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AERIAL MONITORING OF POLLUTION AND ODOUR

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Outline

- Drone-based environmental chemical sensing
  - Introduction
  - Chemical instrumentation
  - Integration strategies
  - Tasks developed
  - Current limitations and future perspectives

- Chemical and Odour monitoring in industrial plants
  - The SNIFFIRDRONE project
  - Drone prototype
  - Custom multisensor system
  - Measuring campaigns
  - Odour prediction model
  - Static vs. dynamic calibration
  - Odour map
  - Conclusions

Small drones

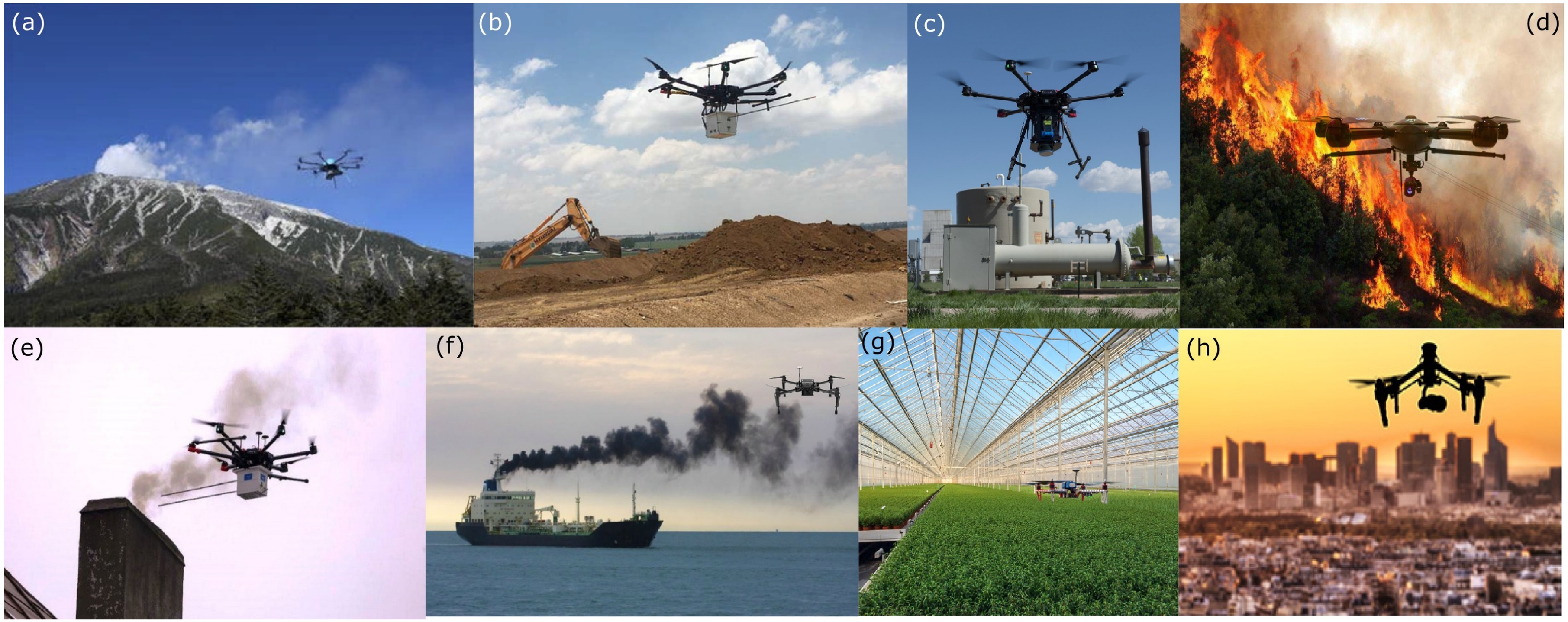
- Definition
  - *Remotely piloted aircraft system (**RPAS**) or unmanned aircraft system (**UAS**) with a maximum take-off weight (MTOW) of **<25 kg***
- Also known as …
  - Microdrones or small UAS
- Two Types

(1) Fixed wings

(2) Rotary wings

Wide range of applications

a) Volcanic research
b) Landfill emission monitoring
c) Chemical monitoring in industrial sites
d) Early fire detection
e) Residential emissions monitoring
f) Ship emission monitoring
g) Precision agriculture
h) Urban air quality



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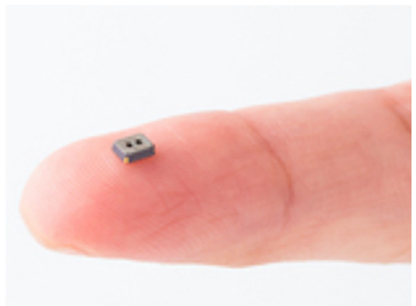
Chemical instrumentation

- Instrumentation constraints
  - Light weigh
  - Low power consumption
- Several sensing element types are commonly used
  - Low cost chemical sensors
    - Electrochemical, Metal Oxide, NDIR, PID
  - High precision optical analysers
  - Optical gas imaging
- Chemical instruments
  - Multi-sensor system
  - Electronic nose

Low cost chemical sensors

- **Electrochemical sensors**
  - Electrochemical reaction within an electrochemical cell
  - Selectivity controlled by the catalyst
  - O_2, CO, SO_2, NO,NO_2, O_3, NH_3, and H_2S
  - PPMs and PPBs concentrations
  - Consumption < **1mW**
  - Response / recovery times
    - **30 - 60 s**

- **Metal Oxide (MOX) sensors**
  - Chemoresistive sensors
  - Few mm^2 footprint
  - Response time 5-10s
  - Consumption 15-30 mW
  - Broad selective, but tunable sensitivity



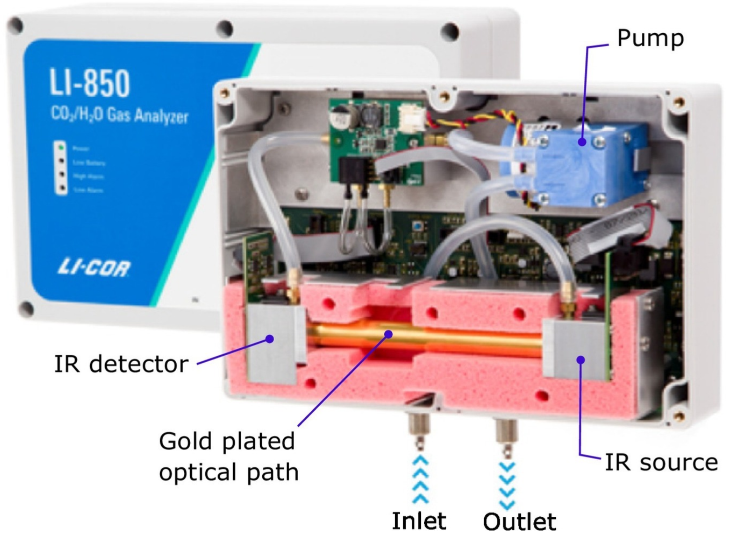
Low cost chemical sensors

- **Non-dispersive Infrared (NDIR)**
  - Miniaturized Optical analyzers
  - Based on optical absorption on IR band
  - Cross-sensitivity to temperature and humidity limits accuracy
  - As a physical sensor, it avoids poisoning and inter-device variability
  - Power consumption 50mW
  - Well suited for CO_2

- **Photo ionization detectors (PIDs)**
  - Broad band sensors
  - Based on UV light ionization of gases
  - Wide range of VOC and some inorganic gases
  - From 10 ppb to 10,000 ppm
  - Very low response time of even a few ms
  - Cannot detect componds with high ionization energy (CO, CO_2, SO_2)

High precision optical analyzers

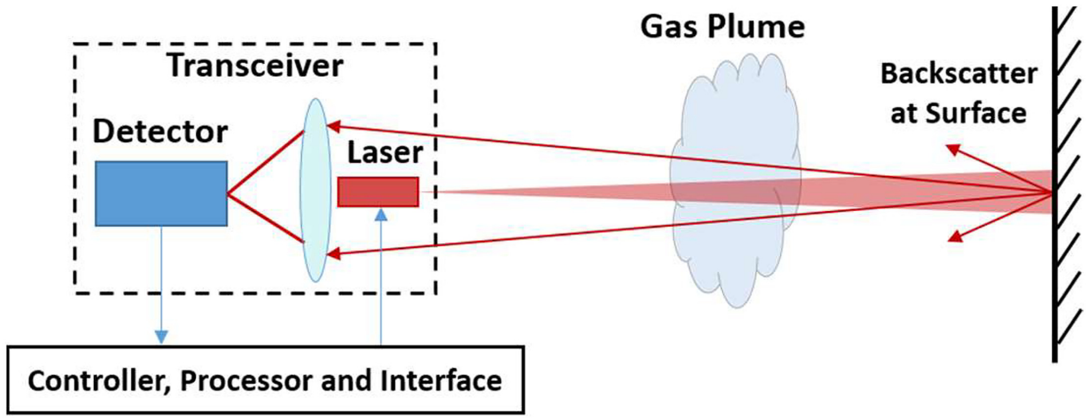
- Optical analyzers based on IR or UV absorption
- Composed of
  - IR source
  - Optical path
  - IR detector
  - Fluidic system
- Detects
  - CO_2 and CH_4 in mid-IR
  - O_3 in the near-UV
- Faster than chemical reactions based sensors
- Weights 1,3 Kg
- Power consumption 5 W



