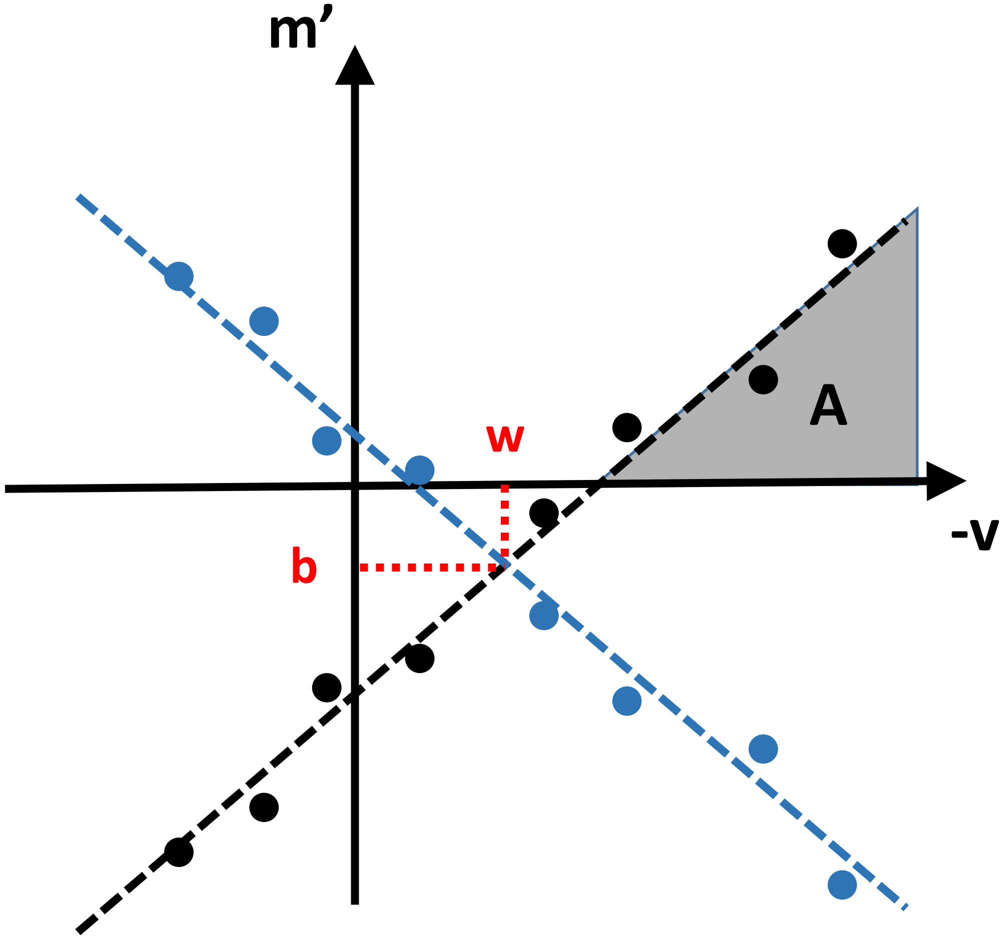
Calibration of the anemometer

With ambient wind (w≠0)