Closed-path LI-850 NDIR CO_2 analyzer

High precision optical analyzers

- **Laser absorption spectroscopy (LAS)**
  - Most common technique tunable diode LAS (TDLAS)
- Two types according to optical path
  - Closed path
    - More accurate but slower
    - Closed path Tunable Diode Laser (CP-TDL)
    - Off-axis integrated cavity output spectroscopy (OA-ICOS)
  - Open path
    - Open path Tunable Diode Laser (CP-TDL)



Optical gas imaging (OGI)

- Thermal contrast between backgroung and gas
- Based on an IR or thermal camera with optical filter
- Shortcommings
  - High cost
  - Difficult to quntify leak rate
  - High detection limit - 10,000 ppm

Multi-sensor systems

- Need to monitor more than one gas in environmental applications
  - Include sensors to target different gases
  - Even different sensor technologies

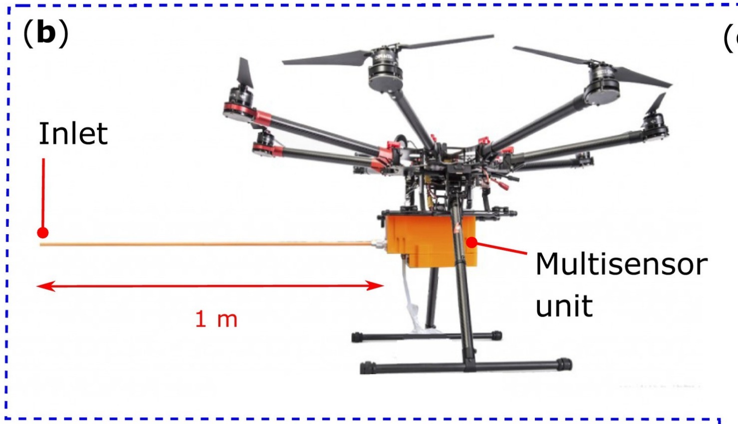
- Also ususally integrates…
  - Necessary electronics
  - Data logging
  - Sensor chamber
  - Fluidic delivery system
  - Communications
    - GPS, radio link

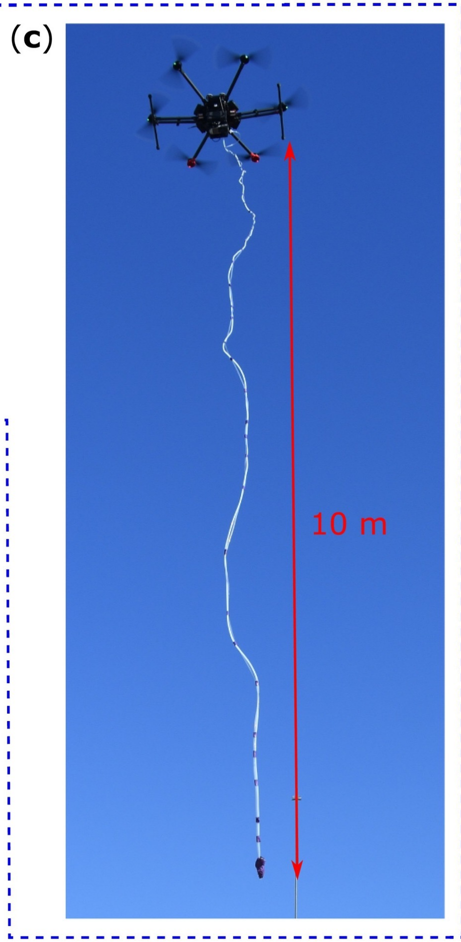
Sniffer 4D equipped with 5 Electrochemical sensors, 1 PID and 1 NDIR sensor.

Integration strategies (1/3)

Protruding boom

Pumped systems with horizontal/vertical inlet

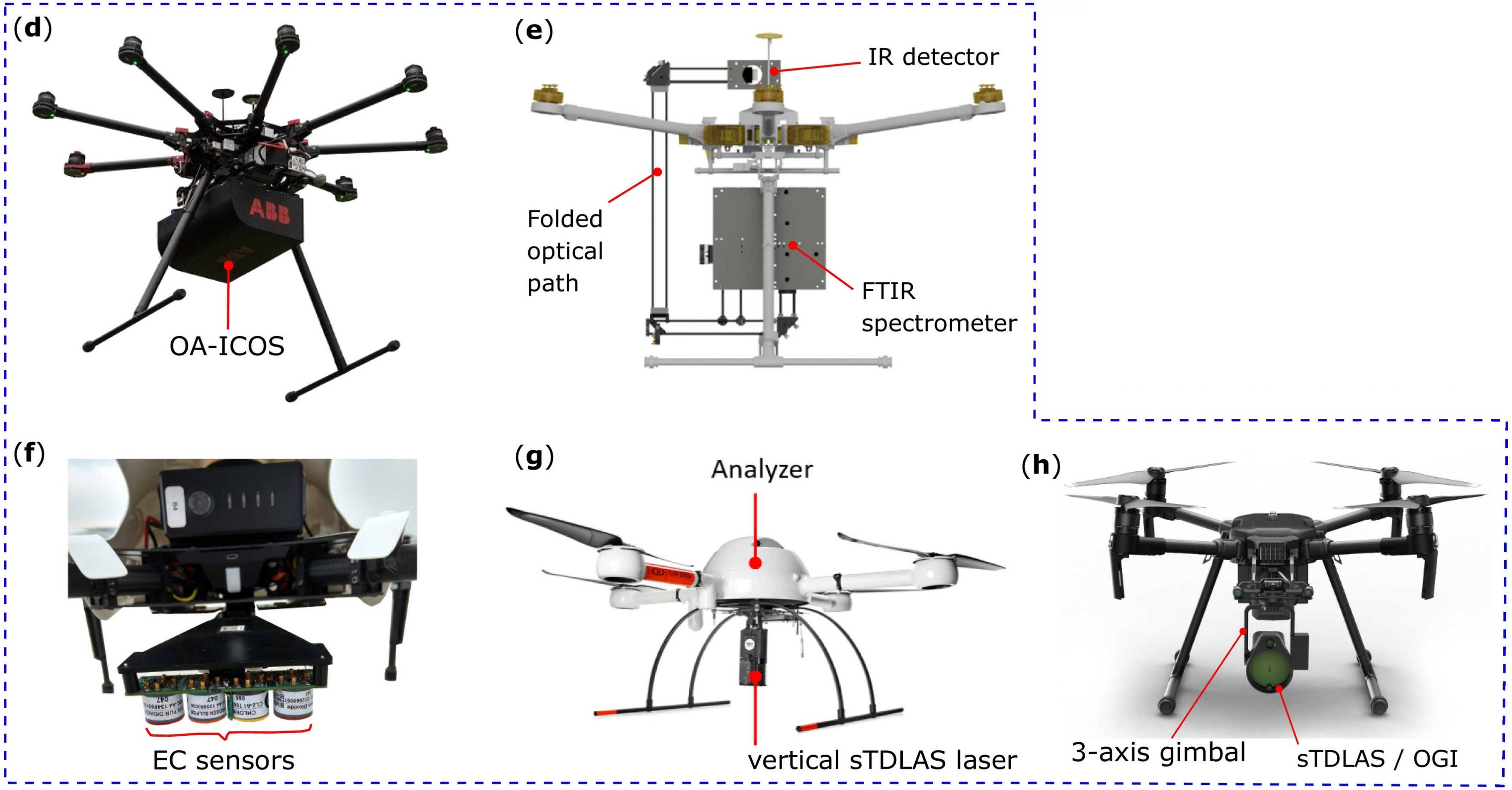




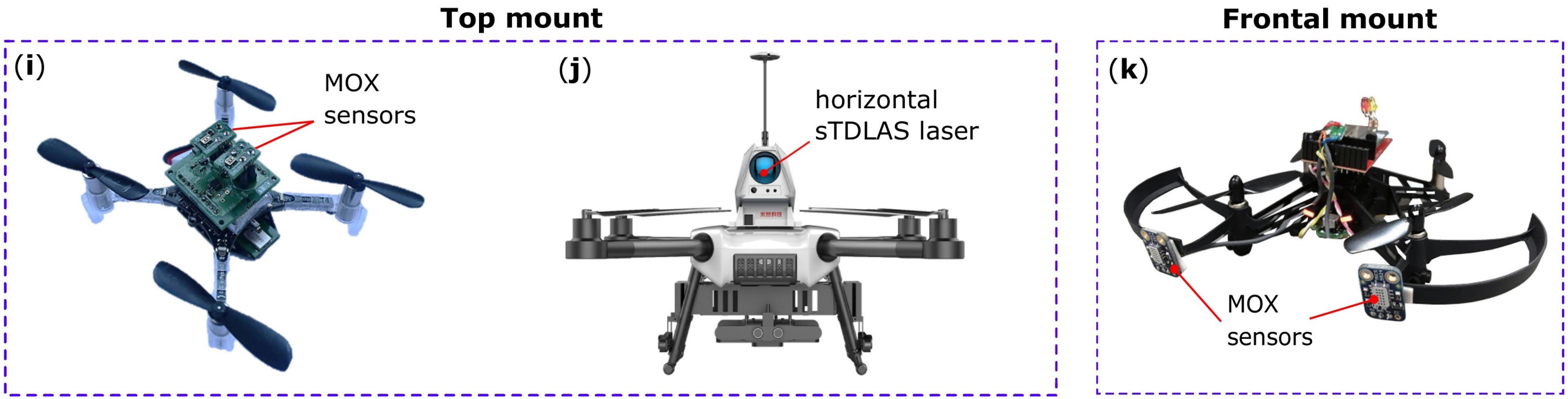
Downwash

Integration strategies (2/3)

Bottom mount



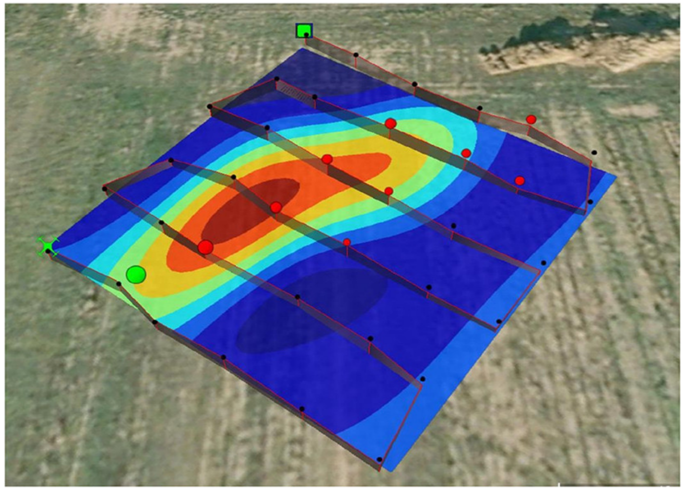
Integration strategies (3/3)



Tasks developed by chemical sensing drones (1/2)

- **Gas concentration mapping**
  - Building spatial representations of gas concentrations
  - The drone follows a predefined navigation path
  - Map reconstruction based on spatial interpolation
    - Gaussian kernels
    - Polynomial

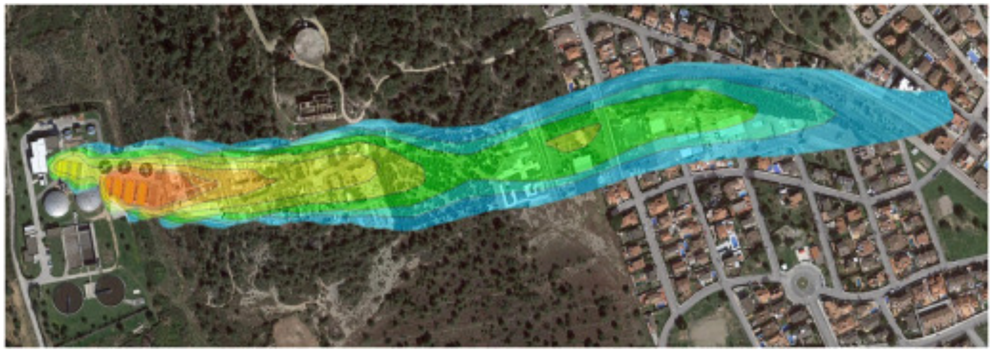
25 m × 25 m concentration map
Equidistant grid points
DJI Matrice 100 with a PID sensor
Flying at constant height



Tasks developed by chemical sensing drones (2/2)

- **Gas source localization**
  - Find the source based on chemical cues on the environment
  - Application
    - Finding gas leaks
    - Finding mal odour sources
  - Many GSL algorithms have been proposed
    - Reactive plume tracking

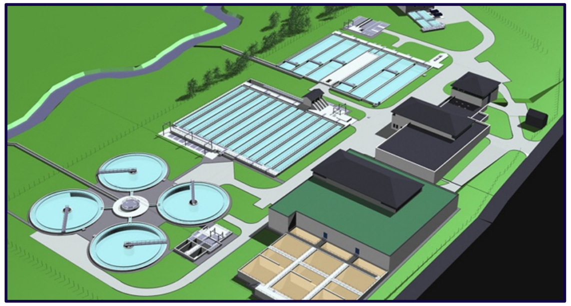
- **Gas source identification**
  - Deciding whether a candidate source is currently emitting a chemical or not



Limitations and future perspectives

- Limited operational capacity
  - Endurance
  - Autonomy
  - Flight range
  - Current regulations
- Limited payload capacity
  - Precludes more accurate chemical instruments to be used
- Downwash
  - It dificults the measurements distorting the concentration distribution
  - Smaller drones with lower total payloads

SNIFF**IR**DRONE project



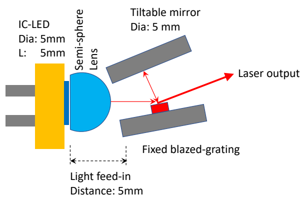
- European ATTRACT project
- Previous phase 1 project
- 6 European Partners

Universitat de Barcelona · DAM Depuración de Aguas del Mediterráneo · IBEC · Lancaster University · GSS Gas Sensing Solutions · SINTEF

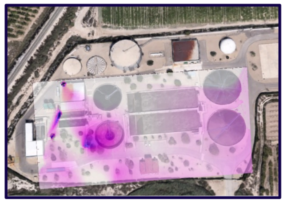
We will build and demonstrate a drone-based system to monitor volatile chemicals and odours emitted by waste water treatment plants.

SNIFFIRDRONE objectives

1 Development of a high performance multi-gas NDIR sensing unit

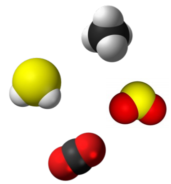


2 Multi-gas NDIR unit demonstration in relevant environment

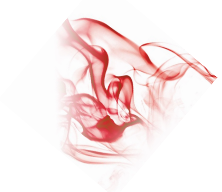


TRL 7

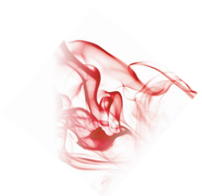
3 3D mapping of waste water treatment plants emissions



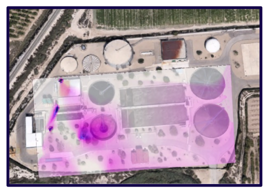
4 Estimation of odour perception from waste water treatment plant emissions



5 3D mapping of odour perceptions in composting plants



6 Drone-based system demonstration in relevant environment

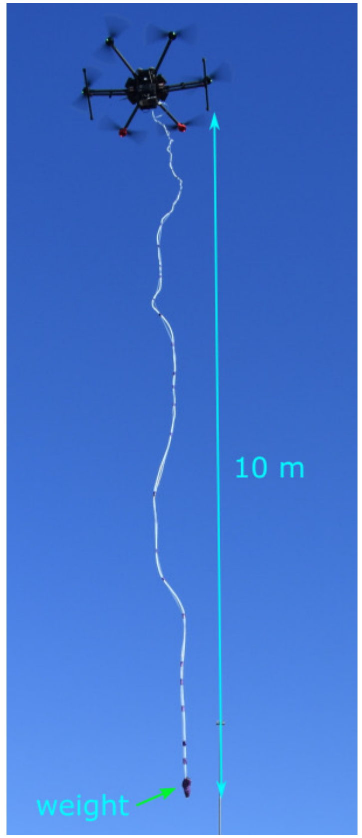


SNIFF**IR**DRONE challenges

- Improving the speed of mesuraments
  - Faster sensors
  - Faster air dynamics
- Reducing the downwash
- Improve robustness of the System
- Bring the prototype to TRL7
- Obtain enough experimental data
  - ... to train and validate the odour prediction models