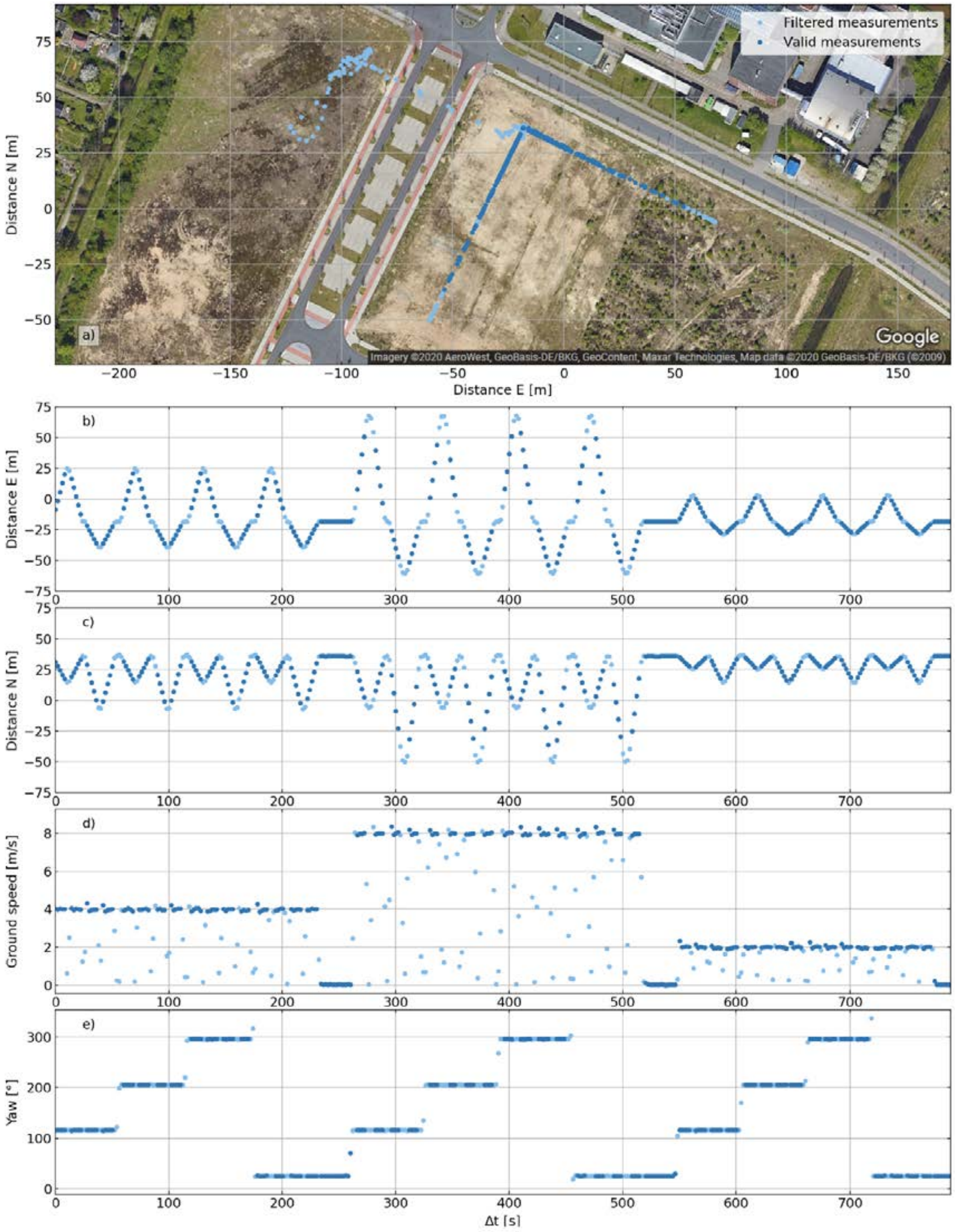
Calibration function: u’ = A m’ + b

u’ = calibrated measurement
m’ = raw anemometer measurement
A = calibration coefficient
b = constant bias