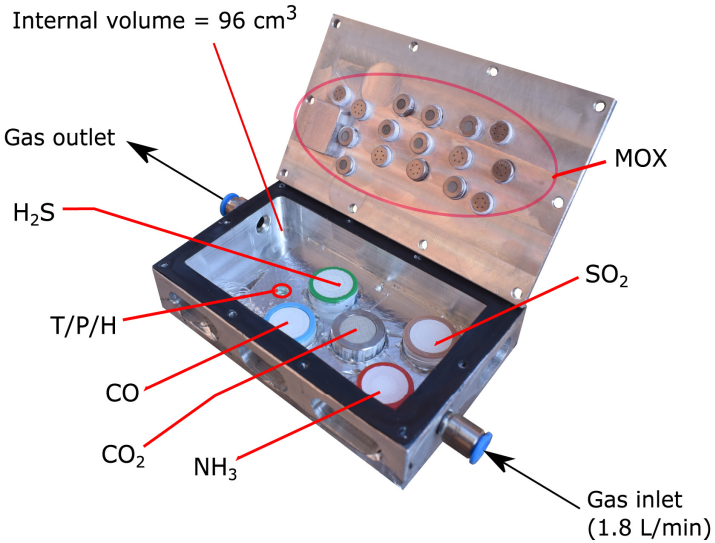
Drone-based sensing system

- DJI Matrice 600 drone



Drone-based sensing system

Custom IOMS

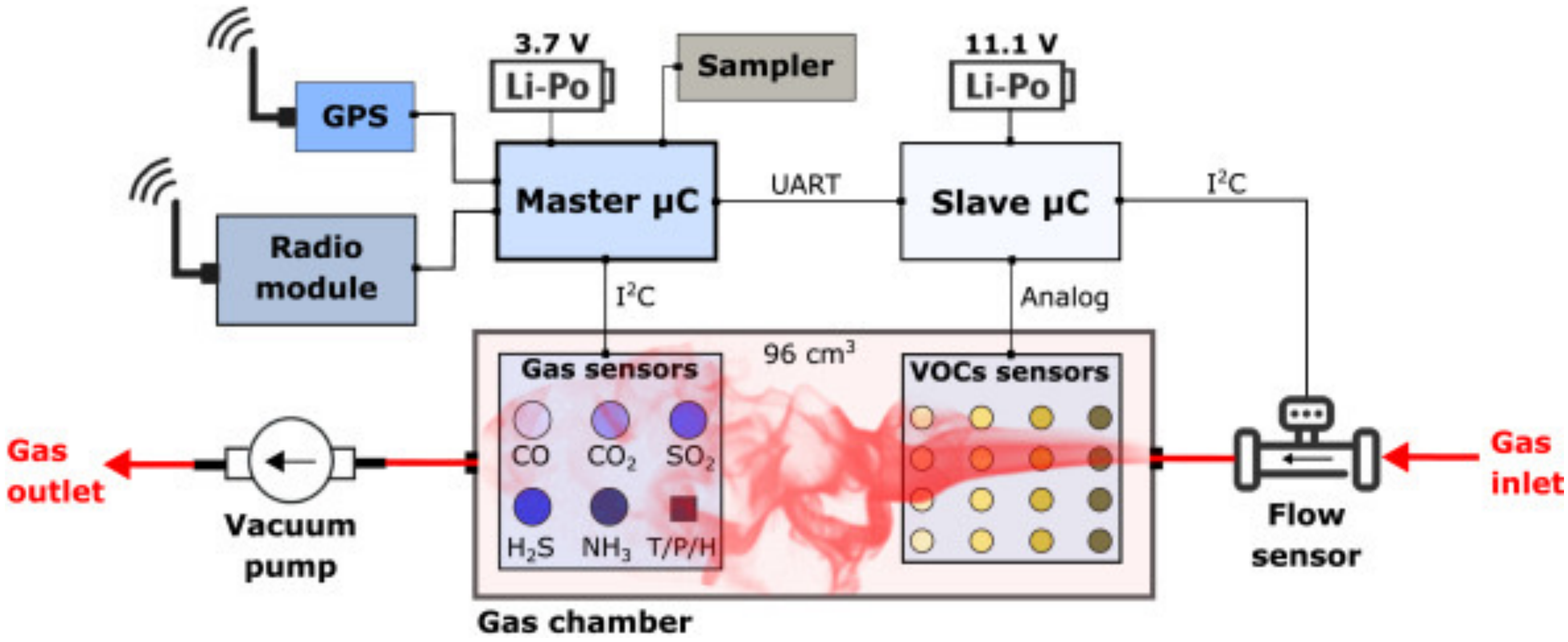


	Technology	Range
Temperature	Integrated	−40 to +85°C
Humidity	Integrated	0 to 100% RH
Pressure	Integrated	30 to 110 kPa
Flow rate	Ultrasonic	−33 to +33 L/min
CO_2	NDIR	0 to 5000 ppm
CO	Electrochemical	0 to 100 ppm
H_2S	Electrochemical	0 to 20 ppm
NH_3	Electrochemical	0 to 100 ppm
SO_2	Electrochemical	0 to 20 ppm

Model	Target gases
TGS 2600	H_2, CO, Ethanol
TGS 2600	H_2, CO, Ethanol
TGS 2600	H_2, CO, Ethanol
TGS 2600	H_2, CO, Ethanol
TGS 2602	H_2S, NH_3, Toluene
TGS 2602	H_2S, NH_3, Toluene
TGS 2602	H_2S, NH_3, Toluene
TGS 2602	H_2S, NH_3, Toluene
TGS 2611	CH_4, Hydrocarbons
TGS 2611	CH_4, Hydrocarbons
TGS 2611	CH_4, Hydrocarbons
TGS 2611	CH_4, Hydrocarbons
TGS 2620	Alcohols, ketones
TGS 2620	Alcohols, ketones
TGS 2620	Alcohols, ketones
TGS 2620	Alcohols, ketones

[Burgués, et al. ***iScience*** 24(12), 2021]

Custom IOMS block diagram

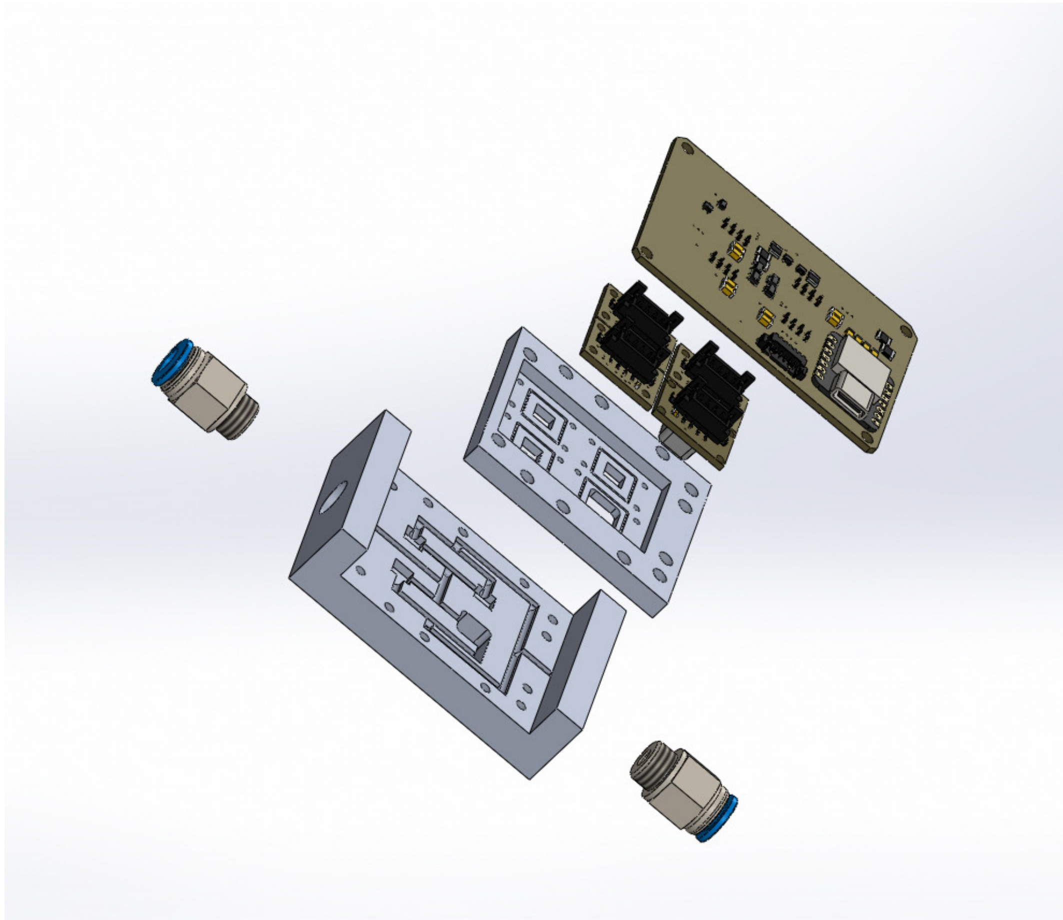


[Burgués, et al. ***iScience*** 24(12), 2021]

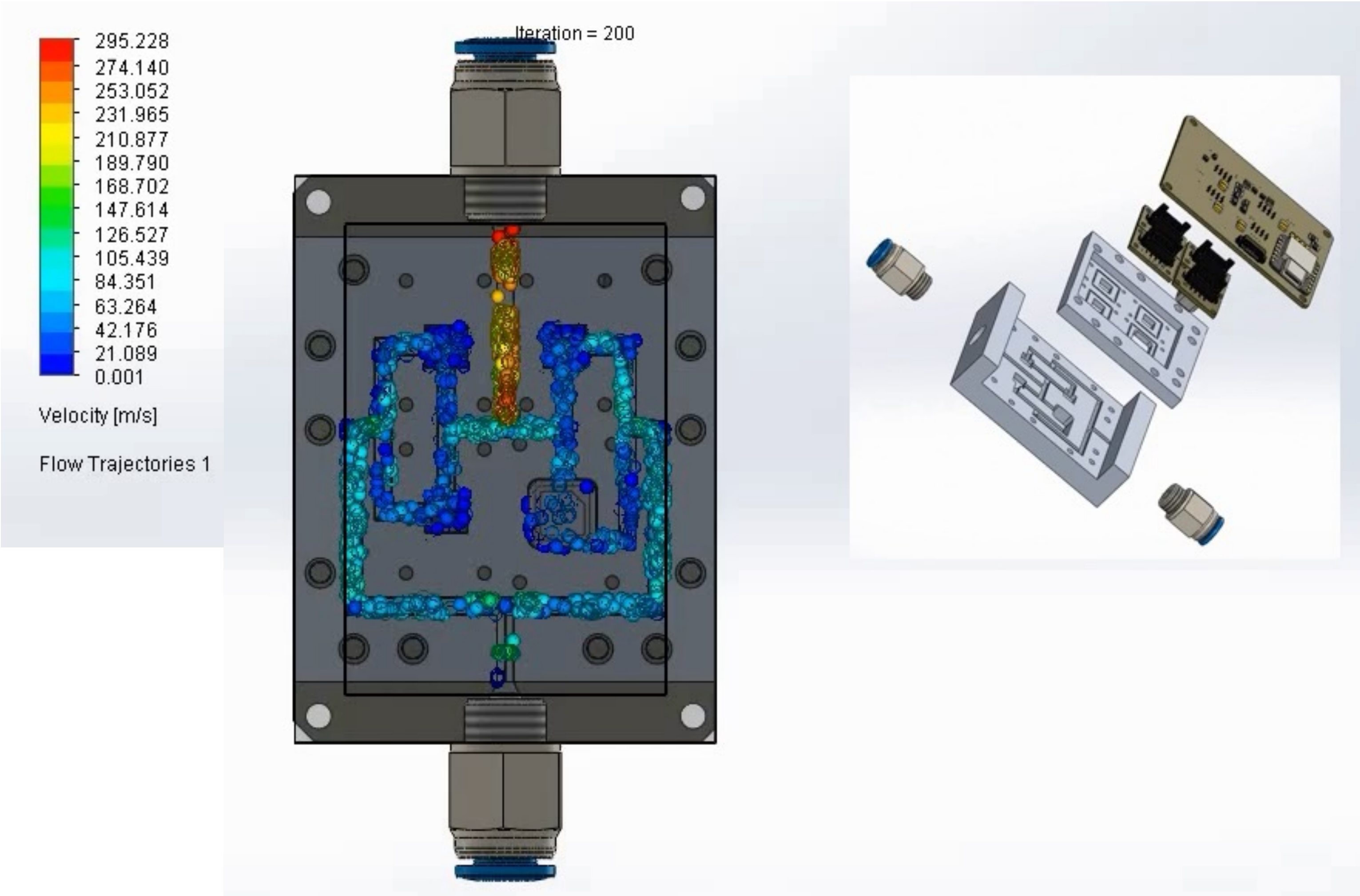
Next generation sensor chamber

- Reduced size
  - 50x67x22 mm
- 4 digital MOX sensors
- 3 cavities
  - 5 x 5 x 4 mm = 25 mm^3
  - ENS 160 