Various velocities, forward+backward, different orientation

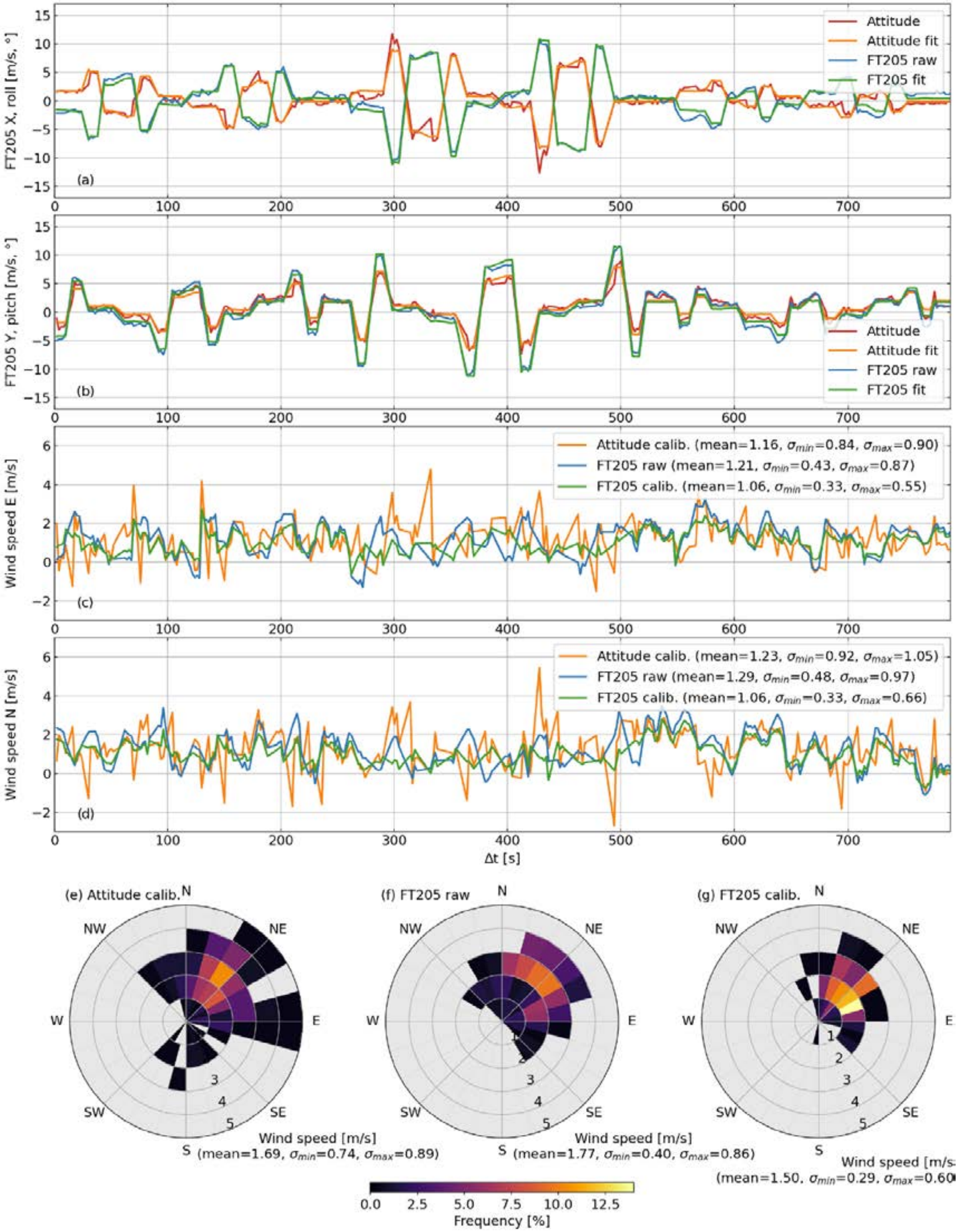


Calibration of the anemometer: Flight pattern



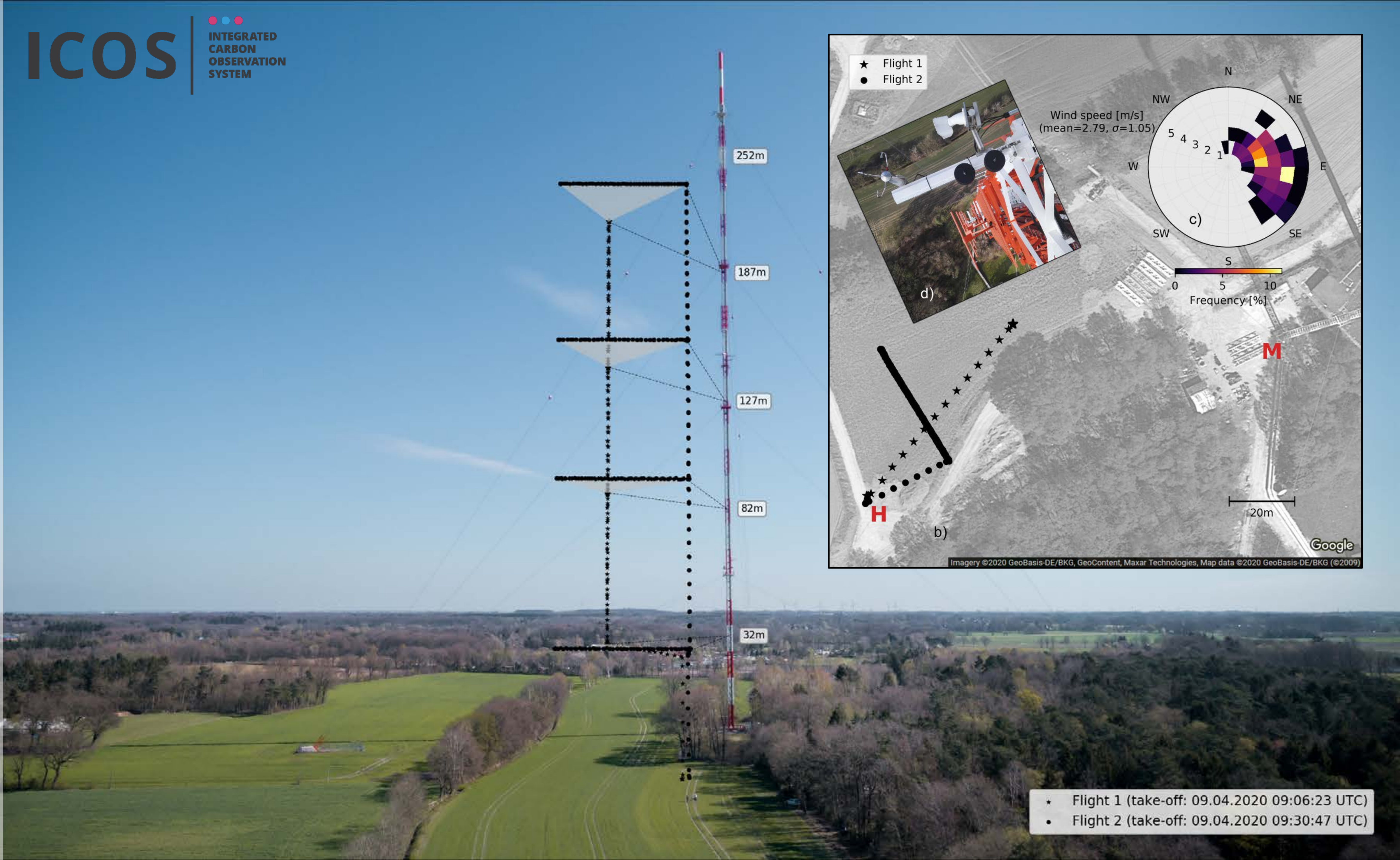
- In **2D**, the calibration function becomes a **vector function**:
  u' = **A** m' + b
  (m' = raw anemometer measurement in UAV coordinates, A = calibration matrix accounting for scaling and rotation, b = offset)
- Solving for m':
  m' = **A**$^{-1}$ [u' - b]
- Substitute u':
  m' = **A**$^{-1}$ [**R** u - b]
  (R = rotation matrix, u = wind at UAV in geo.c.)
- Substitute u:
  m' = **A**$^{-1}$ [**R** (w - v) - b]
  (w = wind, v = velocity of UAV)
- Find coefficients of **A**, b, and w by least squares fitting and assuming stationary winds
- This requires a flight pattern with two ideally perpendicular paths and varying ground speeds, backward/forward motions, and orientations of the UAV.

Calibration of the anemometer: Results

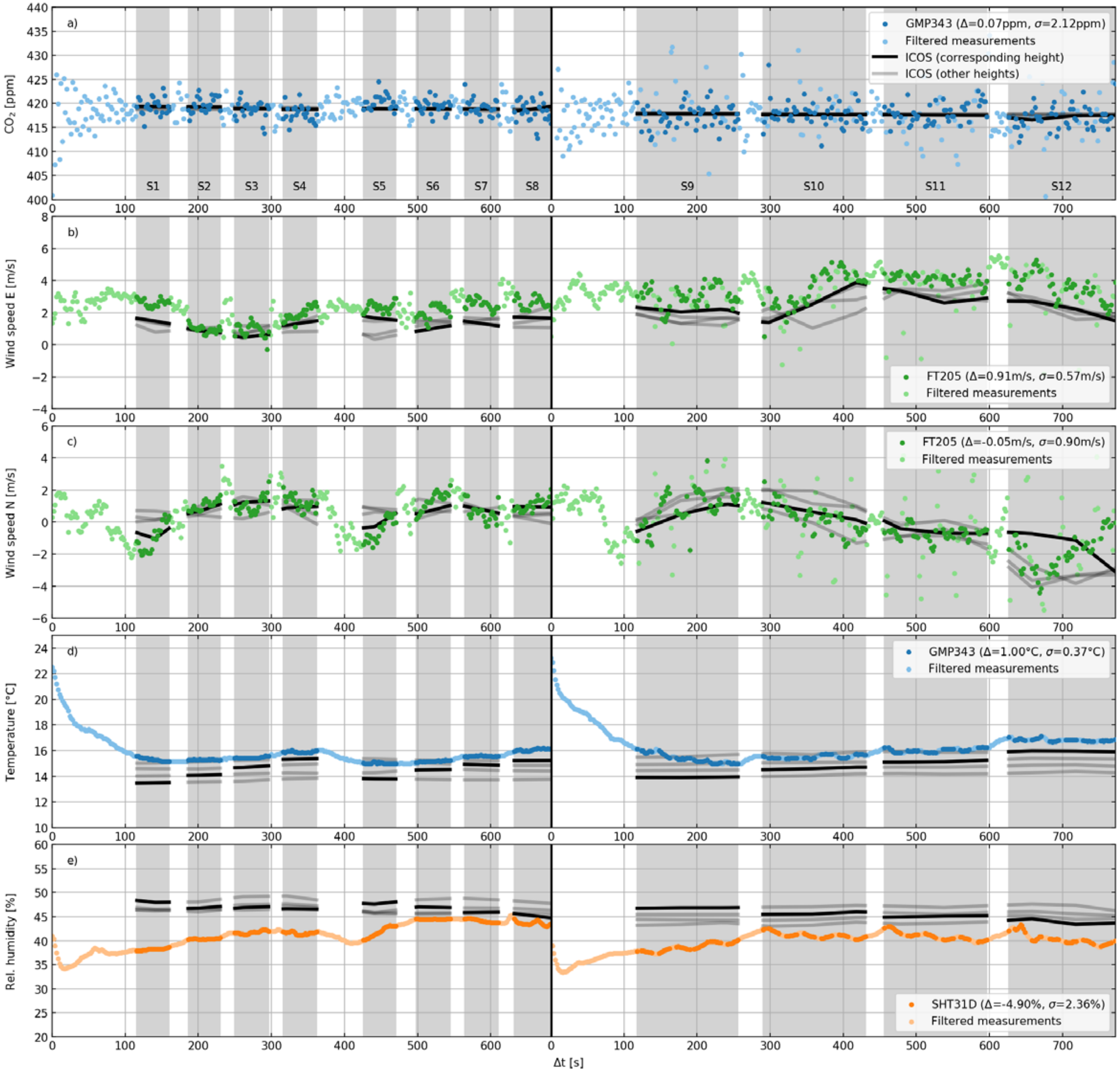


- $A = \begin{pmatrix} 0.88 & 0.02 \\ -0.02 & 0.83 \end{pmatrix}, \mathrm{b} = \begin{pmatrix} 0.07 \\ -0.06 \end{pmatrix} m/s, w = \begin{pmatrix} 1.06 \\ 1.06 \end{pmatrix} m/s$
- Correction of an overestimation by 10-20%.
- Basically no rotation.
- Little constant offset below 0.1m/s.
- Average wind speed of 1.5m/s during the calibration flight.
- After calibration, the expected wind at the sensor agrees well with the measured wind.
- The calibrated wind relative to ground scatters less around the average compared to the un-calibrated wind.
- The calibration narrows the wind histogram.
- After calibration, we expect the precision of the wind speed relative to ground to be in the range of 0.3-0.6m/s.
- In principle, UAV attitude can also be used for wind measurement, but with larger noise (0.7-0.9m/s) despite stricter filter requirements.