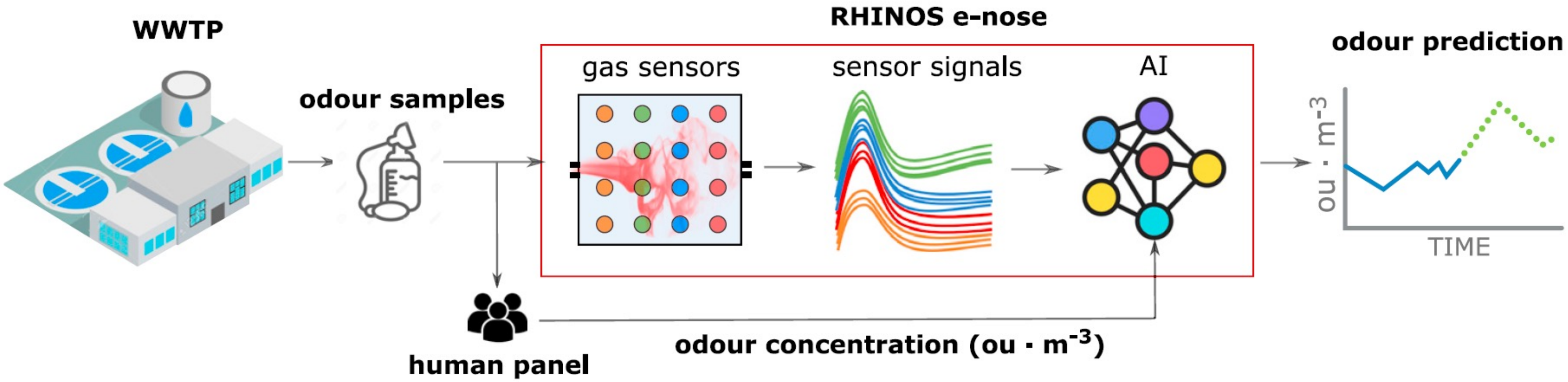
  - SGP 41 
  - BME 688 
- 1 larger cavity
  - 10 x 10 x 0,6 mm = 60 mm^3
  - SCD41 



Air speed simulation within the chamber



Odour prediction model



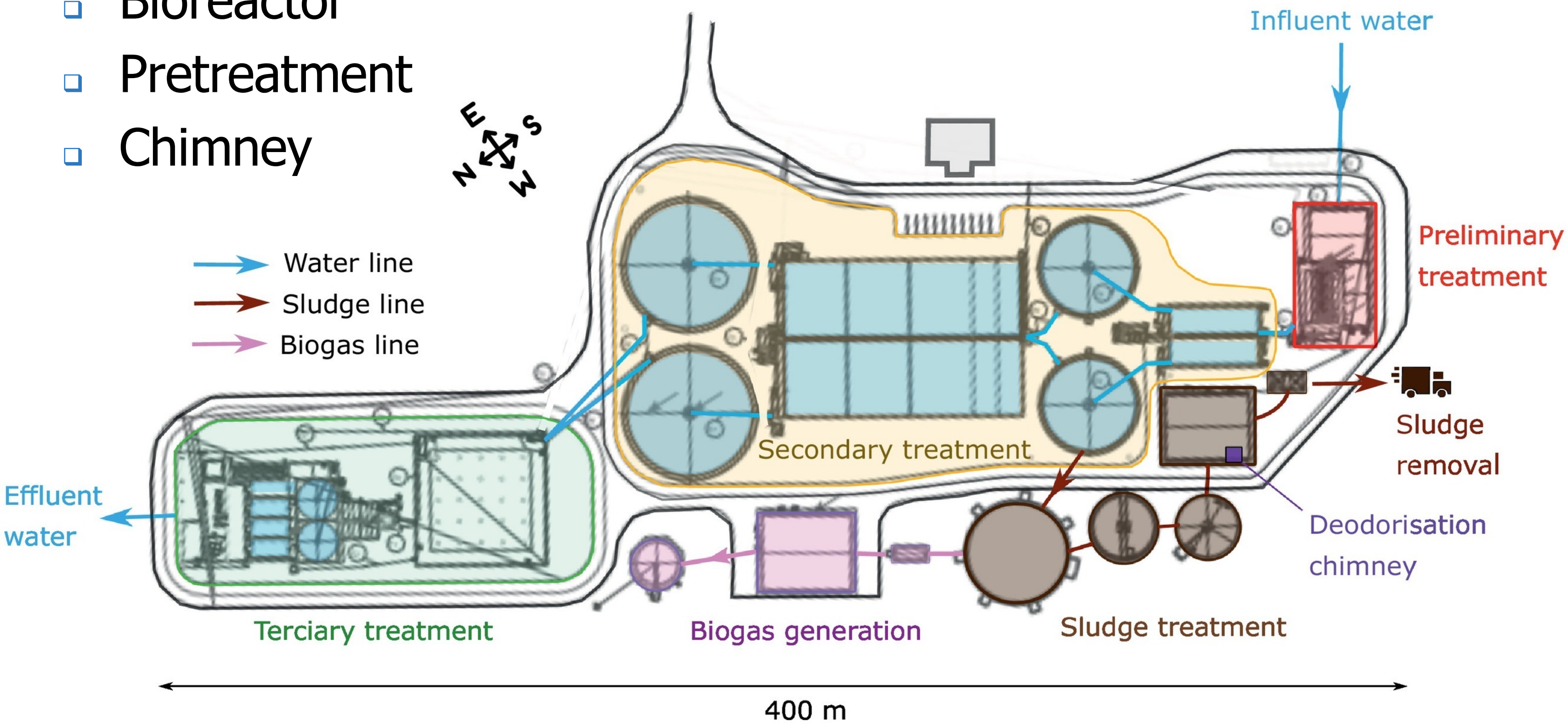
[Burgués, et al. ***Science of The Total Environment*** 846, 2022]

Molina de segura WWTP

- Medium size WWTP
- 35,000 m^2
- Water origing
  - 70% Civil
  - 30% Industrial

Molina de segura WWTP

- Target areas
  - Settler
  - Bioreactor
  - Pretreatment
  - Chimney



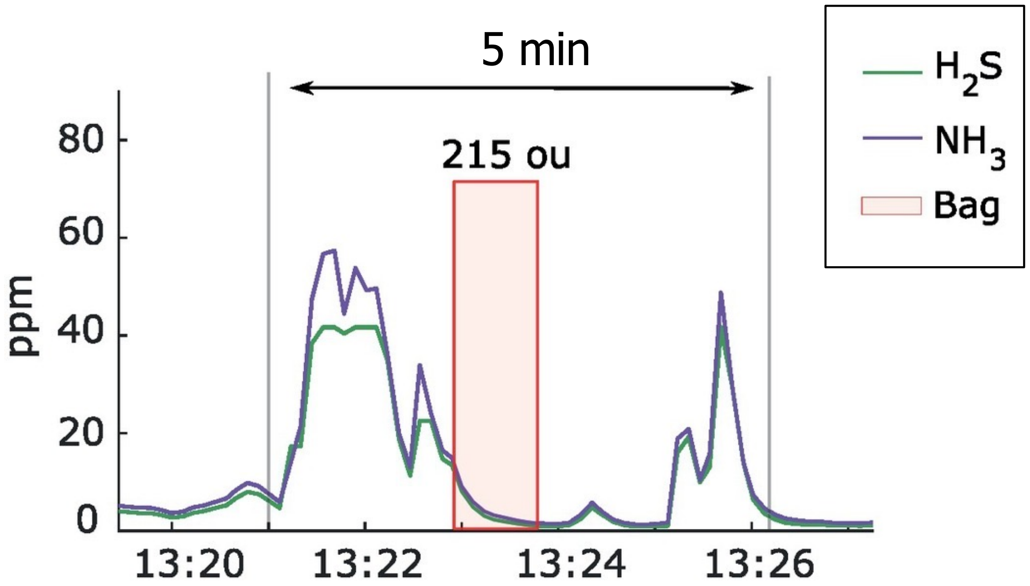
Campaigns and measurements

Day	Date	Settler	Bioreactor	Pretreatment	Chimney	Total (odour)	Blanks	Total
1	24/06/2020	3	3	2	2	10	7	17
2	25/06/2020	2	2	2	2	8	6	14
3	14/07/2020	3	3	3	3	12	11	23
4	15/07/2020	3	3	3	3	12	7	19
Total		11	11	10	10	42	31	73

Measurement procedure

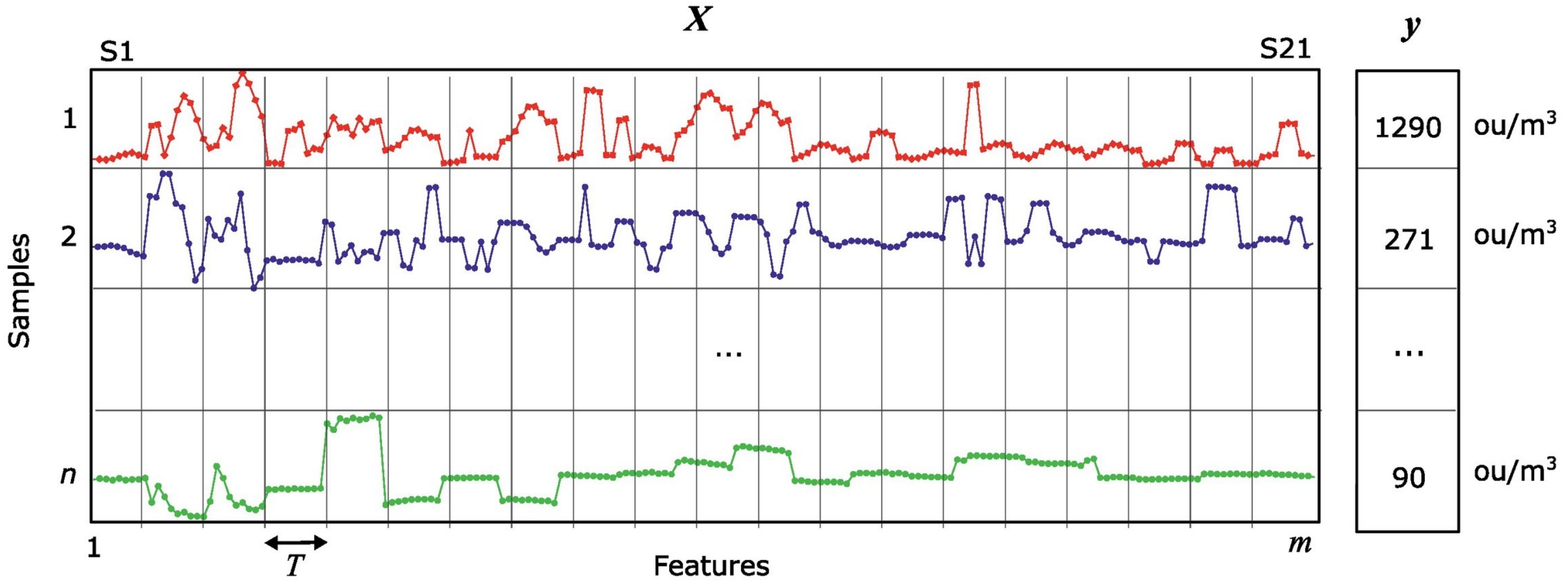
- 5 minutes mesurement per sample/source
  - 45 data points in 5 minutes
- 1 minute filling sampling bag

Chimney – 2 meters

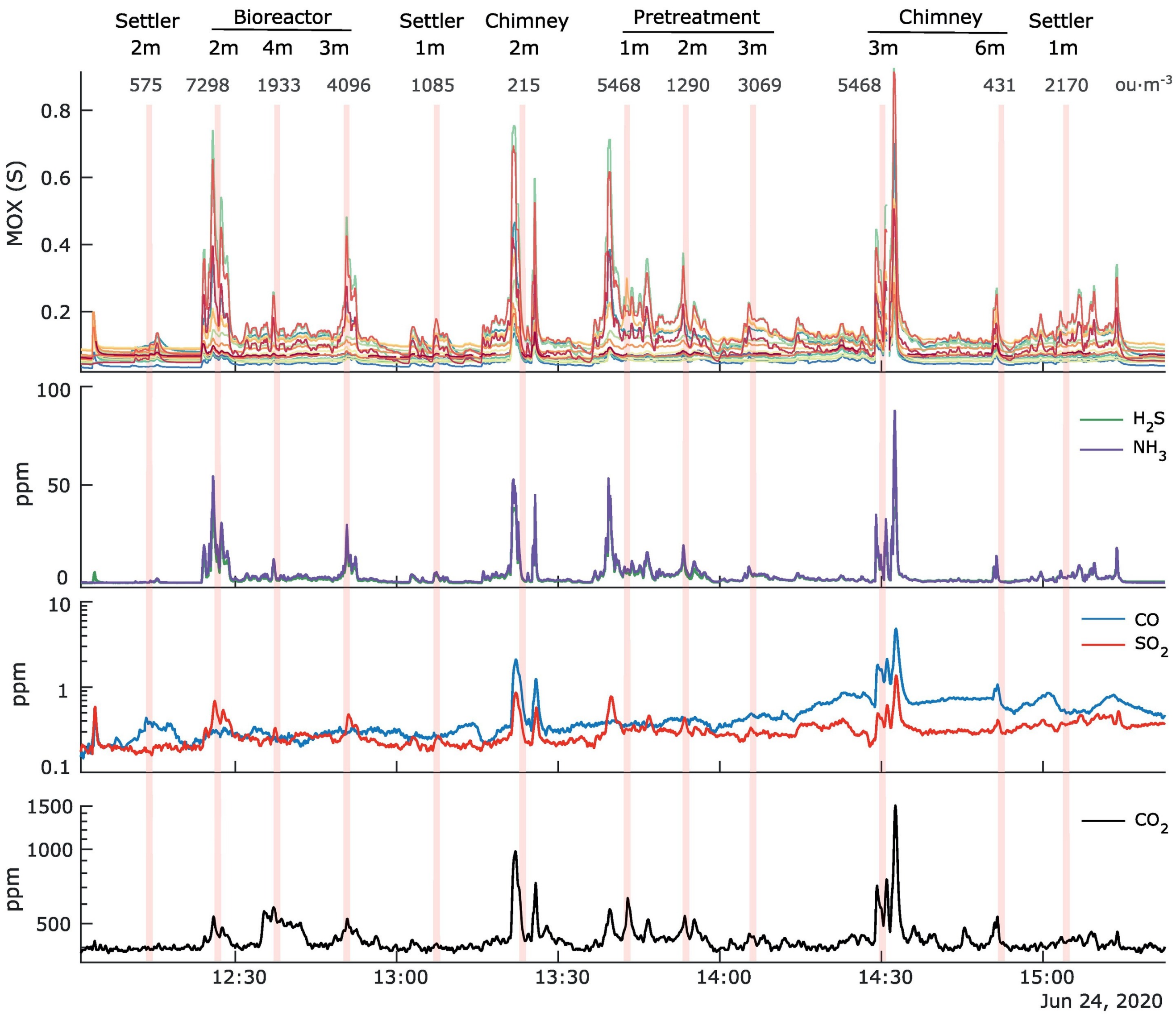


Resulting feature matrix

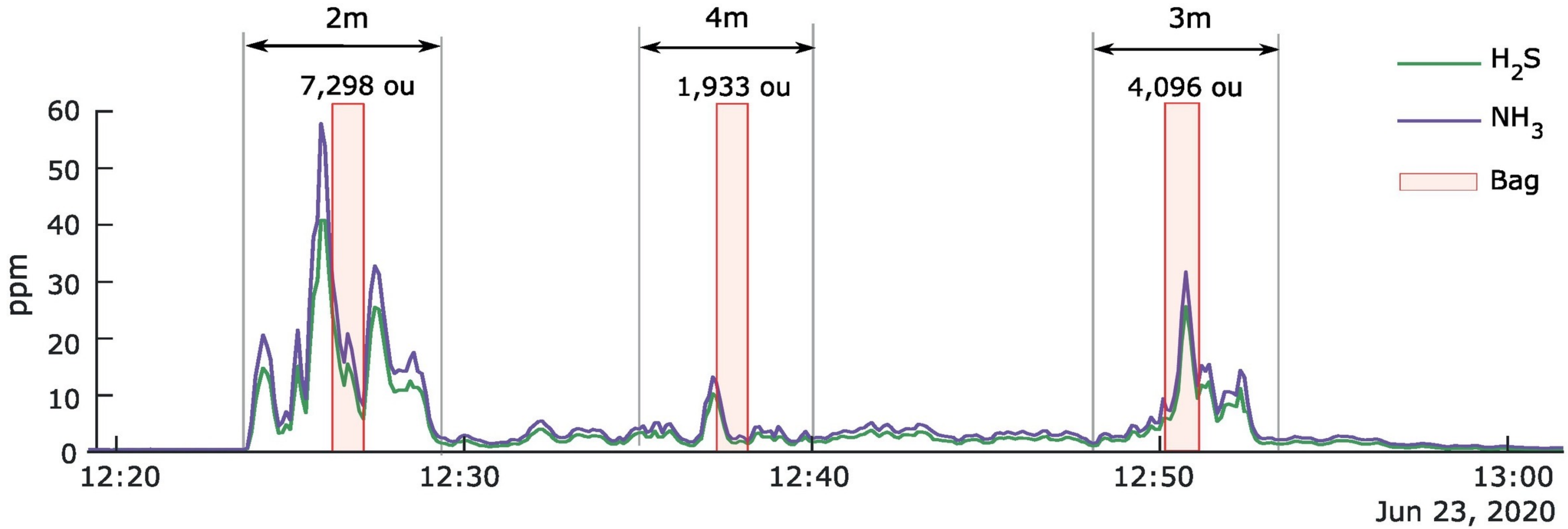
- ***X*** *: 73 (samples) x 945 (features)* ***y*** *: 73 x 1*
  - *n : 73*
  - *m : 975 = 21 (sensors) x 45 (samples/sensor)*