Validation with ICOS in Steinkimmen: **Overview**

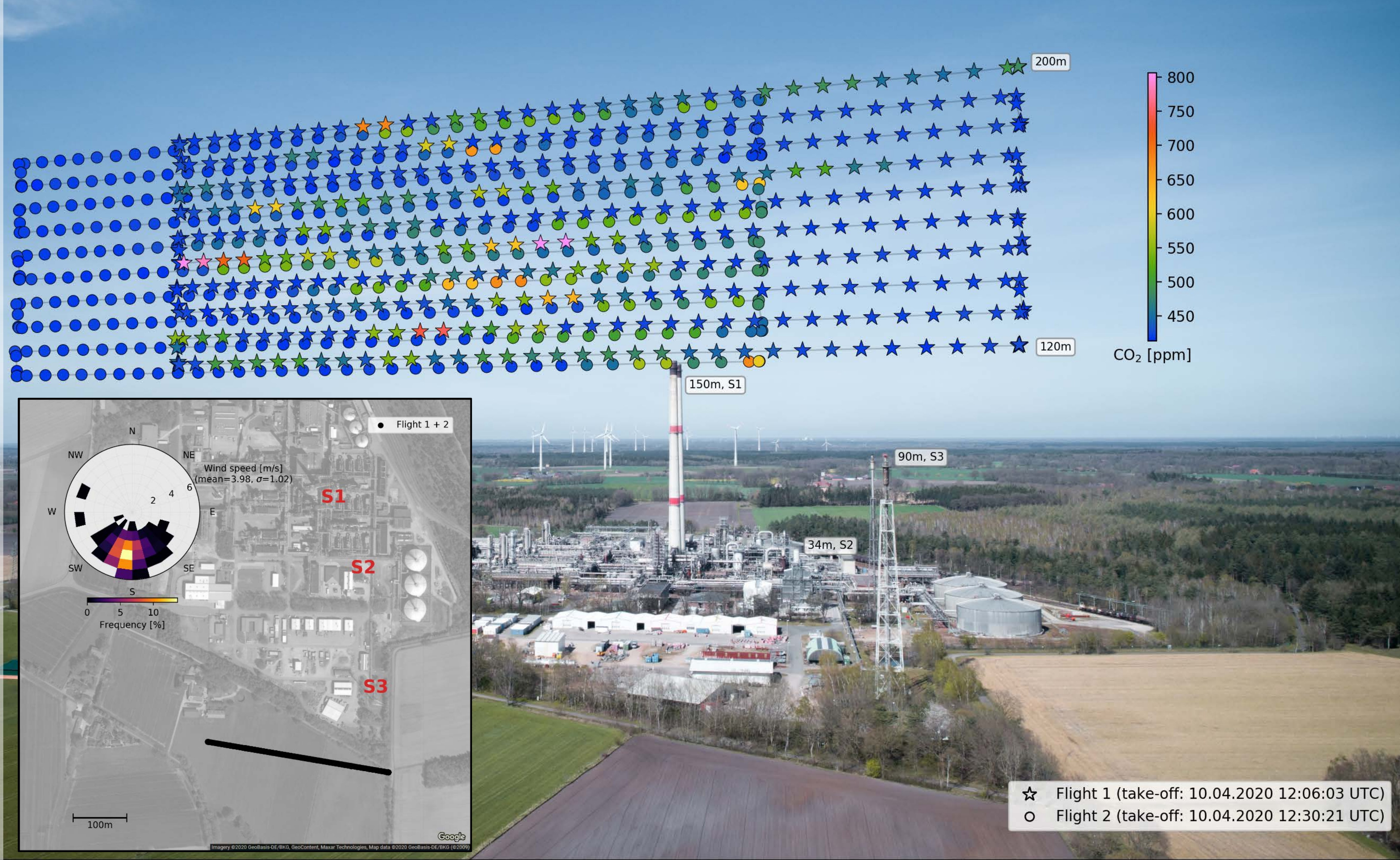


Validation with ICOS in Steinkimmen: **Results**

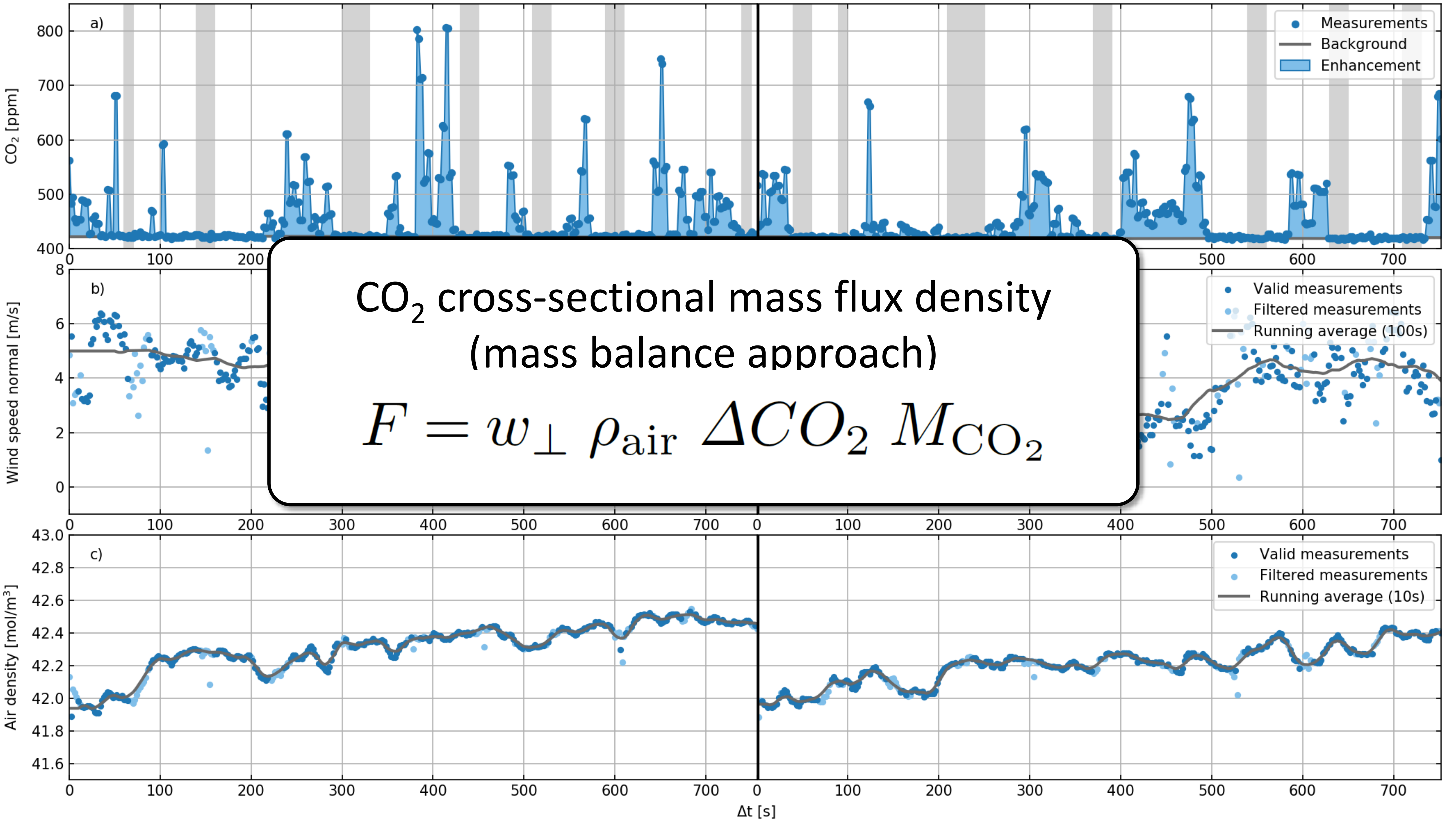


- CO_2: Bias 0.1ppm, scatter 2.1ppm, no flight-to-flight differences, somewhat larger scatter when UAV moves
- Wind north component: Bias 0.10m/s, scatter 0.90m/s (0.67m/s without last sequence at 32m)
- Wind east component: Bias 0.91m/s, scatter 0.57m/s. Bias likely due to ICOS (wind blockage). UAV operated with different orientations but bias of east component persisted. ICOS instrument mounted in wind direction.