Sensor responses first day

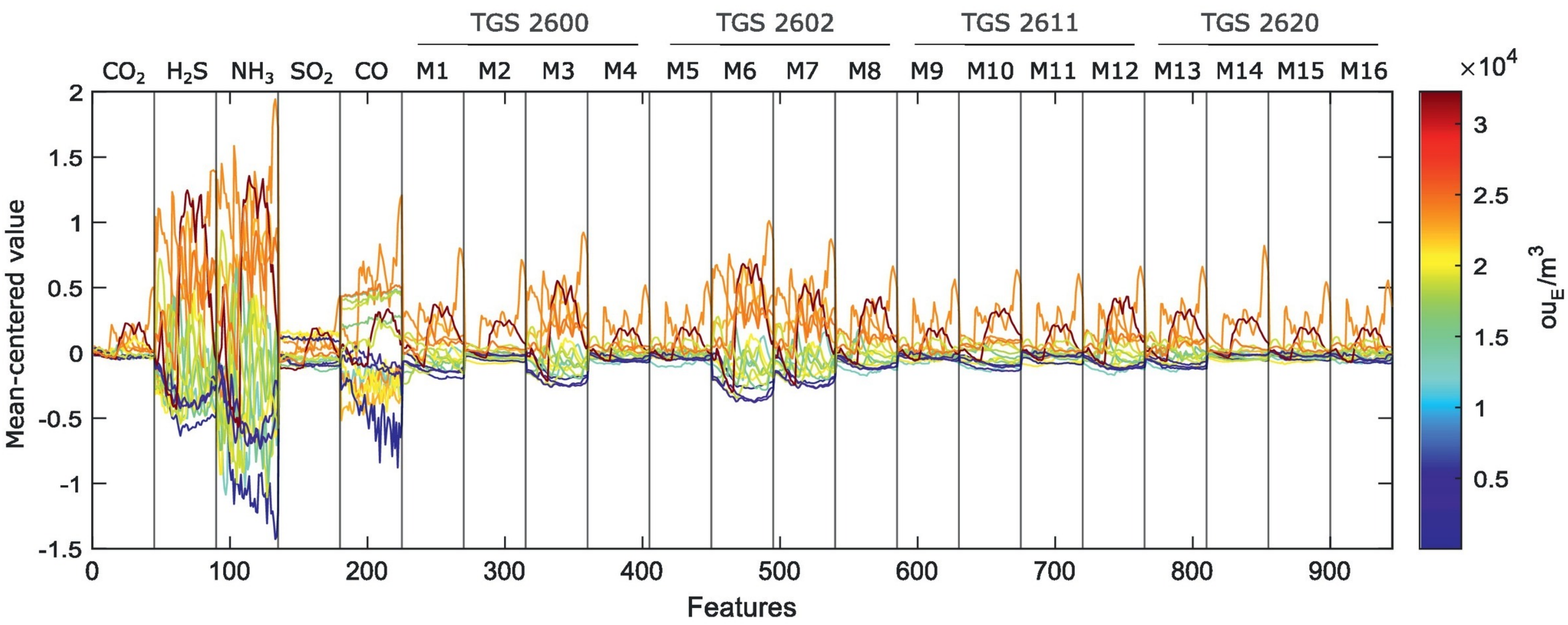


Decay gas and odour concentration with height



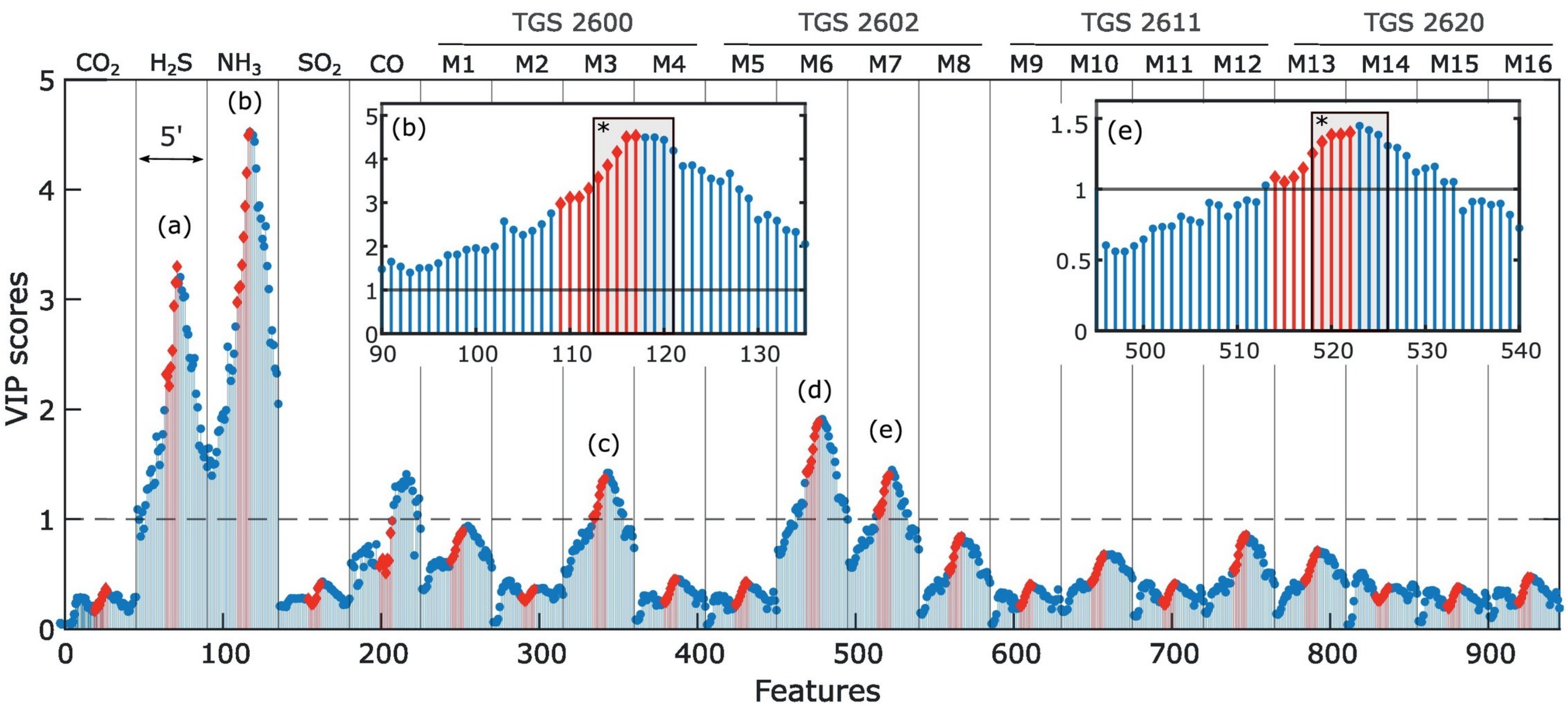
Ferature extraction requiered

- Sensor response of first three days of measurement
- Colored by odour concentration



Feature extraction with VIPs

- Variable importance in projection (VIP) scores as a function of the
- 5 sensors (a), (b), (c), (d), and (e) are selected – **VIP > 1**
- Optimum window delayed 30s from air sampling window



Cross-validation of PLS models

External validation

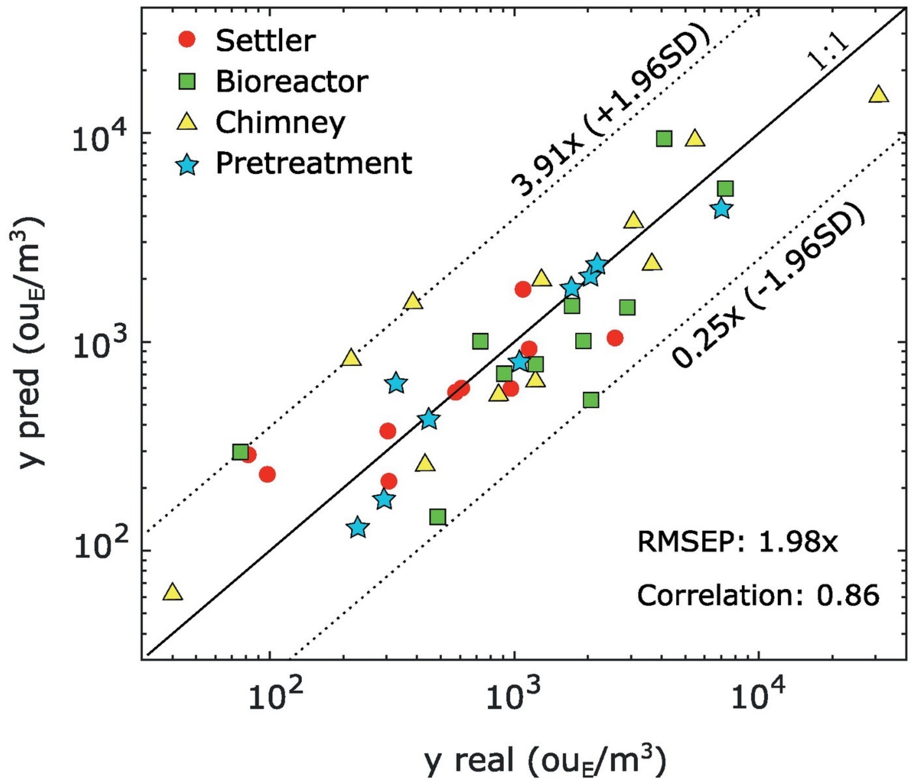
Model	Day 1	Day 2	Day 3	Day 4
Model 1 (β_1, LV_1)	X	C	C	C
Model 2 (β_2, LV_2)	C	X	C	C
Model 3 (β_3, LV_3)	C	C	X	C
Model 4 (β_4, LV_4)	C	C	C	X