ExxonMobil Natural gas processing facility in Großenkneten: Overview



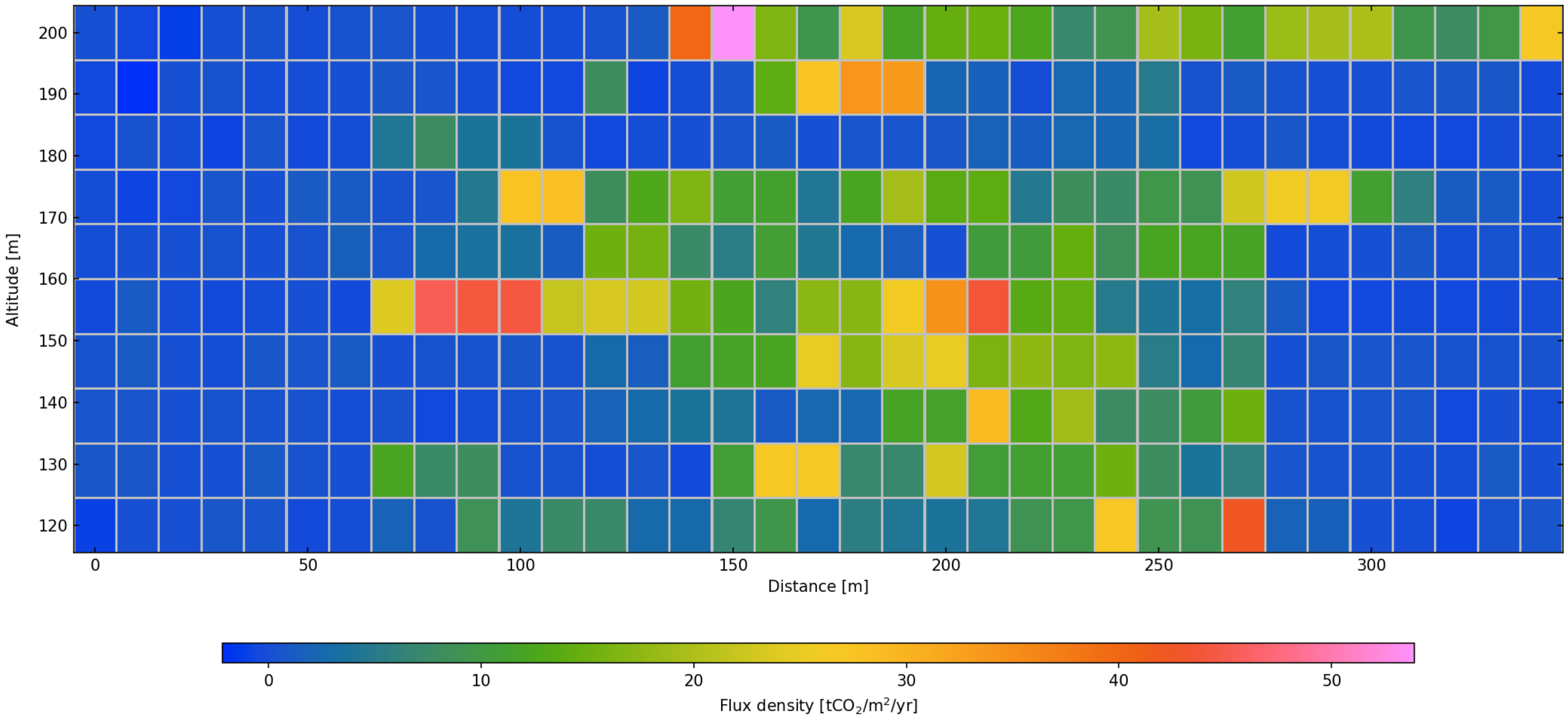
ExxonMobil Natural gas processing facility in Großenkneten: **Measurements**



CO_2 cross-sectional mass flux density
(mass balance approach)

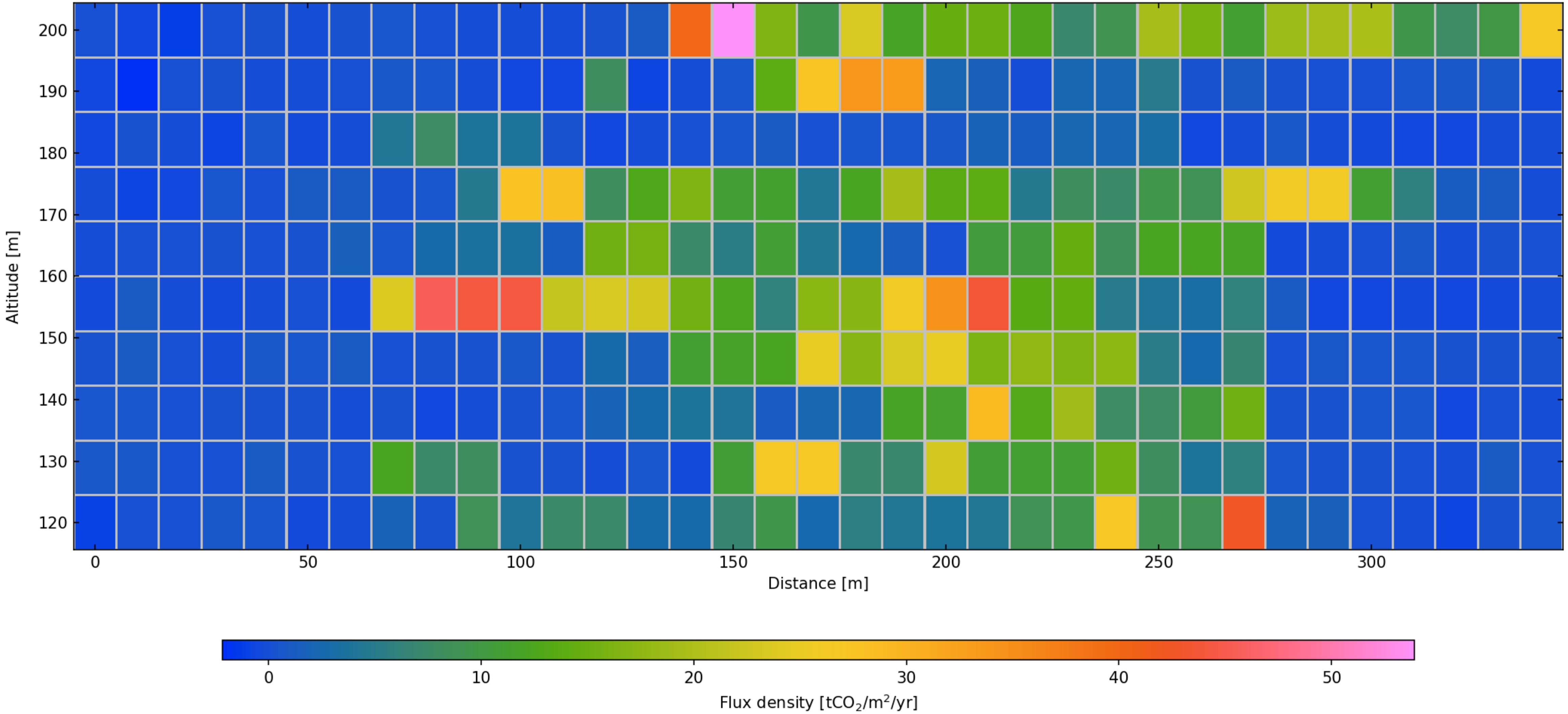
$$F = w_{\perp}\ \rho_{\mathrm{air}}\ \Delta CO_2\ M_{\mathrm{CO_2}}$$

ExxonMobil Natural gas processing facility in Großenkneten: **Cross-sectional flux**



- Good horizontal position of the flight pattern.
- Very scattered plume. The Gaussian plume approximation applies only on average.
- Integral of flux density results in a total flux of 196±17 ktCO2/year.
- Reported annual flux is about 3-4 times larger.
- Discrepancy likely due to plume above the flight pattern which ends at 200m because of flight regulations.

ExxonMobil Natural gas processing facility in Großenkneten: **Uncertainties**



- **Total flux uncertainty** (only considering instrumental effects)**: 8.7%** (systematic uncertainties: 8.3% wind, 1.3% CO_2, 3.5‰ temperature; stochastic uncertainties 1.3%)
- **Turbulence** and under sampling of the plume can introduce **larger uncertainties**
- Such uncertainties can average out with increasing number of flights or increasing flight time

Summary and Conclusions

- **A sUAS has been developed** which is capable to determine atmospheric CO2 mass fluxes from its own sensor data independently from external data sources.
- The CO2 sensor has been characterized by comparisons with a lab instrument.
- The wind measurements have been calibrated using the head-wind.
- The calibration and validation measurements show that **all sensors perform well** also under flight conditions.
- Two demonstration flights suggest that the **plume cross-sectional flux can be determined with an error below 10%** (considering only instrumental effect).
- The wind measurement dominates this error budget.