Internal validation model 1

	Day 2				Day 3				Day 4			
Iteration	S	B	P	C	S	B	P	C	S	B	P	C
1	V	T	T	T	T	T	T	T	T	T	T	T
2	T	V	T	T	T	T	T	T	T	T	T	T
3	T	T	V	T	T	T	T	T	T	T	T	T
…	…	…	…	…	…	…	…	…	…	…	…	…
N	T	T	T	T	T	T	T	T	T	T	T	V

Prediction results of PLS model

- Four emision sources predicted with similar errors
- Negligible bias between predicted and real values
- Limits of agreement (LoA) [0.25 ×, 3.91 ×]



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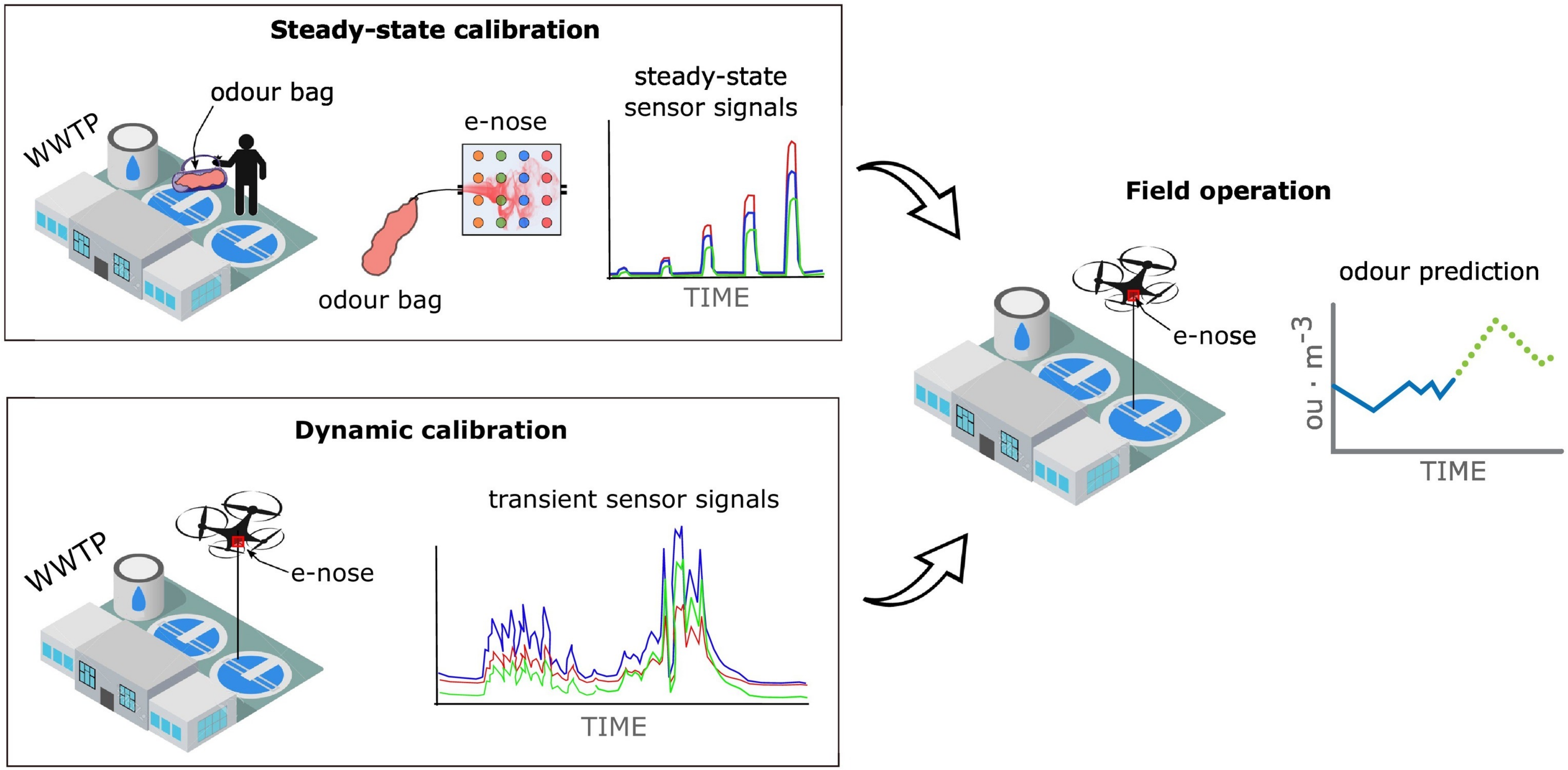
Static vs. Dynamic calibration



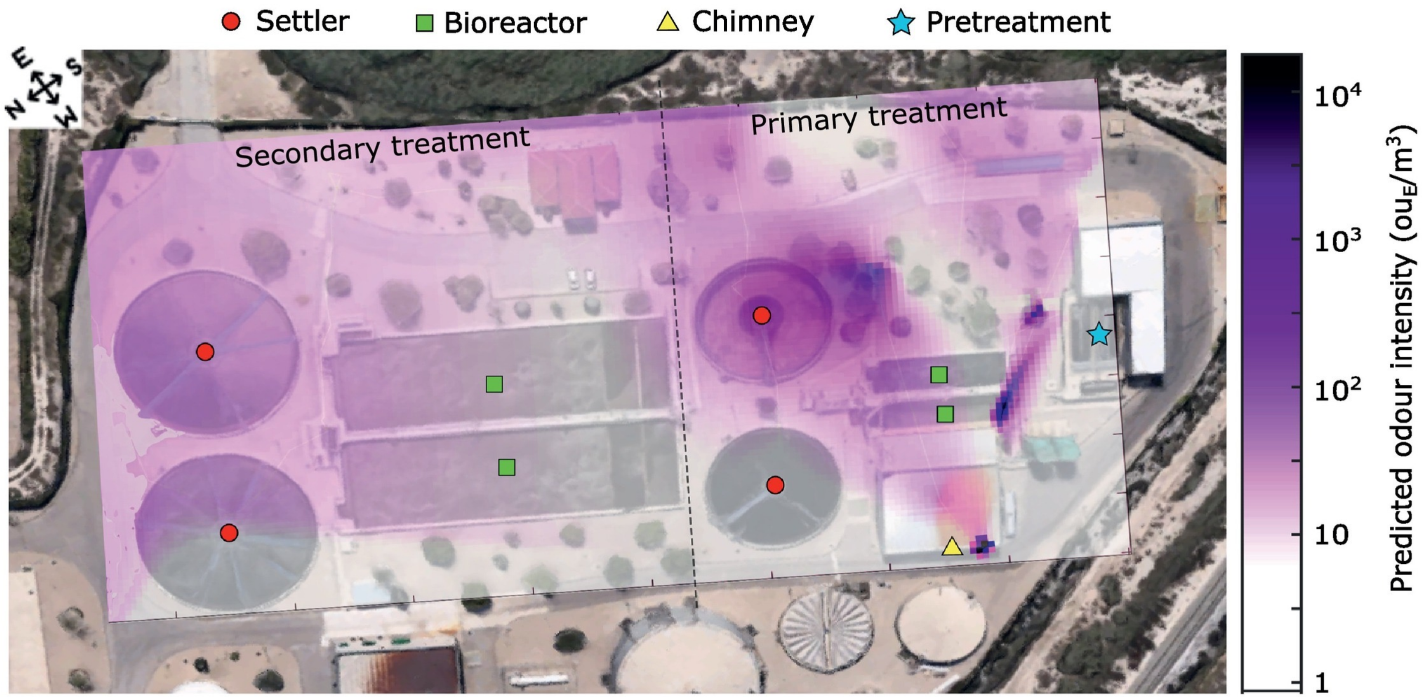
[Burgués, et al. ***Science of The Total Environment*** 846, 2022]

Static vs. Dynamic calibration

	RHINOS (Burgués et al., 2021a)		SNIFFDRONE
Calibration	Lab (odour bags)	Lab (odour bags)	Field (drone)
Validation	Lab (odour bags)	Field (drone)	Field (drone)
RMSEP	1.8×	2.46×	1.98×
Correlation	0.97	0.75	0.86
Bias	0	0.01	0.01
LoA	[0.41×, 1.97×]	[0.17×, 6.10×].	[0.25×, 3.91×].

Odour map

- Specific drone path to cover the WWTP
  - Drone speed was set to ~0.5 m/s
  - 225 measurement points (25 min flight × 9 samples/min)
  - Area 200 × 100 m^2
  - Spatial resolution of 3 m (0.5 m/s × 6 s/sample)



Conclusions

- There are still a number of challenges in front of us to improve environmental monitoring with drones
- The results show that dynamic calibration can substitute static calibration
- Environmental monitoring in industrial plants with drones can be an alternative to olfactometries
- The approach will benefit from a larger dataset with more campaigns